TECHNICAL MEMORANDUM WCT-TM-59-3

TECHNICAL AND PRACTICAL ASPECTS
OF SYSTEMS FOR SIMULATING CLOUDS
FOR FLIGHT TEST EVALUATIONS

Prepared by
James K. Thompson
Directorate of Flight and All-Weather Testing

14 September 1959

Wright Air Development Center
Air Research and Development Command
United States Air Force
Wright-Patterson Air Force Base, Ohio

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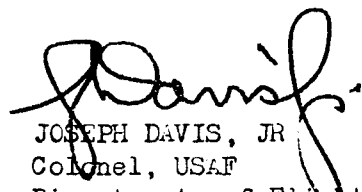Wright-Patterson Air Force Base, Ohio

ABSTRACT

A study of the physics of cloud simulation with water spray systems in tanker aircraft indicates that cloud diffusion is primarily a result of nozzle wake effects in such a manner that cloud diameter is a function of distance behind the tanker. The study shows that initial velocity of water jets determines mean droplet diameters and droplet range; droplet range and terminal velocity are quite small for cloud sized droplets but are significant for large droplets; and that droplet range and terminal velocity can be used to cause tendencies for the location of large droplets in the outer and lower cloud edges, respectively. Tables and graphs are presented for use with problem solutions and with the present nozzle assembly. A manifold type air-water nozzle is also discussed and should provide a major improvement in cloud simulation capability and effectiveness.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

JOSEPH DAVIS, JR
Colonel, USAF
Directorate of Flight and
    All-Weather Testing

INTRODUCTION

A practical method for using tanker aircraft to simulate all types of ice and rain conditions has been the subject of considerable concern within the WADC Directorate of Flight and All-Weather Testing for several years. While several methods were technically feasible, none were generally acceptable because of problems relating to aircraft utilization which required aircraft availability for both the icing and rain tests and for refueling operations. One method of known capability, for example, involved the complication of many electrically heated nozzles on a large spray frame attached to the aircraft and could not possibly be tolerated. A simple test apparatus that could easily be attached to the tanker boom plus minor changes in the plumbing have been used therefore, to enable simulation of all types of rain and large droplet type icing conditions. The very simplicity of the apparatus has complicated tests and considerable judgement on the part of experienced personnel plus flights in natural icing conditions have been required whenever icing test problems required small droplet icing conditions similar to Air Force-Navy design standards. This use of natural icing flights is objectionable because of the general lack of natural icing conditions at any particular time. Also, a demonstrated failure of a particular ice protection system when tests are limited to tanker simulated icing conditions may occur only becuase design standards were exceeded by the tanker. The general evolution of ice protection systems toward cyclic types has further complicated the simulation problem and the lack of complete simulation capability is now a serious handicap. Therefore, this report has been prepared to present technical information pertinent to the use and possible modification of tanker aircraft for more complete icing simulation.

HISTORY

The history of initial efforts to simulate aircraft icing conditions for flight test purposes is rather obscure. The technique was the subject of much informal discussion in the late 40's and was in general use for component testing by 1952. One of the first attempts to cause icing of an entire aircraft occurred sometime in 1948 when a T-6 aircraft was flown behind the Aeronautical Research Laboratories C-54 propeller spray rig. Water contents were too low, however, and no significant aircraft icing was caused. Early in 1953, Lockheed Aircraft Company flew an F-94 behind a Constellation which was dumping water out of a two inch pipe at a rate of about 100 pounds a minute. The water broke into rain drops and froze in much the same manner as freezing rain. By 1954, Boeing Aircraft Company was using a KC-97 to cause heavy rain for tests on the B-47 and the Directorate of Flight and All-Weather Testing at WADC had used the tanker technique to determine the effects of severe freezing rain on C-124 aircraft. The use of tanker aircraft for ice and rain simulation continued to grow during the next few years and is now a standard test technique at WADC. The scope of these tests is illustrated in Table I.

KB-29P #44-83951

PROJECTS SUPPORTED

NUMBER	TITLE	AIRCRAFT	# FLIGHTS	TIME
116A	Effects of rain on ignition harness	B-50	5	5:05
T-07-P-101A	Phase V Icing Tests	B-52	5	11:45
30288	Refueling Probe Icing	B-66	1	1:50
	Cooke Ice Detector Tests	B-66	2	5:55
T-01-P-308L	Phase V Icing Tests	RB-66	3	7:15
912A(12)	Carburetor Rain Tests	B-25	13	19:40
	(Hayes Aircraft Corporation)			
T-07-P	Radome Icing	RC-121	6	16:20
913A	Power Pod Icing	C-131	1	2:05
400L	Phase V Icing Tests	C-130A	2	3:35
402L(2)	Phase V Icing Tests	C-133	8	14:00
402L(2)	Vortex Generator Icing	C-133	2	5:10
402L(1)	Ice Ingestion Tests	C-133	16	39:00
913A	Pitot Tube Icing	KC-135	1	2:30
422L	Phase V Icing Tests	KC-135	4	8:05
910A	Redesigned Intake Scoop	C-124	1	3:25
T-07-P-205B	Radome Icing	F-89	1	1:50
912A(18)	Icing Cloud Evaluation	F-94C & B-50	14	33:50
T-01-P-305A	Phase V Icing Tests	F-100C	3	4:10
305C	Rain Removal Tests	F-100C	10	15:10
	(North American Aviation Inc)			
305C	Pitot Static Heat Icing	F-100D	2	5:05
913A-105A	Phase V Icing Tests	F-101	3	9:25
105A(6)	Continuous Ignition Test	F-101	4	7:00
T-01-P-201A	Radome Icing	F-102	10	24:40
921B(1)	Rain and Ice Test	F3H	9	14:00
913A	NACA Cloud Evaluation	S2F	1	3:00
T-07-R	Ice Evaluation (Army)	L-23A	6	11:50
921C	Ice Evaluation (Army)	L-23D	2	5:30
721C(7)	Windshield Icing (Army)	L-23D	2	4:00
921A	Phase V Icing Tests	L-27	7	16:00
921A	Icing Tests	Cessna 310	2	3:25
424L-1	Phase V Icing Tests	T-37	4	6:00
208A	Nose Cone Icing Tests	Falcon Missile	4	9:00
				319:35

SAC KC-97 #2787

NUMBER	TITLE	AIRCRAFT	# FLIGHTS	TIME
T-07-P-101A	Phase V Icing Tests	B-52	2	4:10
913A	APU Pod Icing Tests	C-131	1	3:00

NUMBER	TITLE	AIRCRAFT	#FLIGHTS	TIME
T-07-P-413L	Icing Tests	C-123	2	4:00*
S416-320	Icing Tests	C-124	3	6:00*
T-01-M	Phase V Icing Tests	SA-16B	7	14:00*
T-07-R	Icing Tests	L-26	4	6:00*
T-07-P-201A	Icing Tests	F-102	16	24:00*
T-07-P	Radome Icing	RC-121	2	4:00*

KB-29

217A	Continuous Ignition	F-101A	6	11:35
402L	T-34 Ice Ingestion Investigation	C-133	2	1:50
921Z	Icing Test	Gruman Gulfstream	4	7:55
217A	Continuous Ignition	F-101B	3	5:50
921Z	Icing	Lock Need Electra	2	4:20
913A-U-3A	De-Icer Boots	U-3A	2	4:45
217A	Glow Plug	F-101A	2	3:50
402L	Wing De-Icer Evaluation	C-133	7	14:40
912A	Water Droplet Size Evaluation	WB-50	5	10:25

KC-135

102A	B-58 Engine Nacelle Icing Tests	B-58	3	7:20
912A	High-Speed Evaluation of Simulated Icing Cloud	T-33	2	4:35
306A	F-105 Adverse Weather Test	F-105	2	4:05
913A	Ice Crystal Flameout Tests	F-102	8	25:25

*Estimate

TOTAL NUMBER OF TANKER SUPPORT FLIGHTS

SAC KC-97	3
WADC KC-97	34
KC-135	15
KB-29P	187
	239 Total for all tankers

TECHNICAL CONSIDERATIONS

Droplet Velocity Effects

Considerable kinetic energy is expended in most water spray systems used to cause artificial clouds. The effect of this energy on droplet velocities is of initial concern. As shown in Figure 1, orifice size is of little concern in that droplet size is mostly a function of the velocity of the jet. At very low velocities, however, the mean droplet size approaches twice the orifice diameter. The relation shown in the figure between jet velocity and mean droplet size is largely empirical, but is known to yield reasonable results. Results of applications to the tanker spray problem have also yielded reasonable results providing that droplet velocities are defined with respect to ambient air velocities. Since maximum available pressure is limited in the tanker aircraft, it is apparent that orifice sizes should be chosen to provide the maximum possible jet velocity consistent with an adequate total flow of water. It is also apparent that initial velocities of the order of 2,000 to 3,000 feet per second are required to achieve droplet sizes near design (20 microns).

"Droplet range" is an expression used in literature to describe the horizontal distance traveled by droplets after ejection into still air. This distance is of interest since it represents the maximum interval during which cloud shape is affected by initial droplet velocity. As shown by Figure 2, droplet ranges are generally small for cloud size droplets with diameters of 10 to 50 microns and are large for rain droplets with diameters in excess of 1,000 microns. In either instance, the ranges are of little consequence if the velocity is directed along the line of flight. Components of velocity in lateral or vertical directions to the line of flight have two significant effects, however, for in addition to changing the cloud diameter, there is a sorting effect which tends to throw the larger droplets toward the cloud edge. This sorting effect can be used to good advantage in some applications, since the larger droplets are placed in the areas of greatest evaporation.

Another velocity that is important to the cloud simulation problem is the terminal velocity of water droplets. These velocities are known and are plotted on Figure 2. Droplets with less than 100 micron diameters fall at less than one foot per second which is small when compared to turbulent velocities of the air. The terminal velocity of rain droplets are of the order of 10 to 20 feet per second and are sufficient to cause these droplets to separate themselves from the clouds of smaller droplets by falling out of the cloud. As an example, assume that a cloud consists entirely of 10, 100, and 300 micron droplets. After a period of 5 seconds, the 100 and 300 micron droplets would have fallen about five feet and 20 feet further than the 10 micron droplets, respectively. These distances are less than cloud diameter, but are sufficient to cause a tendency for the occurrence of large droplets in the bottom of the cloud. The tendency is confused by turbulent velocities in the cloud, due to nozzle wake effects, and the sorting effect may not be of practical consequence unless a wide variety of droplet sizes exist.

Empirical Cloud Growth Relation

As discussed in the previous sections of this report, the initial velocities of water droplets are mostly dissipated in the first few feet of travel from the point of ejection. Cloud growth is controlled almost entirely by diffusion processes which become complicated at great distances when the cloud merges with the trailing vortex system created by the tanker aircraft. Mathematical relations from conventional diffusion theory were applied to the cloud growth problem, but did not yield satisfactory results since the diffusion processes are not exactly similar. That is, the wake caused by dragging the nozzle assembly through the air is the cause of turbulent motions which are greater than those of the free air but are much less than those caused by the wake of a solid body. Therefore, it was convenient to investigate cloud growth as a function of distance from the tanker aircraft. The results of this investigation are shown in Figure 3. Data for a wide variety of altitudes and flight conditions are plotted on the figure. It is apparent that a single empirical relation between cloud diameter and distance behind the tanker exists with sufficient accuracy for most practical purposes. It should be understood, that a different relation may exist for each new nozzle or for radical changes in flight conditions. It should also be understood that the rate of cloud growth can be increased if additional turbulence is created in the wake by apparatus such as vortex generators. The cloud should eventually merge with the aircraft vortex systems.

Photographic Calculations

The distance to an aircraft in a photograph can be determined if only the amount of magnification is known. This technique applies to movie film projected on a screen and to still photographs. The degree of magnification can be determined in one of several methods but the most reliable value uses the ratio of projected frame size to the actual frame size. The frame size can be either the film frame or the projector frame as long as the ratios are consistant with principles of magnification. The equation for this type calculation is as follows:

$$ X = \left[\frac{12 S}{S_p \, Y/Y_p} - 1 \right] \frac{F}{12} $$

X Distance to Aircraft, feet
S Distance between 2 points on aircraft, feet
S_p Apparent dimension of "S" after projection, inches
Y Actual frame size, inches
Y_p Projected frame size, inches
F Focal length of camera lens, inches

The distance to an aircraft in a photograph can also be calculated if a dimension of the object and the dimension and distance to a reference object in the photograph are known. These calculations are made from the following equation:

$$ X = (X_1 + F) \left(\frac{I_1}{I_2} \right) \left(\frac{S_2}{S_1} \right) - \frac{F}{12} $$

X Distance to aircraft, feet
X_1 Distance to reference object, feet
S_1 Dimension of reference object, feet
S_2 Dimension of aircraft, feet
I_1 Dimension of S_1 on photograph, millimeters
I_2 Dimension of S_2 on photograph, millimeters
F Focal Length of the camera lens, inches

Mathematical Representation of a Circular Cloud
(No Evaporation)

The variation of liquid water content with distance behind the tanker and with distance from the cloud axis must be known for effective planning and conduct of test programs. Several conventional expressions for diffusion problems were considered for application to this particular problem, but the general lack of data complicates their use and verification in most instances. The most reasonable results to date have been provided by the following expression.

$$\rho = \rho_0 \, e^{-\left(\frac{\lambda^2}{R^2 - \lambda^2}\right)}$$

ρ Density of cloud water content gr/m^3
ρ_0 Density of cloud water content at the cloud axis
λ Cloud radius to point in cloud
R Total cloud radius

The total liquid water content per unit meter cross section of the cloud is the integral of the expression for density at a point and is as follows:

$$\Sigma \rho \doteq .0295 \, \rho_0 \, D^2$$

Where the cloud diameter "D" is measured in feet.

Since water is ejected into the cloud at a fixed rate per mile of flight, another expression for the total liquid water content per unit meter cross section is as follows:

$$\Sigma \rho = 123 \, \frac{GPM}{KTS}$$

Where

    GPM, Gallons of water flow per minute
    KTS, Knots true air speed

Combining the two equations,

$$\rho_0 = \frac{4170}{D^2} \, \frac{GPM}{KTS}$$

$$\rho = \frac{4170}{D^2} \, \frac{GPM}{KTS} \, e^{-\left(\frac{\lambda^2}{R^2 - \lambda^2}\right)}$$

6

$$\overline{P} = \frac{1395}{D^2} \frac{\beta P m}{KTS}$$

Evaporation of Water Droplets

Evaporation effects both the size of water droplets and liquid water contents of the simulated cloud. While evaporation rates are large during the period of droplet deceleration, this evaporation occurs in a relatively small volume of air and is of no significance to the spray problem. The initial volume of air is saturated almost immediately, however, and further evaporation is dependent upon cloud growth by diffusion processes which continually mix humid air and water droplets from the simulated cloud with surrounding dry air. The time history of droplet evaporation during this process is of extreme significance to the tanker spray problem and accounts for complete loss of the simulated cloud at a point a few thousand feet behind the tanker. Since the relative velocity of the water droplets is nearly zero with respect to ambient air at droplet terminal velocity, the following equations are of value as a basis for estimating these evaporation effects:

$$d/d_o = \sqrt{1 - \frac{70.5 \, (T_d - T_w) \, t}{d_o^2}}$$

$$t_{d \to o} = \frac{d_o^2}{70.5 \, (T_d - T_w)}$$

$$w/w_o = (d/d_o)^3 = \left(1 - \frac{t}{t_{d \to o}}\right)^{3/2}$$

Where

d Droplet diameter, microns

d_o Initial droplet diameter, microns

T_d Dry bulb temperature of air surrounding the droplets, °C

T_w Wet bulb temperature of air surrounding the droplets, °C

t Time elapsed, seconds

w Water content, gr/m^3

w_o Initial water content, gr/m^3

The effects of droplet evaporation have been calculated from pertinent equations and are summarized in Table II. The table shows that 100 micron droplets are evaporated to 20 micron droplets after all but 0.8% of the liquid water content has been lost at a point equal to 96 percent of the time to cause complete evaporation. When half of the evaporation period has elapsed, the droplets are reduced to only 71 microns with a loss of all but 36% of the initial liquid water content. It is apparent that evaporation does cause droplet size reductions,

but that the desired reduction is accomplished with excessive loss of water content. Optimum initial droplet sizes are not apparent from this table, but cannot differ greatly from the desired diameter.

Evaporation periods for various size droplets are shown in Table III for given differences between wet and dry bulb temperatures. The table shows that small droplets may last a fraction of a second while the larger droplets require 1 to 2 minutes to evaporate. Since small droplet sizes are desired and difficult to achieve initially, it is apparent that the existence of large droplets in the initial cloud can defeat attempts to achieve given droplet diameters through evaporation. However, droplet evaporation could be used to good advantage if the larger droplets can be projected into the drier edges of the cloud. This can be accomplished by spraying water in a direction normal to the flight path. While this technique would tend to cause a more uniform type cloud, a more practical technique could be to spray the droplets down from the nozzle so that terminal velocity and droplet range would segregate the droplets. Most of the cloud would then be farther from the tanker wake and flights in the upper cloud areas would encounter the smallest possible droplet sizes from a specific nozzle.

TABLE II

Effect of Evaporation on Droplet Size and Water Content

t/t_0	n/n_0	w/w_0	w_0*
.00	1.00	1.00	0.5 gr/m^3
.10	.95	.85	.59
.20	.89	.71	.70
.30	.84	.59	.86
.40	.78	.47	1.06
.50	.71	.36	1.39
.60	.63	.25	2.00
.70	.55	.16	3.12
.80	.45	.09	5.55
.90	.31	.03	16.66
.96	.20	.008	62.5

t/t_0 Fraction of total time required to evaporate droplets
n/n_0 Fraction of initial droplet diameter
w/w_0 Fraction of initial liquid water content
w_0*   Initial liquid water content required for $w = 0.5$ gr/m^3 at $t/t_0 = 0$

TABLE III

Approximate Evaporation Periods for Given Size Water Droplets Falling at Terminal Velocity

Evaporation Periods - Seconds

Droplet Size - Microns

(T_d-T_w)*	5	10	20	40	60	80	100
1	.37	1.47	5.90	23.5	54.0	94.0	147.0
2	.18	.73	2.95	11.7	27.0	47.0	73.5
4	.09	.37	1.47	5.9	13.5	23.6	36.8
6	.06	.25	.98	3.9	9.0	15.7	24.5
8	.05	.18	.74	2.9	6.7	11.7	18.4
10	.04	.15	.59	2.3	5.4	9.4	14.7
20	.02	.07	.30	1.2	2.7	4.7	7.3
30	.01	.05	.20	0.8	1.8	3.1	4.9

T_d-T_w Dry bulb temp minus wet bulb temp

Density of Water Vapor

The temperature and density of water vapor in ambient and cloud air controls the maximum possible amount and rate of droplet evaporation. Since icing intensities are described in terms of grams of water per cubic meter, it is convenient to express the density of water vapor in the same units by the following equation:

$$\rho_e = \left(.621 \, \frac{e}{P-.379e}\right) \rho_a$$

$$\rho_e = 216\left(\frac{e}{273+T}\right)$$

ρ_e Water vapor density, gr/m^3
e Vapor pressure, millibar
P Atmospheric pressure, millibar
T Air temperature, °C
ρ_a Air density, gr/m^3

The density of water vapor for various air temperatures and relative humidities is shown in Table IV.

TABLE IV

Density of Pure Water Vapor In
Air At Saturation Vapor Pressures Over Water and Over Ice

T_c	Water	Ice	T_c	Water	Ice
20 °C	17.3 gr/m^3	_____ gr/m^3	-25 °C	.7047 gr/m^3	.5521
15	12.83	_____	-30	.4534	.3385
10	9.399	_____	-35	.2856	.2032
5	6.797	_____	-40	.1757	.1192
0	4.847	4.847	-45	.1055	.06836
- 5	3.407	3.246	-50	.06171	.03821
-10	2.358	2.139	-55	_____	.02078
-15	1.605	1.387	-60	_____	.01098
-20	1.074	.8835	___	_____	_____

10

Heat Effects

The magnitude of heating and cooling effects in the water spray is of concern during icing tests since it effects evaporation rates and test condition temperatures. Several methods of estimating these effects were considered and difficulty was encountered in efforts to achieve practical simplification. It was convenient to use water content per cubic meter of air as developed by the following equations:

$$q_c = c_p \rho_a (T_c - T_a)$$ Heat added to the cloud
$$q_w = c_w \rho_w (T_w - T_c)$$ Sensible heating from water
$$q_e = \rho_{we} (595 - \tfrac{1}{2} T_c)$$ Latent heat effects from evaporation
$$q_a = c_p \rho_{a_m} (T_m - T_c)$$ Heat from air nozzles

$$q_c = q_w - q_e + q_a$$ Heat Balance

$$T_c = \frac{T_a + 4.16 \frac{\rho_w}{\rho_a} T_w - 2480 \frac{\rho_{we}}{\rho_a} + \frac{\rho_{a_m}}{\rho_a} T_m}{1 + 4.16 \frac{\rho_w}{\rho_a} - 2.08 \underbrace{\frac{\rho_{we}}{\rho_a}}_{< .01} + \frac{\rho_{a_m}}{\rho_a}}$$

The variables on the right side of the cloud temperature equation are independent variables except for the amount of water evaporated ρ_{we} which is dependent upon a combination of cloud temperature and humidity. The equation can be solved by iteration processes or treated as an independent variable by assuming a ρ_{we} and calculating the dew point temperature of the condition less than T_c which would allow the assumed evaporation. That is:

$$\rho_{we} = 216 \left(\frac{e_c}{273 + T_c} - \frac{e_a}{273 + T_a} \right)$$

An example of the heat effects is obtained by assuming that the tests are conducted in -15°C dry air at 500 millibar pressure altitudes. Water temperatures before ejection are 20°C with water being ejected at a rate, GPM ÷ KTS = 1/2. As shown in Table V, cloud air temperatures are initially warmed, but evaporation quickly cools the air to temperatures a few degrees colder than ambient air temperatures. The table also shows liquid water content at the cloud center, ρ_{lwc} and indicates complete evaporation at a distance somewhat less than 1000 feet behind the tanker where cloud diameters are 30 to 35 feet. This conflicts with actual observations and indicates that evaporation processes are not fast enough to saturate the cloud. Therefore, temperature differences from ambient are less than indicated by the equation and in Table V.

11

TABLE V

Example of Evaporation and Cooling Effects

Distance	Diameter	ℓ_w	T_c	ℓ_{we}	ℓ_{lwc}
250 ft	10 ft	12.5 gr/m³	-17.8 °C	1.55 gr/m³	10.95
375	15	5.6	-18.8	1.43	4.17
500	20	3.1	-19.4	1.37	1.73
625	25	2.0	-19.6	1.36	.64
750	30	1.4	-19.8	1.34	.06
875	35	1.0	-19.8	____	.00
1000	40	.78	-19.8	____	____

Evaporation At the Cloud Edges

One approach to the evaporation problem is to consider the maximum magnitude and effect of evaporation at the cloud edges. This occurs if we assume that droplets initially at the cloud edge move radially at a constant rate without change in the relative position of the droplets within the cloud. Droplets at the cloud edge are therefore in the driest air and the maximum time to evaporate is allowed. In this instance the droplet radial velocity for the existing nozzle assembly is expressed as follows:

$$\frac{dR}{dt} = \frac{dR}{dx}\frac{dx}{dt} \doteq .015\frac{dx}{dt}$$

The time to move to radius "R" is $\quad t = \dfrac{R - 1.8}{.015\ dx/dt}$

which is the time allowed for evaporation.

Comparisons of time allowed for evaporation with the time required to evaporate are shown in Table VI. The table shows that even at the edge of the cloud, evaporation processes are not sufficient to be significant for large sized droplets. Only 8% of the time required for 75 micron droplets to evaporate would have elapsed in the first 1500 feet. However, the 10 micron droplets at the cloud edge would have evaporated in the first 500 feet. These calculations agree well with actual measurements of cloud water content which show a general lack of sufficient evaporation to effect liquid water content. Since the small droplets evaporate quickly, cloud mixing, due to turbulent motion, will eliminate small droplets by exposure to dry ambient air and would cause an apparent increase in mean droplet diameter with distance behind the water spray nozzle.

TABLE VI

Droplet Evaporation At the Cloud Edge At 180 Knots

True Air Speed and Typical Test Conditions

Distance	Diameter	t	de*	Time to Evaporate		
				10n	30n	75n
250 ft	10 ft	.7 sec	7.0 n	49%	5%	1%
500	20	1.82	11.3	127	14	2
750	30	2.93	14.4		23	4
1000	40	4.03	16.9		31	5
1250	50	5.13	19.0		40	6
1500	60	6.27	21.0		49	8

de*, Maximum diameter of droplet that would have evaporated
t, Time allowed for evaporation
n, Microns

NOZZLE APPARATUS

Nozzles used in connection with icing tests have been simple. Initial tests used a steering wheel apparatus with small holes pointing aft along the line of flight. This nozzle was modified so that the holes directed the water spray laterally. Later tests used a fire fighting fog nozzle and finally a spray ring with 66 fuel injection nozzles. None of these spray systems have achieved droplet diameters equivalent to those for design or to typical icing conditions. While considerable study has been conducted by various organizations to determine methods for creating small droplets from spray nozzles, none has been concerned with problems similar to the subject test problem. Nozzles that develop suitable droplet sizes have had such low flow rates that much heat was required to protect each nozzle from freezing and an unreasonable number of nozzles has been required.

Air-Water Manifolding Nozzle

Spray nozzles using air to atomize jets of water cause adequately small water droplets, but the nozzles are complex, large, and too many are required. An experimental manifold type air-water nozzle was invented, so that the many nozzles can be arranged in a compact, light-weight spray assembly. A one inch diameter pipe was welded inside a three inch diameter pipe with a space of about 1/8 inch between the pipes on one side, through which 240 holes with diameters equal to .041 inches were drilled through both pipes. The holes in the outside pipe were then enlarged to 1/8 inch. Water was forced through the small holes and projected through the center of the 1/8 inch holes. Air was forced through the outside pipe around the water jets to atomize the small streams of water droplets. The nozzle was constructed so that it could be mounted to eject the water either downwards or aft. Estimates for this nozzle were obtained from ground tests using an MA-1A air compressor unit and the KB-29 tanker and are as follows:

Water Flow Rates	95 Gallons/minute
Pump Pressure	90 Psi
Water Velocity at Nozzle	103 ft/sec

13

Air Flow Rate	2 lbs/sec
Air Pressure	50 Psi
Air Velocity	1500 ft/sec
Mean Droplet Diameters	30 to 1000 microns

The advantage of this type nozzle in addition to simplicity is the ability to vary both droplet sizes and water flow rates during flight. Tests that would otherwise take at least two flights can be combined into one flight. For example, descent through icing conditions into rainclouds is of practical concern and could be simulated with realistic variations of all flight parameters. There is also the fact that the temperature of the compressed air will be above the freezing point and will prohibit nozzle freeze-up. (Expansion during ejection through the nozzle cools the air to temperatures not too different from ambient.)

Droplet size estimates for the air-water nozzle are of interest. Without air, mean droplet diameters would be about 170 and 70 microns at 200 and 500 knots respectively. A decrease of water pressure would decrease water jet velocities and would increase these droplet sizes to the order of rain, 600 to 1000 microns. Inverting the nozzle so that the water is ejected aft and using low air flow rates to alleviate wind shear would cause even further increases and might increase droplet sizes to 1000 to 2000 microns.

Droplet sizes can be gradually reduced by increasing air flow rates. The MA-1A air compressor was operating at near full capacity during ground tests of the nozzle. Considerable increase in both mass flow rates and air velocity was required to establish minimum possible droplet diameters with the subject nozzles. However, even these flow rates and velocities offer large reductions in mean droplet sizes as compared to our present nozzle. Mean droplet sizes should be of the order of 30 to 40 microns at most flight speeds. In an aircraft such as the C-130 or the KC-135 where the equivalent of two MA-1A air compressor units are or could be available, both mass flow rates and velocities could be increased by slight increases in the air orifice diameters and mean droplet diameters could then be reduced to near design standards. (This type nozzle would cause clouds to form at a lower level and aircraft wake effects would be less objectionable.)

Future Air-Water Manifolding Nozzles

An improved air-water nozzle is both desirable and practical, but should not be constructed until after flight tests have been conducted with the present apparatus. Air and water flow rates and air orifice diameters should be optimized for the particular capacity of test aircraft. A homogeneous cloud is desirable in which droplet sizes are controllable. A circular type manifolding nozzle is warrented if droplet sizes are made adequately small. Further decreases in the diameter of the water orifice would seem to be warrented to increase water jet velocities. Both theory and experiment show, however, that water velocities will not be increased by decreasing orifice diameters further and that only an increase in water pressure will increase jet velocities. These increases are considerable and are without sufficient reward. Experiments by nozzle manufacturers have obtained mean droplet diameters no smaller than 40 microns with pressures up to 600 Psi. Therefore, the only valid reason for

reducing water orifice diameters is to increase the ratio of air to water flow rates. This same affect may also be provided by an increase in air orifice diameters provided air flow capacity and pressures are available.

Helicopter Testing

Simulation of ice and rain conditions for helicopter flight tests is a problem that has been given considerable thought by personnel in a number of organizations. Free flight is important to any realistic test program and neither Mt Washington nor the Climatics Hangar at Eglin Field provides this capability. The Canadian water spray rig at Uplands uses steam rather than air to atomize individual water jets and has proven adequate for helicopter icing tests. This type apparatus is not suitable for test programs conducted by this directorate because such installations are not portable. We prefer tests conducted at WPAFB when possible, but would also like to extend test seasons by using bases further North.

The manifold type air-water nozzle is easily applicable to this particular problem. Air compressor units are available on most Air Bases and in the C-130 aircraft to provide adequate amounts of compressed air at the nozzles. Several methods are possible for providing water under pressure at altitudes above 50 feet. The MB-3 Aircraft De-Icer (Cherry Picker) for example, provides 30 gallons of water a minute at 100 Psi, and can also heat the water as required. A simple pipe assembly and winch connected to a fire truck or a tanker aircraft would also provide adequate water at test altitudes.

A more novel and possibly superior apparatus is practical through use of ground noise suppressor units which use water for cooling and for noise suppression. Kittell -Lacy Incorporated" Class II and Class III noise suppressors should be investigated in this connection. The units provide 3500 gallons of water at flow rates up to 650 gallons per minute. The water is ejected into the suppressor adapter section. High velocity, high temperature air carries the water to altitudes of 100 to 300 feet depending upon ambient conditions and engine thrust where air currents then carry the cloud plume down wind. Testing would be accomplished in this area of the plume. Large water droplets tend to fall out of this type cloud or to break into smaller droplets. Also, cooling of the air to ambient temperatures during ascent will cause condensation of evaporated water into cloud sized droplets. The one big problem with this type test apparatus is the high velocity turbulent jet of air and care is required that the aircraft is not inadvertently operated in the ascending currents.

15

CONCLUSIONS

Ejection velocity of water jets exercises primary control over mean droplet diameters in the resulting clouds of water droplets.

Droplet range and terminal velocity are not significant for cloud size droplets but can be used to place large droplets in the general edge or bottom of clouds.

Cloud growth is primarily by diffusion processes resulting from nozzle wake, is a function of distance behind the tanker, and is not defined by airspeed.

Evaporation processes are significant for design size cloud droplets, but are not significant for 50 to 100 micron droplets.

Small droplets evaporate prior to significant reduction in the diameter of large droplets.

The air-water manifold type nozzle is practical and can provide control of mean droplet diameters through a very wide range of mean droplet diameters.

Tests to determine capabilities of apparatus for helicopter tests are warrented.

FIGURE 1 MEAN DROPLET DIAMETER AS A FUNCTION
OF INITIAL JET VELOCITY AND WATER TEMPERATURE

$$\bar{D} = 1640 \; N^{1/5} \; (100/V)$$

N KINEMATIC VISCOSITY, CM^2 /SEC
D DROPLET DIAMETER, MICRONS
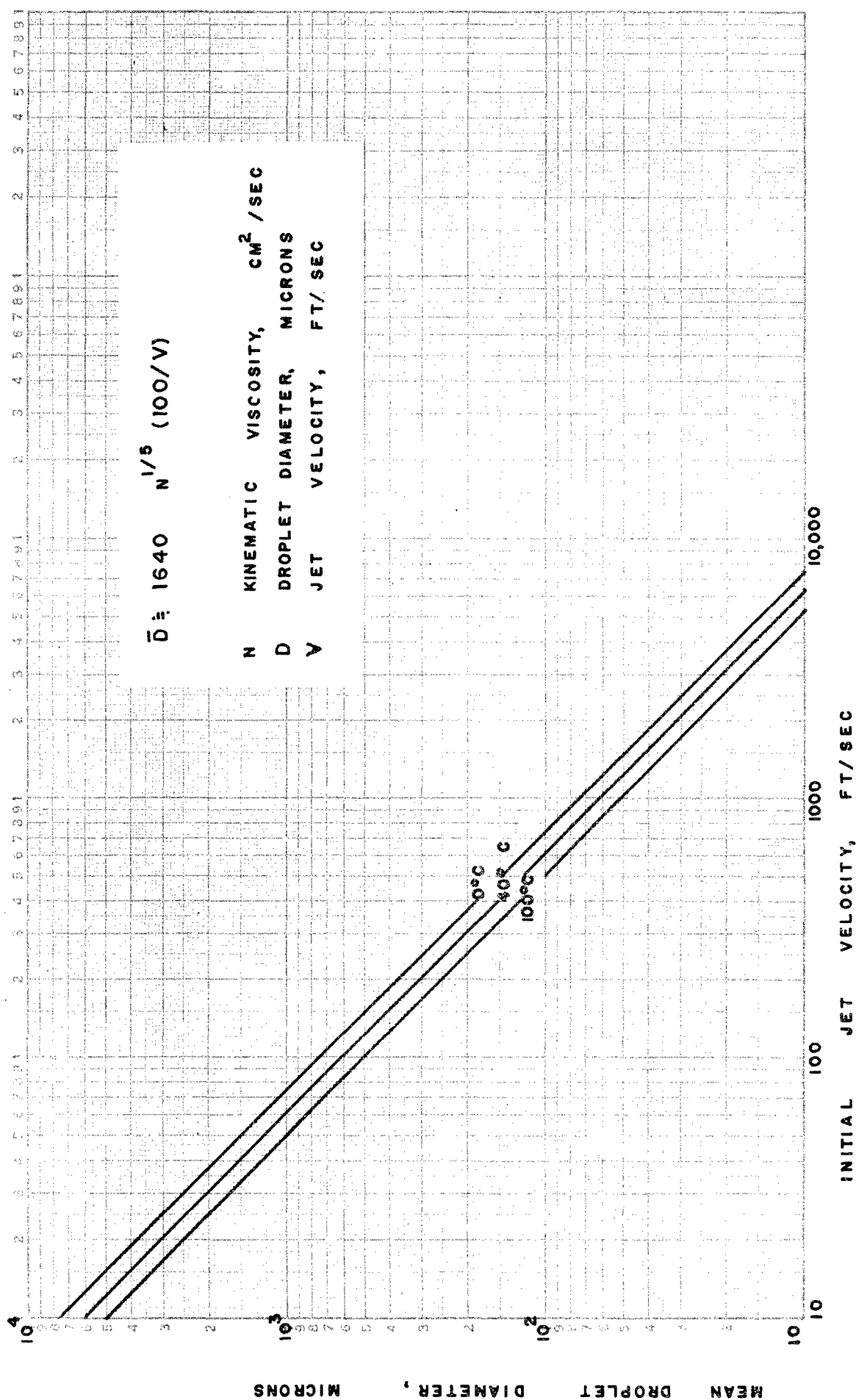V JET VELOCITY, FT/SEC

FIGURE 2 DISTANCE TRAVELED BY WATER DROPLETS EJECTED INTO STILL AIR AT GIVEN VELOCITIES AND TERMINAL FALLING VELOCITIES FOR VARIOUS SIZE DROPLETS
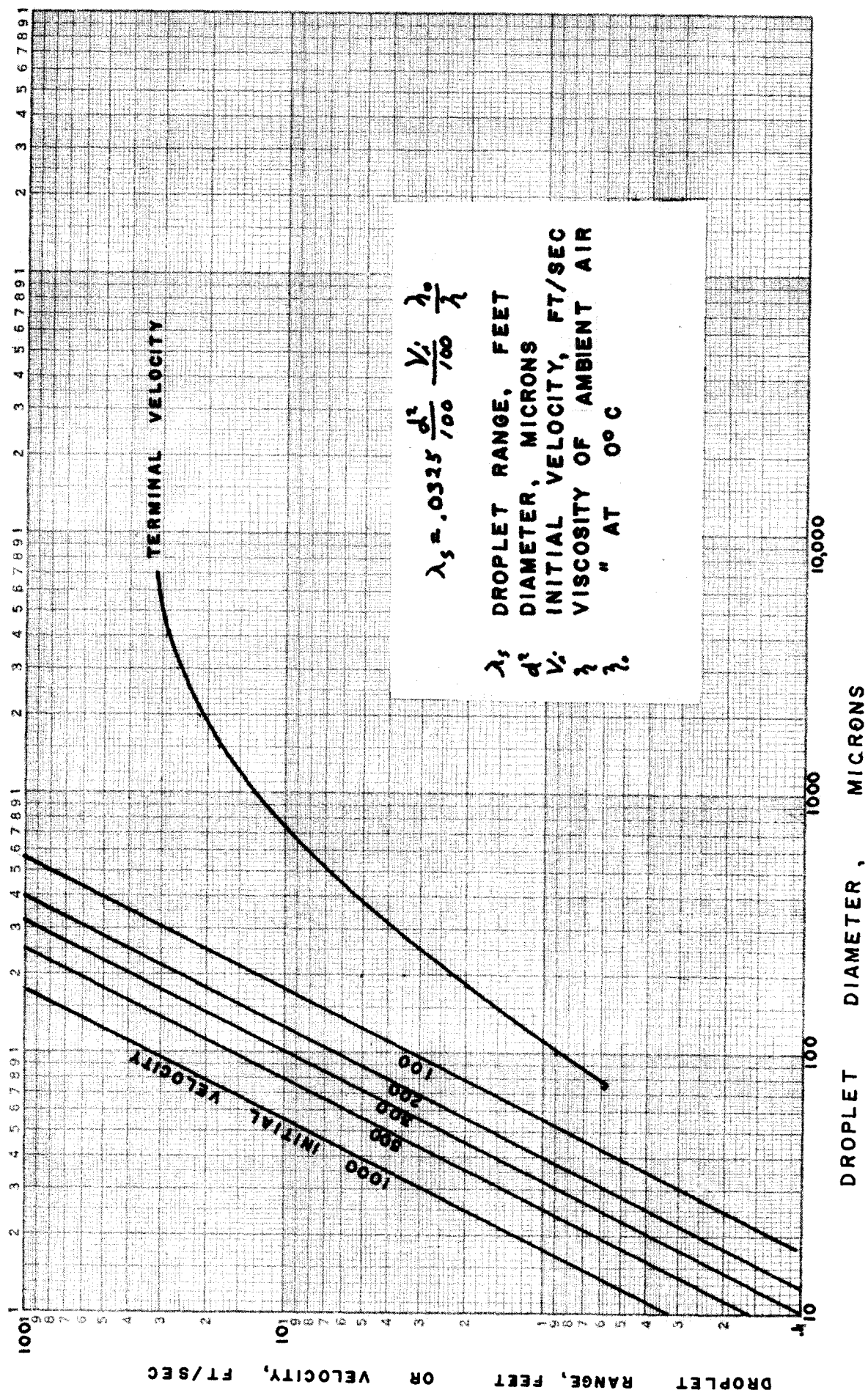
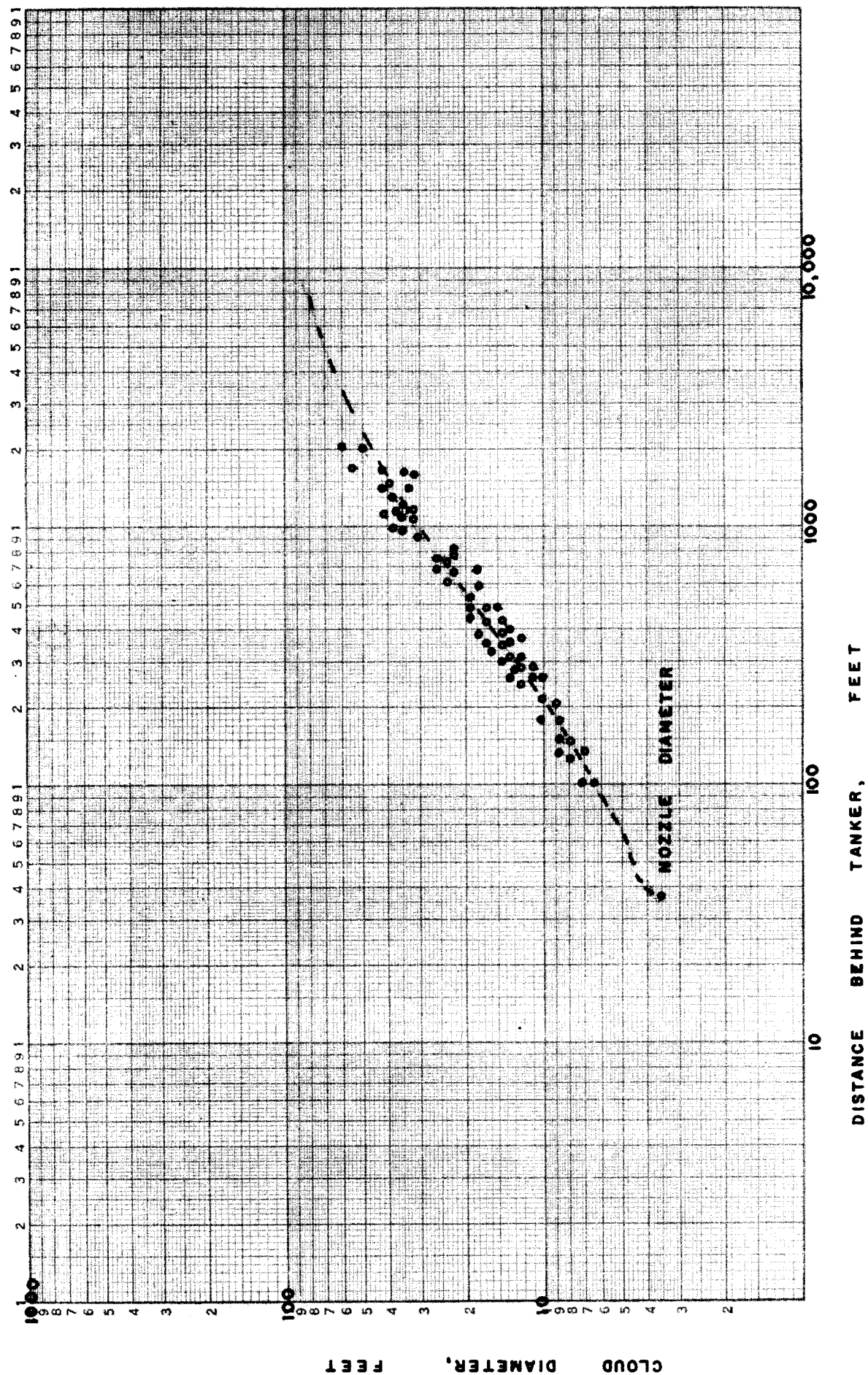FIGURE 3   OBSERVED RELATION BETWEEN CLOUD DIAMETER AND RANGE

FIGURE 4   DIAGRAM FOR ESTIMATING WATER CONTENT IN CLOUDS CAUSED BY STEERING WHEEL NOZZLE ASSEMBLY