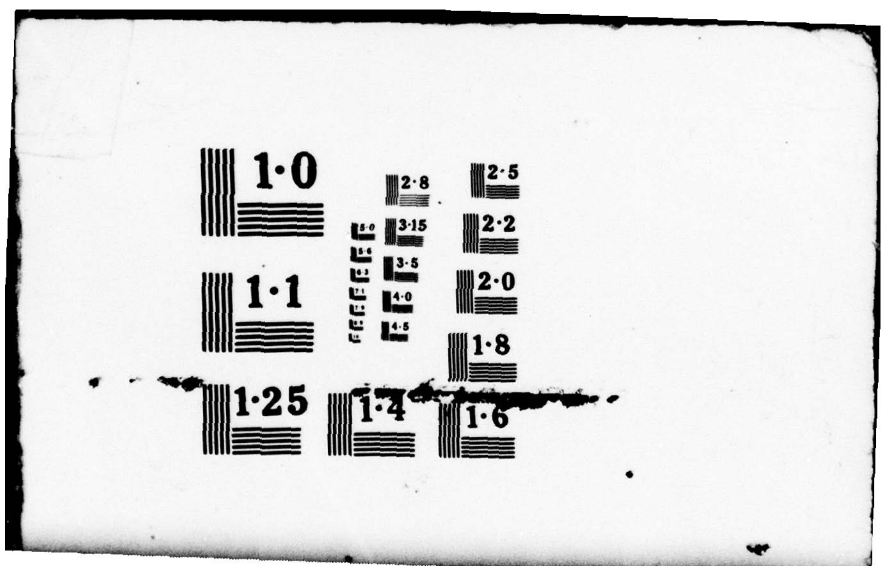
AD-A067 742 DAVID W TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CE--ETC F/G 1/3
THE CHARACTERISTICS OF THE SPRAY GENERATED BY THE EFFLUX OF VAR--ETC(U)
JUN 78 B S PAPADALES

UNCLASSIFIED DTNSRDC/ASED-78/07 NL

1 OF 1
ADA
067742

END
DATE
FILMED
6-79
DDC


1·0
2·8
2·5
5·0
3·15
2·2
3·5
1·1
2·0
4·0
4·5
1·8
1·25
1·4
1·6

AD A067742

(12)

LEVEL II

THE CHARACTERISTICS OF THE SPRAY GENERATED BY THE EFFLUX OF VARIOUS AIRCRAFT PROPULSORS IMPINGING NORMALLY ON WATER

by

Basil S. Papadales, Jr.

Approved for Public Release: Distribution Unlimited

AVIATION AND SURFACE EFFECTS DEPARTMENT

DTNSRDC/ASED-78/07

June 1978

DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

BETHESDA MARYLAND 20084

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

14

1. REPORT NUMBER DTNSRDC/ASED-78/07	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER 9
4. TITLE (and Subtitle) 6 THE CHARACTERISTICS OF THE SPRAY GENERATED BY THE EFFLUX OF VARIOUS AIRCRAFT PROPULSORS IMPINGING NORMALLY ON WATER,		5. TYPE OF REPORT & PERIOD COVERED ASED Report. for May - September 1978 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) 10 Basil S./Papadales, Jr.		8. CONTRACT OR GRANT NUMBER(s) 16 F41421
9. PERFORMING ORGANIZATION NAME AND ADDRESS David W. Taylor Naval Ship R&D Center Aviation and Surface Effects Department Bethesda, Maryland 20084		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Program Element 62241N 17 Task Area WF 41 421 091 Work Unit 1-1600-078
11. CONTROLLING OFFICE NAME AND ADDRESS Commander Naval Air Systems Command (AIR-320D) Washington, D.C. 20361		12. REPORT DATE 11 June 1978 13. NUMBER OF PAGES 50
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) 12 52p.		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release: Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Spray
VTOL Propulsors
VTOL Aircraft
Spray Ingestion

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A review of previous model tests of the efflux from aircraft propulsors impinging normally on water is presented. The height of the resulting spray cloud was found to be a function of the maximum dynamic pressure at the surface after impingement, and the propulsor diameter. A generalized relationship using these variables, based on Froude scaling and which favorably compares with the existing model data is presented. Other characteristics over

(Continued on reverse side)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

387 695

LB

(Block 20 continued)

of the water surface and spray cloud are discussed, although there are insufficient data to formulate any general conclusions. Results from tests with Froude-scaled vertical takeoff and landing aircraft models are presented. These results are tentative due to the lack of substantiating full-scale data. The height of a spray cloud and the water depression diameter obtained during Froude-scaled tests of a conceptual ducted fan propulsor are also presented. The spray cloud height compares favorably with the generalized relationship derived from previous tests. The water depression diameter was found to differ substantially from that determined from previous model tests. Spray cloud heights and water depression diameters are predicted for two conceptual full-scale aircraft propulsors.

TABLE OF CONTENTS

79 04 23 097

LIST OF FIGURES

LIST OF TABLES

NOTATION

A	Propulsor area, ft^2 (m^2)
D	Propulsor diameter, ft (m)
d	Droplet diameter, in. (mm or μ)
F	Froude number
f	Functional relationship
g	Gravitational acceleration, ft/s^2 (m/s^2)
H	Height, ft (m)
p	Pressure, lb/ft^2 (N/m^2)
q	Dynamic pressure, lb/ft^2 (N/m^2)
R	Reynolds number
T	Thrust, lb (N)
V	Velocity, ft/s (m/s)
W	Weber number
x,y,z	Orthonormal dimensions, ft (m)
θ	Spray trajectory angle, deg
λ	Scale ratio
μ	Viscosity, $lb\text{-}s/ft^2$ ($N\text{-}s/m^2$)
ξ	Nondimensional spray characteristic
π	Mathematical constant, 3.1416
ρ	Density, sl/ft^3 (kg/m^3)
σ	Surface tension, lb/ft (N/m)

Subscripts

a	Air
d	Depression

hub	Fan hub
j	Jet exit conditions
max	Maximum condition
s	Spray cloud
t	Total (stagnation) conditions
w	Water
x,y,z	Orthonormal directions
o	Minimum spray generation conditions

Superscript

*	Correction for spray generation conditions

ABSTRACT

A review of previous model tests of the efflux from aircraft propulsors impinging normally on water is presented. The height of the resulting spray cloud was found to be a function of the maximum dynamic pressure at the surface after impingement, and the propulsor diameter. A generalized relationship using these variables, based on Froude scaling and which favorably compares with the existing model data is presented. Other characteristics of the water surface and spray cloud are discussed, although there are insufficient data to formulate any general conclusions. Results from tests with Froude-scaled vertical takeoff and landing aircraft models are presented. These results are tentative due to the lack of substantiating full-scale data. The height of a spray cloud and the water depression diameter obtained during Froude-scaled tests of a conceptual ducted fan propulsor are also presented. The spray cloud height compares favorably with the generalized relationship derived from previous tests. The water depression diameter was found to differ substantially from that determined from previous model tests. Spray cloud heights and water depression diameters are predicted for two conceptual full-scale aircraft propulsors.

ADMINISTRATIVE INFORMATION

This investigation was conducted by the Aviation and Surface Effects Department (Code 1612) of the David W. Taylor Naval Ship Research and Development Center (DTNSRDC) and funded by the Naval Air Systems Command (AIR-320D) under Project Element 62241N, Task Area WF 41.421.091, Work Unit 1-1600-078.

INTRODUCTION

The Navy is currently investigating the feasibility of operating vertical takeoff and landing (VTOL) aircraft from small surface ships. Such operations would significantly improve tactical flexibility and reduce the vulnerability of ship-based aircraft. Among the many types of aircraft under investigation are several which employ lift fans for propulsion during takeoff and landing. The fan pressure ratios are large enough to generate spray while the aircraft is hovering at low altitudes during landing approaches to small surface ships.

The generation and potential recirculation of spray is a relatively unknown phenomenon. Several investigations have been conducted under Navy sponsorship to assess this problem for VTOL seaplanes which would hover at much lower altitudes and have much lower disk loadings than the currently proposed ship-based VTOL aircraft. A limited study was undertaken at DTNSRDC to assess the problem as it specifically pertains to the currently projected Navy VTOL aircraft. (A limited study was undertaken at DTNSRDC). This report presents the results of this study.

BACKGROUND

SINGLE JET IMPINGEMENT OF WATER

A jet impinging normally on a water surface is shown in Figure 1. A depression is formed in the impingement area. This depression is deepest at the flow stagnation point where the static pressure at the surface is greatest. A lip which rises above the undisturbed water level is formed around the perimeter of the water depression. Banks and Chandrasekhara[1*] observed water depressions of these kinds with a small experimental apparatus. Olmstead and Raynor[2] showed that such a depression could be predicted by a potential flow analysis of the impinging jet.

---

*A complete list of references is given on pages 42-43.

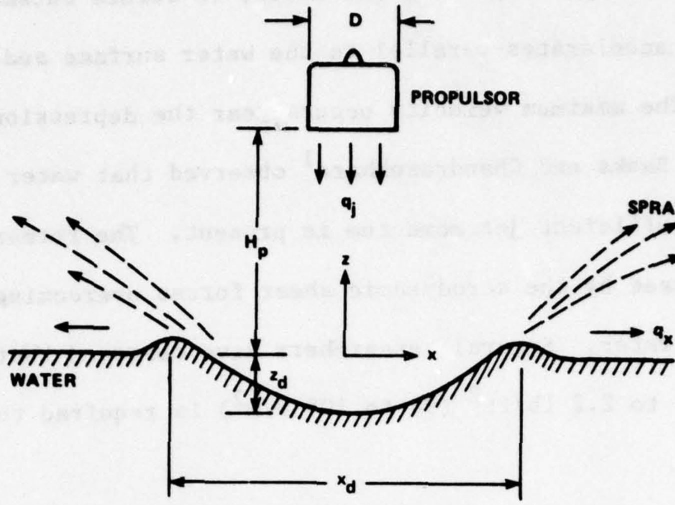


Figure 1 - Jet Impinging on Water

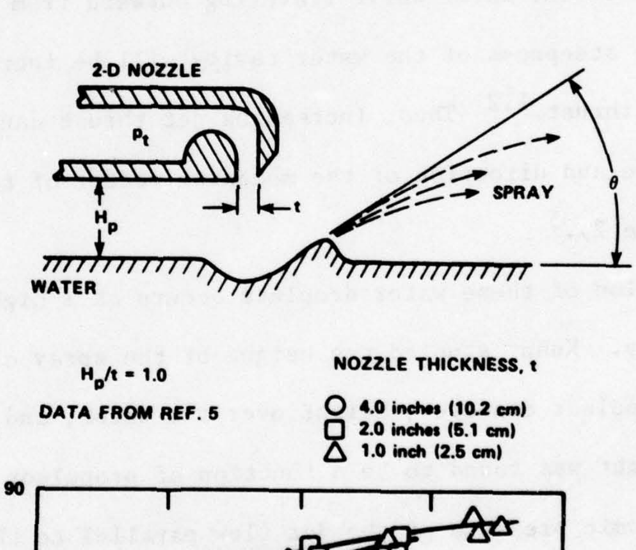


Figure 2 - Spray Trajectory Data from a Two Dimensional Nozzle

The jet flow, upon impinging the water, is turned outward. The flow velocity first accelerates parallel to the water surface and then slowly decelerates. The maximum velocity occurs near the depression lip.[2] At this point, Banks and Chandrasekhara[1] observed that water droplets are formed if sufficient jet momentum is present. The formation of these droplets is caused by the aerodynamic shear forces overcoming the surface tension of the water. Several researchers have observed that a dynamic pressure of 2.0 to 2.2 lb/ft^2 (96 to 105 N/m^2) is required to form water droplets.[1,3,4]

If water droplets are generated, the droplets will rise to some height and fall to the water while traveling outward from the impingement area. The steepness of the water cavity will be increased with increasing jet thrust.[1,2] Thus, increasing jet thrust causes a change in the magnitude and direction of the momentum vector of the water droplets (Figure 2).[5]

The formation of these water droplets occurs at a high rate forming a cloud of spray. Kuhn[3] studied the height of the spray cloud as a function of propulsor diameter, height over the water, and thrust. The spray cloud height was found to be a function of propulsor diameter and the maximum dynamic pressure of the jet flow parallel to the surface of the water (Figure 3). Kuhn[3] showed this dynamic pressure to be a function of the propulsor height diameter and thrust (Figure 4). By employing the maximum dynamic pressure at the surface as an independent variable, the spray cloud height was reduced to a function of two variables.

The flow along a solid surface with an impinging jet was not observed to be a function of the small-scale turbulence within the jet. In Kuhn's

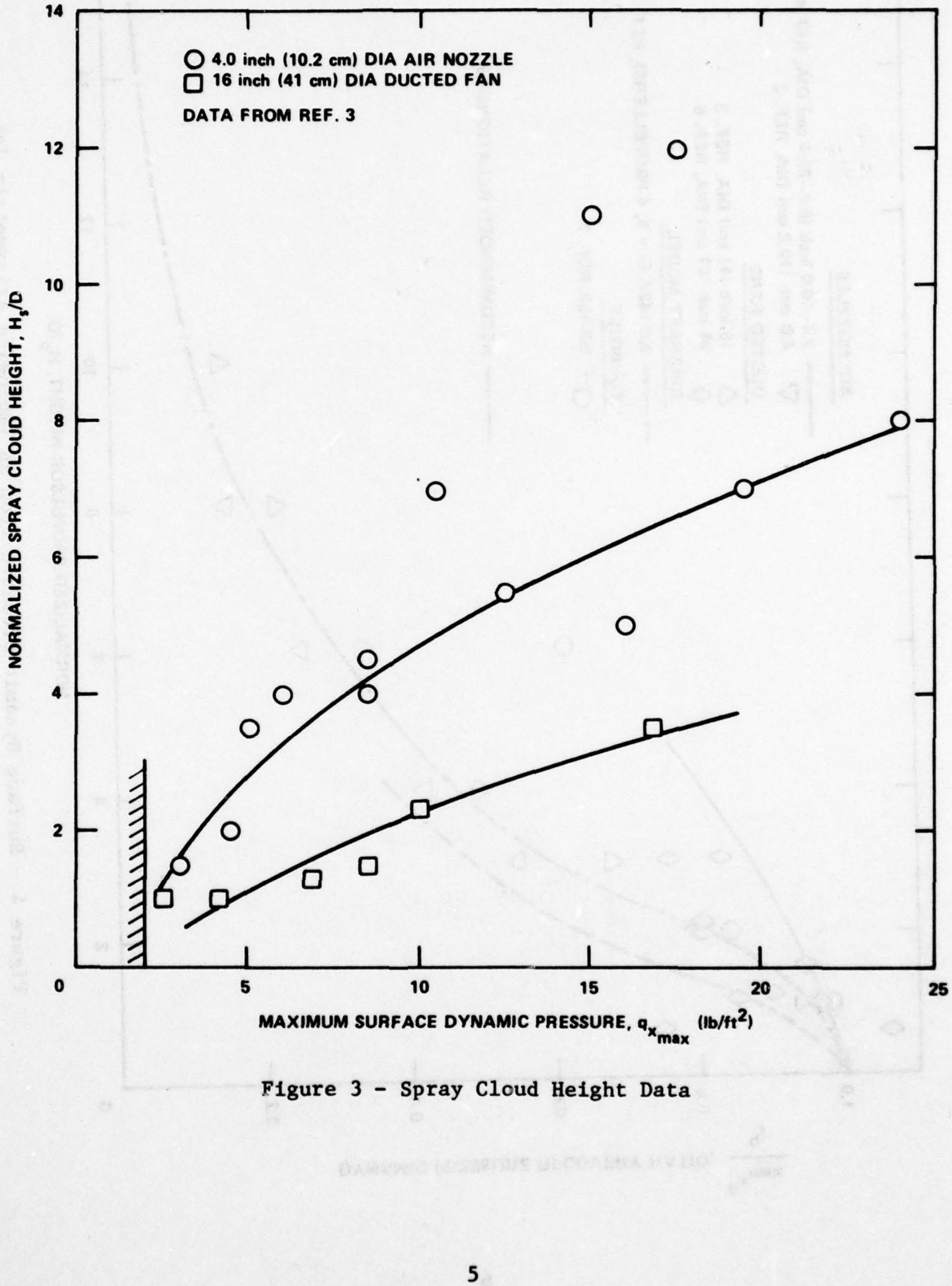


Figure 3 - Spray Cloud Height Data

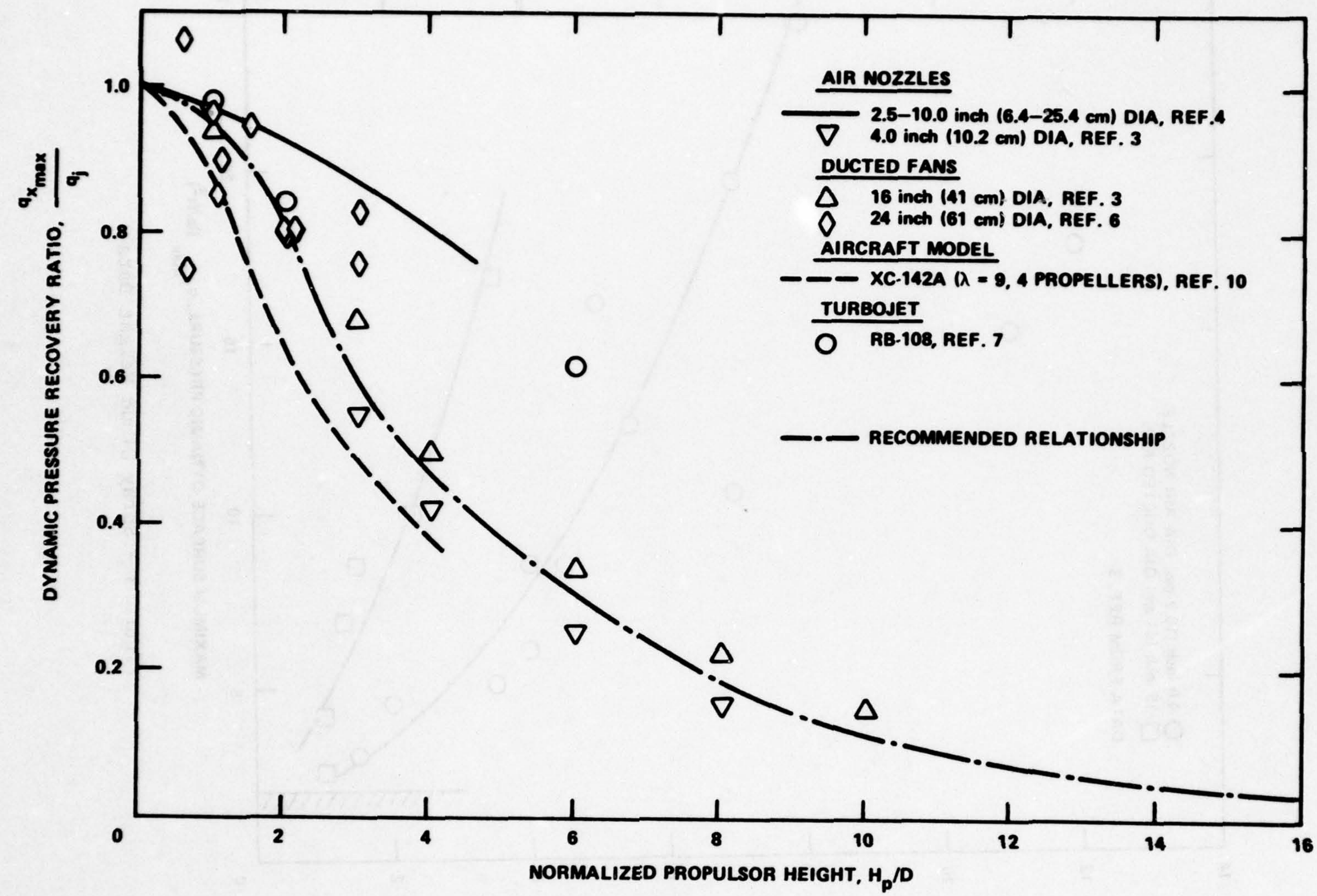


Figure 4 - Surface Dynamic Pressure from an Impinging Axisymetric Jet

experiments,[3] an axisymmetric air nozzle and a ducted fan had similar dynamic pressure profiles along the surface (Figure 5). The velocity profiles are assumed to be similar over water. However, subsequent experiments[3,4,6,7] have shown that the maximum velocity observed in the ground flow is not independent of the propulsor efflux characteristics. Substantial differences have been reported, including differences of 50 percent in the maximum dynamic pressure ratio (Figure 4).

The relationship between the maximum surface dynamic pressure, the propulsor diameter, and the spray cloud height was found by Dyke[4] to be

$$\frac{H_s}{D} \simeq \left(\frac{q_{x_{max}} - q_{x_o}}{D} \right)^{1/2} \qquad (1)$$

where q_{x_o} is the dynamic pressure at the surface of the water required to initiate spray. Use of this parameter results in a collapsed curve of spray cloud height (Figure 6). Dyke also studied the height of the spray cloud with a series of single axisymmetric air nozzles and found spray cloud height to be a function of nozzle diameter, thrust, and height over water as shown in Figure 6. The spray cloud height data from Kuhn[3] and Dyke[4] compare favorably when the spray cloud height is normalized by the propulsor diameter and is considered a function of a corrected Froude number defined as

$$F^*_x = \left(\frac{q_{x_{max}} - q_{x_o}}{g\rho_w D} \right)^{1/2} \qquad (2)$$

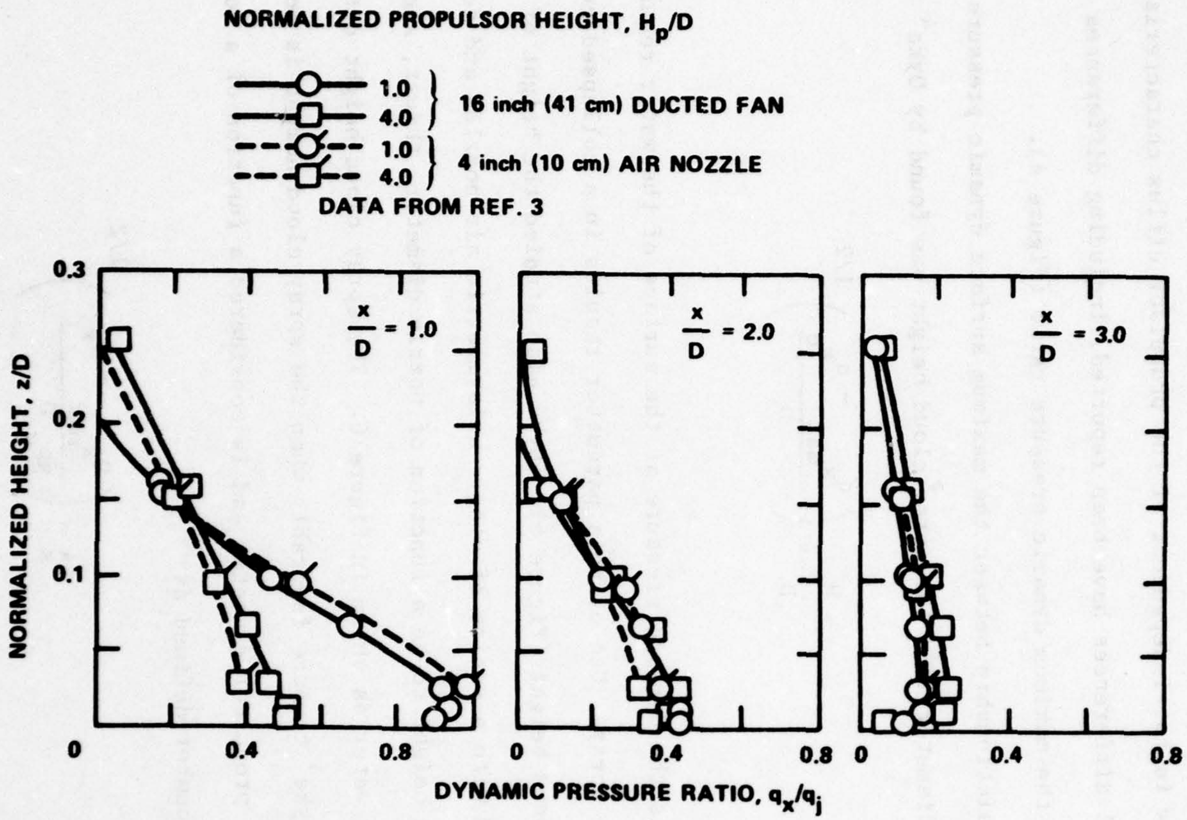


Figure 5 - Surface Dynamic Pressure Profiles

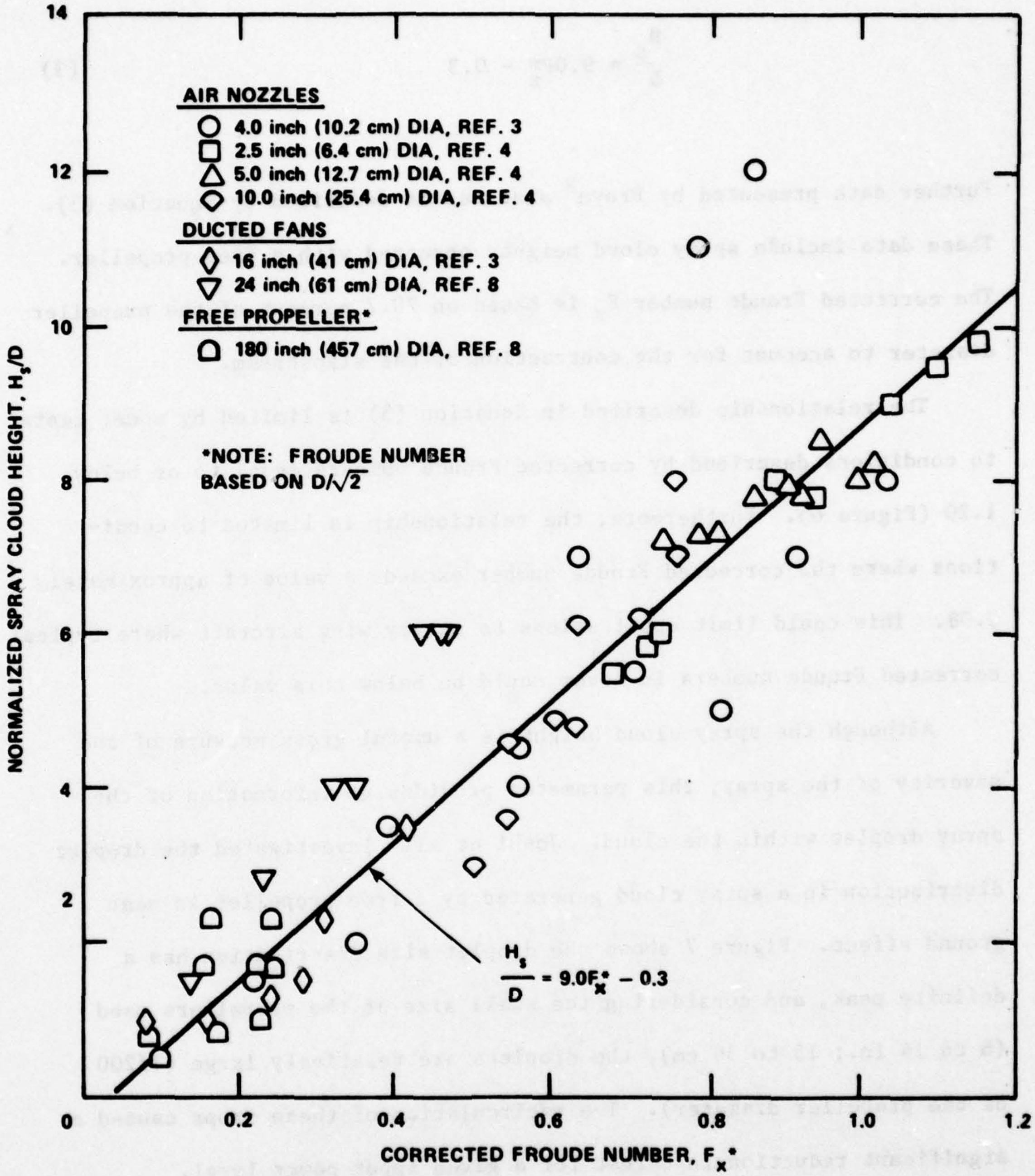


Figure 6 - Generalized Spray Cloud Height Relationship

The spray cloud height can be determined from

$$\frac{H_s}{D} = 9.0F_x^* - 0.3 \qquad (3)$$

Further data presented by Pruyn[8] also can be described by Equation (3). These data include spray cloud heights observed with a free propeller. The corrected Froude number F_x is based on 70.7 percent of the propeller diameter to account for the contraction of the slipstream.

The relationship described in Equation (3) is limited by model tests to conditions described by corrected Froude numbers equal to or below 1.20 (Figure 6). Furthermore, the relationship is limited to conditions where the corrected Froude number exceeds a value of approximately 0.08. This could limit applications to rotary wing aircraft where typical corrected Froude numbers in hover could be below this value.

Although the spray cloud height is a useful gross measure of the severity of the spray, this parameter provides no information of the spray droplet within the cloud. Joshi et al.[9] investigated the droplet distribution in a spray cloud generated by a free propeller in near ground effect. Figure 7 shows the droplet size distribution has a definite peak, and considering the small size of the propellers used (6 to 14 in.; 15 to 36 cm), the droplets are relatively large (1/200 of the propeller diameter). The recirculation of these drops caused a significant reduction in thrust for a given input power level.

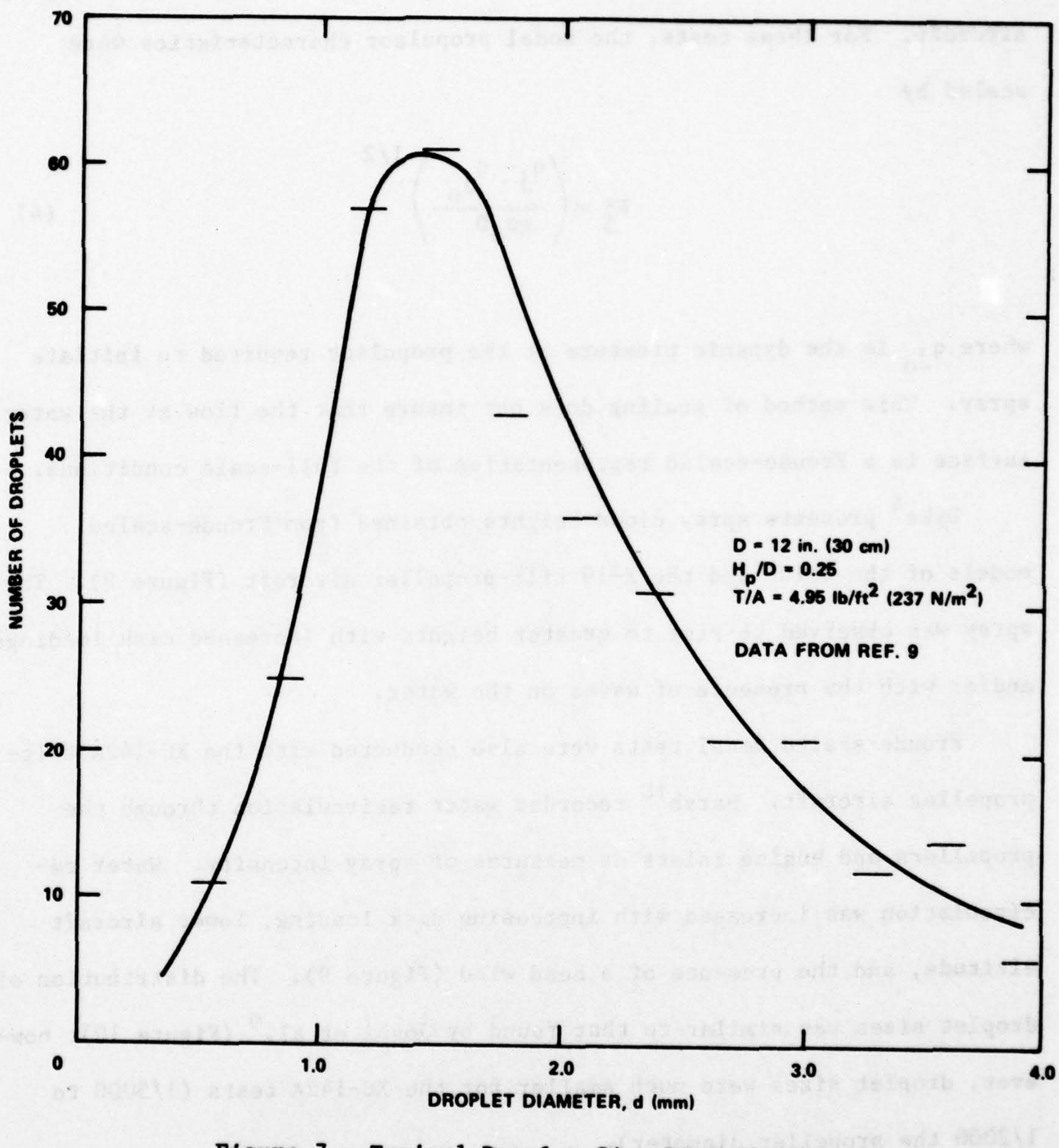


Figure 7 - Typical Droplet Size Distribution

TESTS WITH FROUDE-SCALED MODEL AIRCRAFT

Subscale aircraft models based on Froude-scaling relationship were tested to determine the severity of the spray generated by a full-scale aircraft. For these tests, the model propulsor characteristics were scaled by

$$F_j^* = \left(\frac{q_j - q_{j_o}}{g \rho_w D} \right)^{1/2} \tag{4}$$

where q_{j_o} is the dynamic pressure at the propulsor required to initiate spray. This method of scaling does not insure that the flow at the water surface is a Froude-scaled representation of the full-scale conditions.

Dyke[4] presents spray cloud heights obtained from Froude-scaled models of the X-100 and the X-19 tilt-propeller aircraft (Figure 8). The spray was observed to rise to greater heights with increased disk loadings and/or with the presence of waves on the water.

Froude-scaled model tests were also conducted with the XC-142A tilt-propeller aircraft. Marsh[10] recorded water recirculation through the propellers and engine inlets as measures of spray intensity. Water recirculation was increased with increasing disk loading, lower aircraft altitude, and the presence of a head wind (Figure 9). The distribution of droplet sizes was similar to that found by Joshi et al.[9] (Figure 10); however, droplet sizes were much smaller for the XC-142A tests (1/5000 to 1/2000 the propeller diameter).

The geometry of the water depression was observed during these experiments. The maximum depression depth was found to be a function

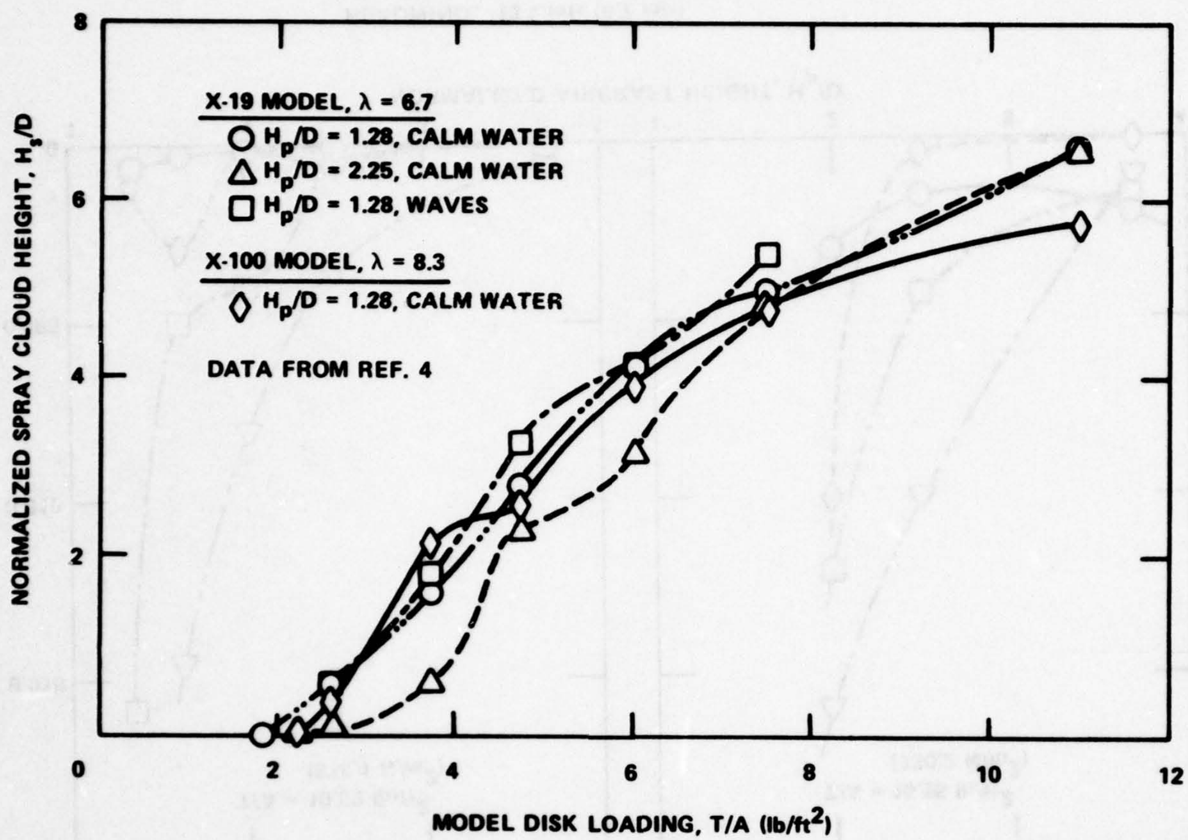
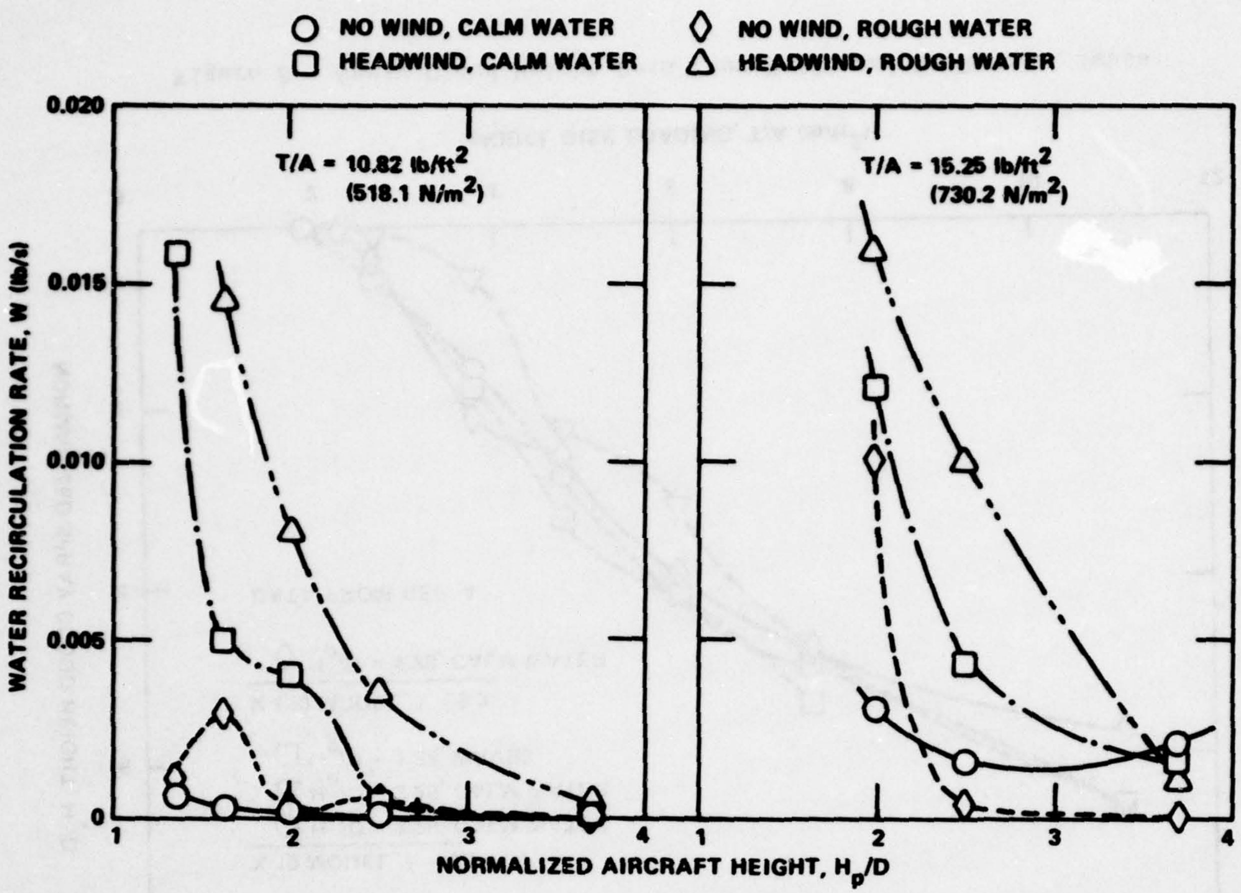


Figure 8 - Spray Cloud Height Data from X-100 and X-19 Model Tests



HEADWIND: 13 knots (6.7 m/s)
ROUGH WATER: WAVE LENGTH = 7.5 ft (2.3 m)
WAVE HEIGHT = 0.50 ft (0.15 m)

DATA FROM REF. 10

Figure 9 - Water Recirculation from XC-142A Model Tests

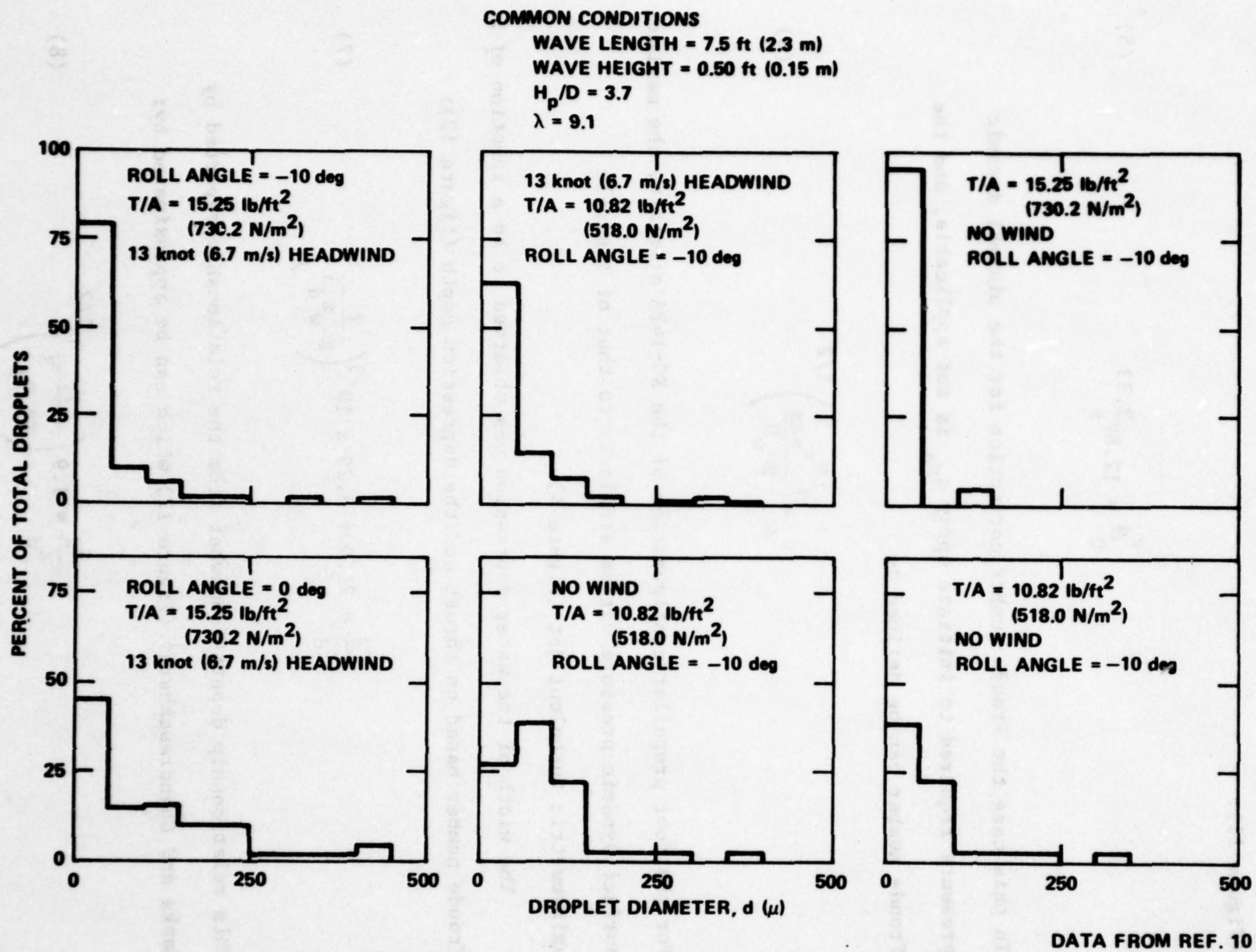


Figure 10 - Droplet Size Distribution from XC-142A Model Tests

of the Froude number based on the maximum surface dynamic pressure (Figure 11):

$$\frac{z_d}{D} = 12.8F_x^{3.33} \tag{5}$$

In this case the Froude number correction for the minimal dynamic pressure required to initiate spray q_{x_o} is not applicable, and the Froude number can be defined as

$$F_x = \left(\frac{q_{x_{max}}}{g\rho_w D}\right)^{1/2} \tag{6}$$

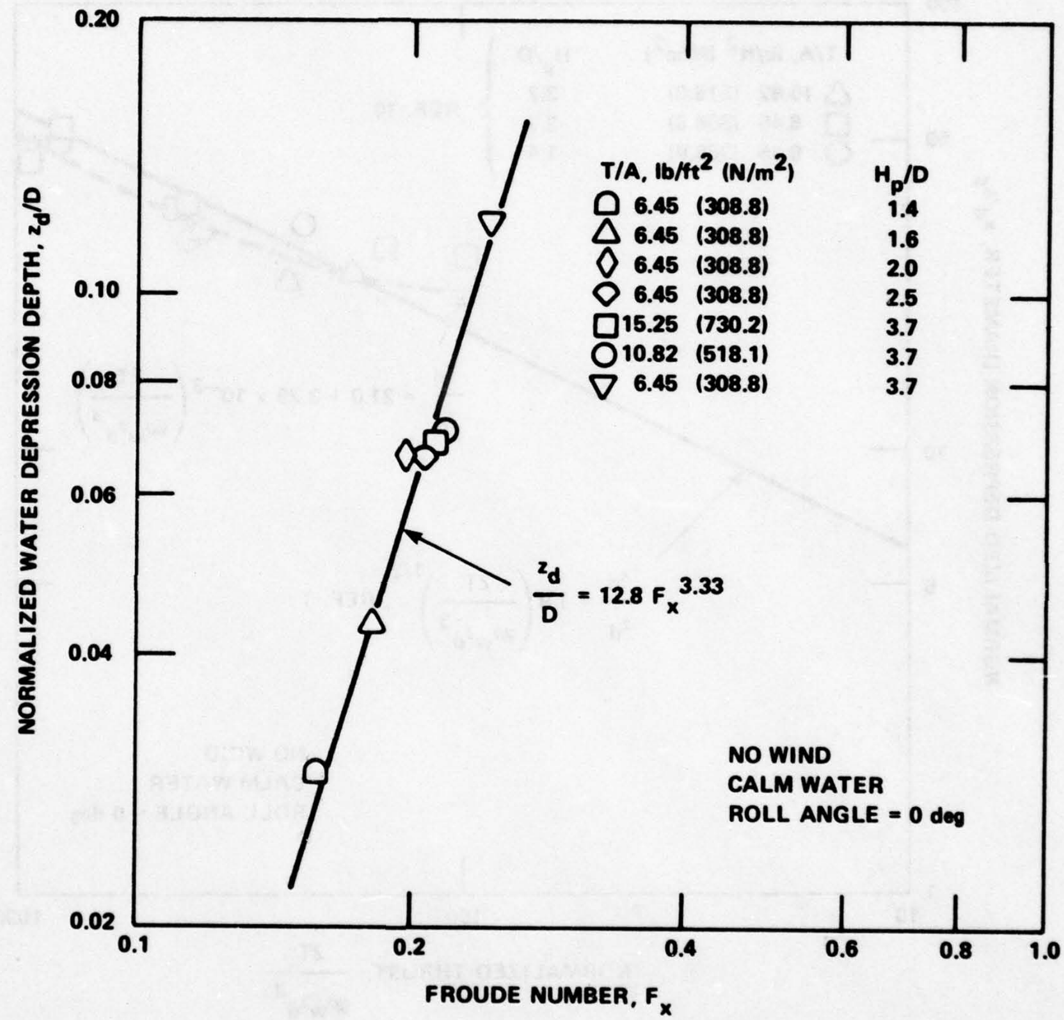
For the four propeller configuration of the XC-142A aircraft, the maximum surface dynamic pressure varies similarly to that of a single axisymmetric turbulent jet (Figure 4).

The width of the water depression was observed to be a function of a Froude number based on thrust and the depression depth (Figure 12):

$$\frac{x_d}{z_d} = 21.0 + 8.29 \times 10^{-3}\left(\frac{T}{g\rho_w z_d^3}\right) \tag{7}$$

This relationship departs somewhat from the relationship reported by Banks and Chandrasekhara[1] (Figure 12) which can be approximated by:

$$\frac{x_d}{z_d} = 1.9\left(\frac{2T}{g\rho_w z_d^3}\right)^{1/2} \tag{8}$$



DATA FROM REF. 10

Figure 11 - Water Depression Depth Relationship

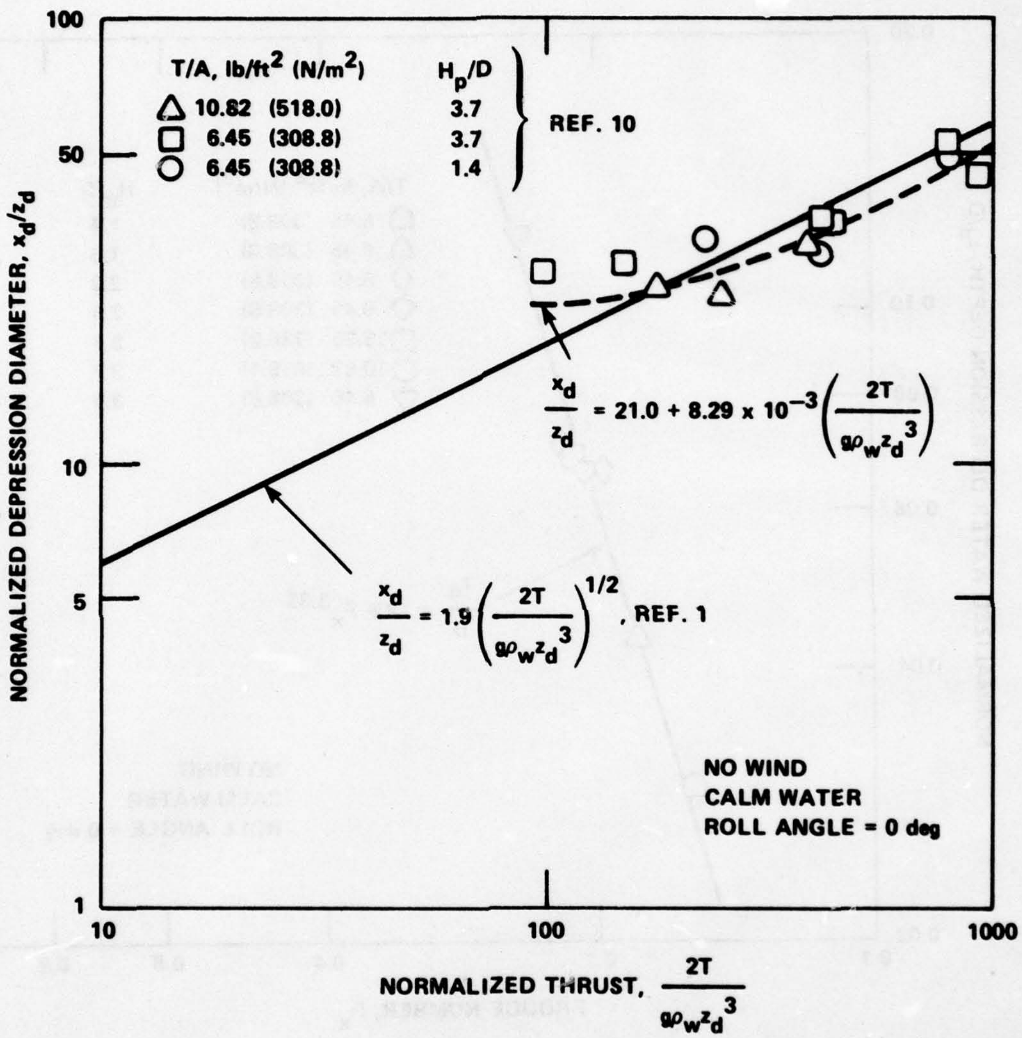


Figure 12 - Water Depression Diameter Relationship

The geometry of the water depression was measured throughout the slipstream impingement area. The water depression had a single low point under each set of two propellers (Figure 13). The depression moved outward when the aircraft was rolled, and the depression on the lower propeller side of the aircraft became deeper.

Although the data from these tests were Froude-scaled to predict the spray environment under full-scale conditions, Marsh[10] reported that

> "Comparisons of motion pictures of the model and the XC-142A actual airplane under similar conditions indicate that the wave patterns and heavy spray characteristics are better represented by a model disk loading approximately 50 percent higher than that derived from the (Froude-scaling) relationship."

The visibility through a spray cloud based on this unique scaling relationship was investigated by Kurylowich and Ritter[11] with models of the XC-142A and the X-22A aircraft. Results showed visibility was strongly affected by propulsor location (Figure 14). The X-22A configuration (with four ducted propellers arranged in a square) was observed to provide better pilot visibility.

FULL-SCALE DATA

Limited full-scale data are available with which to compare subscale model data. Kuhn[3] reported a single data point from the X-13 turbojet aircraft. Dyke[4] favorably compared subscale and full-scale spray cloud heights for the X-100 tilt-propeller aircraft. Pruyn[8] presents spray height data for a full-scale model of a conceptual tandem ducted-propeller VTOL aircraft. Spray cloud height data for two of these tests are summarized in Figure 15. The X-13 aircraft spray cloud height is much higher than would be predicted by Equation (3). The full-scale tests of

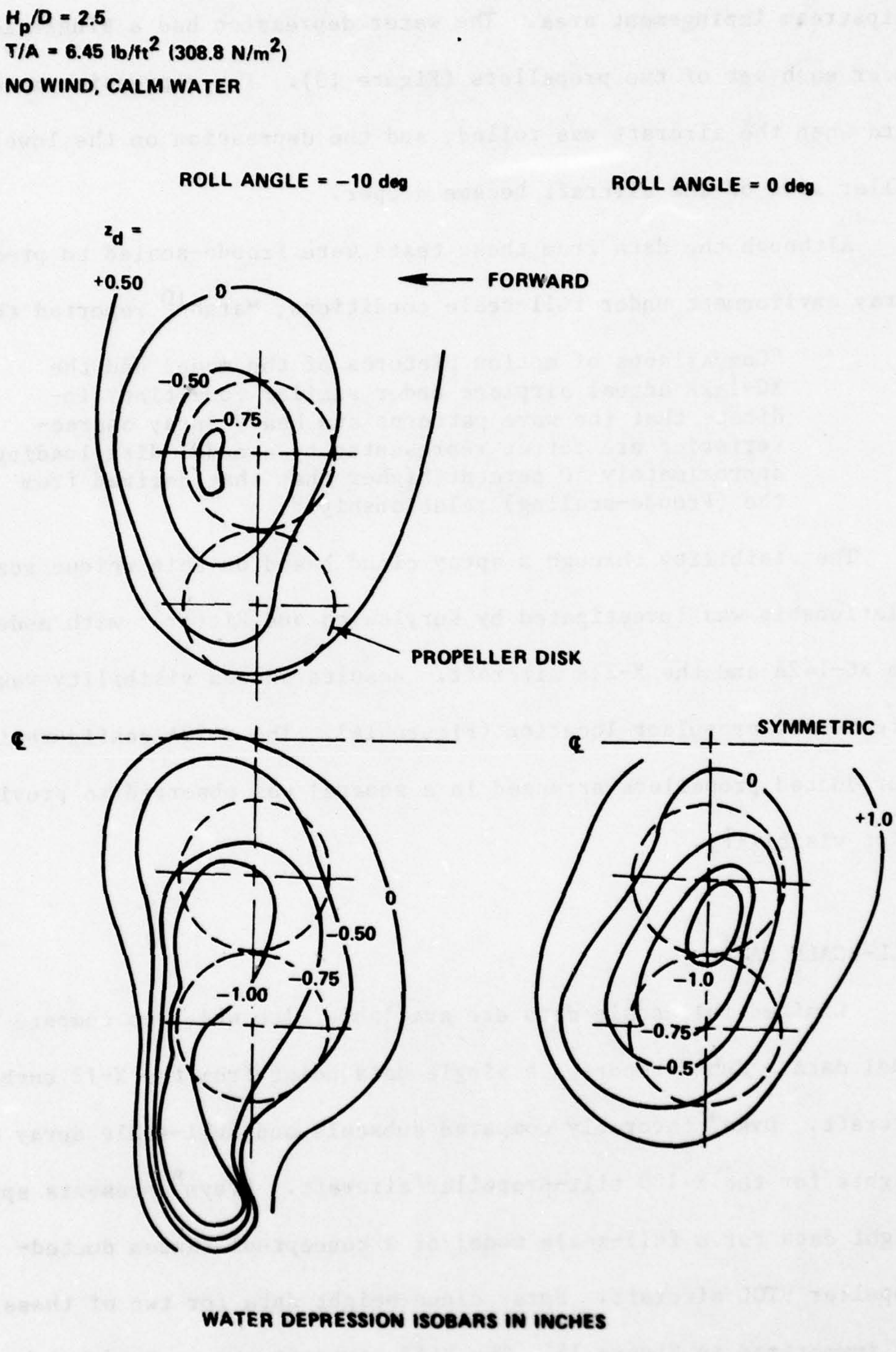


Figure 13 - Water Depression Contours from XC-142A Model Tests

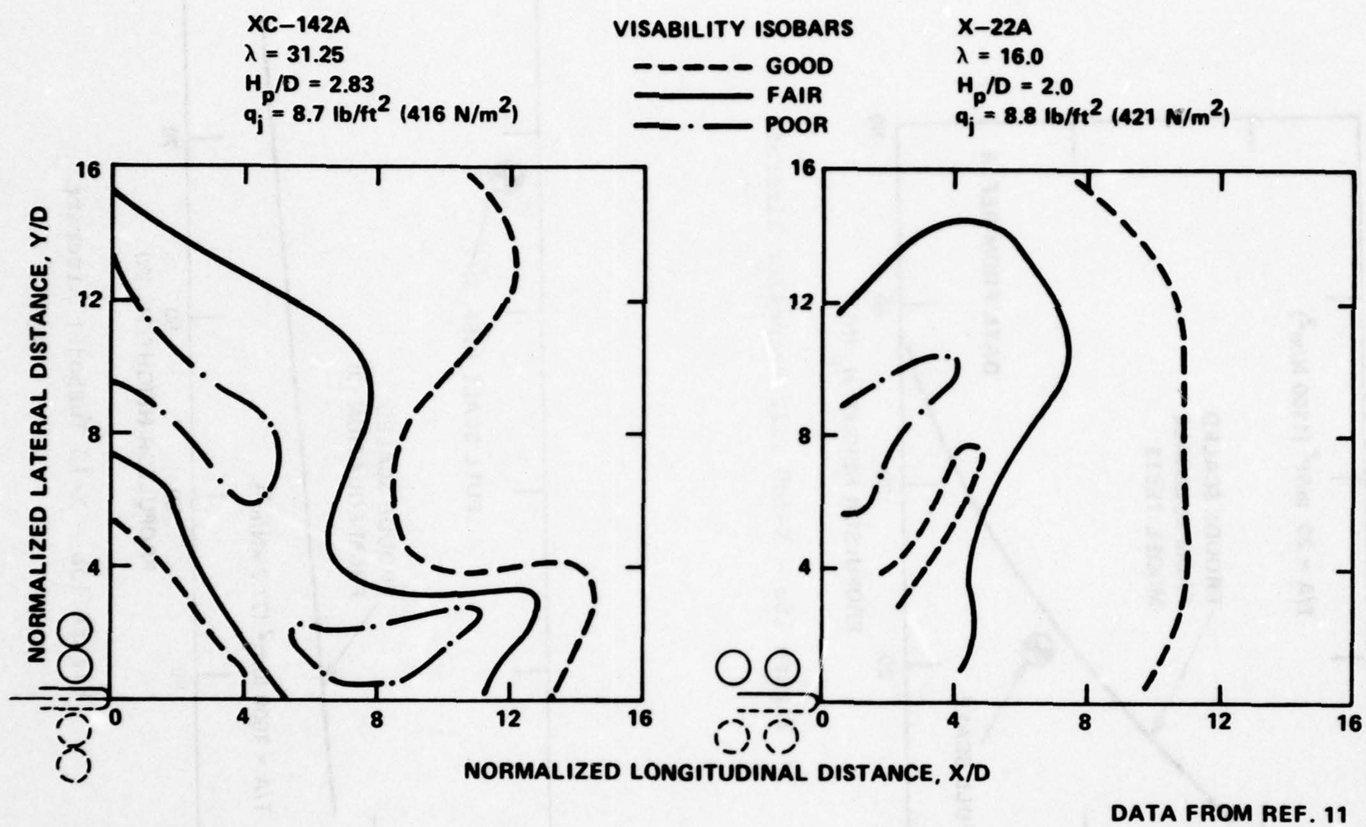


Figure 14 - Visibility Through the Spray Cloud from XC-142A and X-22A Model Tests

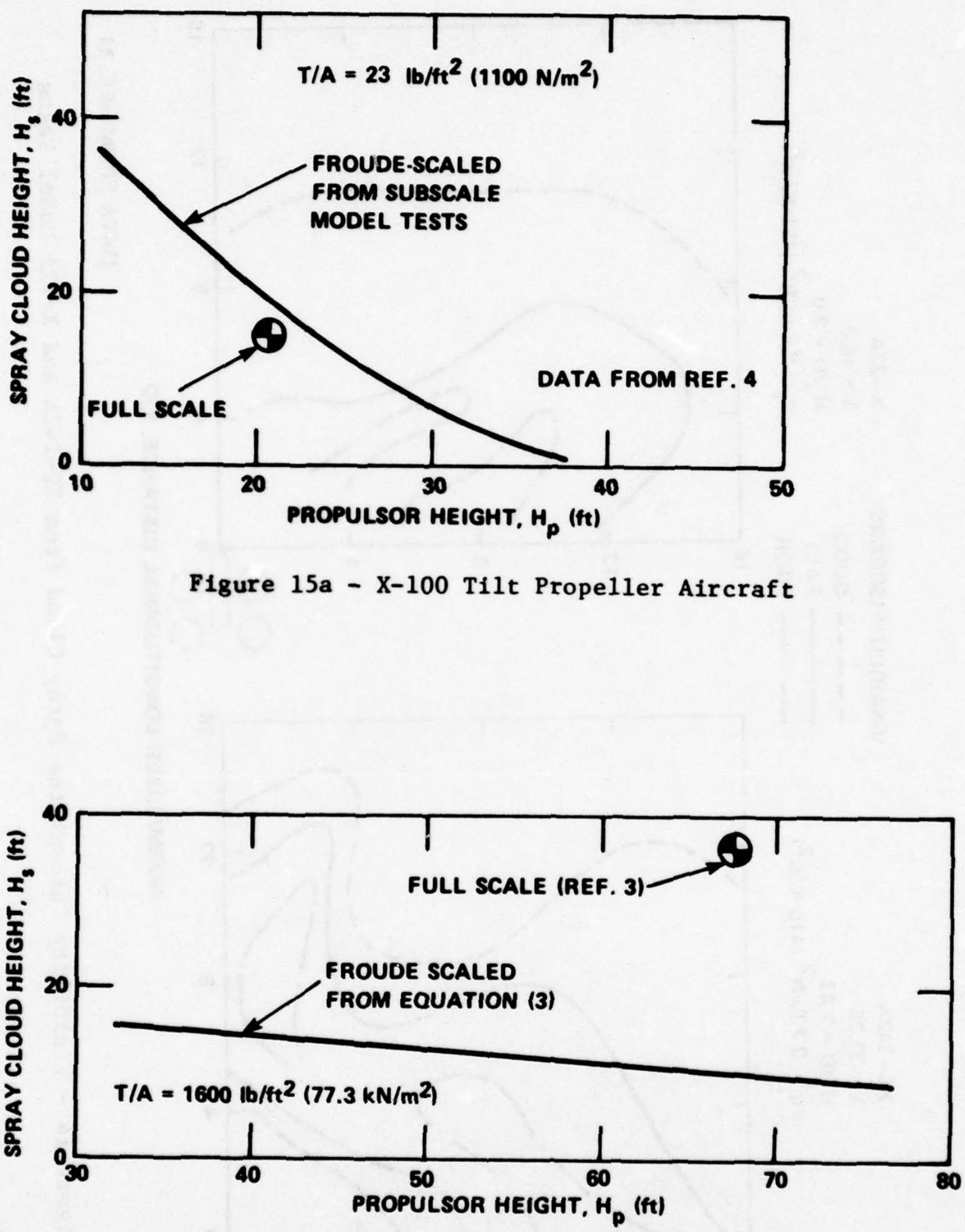


Figure 15a - X-100 Tilt Propeller Aircraft

Figure 15b - X-13 Turbojet Aircraft

Figure 15 - Comparison between Sub-Scale Model and Full-Scale Test Data

the X-100 aircraft resulted in spray cloud heights that can be predicted from Equation (3) or Froude-scaled model tests.

SCALING CONSIDERATIONS

For the case of a single axisymmetric jet impinging normally on water, the following variables can contribute to the spray that may be generated:

- propulsor diameter, D
- maximum flow velocity at the surface, $V_{x_{max}}$
- water surface tension, σ_w
- water density, ρ_w
- air density, ρ_a
- air viscosity, μ_a
- gravitational acceleration, g

A nondimensional characteristic of the spray ξ can be considered a function of these variables:

$$\xi = f(D, V_{x_{max}}, \sigma_w, \rho_w, \rho_a, \mu_a, g) \tag{9}$$

Application of the Buckingham Pi Theorem yields the following dimensional groupings whose product describes the nondimensional spray characteristic:

$$\xi = \left(\frac{V_{x_{max}} D\rho_a}{\mu_a}\right)\left(\frac{V_{x_{max}}}{\sqrt{gD}}\right)\left(\frac{\rho_w V_{x_{max}}^2 D}{\sigma_w}\right)\left(\frac{\rho_w}{\rho_a}\right) \tag{10}$$

The first three groupings represent the Reynolds, Froude, and Weber numbers and are the ratios of the viscous, gravitational, and surface tension forces to the inertial forces, respectively. The four nondimensional groupings cannot be simultaneously satisfied with a subscale model.

Other investigators have employed different variables to characterize the propulsor and spray. The most common difference has been to employ the propulsor height and thrust in place of the maximum flow velocity at the water surface.[1,4] This procedure involves the addition of another variable and increases the complexity of the functional relationship by adding the details of the jet decay and impingement (Figure 4). Although Kuhn[3] and Morse[6] have shown that differences in propulsor efflux characteristics have no substantial effect on the velocity profiles after impingement (Figure 5), a large variation is observed between the maximum dynamic pressures at the surface after impingement (Figure 4). Gray and Kisielowski[12] show that these variations are most likely due to viscous and thermal effects. Neither of these effects are considered with direct Froude scaling. Introducing the details of the propulsor dynamic pressure decay into the spray generation analysis adds considerable uncertainty to the problem. Hence, all spray generation analyses were based on the flow conditions at the surface (after impingement).

Also in question are the correct variables to characterize the spray cloud. The spray cloud height (divided by the propulsor diameter) is difficult to measure and provides no information concerning the interior of the cloud.[3,4,8] Water ingestion rates, although the most applicable to full-scale design problems, are only local measures of the spray.[9] The droplet distribution throughout the cloud is the most useful measure of the spray cloud; however, such data require that information be gathered throughout the interior of the spray cloud.[9] The unsteady nature of the spray generation makes this a difficult task. For preliminary purposes, the spray cloud height provides a practical altitude envelope above which spray ingestion can be considered negligible.[3,4,8]

The scaling of the dimensions of a spray cloud envelope generated by a subscale model has been examined for applications in predicting the spray patterns of seaplane hulls. Experience has shown that the dimensions of the envelope from seaplane hulls can be Froude-scaled, although the character of the spray from a subscale model is quite different from that in full-scale. The model spray is composed of much larger droplets (when compared to some characteristic dimension of the experiment).[3]

The proportionally larger droplet size in subscale model testing is a result of the surface tension of the water. For a given airflow velocity, there is a maximum droplet diameter which can be maintained. Hanson et al.[13] showed this relationship to be

$$W = \frac{\rho_w V_x^2 d_{max}}{\sigma_w} = 7840 \tag{11}$$

Marsh[10] showed similar test results (Figure 16) for the XC-142A model. Using this relationship the maximum droplet diameter d_{max} which can exist in the spray cloud can be determined. For a typical VTOL aircraft propulsor and a 1/10-scale model, the model propulsor flow will support droplets which are 34 times larger than in full scale; the droplet diameter-to-propulsor diameter ratio would be increased by a factor of 340 (Figure 17). These increases, however, do not invalidate the Froude scaling assumption. Consideration of the forces on each droplet shows that the weight of the droplet

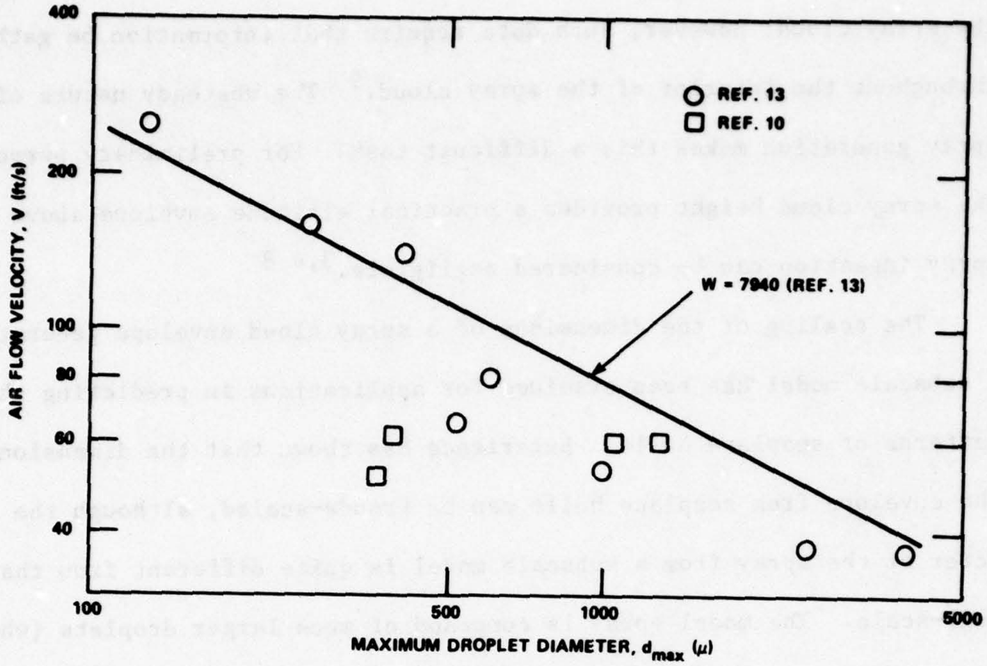


Figure 16 - Maximum Droplet Diameter in an Airstream

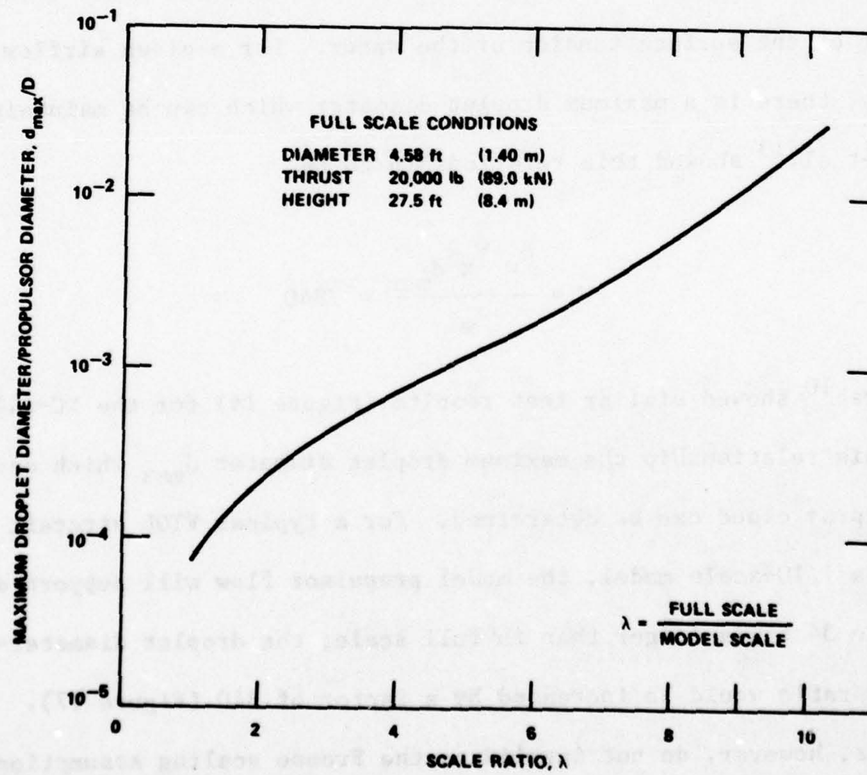


Figure 17 - Effect of Scale Ratio on the Maximum Droplet Diameter

is the dominant force in all scale regimes. Figure 18 shows results from a calculation of droplet Reynolds number and weight-to-drag ratio. In this example, Stokes flow was assumed so that the aerodynamic drag was considered to be directly proportional to the flow velocity. In all cases the droplet weight is at least 180 times greater than the aerodynamic drag. This confirms that the droplet trajectory will be primarily influenced by the magnitude and direction of the momentum initially transferred to the droplet.

EXPERIMENTAL PROGRAM

Limited tests of a ducted fan were conducted to gather further data on spray generation. Spray cloud height and water depression diameter were the primary variables of interest. The tests were designed to simulate a single ducted fan typical of projected subsonic VTOL aircraft (assuming Froude scaling).

TEST FACILITY

Tests were conducted at DTNSRDC in the Carriage 3 facility with a towing basin 20 ft (6.1 m) wide by 10 ft (3.0 m) deep. The carriage was parked 120 ft (36.6 m) from one end of the 2100 ft (640 m) long basin. The ducted fan was fixed to the model support mechanism at one end of the carriage. The fan could be set between 25 and 60 in. (64 and 152 cm) above the water surface. Photographs were taken from the side and the top of the fan. Adequate lighting was provided by flood lights around the perimeter of the test area.

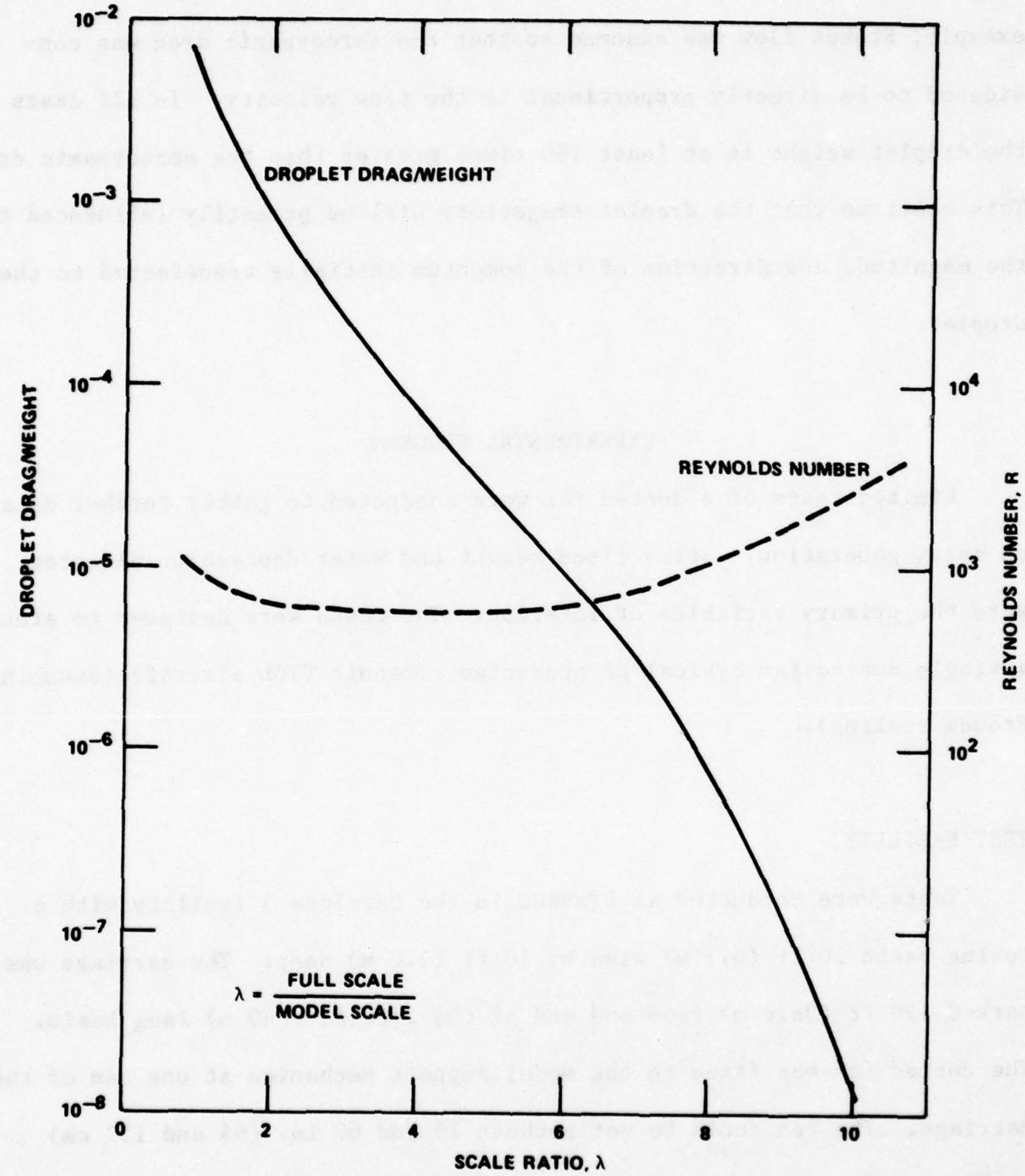


Figure 18 - Effect of Scale Ratio on Droplet Aerodynamics

APPARATUS

Tests were conducted with a Tech Development TD-457Q tip-driven ducted fan, Table 1. This device (Figure 19) has an exit diameter of 5.50 in. (14.0 cm) with a hub diameter of 2.94 in. (33.5 cm). The fan hub was blunt with no fairing. The fan was driven from an external compressed air supply carried through a flexible hose to the fan housing. The fan was supported by an aluminum frame (Figure 19) with a square base measuring 8.25 in. (21.0 cm) on each side.

The fan rotational speed was recorded with a magnetic sensor in the fan hub. Thrust was measured with two strain gage blocks mounted between the fan support frame and the carriage model support (Figure 19). The fan could be operated at speeds up to 17,500 rpm resulting in a thrust of 27.6 lb (123 N). Air mass flow limitations of the facility made higher thrust levels unattainable.

TABLE 1 - DUCTED FAN CHARACTERISTICS

Outside Diameter	5.50 in. (13.97 cm)
Hub Diameter	1.925 in. (4.890 cm)
Maximum Thrust	87.3 lb (389 N)
Maximum Fan Flow Rate	5.50 lb_m/s (2.52 kg/s)
Maximum Rotational Speed	35,800 rpm
Maximum Pressure Ratio	1.25
Model	Tech Development Model 457Q

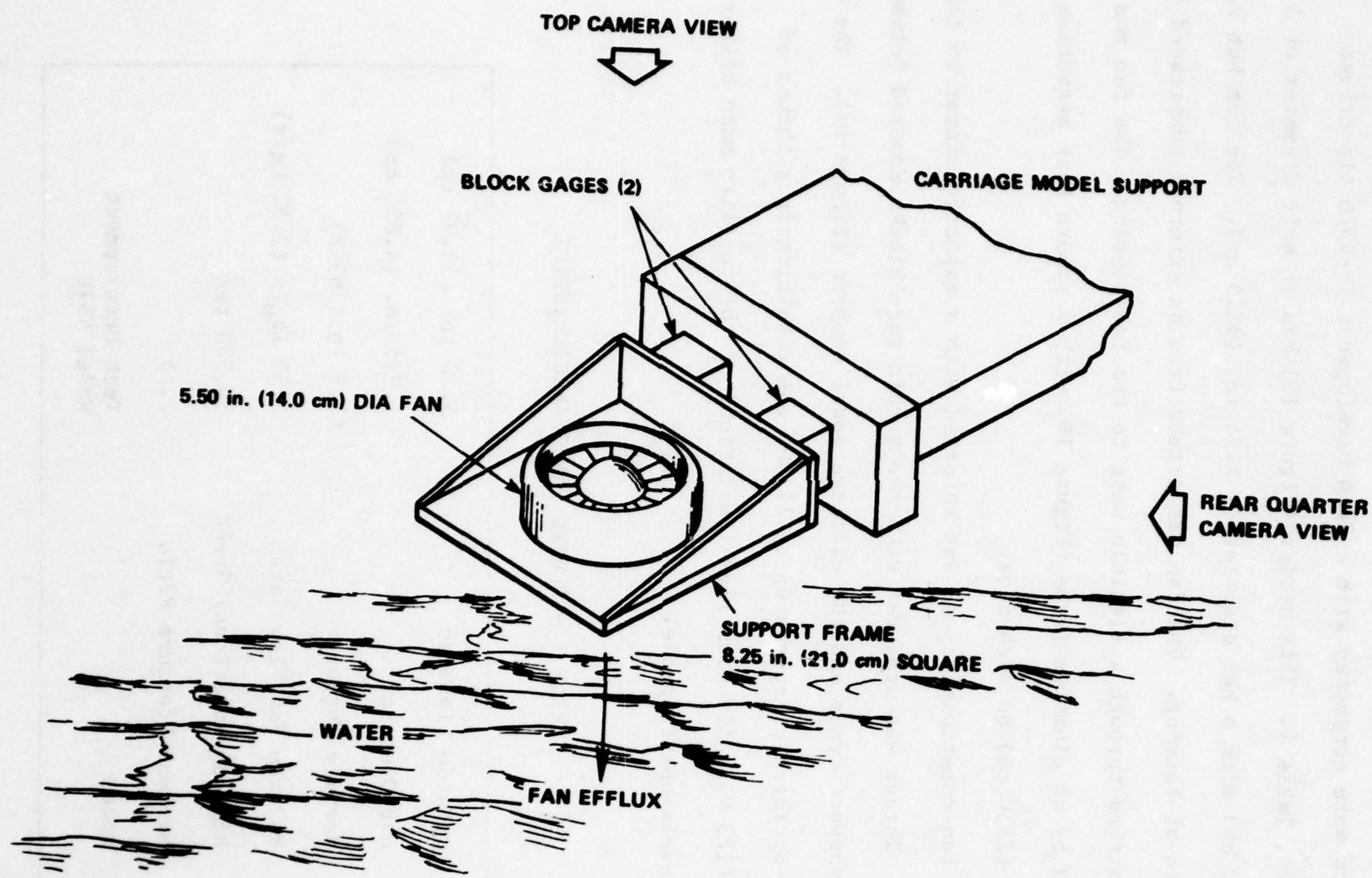


Figure 19 - Arrangement of Spray Generation Experiment

TEST PROCEDURE

For each fan test height, calibration photographs were taken with a target of known size placed on the water surface. Five different fan thrust levels were obtained at each fan height. At each thrust level, side and top photographs were taken, and fan thrust and rotational speed were recorded.

Photographs from these tests were analyzed to determine the spray cloud height. The diameter of the water depression lip was also recorded when visible. Cloud height measurements could be obtained with an approximate accuracy of ± D/2; the depression diameter measurement accuracy was approximately ± D/4.

Ground flow data presented by Kuhn[3] were used to estimate the maximum dynamic pressure at the water surface (Figure 4). Use of these data requires an equivalent jet exit dynamic pressure defined as

$$q_j = \frac{T}{2A} \tag{12a}$$

For this experiment, the fan exit area was corrected for the presence of the relatively large hub. Thus,

$$q_j = \frac{2T}{\pi(D^2 - D_{hub}^2)} \tag{12b}$$

This correction results in a 40-percent increase in the dynamic pressure as compared to the increase in dynamic pressure if calculated from the fan outside diameter alone.

TEST RESULTS AND DISCUSSION

At high values of surface dynamic pressure over water, the depression geometry was highly unstable. Motion pictures of the experiment showed that at high thrust levels and low propulsor heights (i.e., high surface dynamic pressures corresponding to corrected Froude numbers of 1.0), the water depression would periodically collapse on itself and, at times, more than one depression lip was evident. The spray cloud height was observed to vary much less than the cloud width or depression diameter under these conditions. Although no attempt was made to measure water droplet size, distinct droplets as large as 1/50 the fan diameter were noticed in some photographs. However, under most conditions individual droplets could not be distinguished.

The spray generated was observed to be recirculated through the fan at corrected Froude numbers in excess of approximately 0.60 ($H_p/D < 7.3$). At values above 0.80 the fan was completely immersed in heavy spray. While at higher Froude numbers (above approximately 1.0), the spray cloud rose to heights beyond the camera field of view.

Spray cloud heights from photographs are presented in Figure 20 as a function of the corrected Froude number at the surface, F_s^*. The data compare favorably with Equation (3) and the results of other investigators.[3,4,8] The diameter of the depression in the water caused by the flow impingement was a function of the Froude number at the surface (uncorrected):

$$\frac{x_d}{D} = 4.0\, F_x^{1.2} \qquad (13)$$

This relationship is presented with the model test data in Figure 21. The water depression diameter can also be determined from previous experiments;[10] Equations (5) and (8) were derived from these experiments. Combining these two equations yields

$$\frac{x_d}{D} = 0.73 \left(\frac{T}{g\rho_w D^3 F_x^{3.33}} \right)^{1/2} \tag{14}$$

The current model data were applied to Equation (14) and the calculated depression diameter was compared to the measured value. This comparison, as shown in Figure 21, is unfavorable, particularly at low Froude numbers. This discrepancy is probably due to the omission of the thrust term in Equation (13), although this cannot be substantiated. Comparing Equations (13) and (14) shows the contradictory relationship between the water depression diameter and the Froude number with all other variables fixed. The measurement of the depression depth z would have provided an explanation for this discrepancy since earlier tests[1,10] showed thrust to be important in determining depth; however, with the current available information, no explanation of this contradictory functional relationship can be postulated.

APPLICATION TO FULL-SCALE PROPULSORS

As previously stated, the spray cloud height can be used as a boundary above which little or no spray would be ingested or recirculated through a propulsor. Using Equation (3) and the characteristics of the propulsor, the spray cloud height can be determined by corrected Froude scaling. The trends in Figure 4 can be used to predict the propulsor flow at the water

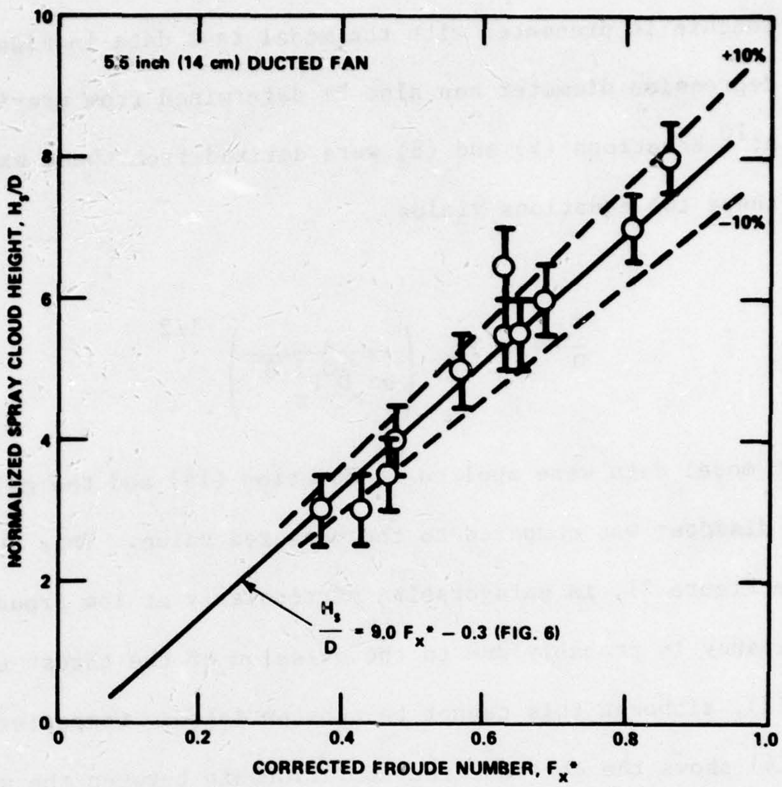
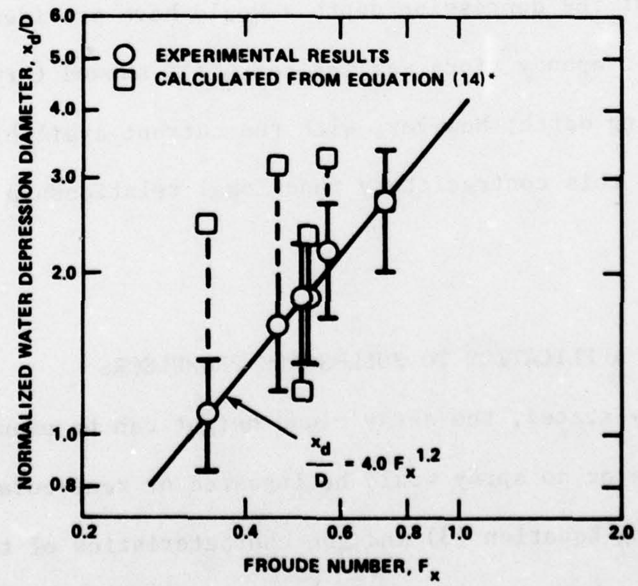


Figure 20 - Spray Cloud Height Data from Model Tests



*RELATIONSHIP BASED ON THRUST AND FROUDE NUMBER

Figure 21 - Water Depression Diameter Data from Model Tests

surface. The results from such a scaling calculation, however, must be considered tentative since the validity of corrected Froude scaling has not been demonstrated. For full-scale applications, the inflow into a propulsor is assumed to have negligible effects on the spray cloud height. This assumption is substantiated by the good correlation between results with air nozzles and ducted fans (under subscale model conditions), as shown in Figures 5 and 6. Furthermore, the effects of hot exhaust gas under full-scale conditions are also neglected. The dominance of the droplet weight over drag (Figure 18) supports the assumption that thermal buoyancy would not have a substantial effect on the spray cloud height. However, the single full-scale data point with a hot jet (Figure 15) indicates some strong effects may be involved.

Using this scaling procedure, the spray cloud heights can be determined for a variety of propulsors. Two conceptual propulsors were considered for analysis (Table 2). The larger propulsor has a diameter of 4.58 ft (1.40 m) with a thrust of 20,000 lb (89.0 kN); this device is assumed to be a subsonic ducted fan. The other propulsor is 3.20 ft (0.98 m) in diameter with 30,000 lb (134 kN) thrust with a hot gas exhaust typical of supersonic VTOL turbojet engines. The flow conditions at the surface were calculated from the relationship given in Figure 4. Equations (2) and (3) were used to predict the full-scale spray cloud heights. Results from these calculations, shown in Figure 22, show that at an altitude of 26 ft (7.9 m) the ducted fan propulsor would enter the spray cloud. The turbojet would enter the spray cloud at a height of 31 ft (9.5 m). In both cases, the corrected Froude number of the condition where the propulsor height equals the spray cloud height is within the range of subscale model test data ($F_x^* < 1.2$).

TABLE 2 - CONCEPTUAL PROPULSOR CHARACTERISTICS

	Ducted Fan	Turbojet
Diameter, ft (m)	4.58 (1.40)	3.20 (0.98)
Thrust, lb (kN)	20,000 (89.0)	30,000 (134)
Pressure Ratio	1.29	1.88
Flight Regime	Subsonic	Supersonic
Exhaust Temperature (C)	200	2000

The water depression diameter can be predicted using Equations (6) and (13) and Figure 4. Using these expressions, the water diameter was found to decrease with increasing propulsor height (Figure 23). The ducted fan has a depression diameter consistantly smaller than the turbojet for the same propulsor height. The depression diameter can also be calculated using Equation (14), which describes earlier test results.[1,10] The spray water depression diameters were found to increase with increasing propulsor height and the ducted fan was found to have the larger depression diameter. The predicted depression diameters, using Equation (13), represent full-scale conditions outside the range of Froude-scaled model test conditions.

The predicted spray cloud heights and depression diameters shown in Figures 22 and 23 are applicable only to single, axisymmetric propulsors. For situations where multiple propulsor arrangements are of interest, the

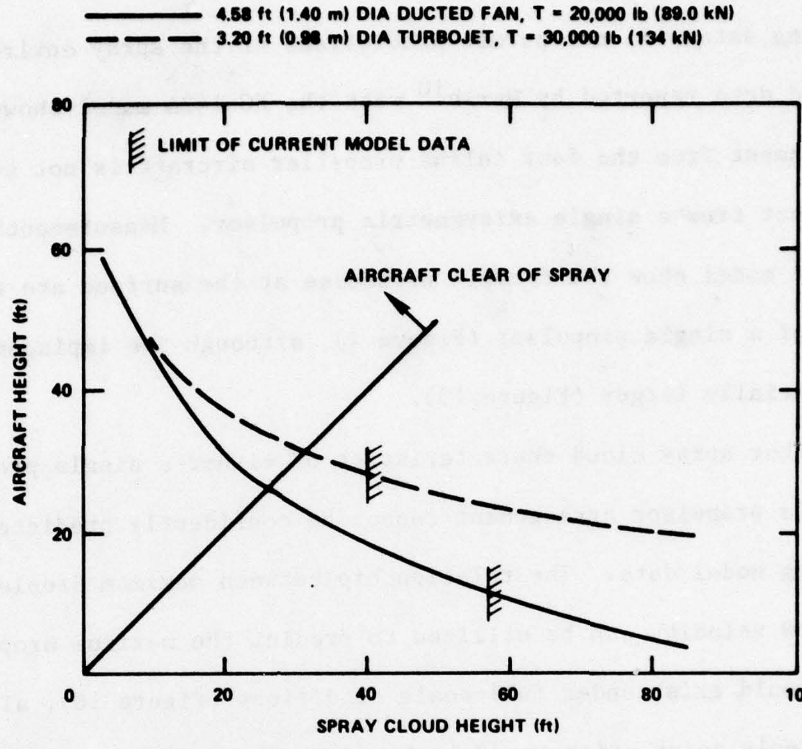


Figure 22 - Predicted Spray Cloud Heights for Two Conceptual Propulsors

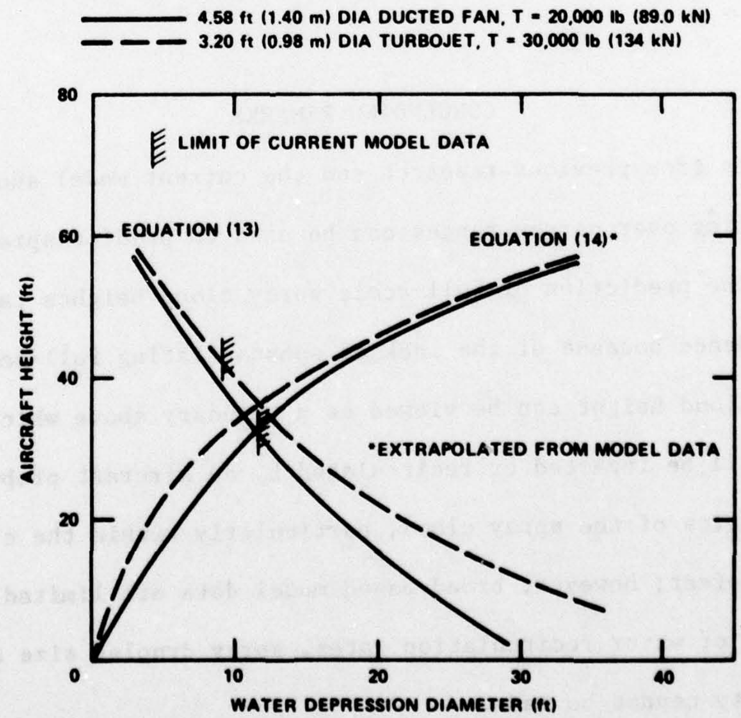


Figure 23 - Predicted Water Depression Diameters for Two Conceptual Propulsors

existing data will not permit predictions of the spray environment. The limited data reported by Marsh[10] with the XC-142A model shows that the flow environment from the four inline propeller aircraft is not substantially different from a single axisymmetric propulsor. Measurements from the XC-142A model show the dynamic pressures at the surface are similar to those of a single propulsor (Figure 4), although the impingement area is substantially larger (Figure 13).

Other spray cloud characteristics of either a single propulsor or multiple propulsor arrangement cannot be confidently predicted from existing model data. The relationship between maximum droplet diameter and flow velocity can be utilized to predict the maximum droplet diameter which would exist under full-scale conditions (Figure 16), although even this simple calculation would be based on data which are substantially scattered.

CONCLUDING REMARKS

Results from previous research and the current model show that Froude-scaling over narrow ranges can be used to predict spray cloud heights. The prediction of full-scale spray cloud heights cannot be made with confidence because of the lack of substantiating full-scale data. The spray cloud height can be viewed as a boundary above which little or no spray will be ingested or recirculated by an aircraft propulsor. The characteristics of the spray cloud, particularly within the cloud, are of greater interest; however, broad-based model data are limited. Full-scale predictions of water recirculation rates, spray droplet size and density, or visibility cannot be made.

The water depression caused by an impinging VTOL aircraft propulsor is of some interest since the geometry of this depression determines, to some extent, the spray trajectory. There is a considerable discrepancy between the depression diameter and the propulsor characteristics relationships determined from various model tests.

The spray generated by multiple propulsors and the effects of the aircraft body and the proximity of a ship are unknown. The effects of reasonable values of relative wind (typical of moderate sea conditions) have been shown to be negligible for lightly loaded propulsors (free propellers). The effects on the spray generated from highly loaded propulsors is unknown.

The current data permit only the spray cloud height to be predicted for axisymmetric propulsors under conditions where the flow at the water surface has a relatively low velocity or the propulsor has a large diameter (i.e., $F_x^* < 1.20$). Under other conditions little information, if any, can be predicted. The current understanding of the phenomenon is also limited to propulsors with diameters less than and disk loadings greater than current or projected rotary wing aircraft.

RECOMMENDATIONS

The current ability to predict full-scale spray characteristics is very limited due to a lack of coordinated investigation of the spray generation phenomenon. To develop such a predictive capability the following are recommended:

1. Full-scale testing of simple propulsor configurations must be conducted. The spray clouds in such tests should be investigated in detail to provide droplet and flow characteristics.

2. Further subscale model testing must be conducted (over a spectrum of physical conditions) to compare results with earlier subscale tests. This is a necessary procedure to develop a valid scaling relationship.

3. Tests with subscale models of complex aircraft/propulsor configurations must be conducted to assess the realistic characteristics of the spray generated by a VTOL aircraft.

4. Finally, the effects of propulsor efflux characteristics, relative wind, waves, and the proximity to a ship must be investigated to provide operational guidance.

In all cases, the meaningful characteristics of the spray cloud (and water depression) must be observed; and in most cases, the rate of water ingestion (recirculation) or the visibility through the spray will be the most important characteristics. Observation of other parameters, however, may provide better insight into the fundamental aspects of the spray generation phenomenon.

ACKNOWLEDGEMENTS

The assistance of Lieutenant Colonel Roger W. Gallington, USAF, and Commander William J. H. Smithey, USN, was invaluable during this effort. Mr. David G. Rousseau contributed in the reduction of the data and in the formulation of the empirically derived results. The author especially wishes to thank Mr. Richard E. Kuhn for his continued assistance and guidance during this study.

REFERENCES

1. Banks, R.B. and D.V. Chandrasekhara, "Experimental Investigation of the Penetration of a High-Velocity Gas Jet through a Liquid Surface," J. Fluid Mech., Vol. 15, pp. 13-34 (Jan 1963).

2. Olmstead, W.E. and S. Raynor, "Depression of an Infinite Liquid Surface by an Incompressible Gas Jet," J. Fluid Mech., Vol. 19, pp. 561-576 (Aug 1964).

3. Kuhn, R.E., "An Investigation to Determine Conditions under which Downwash from VTOL Aircraft Will Start Surface Erosion from Various Types of Terrain," NASA TN D-56 (Sep 1959).

4. Dyke, R.W., "An Investigation of the Over Water Aspects of VTOL Airplanes at High Disk Loading," Curtis-Wright Report 012-26 (Dec 1963).

5. Kuhn, R.E. et al., "Over-Water Aspects of Ground-Effect Vehicles," Inst. Aero. Sci. Paper 60-14 (Jan 1960).

6. Morse, A., "VTOL Downwash Impingement Study, Velocity Survey," U.S. Army Transportation Research Command Report 60-58 (Aug 1960).

7. Fearom, J.R.C. and D.H. Norman, "VTOL and STOL: Simple Solutions to Some of the Operating Problems during Takeoff and Landing," J. Royal Aero. Sci., Vol. 66, No. 614, pp. 67-76 (Feb 1962).

8. Pruyn, R.R., "Effects of Airframe Geometry on Downwash Problems of Tandem Ducted-Propeller VTOL Aircraft," Kellett Aircraft Corp. Report 179T80-6 (Jan 1964).

9. Joshi, P.B. et al., "Final Report on Experimental Studies of Spray Patterns and Thrust Characteristics Produced by Vertical Disk Thrusters above a Water Surface," Virginia Polytechnic Institute and State University Report VPI-AERO-062 (Feb 1977).

10. Marsh, K.R., "Research on VTOL Water Hover Effects of Wind and Waves," Ling-Tempo-Vought Report 2-55400/8R-6140 (Apr 1968).

11. Kurylowich, G. and A. Ritter, "Experiments on Pilot Visibility from a V/STOL in Overwater Hover," J. American Helicopter Soc., Vol. 16, No. 4, pp. 19-28 (Oct 1971).

12. Gray, L. and E. Kisielowski, "Practical Engineering Methods for Predicting Hot Gas Reingestion Characteristics of V/STOL Aircraft Jet-Lift Engines," NASA CR-111845 (Feb 1971).

13. Hanson, A.R. et al., "Shock Tube Investigation of the Breakup of Drops by Air Blasts," Physics of Fluids, Vol. 6, No. 8, pp. 1070-1080 (Aug 1963).

DTNSRDC ISSUES THREE TYPES OF REPORTS

1. DTNSRDC REPORTS, A FORMAL SERIES, CONTAIN INFORMATION OF PERMANENT TECHNICAL VALUE. THEY CARRY A CONSECUTIVE NUMERICAL IDENTIFICATION REGARDLESS OF THEIR CLASSIFICATION OR THE ORIGINATING DEPARTMENT.

2. DEPARTMENTAL REPORTS, A SEMIFORMAL SERIES, CONTAIN INFORMATION OF A PRELIMINARY, TEMPORARY, OR PROPRIETARY NATURE OR OF LIMITED INTEREST OR SIGNIFICANCE. THEY CARRY A DEPARTMENTAL ALPHANUMERICAL IDENTIFICATION.

3. TECHNICAL MEMORANDA, AN INFORMAL SERIES, CONTAIN TECHNICAL DOCUMENTATION OF LIMITED USE AND INTEREST. THEY ARE PRIMARILY WORKING PAPERS INTENDED FOR INTERNAL USE. THEY CARRY AN IDENTIFYING NUMBER WHICH INDICATES THEIR TYPE AND THE NUMERICAL CODE OF THE ORIGINATING DEPARTMENT. ANY DISTRIBUTION OUTSIDE DTNSRDC MUST BE APPROVED BY THE HEAD OF THE ORIGINATING DEPARTMENT ON A CASE-BY-CASE BASIS.