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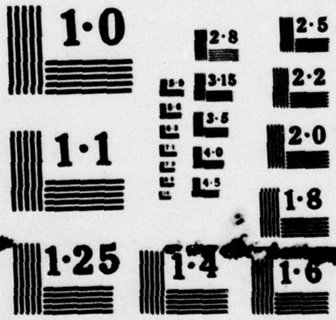
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LEVEL II

HEIGHT OF SPRAY PRODUCED BY VERTICAL TAKEOFF AND LANDING (VTOL) AIRCRAFT

by

Richard E. Kuhn

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AVIATION AND SURFACE EFFECTS DEPARTMENT

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April 1979

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NOTATION

D	Diameter of jet nozzle or rotor, ft (m)
D_e	Effective diameter, diameter of circle having same area as total area of nozzles or slipstreams, ft (m)
H_n	Height of nozzle or rotor above surface, ft (m)
H_s	Height of spray above surface, ft (m)
N	Number of jets or slipstreams; Newton
q_n	Impact dynamic pressure at jet nozzle, $(P_t - P_o)$, or disk loading of rotor, $\frac{W}{2 \frac{\pi}{4} D_e^2}$, lb/ft^2 (N/m^2)
q_s	Maximum impact dynamic pressure measured in surface jet sheet at radial station r, lb/ft^2 (N/m^2)
$q_{s,o}$	Lowest dynamic pressure at which spray is produced, lb/ft^2 (N/m^2)
q_z	Maximum impact dynamic pressure measured in jet or slipstream at station z, lb/ft^2 (N/m^2)
P_t	Nozzle total pressure, lb/ft^2 (N/m^2)
P_o	Ambient static pressure, lb/ft^2 (N/m^2)
r	Radial station at which q_s is measured, ft (m)
R_1	Radial station at which $q_s = q_z$, ft (m)
R_2	Radial station at which dynamic pressure in surface jet sheet has decayed to $q_s = 2.0$, ft (m)
W	Aircraft weight, lb (N)
z	Vertical distance below jet nozzle or rotor, ft (m)
S	Spray height correlation parameter

ABSTRACT

The flow phenomenon involved in the production of spray by a vertical takeoff and landing aircraft hovering over smooth water is examined, and a method for predicting spray height is developed from a correlation of the limited amount of large-scale data available. Suggestions for further work are included.

ADMINISTRATIVE INFORMATION

This investigation was completed in partial fulfillment of Navy contract N00167-78-M2599 for the assessment of V/STOL aerodynamics technology. Mr. Kuhn was engaged in V/STOL aircraft research with the NASA Langley Research Center for many years. He now serves as a V/STOL consultant to both Industry and Government.

INTRODUCTION

The onset of spray and the amount of spray raised up by hovering vertical takeoff and landing (VTOL) aircraft have been the subjects of several investigations (for instance, Kuhn,[1] Dykes,[2] and Pruyn[3*]). However, large-scale data are limited at high pressure ratio and none exist from systematic investigation. Papadales[4] recently reviewed and extended these earlier investigations and concludes that "Froude-scaling over narrow ranges can be used to predict spray cloud heights"; however, "the prediction of full-scale spray cloud heights cannot be made with confidence because of the lack of substantiating full-scale data."

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[*] A complete listing of references is given on page 24.

Recently, additional full-scale data points have been obtained from observations, photographs, and motion pictures of vertical/short takeoff and landing (V/STOL) aircraft operations. The flow fields and the phenomenon involved in producing spray are re-examined in this report. In addition, a correlation is developed and a method is proposed for predicting the height of the spray cloud produced by a hovering VTOL aircraft.

FLOW CONDITIONS

As illustrated schematically in Figure 1, several flow conditions influence when and how much spray is produced by a hovering VTOL aircraft. When the jet stream or slipstream reaches the ground or water surface, it spreads and flows radially outward from the point of impingement in a flat sheet or wall jet. The scrubbing action of this surface flow sets the surface water in motion creating a succession of outwardly radiating concentric wavelets. Observations by Russell and MacMillan[5] of the effects of wind over the open sea and the results of model studies by Kuhn and Dyke[2] of spray produced by jets and slipstreams have shown that no spray is produced when the outward flowing sheet of air has a velocity below 21 to 26 knots (below a dynamic pressure of about 2 lb/ft^2 (95.76 N/m^2)); see Figure 1, Condition I. Above a dynamic pressure of about 2 lb/ft^2 (95.76 N/m^2), the amount and height of the spray increase with velocity or dynamic pressure.

In addition, observations of spray produced by small-scale jets indicate that the depression of the water surface by the impinging jet and the slope of the cavity walls can have a significant effect on the height of the spray. If the dynamic pressure of the impinging stream is small and the diameter of the impingement region is large relative to the depression of the water surface, the outward flow remains relatively flat. Thus, the spray is carried aloft only by the inward flowing recirculating air currents being entrained into the wall jet; see Figure 1, Condition II. At higher pressures of the impinging stream, a pronounced cavity can form in the water surface and spray is given a direct upward vertical component of velocity, Figure 1, Condition III. There is, of course, a very gradual progression from Conditions II to III.

Examination of photographs and motion pictures of actual VTOL aircraft operations indicates that the flow conditions almost always correspond to Condition II. On the other hand, much of the model data of Kuhn[1] and Dyke[2] were obtained at settings where the height of the spray exceeded the height of the nozzle, sometimes by a factor of 5 or 6, and the flow corresponded to Condition III. In the present correlation model, data have been used only from test conditions where the spray height did not exceed the nozzle height.

FREE AIR JET DECAY

A jet or slipstream issuing into still air decays with distance from the nozzle or rotor because of mixing with the surrounding air. Figure 2 presents this decay in terms of the maximum dynamic pressure measured at any station Z downstream from the nozzle or rotor for several models and full-scale (J-85) systems. Küchemann[6] shows that over the first five or six diameters the mixing does not penetrate

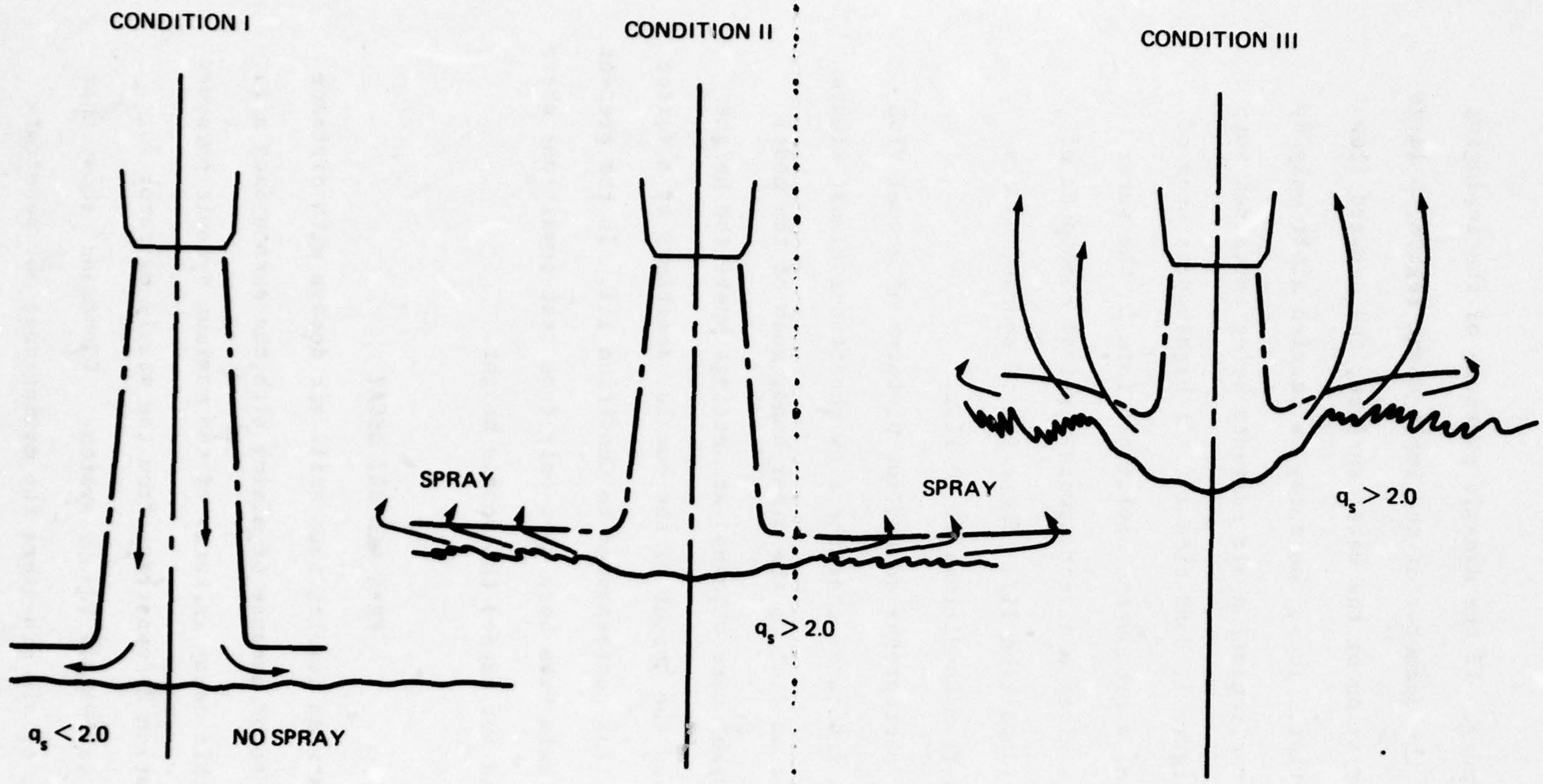

Figure 1 - Flow Conditions Involved in Spray Production

to the centerline, leaving a full velocity (dynamic pressure) core for a distance of five or six diameters. Beyond this point the velocity on the axis decreases in direct proportion to the distance (the dynamic pressure is therefore inversely proportional to the square of the distance). The data of McLemore[7] for the J-85 with both the long and short nozzles are in excellent agreement with this variation. The long nozzle does appear to have a longer core, which is probably due to the longer settling chamber between the turbine and the nozzle exit.

If multiple nozzles are separated far enough so that there is no tendency for them to merge, the dynamic pressure, presented in terms of the distance in effective diameters D_e, would be expected to be reduced by the number of nozzles. The data for the four-nozzle configuration of McLemore[7] is in good agreement with this assumption to a distance of eight or ten effective diameters. Beyond that distance the decay rate reduces, indicating that the jets are beginning to merge. Extrapolation of the data indicates that at a distance of 40 to 60 effective diameters, the jets would be fully merged and the decay would be expected to follow the curve for the single jet.

The variation of dynamic pressure with distance beyond the end of the core can be expressed for circular jets as:

$$\frac{q_z}{q_n} = \frac{36}{N\left(\frac{z}{D_e}\right)^2} \qquad (1)$$

Higgins[8] investigated nozzles designed specifically to promote mixing and a rapid decay. The envelope of the data showing the maximum

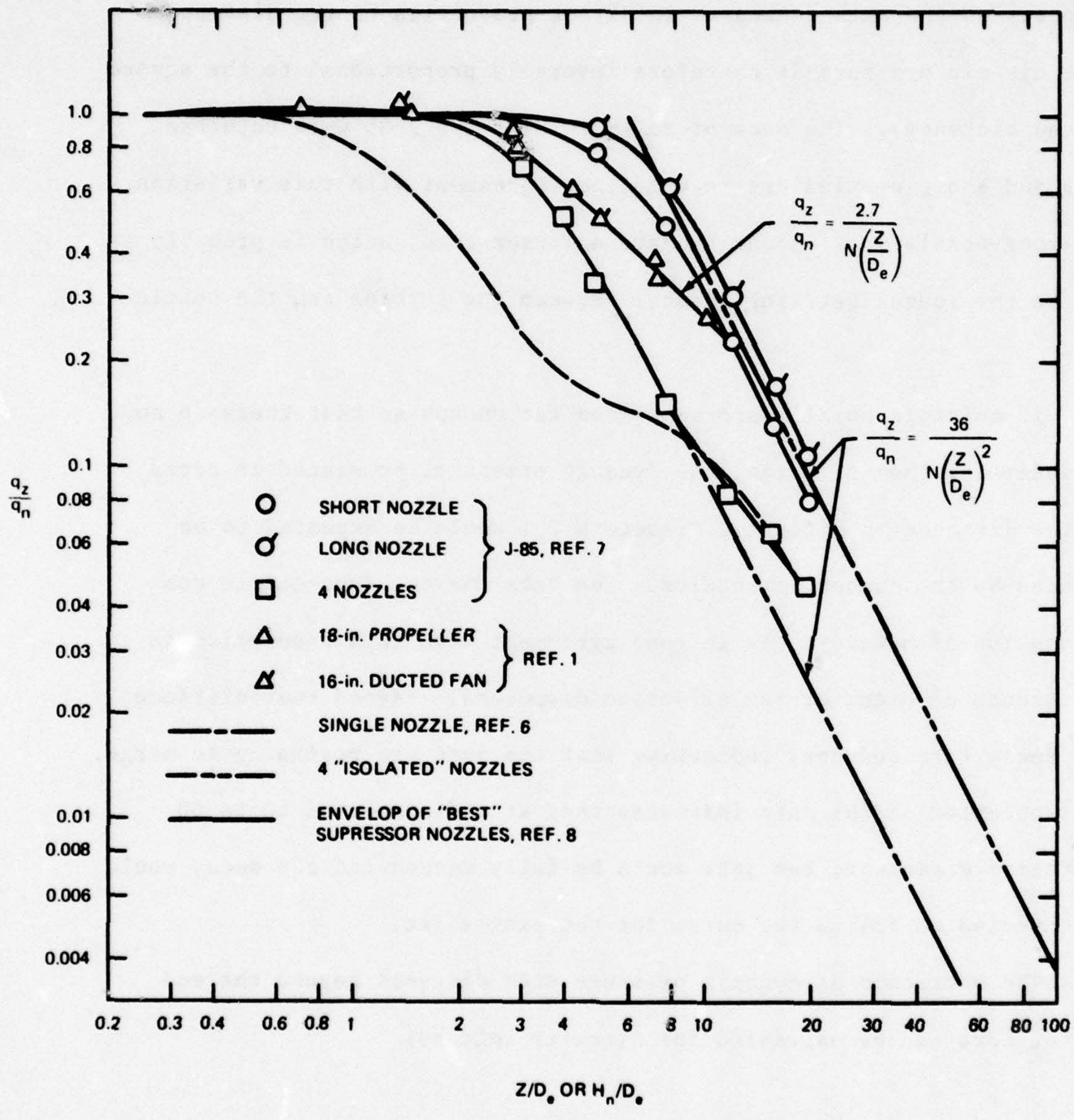

Figure 2 - Slipstream and Jet Decay

decay attained is included in Figure 2. The decay curve for any specific noncircular nozzle must be obtained using these data[8] or from other experimental data.

The decay of dynamic pressure for rotors and ducted fans is shown (Figure 2) to start much closer to the rotor and to be more gradual than for a jet. This difference in behavior is probably due to the highly nonuniform radial load distribution. For rotors and ducted fans, the dynamic pressure variation can be expressed as:

$$\frac{q_z}{q_n} = \frac{2.7}{N\left(\frac{z}{D_e}\right)} \qquad (2)$$

This expression is valid to distances of 12 to 15 diameters. At this point the effects of the nonuniform loading are probably eliminated, and the decay would be expected to follow the curve for the single jet.

DECAY OF SURFACE DYNAMIC PRESSURE

When a jet or slipstream reaches the ground or water surface, it spreads and flows radially outward from the impingement point. O'Bryan[9] observed that this outward flowing jet sheet was essentially constant in thickness. Momentum and continuity considerations therefore would dictate that the velocity of the flow would decrease linearly with radial distance. Thus, the dynamic pressure would be inversely proportional to the square of the distance, which is verified by the data presented in Figure 3.

Data for two of the supressor nozzles used by Higgins[8] are also included in Figure 3. As was observed by Kuhn,[1] the maximum value

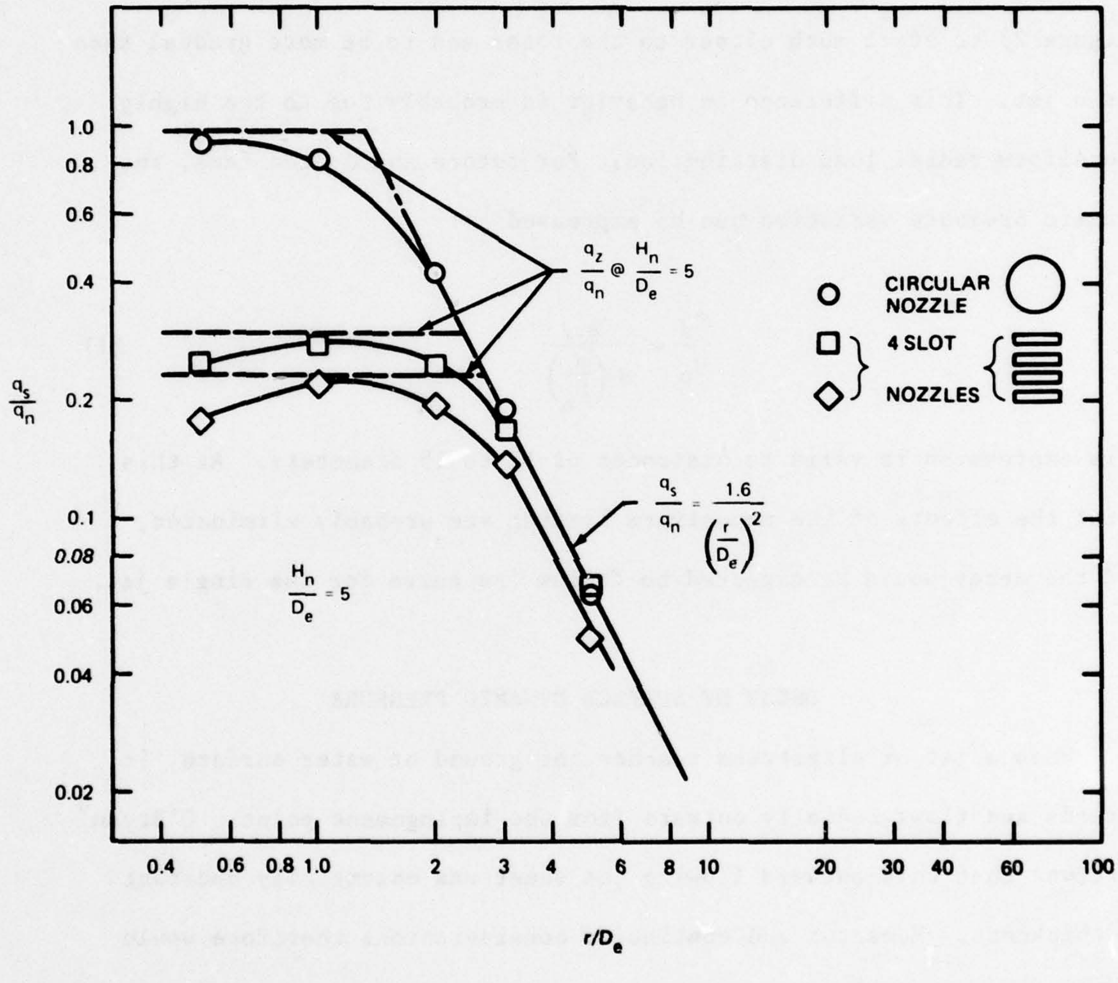

Figure 3 - Radial Variation of Dynamic Pressure in Surface Jet Sheet (from Reference 8)

of dynamic pressure reached is approximately equal to the dynamic pressure that the jet would have decayed to in free air at a distance from the nozzle equal to the height of the nozzle above the surface. The data also indicate, however, that although the maximum surface dynamic pressure has been reduced, the surface dynamic pressure in the outer regions has not. Beyond the radial distance at which $q_s = q_z$, the dynamic pressure in the outward flowing jet sheet is essentially the same as that from the simple circular nozzle. This suggests that, for a given mass flow, the surface dynamic pressure in the outer regions is independent of nozzle configuration and can be expressed as:

$$\frac{q_s}{q_n} = \frac{1.6}{\left(\frac{r}{D_e}\right)^2} \tag{3}$$

LARGE-SCALE SPRAY DATA

There have been no large-scale investigations of the spray produced by high disk loading VTOL's. The limited amount of data available, Table 1, was obtained from visual observations, motion pictures, and photographs of VTOL's being operated for other purposes, for example, demonstrations, shipboard trials, or routine operations. The aircraft height and the spray height have necessarily been obtained by scaling photographs such as Figures 4 and 5. Also, the operating weight of the aircraft is unknown. For the present study, the aircraft weight is assumed to be midway between the empty weight and the maximum hover weight.

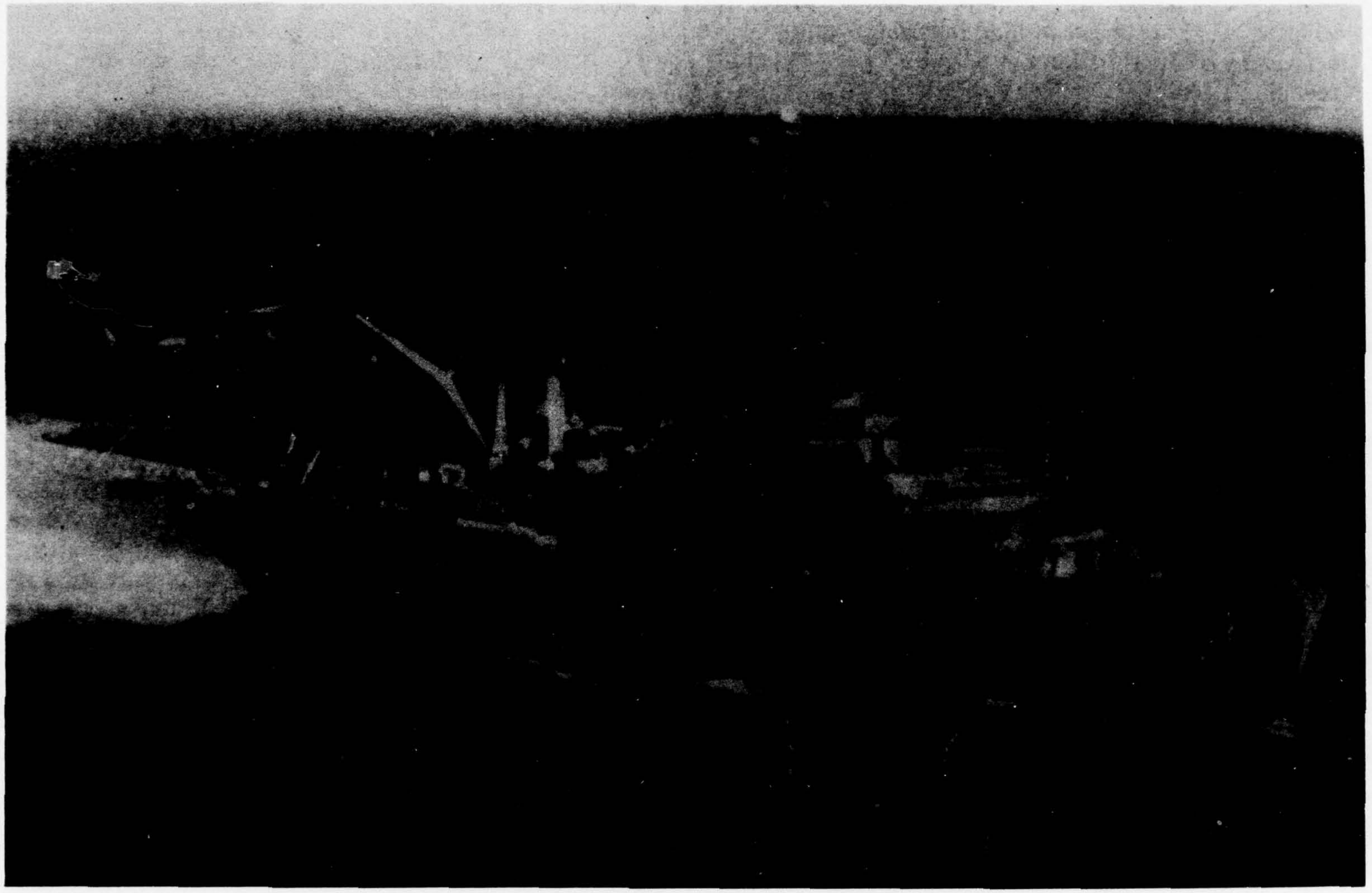

Figure 4 - Spray Produced by a CH-53E Helicopter

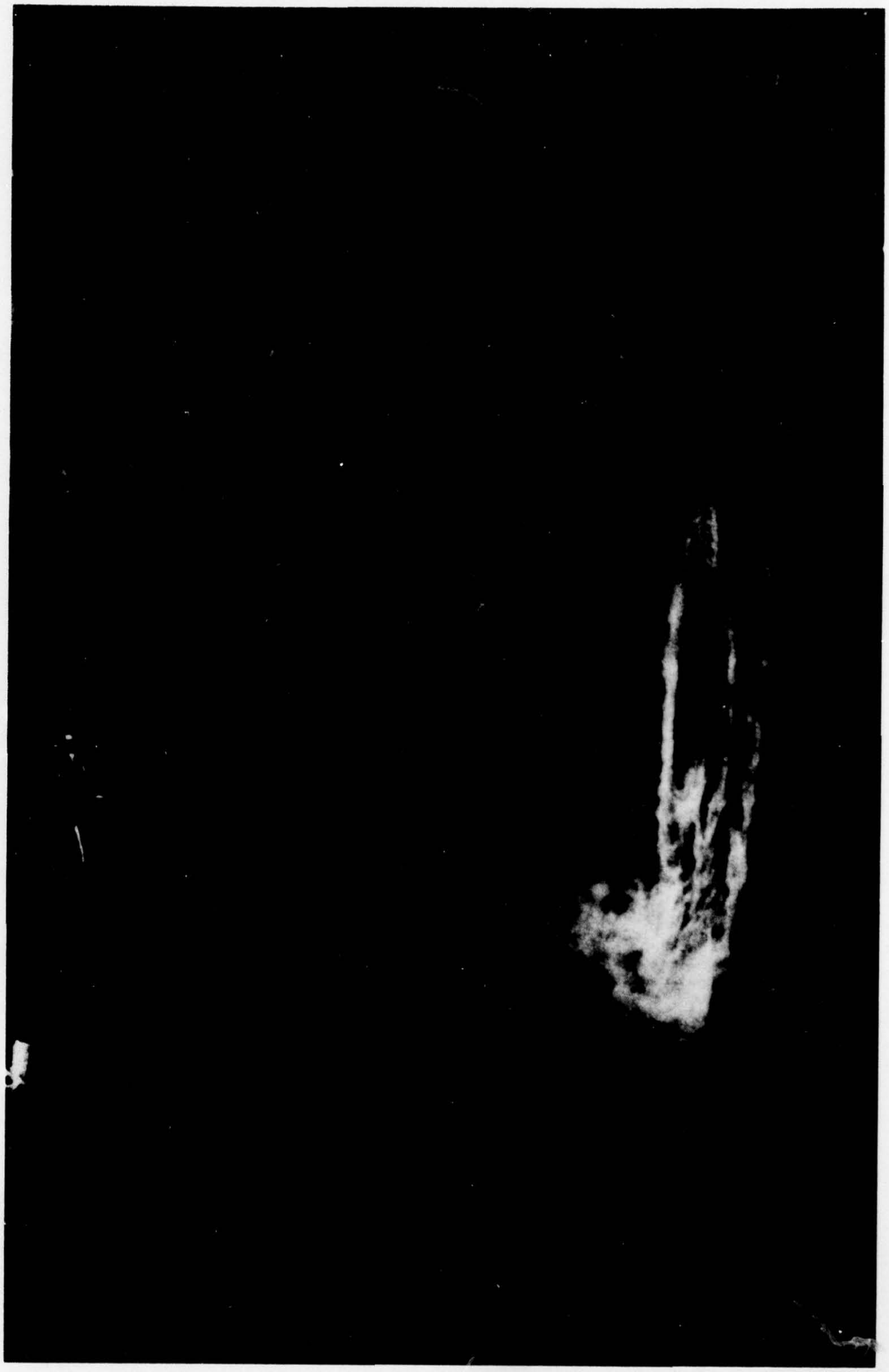

Figure 5 - Spray Produced by a Harrier Aircraft at 150 Feet Altitude Over the Mississippi River

TABLE 1 - FULL-SCALE DATA

Configuration	Assumed Weight lb	D_e ft	q_n lb/ft^2	H_n ft	Hs	q_z lb/ft^2	Source
CH - 53E	41,000	56[1]	8.3	102	68	8.3	Figure 4
X-100	3,900	10.4[2]	23	21	16	15	Reference 2
XV-5A	9,600	7.35[3]	115[6]	25	25	46	Private Communication
X-13	6,500	2.0[4]	1200[6]	68	36	37	Reference 1
AV-8A Harrier	15,000	2.96[5]	1270[6]	150	35	4.5	Figure 5
				100	50	10	Private Communication
				65	65	28	
				60	60	24	

Notes:
1. One rotor - 79-ft diameter
2. Two propellars - 10.4-ft diameter each
3. Two fans-in-wing - 5.2-ft diameter each
4. Single nozzle
5. Four nozzles - 6.88 ft^2 total area
6. Estimated from weight and nozzle area

MODEL DATA

Model data used in the present correlation are taken from References 1 and 2. As indicated, much of the model data were taken at conditions where the spray height exceeded the nozzle height (corresponding to Condition III of Figure 1, a condition not observed in the full-scale data). For the present correlation, only data points were used from References 1 and 2 where the spray height did not exceed the nozzle height. These data are presented in Table 2.

TABLE 2 - MODEL DATA

Configuration	D_e ft	q_n lb/ft^2	H_s/D_e	H_n/D_e	q_z/q_n
4 - In. Nozzle	0.33	100.0	11.0	12	0.15
Reference 1	↓	↓	4.5	18	0.08
	↓	↓	3.5	24	0.05
	↓	70.0	7.0	12	0.15
	↓	↓	4.0	18	0.08
	↓	↓	1.5	24	0.07
	↓	50.0	3.5	12	0.15
	↓	30.0	2.0	12	0.15
	↓	20.0	4.0	5.6	0.42
	↓	10.0	0.5	6.7	0.40
10 - In. Nozzle	0.83	7.3	0.5	4	0.80
Reference 2	↓	18.3	7.4	4	0.80
	↓	21.3	3.5	4	0.80
X-100 Model	1.56	6.0	0.44	5	0.42
Reference 2	↓	7.5	1.72	↓	↓
	↓	9.2	3.0	↓	↓

PREDICTION OF SPRAY HEIGHT

Observation of both model and full-scale devices over water indicates that spray is produced in an annular ring around the impingement point. This effect is shown in photographs of the XV-5A aircraft hovering over water, Figure 6. In the top photograph, the aircraft is high enough so that the streams from the lift fans have merged and only one impingement pattern is present. In the middle photograph, the impingement of the individual wing fans is apparent as is the stagnation line, or fountain flow, between them. In the bottom photograph (the minimum hover height attempted), the spray blocks the view of the surface conditions.

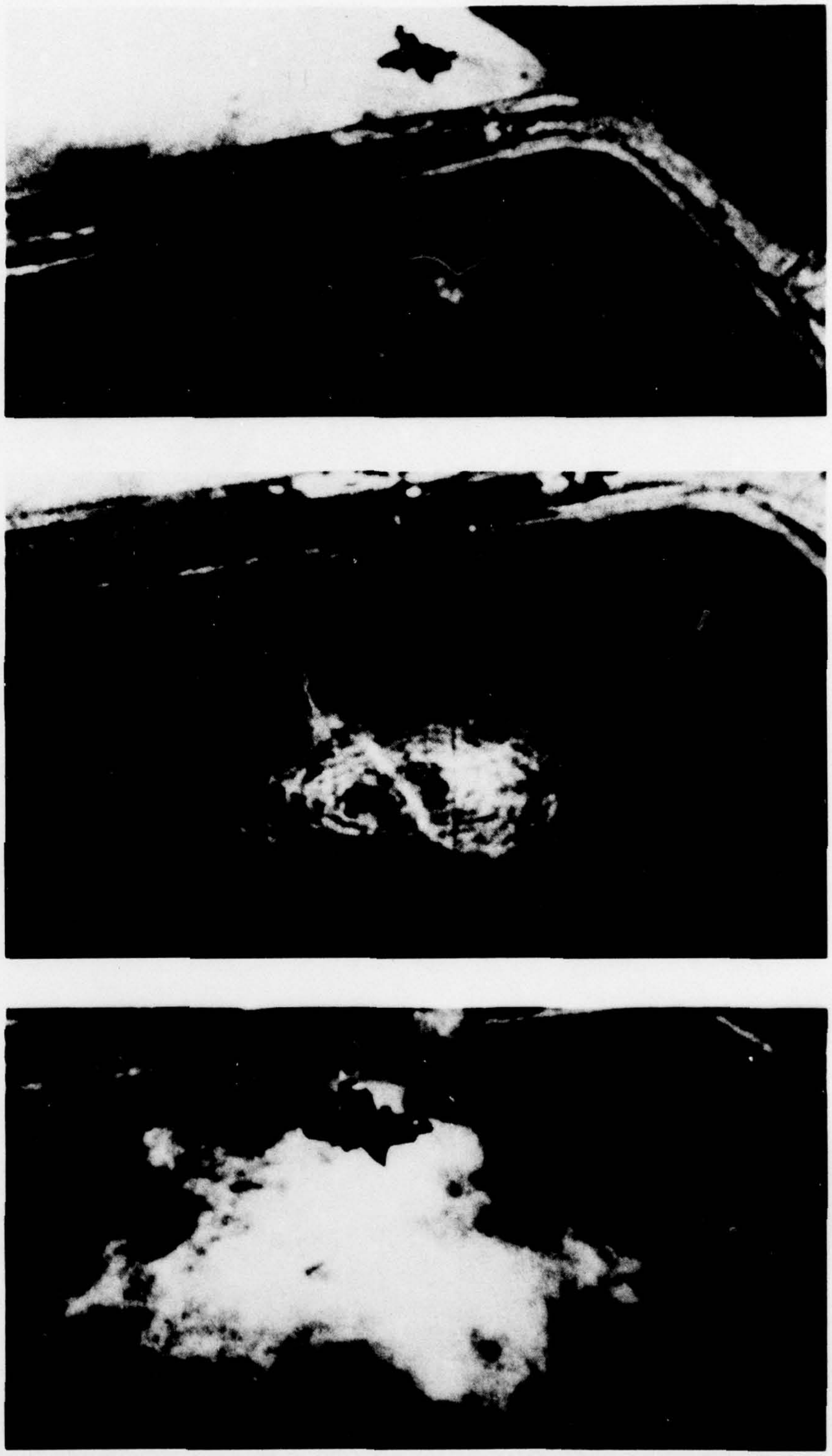

Figure 6 - Spray Produced by the XV-5A Aircraft

As shown in both the top and middle photographs, no spray is being produced in the inner region. In this region the air and, by a scrubbing action, the water are being accelerated from zero at the center where a stagnation point must exist, to a maximum value dictated by the decay characteristics of the jet or slipstream. In the outer region the air is decelerating in accordance with Equation (3) from Figure 3. In this region the wavelets are over-running those ahead of them, breaking and producing spray. The amount of spray produced should be a function of the annular area and the surface dynamic pressure.

The basis of the method suggested for predicting spray height is shown in Figure 7. Spray is assumed to be produced between two radial stations:

1. The inner radius R_1 is defined as the radius at which the surface dynamic pressure (calculated from Equation (3)) is equal to the dynamic pressure to which the jet or slipstream has decayed to in a distance equal to the height of the jet or rotor (calculated by Equations (1) or (2)). Thus,

$$\frac{R_1}{D_e} = \frac{\sqrt{1.6}}{\sqrt{\frac{q_z}{q_n}}} \qquad (4)$$

2. The outer radius R_2 is defined as the radius at which the surface dynamic pressure has fallen below the spray producing threshold of $q_{s,o} = 2.0\ \mathrm{lb/ft^2}$ ($95.76\mathrm{N/m^2}$). Thus,

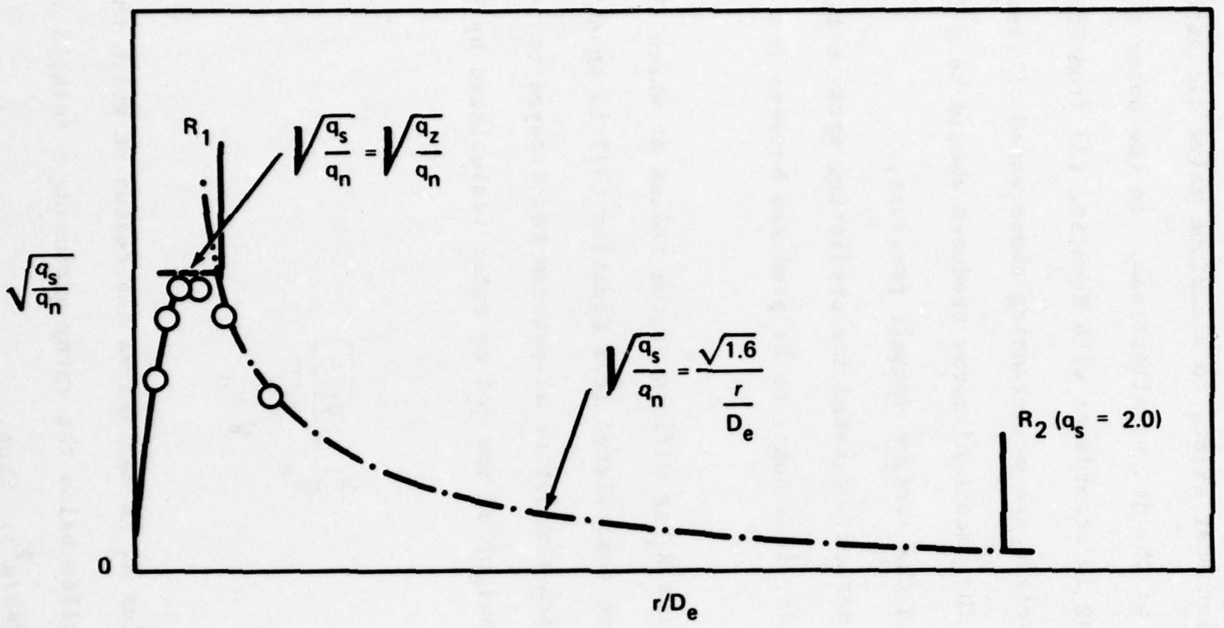

Figure 7 - Basis for Spray Parameter S

$$\frac{R_2}{D_e} = \frac{\sqrt{1.6}}{\sqrt{\frac{q_{s,o}}{q_n}}} \qquad (5)$$

The spray height parameter S is defined as:

$$S = \int_{R_1}^{R_2} \frac{r}{D_e} \sqrt{\frac{q_s}{q_n}} \, d\left(\frac{r}{D_e}\right)$$

and

$$\frac{r}{D_e} \sqrt{\frac{q_s}{q_n}} = \text{constant} - \sqrt{1.6}$$

Thus, paramater S can be written as:

$$S = \sqrt{1.6}\left(\frac{R_2}{D_e} - \frac{R_1}{D_e}\right) = \sqrt{1.6}\left(\frac{\sqrt{1.6}}{\sqrt{\frac{q_{s,o}}{q_n}}} - \frac{\sqrt{1.6}}{\sqrt{\frac{q_z}{q_n}}}\right)$$

or

$$S = 1.6\left(\sqrt{\frac{q_n}{q_{s,o}}} - \frac{1}{\sqrt{\frac{q_z}{q_n}}}\right) \qquad (6)$$

The variation of spray height with the spray parameter S is shown in Figure 8. In this correlation it was assumed that the slipstreams from the two propellers of the X-100 and from the two fans on the XV-5A did not merge because of the low operating heights. Also, it was assumed

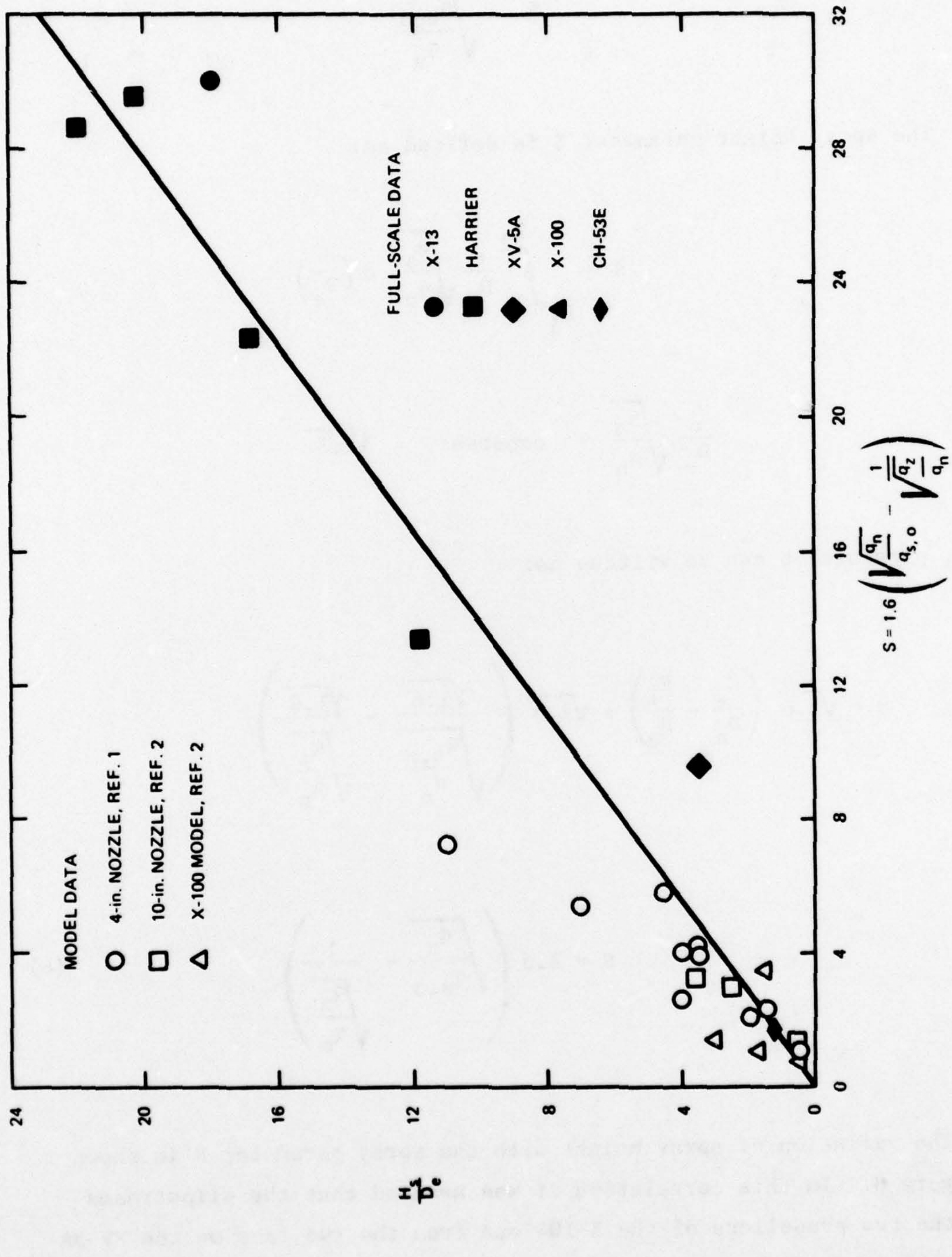

Figure 8 - Spray Height Correlation

that the jets from the Harrier did not merge, even at a height of 50 diameters, because the jets are canted out (5 deg each on the front nozzles and 12.5 deg each on the rear nozzles).

The correlation of Figure 8 indicates that the spray height can be expressed as:

$$\frac{H_s}{D_e} = 1.15\left(\sqrt{\frac{q_n}{q_{s,o}}} - \frac{1}{\sqrt{\frac{q_z}{q_n}}}\right) \tag{7}$$

where q_z/q_n is obtained from Figure 2.

MINIMUM OPERATING HEIGHT

During normal aircraft operations, limiting the hover to heights equal to or greater than the spray height is desirable to minimize corrosion and pilot visibility problems. Equation (7) is used to estimate the height at which spray reaches the nozzle or rotor for a range of disk loadings and for several operating weights and VTOL concepts; see Figure 9. Because the lower loadings require larger diameters to produce the thrust required to support the weight, the limiting height is primarily a function of the operating weight and is only slightly dependent on the disk loading and the lifting configuration. This correlation indicates that the minimum hover height for jet VTOL aircraft is given approximately by:

$$\left(H_n\right)_{min} = 0.6 \quad W$$

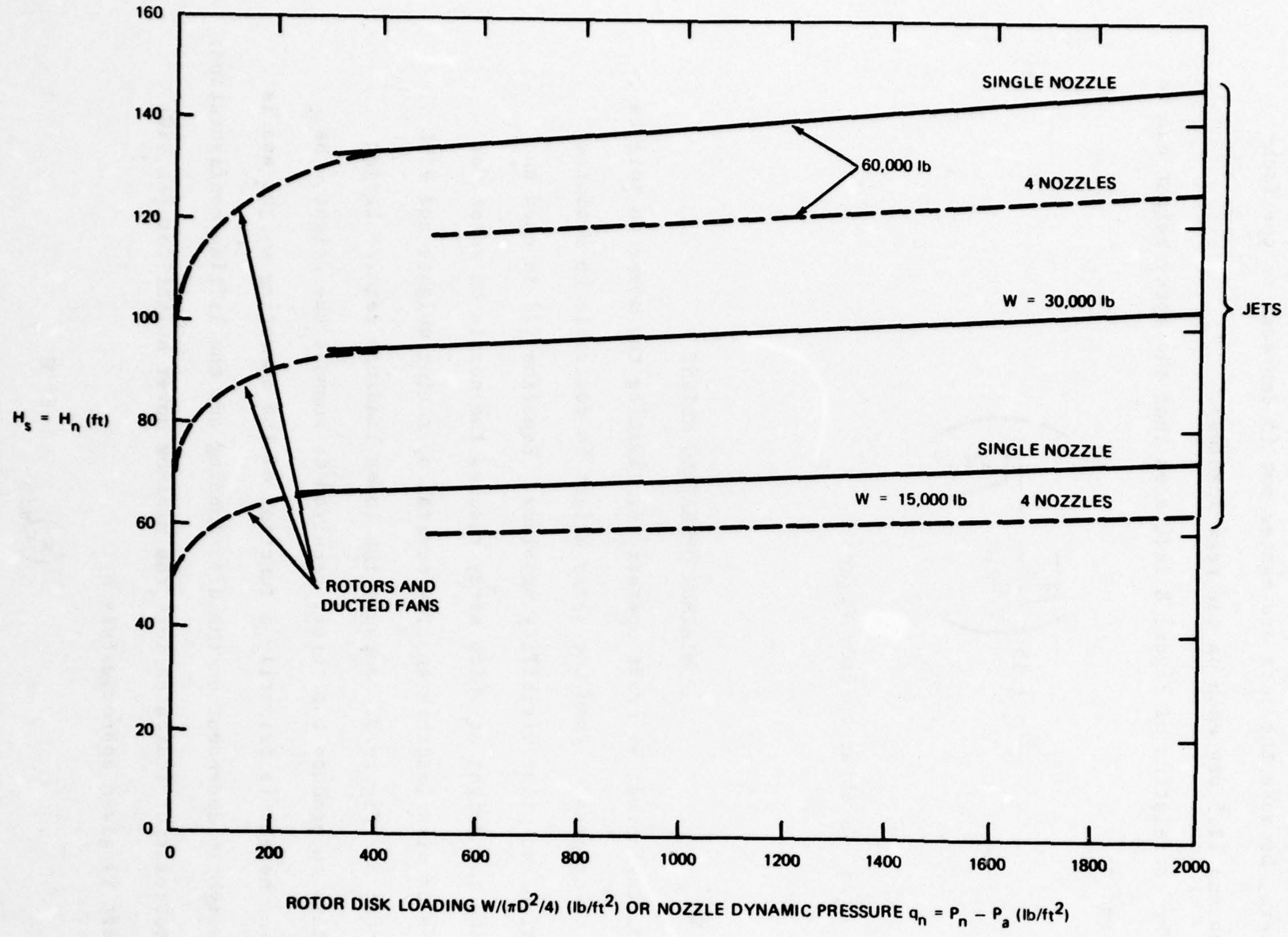

Figure 9 - Minimum Hovering Height to Stay Above Spray

NEED FOR ADDITIONAL WORK

Spray is of concern to investigators because of the possible corrosion implications and the impairment to pilot visibility; neither effect can be evaluated from the data available. In addition, the spray produced in large-scale experiments is considerably different in character from that produced in small-scale experiments. The spray from full-scale aircraft appears fine and misty; whereas, the spray from model experiments appears coarse and glassy. Perhaps the fine spray is not produced in small-scale experiments or is too diffuse to be noticed. Also, the coarser spray could be hidden inside the spray cloud seen in the full-scale photographs. Additional work is required to evaluate the quantity, droplet size, and density of the spray in the cloud for better guidance in determining limiting operating conditions. Various flow deflectors should also be studied to determine the feasibility of lowering the minimum operating height and to protect both the ship gear and the aircraft from spray.

The following specific suggestions are offered:

1. Future work should include tests with full-scale engines which are at least the J-85 size or larger.
2. At least two engines should be used so that the effects of spacing and inclination can be studied.
3. Jet decay and surface jet sheet decay surveys should be carried out to 50 and preferably 100 diameters.
4. Heights above the water should be variable to 50 diameters. Lateral translation should also be provided, with both vertical and lateral movement rates high enough so that

realistic takeoff and landing maneuvers can be simulated.

5. Instrumentation should include:
    a. Remote cameras and background grids to provide an accurate measure of the spray cloud.
    b. Cameras or other instrumentation mounted on the rig at the pilot's eye position to provide a measure of visibility impairment.
    c. A grid of sampling devices at strategic locations in the spray cloud to provide a quantitative measure of droplet size and density distribution.
    d. Accurate measurement of height and thrust.
6. Special attention should be given to the effects of a blockage to the spreading of the surface jet sheet, such as the ship hull, which may project the flow upward and increase the spray height. Also, the possible use of deflectors to divert this up flow, or the jet itself, to surpress or deflect the spray should be investigated.

Once a better understanding of the mechanism of spray generation has been obtained from full-scale experiments, a re-examination of possible small-scale modeling for specific configurations may be appropriate.

Although not included in the studies in this report, there is growing concern over the possible effects of deck heating with afterburning jet VTOL configurations. The rig designed for full-scale spray studies could also be used for deck heating and protection studies, if this use is considered in the design stage.

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CONCLUDING REMARKS

In the present study, an empirical method has been developed for predicting the height of the spray cloud produced by a VTOL aircraft hovering over smooth water. The method is limited to conditions where the spray height does not exceed the nozzle or rotor height and includes VTOL concepts ranging from the helicopter to jet VTOL's. Application of the method shows that the spray height is primarily dependent on the operating weight of the aircraft and is only slightly dependent on the disk loading.

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