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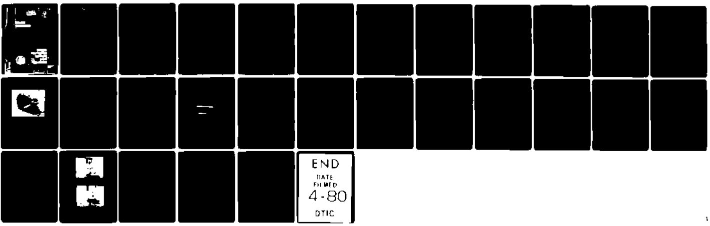

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VPI-AERO-062A

Final Report
on
Experimental Studies of Spray Patterns and Thrust Characteristics Produced by Vertical Disk Thrusters Above a Water Surface

by

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This report is in two parts, and it describes two separate, but closely related, studies of the interaction of a vertical thruster and a water surface. The first study was conducted at DTNSRDC and involved investigations of the effects of thrust loading, height, tilt and surface waves on spray patterns. The data were interpreted in a separate effort at VPI & SU. The main effort at VPI & SU was concerned with droplet size measurements in the spray as a function of thrust loading, propeller diameter and height. The experimental study was planned on the basis of →

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ABSTRACT

This report is in two parts, and it describes two separate, but closely related, studies of the interaction of a vertical thruster and a water surface. The first study was conducted at DTNSRDC and involved investigations of the effects of thrust loading, height, tilt and surface waves on spray patterns. The data were interpreted in a separate effort at VPI & SU. The main effort at VPI & SU was concerned with droplet size measurements in the spray as a function of thrust loading, propeller diameter and height. The experimental study was planned on the basis of a formulation suggested by dimensional analysis.

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1.0 INTRODUCTION

In the early developmental stages of vertical take-off seaplanes, it was found that the propeller slipstream impinging on the water surface generated large amounts of spray, causing deterioration and failure of propeller blades. The present investigation is concerned with the ingestion of droplets of the spray into the propeller disk and the generation of spray patterns. The primary parameters of interest were the thrust loading and the distance of the propeller above the water surface. Additional parameters, such as wave activity on the water surface, forward velocity of the propeller disk, and small amounts of tilt in the impinging slipstream were also of interest with regard to their effects on spray generation and droplet ingestion. This report is in two parts describing the results of tests conducted at DTNSRDC and tests conducted at VPI & SU, respectively. The DTNSRDC tests considered more parameters, including surface waves, forward velocity and disk tilt, than the VPI & SU tests, but the latter included direct measurements of droplet size. The VPI & SU tests were complemented by an analytical study of the relevant dimensionless groups that characterize the problem.

2.0 PART I - THE DTNSRDC TEST SERIES

2.1 Description of Experiments

The tests at DTNSRDC were conducted using a shrouded, compressed air turbine to generate thrust. A cantilever mount was used to support the turbine and provided a means for thrust measurement. A rolling carriage, which was used to introduce velocities, served as the base for the turbine. A wave generator located at the end of the channel was used to initiate waves on the water surface. A 16 mm movie camera, mounted on the carriage in front of and above the turbine, recorded the spray patterns during the tests. A photograph of the test set-up is in Figure 1.

The DTNSRDC tests were made in groups of five. Each test of the group corresponded to a different thrust loading up to a maximum of ten pounds. All other test conditions, such as wave height, forward velocity, etc., were kept constant for each group, but were varied between groups in order to obtain results over a range of conditions. The parameter H/D is defined as the ratio of the turbine height over the mean water level to the turbine diameter. Tests were made for H/D values between one and six, however, the largest number of tests were made at H/D of one, two and three. Using the rolling carriage, forward velocities of zero, one and two feet-per second were tested. A few tests were conducted at higher forward velocities of four and eight knots in order to observe the effect on spray patterns. The surface waves generated during these experiments had a period of 3.68 seconds, a wave height of one foot, and a wavelength of 100 feet. The slipstream angle of incidence was changed by tilting the turbine aft five degrees. The RPM of the turbine was recorded along with the thrust, wave action and forward velocity on a strip chart recorder. Each test after Test number 70 was filmed to record the spray patterns and characteristics under the various test conditions. The strip chart and the films formed a permanent record of the experiment.

2.2 Procedure for Examination of Experimental Data

In the initial stages, it was desired to minimize the number of experimental variables, and therefore tests were chosen with forward velocity, wave activity, and tilt all zero. Forward velocity was chosen zero to avoid the effect of the jet angling back from the turbine. With no waves, the transient thrust variations which result from the presence of the waves can be ignored. Tilt effects can be ignored if tilt is zero. Under these conditions a thrust versus rpm plot led to two main observations. First, the thrust level for H/D = 1 is generally higher than that for H/D = 6 (Figure 2). Secondly, at high rpm, the thrust for H/D = 1 drops off with respect to the thrust for H/D = 6. This thrust drop-off indicated that more tests were necessary at the higher input power.

It should be noted here that data provided by the DTNSRDC tests did not lend itself to the development of any quantitative results concerning droplet size, formation or ingestion. The test films, however, were instrumental in the development of qualitative results regarding the effects of the various conditions. These films provided the means for direct observations of the spray development and patterns, the effects of waves, forward velocity and tilt. These observations, along with the thrust data, led to a qualitative correlation of the test conditions with the resultant spray patterns and droplet ingestion.

As mentioned earlier, a thrust drop-off at high thrust (7 to 10 lbs) and low H/D ($\leq$ 2) was noted. The major contributors to the variations of the thrust level with respect to the input power or rpm and H/D are the ground effect and droplet ingestion.

2.3 Observations and Results

At low thrust levels (approximately 4 lbs or less) the qualitative characteristics of the spray pattern are nearly invarient with H/D. A low, radial splash with small amounts of mist and a low spray angle are typical for these thrust levels.

At high thrust levels, however, the effects of H/D becomes appreciable. A high thrust level at low H/D results in large spray angles frequently resulting in droplet ingestion , radial and tangential components to the spray, and large amounts of spray and mist. There is a marked increase in the vertical component of the spray pattern within some critical range of the thrust loading. This will be referred to as "bowling", since the spray seems to bowl up around the turbine. In the range of the thrust levels investigated, no bowling was evident for the case of high thrust and high H/D (> 3). Under the preceding conditions,moderate spray angles and mist were noted but very little spray ingestion was found.

A jet of air impinging on a water surface creates a depression, which will be called the "dish". The dish is comprised of three rather distinct areas. First is the area directly underneath the propeller hub,and it remains fairly calm regardless of the thrust level or H/D. Second, there is a region just outside the inner where small waves are generated in short circular arcs and are pushed up the sides of the depression. These waves break over the edge of the depression resulting in formation of spray, which becomes airborne due to the action of the air stream. This third section of the dish is called the splash fringe.

The spray angle seems to increase with decreasing H/D, and the ingestion appears to increase with increasing spray angle. It may, therefore, be concluded that ingestion tends to increase with increasing thrust and decreasing H/D.

The effects of small forward velocities (of the order of 2 feet per second) over a smooth water surface are negligible. However, as the dish passes over the water, surface waves are generated; much as if a blunt body were being propelled through the water. At high thrust loadings these waves are washed over by the splash fringe, but are not obliterated by it. A higher forward velocity (4 to 8 knots) results in an increase in the spray angle of the forward section of the pattern ; the mist is pushed back over the turbine and is ingested.

When the turbine disk is stationary, the dish reacts to waves of long period by tilting to follow the slope of the wavy surface. The spray pattern tilts with the dish, and the spray angles in the front and rear of the pattern change with the position of the dish on the wave. Ascending the wave, the forward spray angle is increased and the rear spray angle in decreased. The opposite holds when the dish is descending the wave. Forward velocity over a wave causes a "washover" in which a secondary wave is generated at the rear of the disk as it passes over the wave crest. This secondary wave travels forward and passes through the dish as the dish descends the primary wave. As it passes through the rear of the dish, the secondary wave dramatically increases the rear spray angle. In passing through the rear section of the dish the wave is dissipated so that its effect on the forward section is small.

2.4 Supporting Tests at VPI & SU

A short, supporting test series was run at VPI & SU to investigate the observed "drop-off" in thrust at high thrust and low H/D. The same apparatus as for the main VPI & SU Test Series was used here, and it will be described, in detail, in Part II of this report.

The primary purpose of supporting VPI & SU tests was to estimate the relative strengths of the ground effect and droplet ingestion. With this aim, the propeller was initially mounted at a large distance from the ground ($H/D = \infty$), and thrust readings were taken corresponding to different power settings. Next, the propeller was set at a particular value of H/D (e.g. 1/4) above the ground and again thrust versus power data was obtained. A comparison of these two experiments (Figure 3) enables one to estimate the ground effect over a rigid surface. Finally, the propeller was fixed at $H/D = 1/4$ above the mean water level and the previous procedure was repeated. The last experiment can be considered to consist of both the ground effect above water and droplet ingestion. If it is assumed that the ground effect above water is approximately the same as that above a rigid surface (as suggested by the curves in Figure 2 for low input powers with negligible ingestion), it is possible to separate out the effects of ingestion.

The VPI tests confirm the observation made previously concerning the thrust drop-off at high rpm found in DTNSRDC experiments. Additionally, the VPI tests reveal that the ground effect is overridden by the ingestion effect at high rpm (or input power). This means that more power must be expended to obtain a given amount of thrust when ingestion is present. It was found that more conclusive results concerning the ground and ingestion effects can be obtained through a plot of thrust versus input power rather than rpm. Such a presentation results in easy and direct interpretation of the experimental data. Another interesting observation made during the VPI tests, was that the tips of wooden propellers eroded rapidly by the action of the droplets (Figure 4).

2.5 Conclusions

The following conclusions were drawn from the experimental investigations conducted at DTNSRDC and at the supporting series at VPI & SU.

(i) An impinging jet of air creates a depression in the water surface. Spray formation occurs when the wavelets generated inside this depression break over its edge and resulting droplets become airborne.

(ii) Spray and droplet ingestion increases with increasing thrust level and decreasing H/D (the ratio of disk height above the water surface to the propeller diameter).

(iii) Only fairly high forward velocities have any observable effects on the spray pattern, pushing the forward section of the spray up and over the fan.

(iv) Effects of long period surface waves can be interpreted as due to time-varying H/D. The depression and the spray pattern tilt so as to follow the slope of the wavy surface.

(v) The effects of small amounts of tilt appear to be minimal.

(vi) At low H/D, a thrust drop-off (relative to the high H/D case) at high power becomes apparent. Under these conditions the droplet ingestion effects override the desirable ground effect, resulting in higher input power to produce a given amount of thrust.

2.6 Suggestions for Further Investigation

Several points of interest which this investigation has revealed merit further study. Recommendations for investigations of these points appear below.

(i) For small values of H/D, the thrust drop-off appears to be significant at higher thrust loadings. This required further experiments involving heavily loaded thrusters with large input power.

(ii) A need exists for the development of quantitative droplet size measurement capability.

(iii) Quantifying the amount of droplet ingestion presents a distinct problem. The development of some technique, either direct or indirect, should be the prime focus of investigations in this area.

(iv) Work needs to be done in the area of developing a measure of the relative strengths of the ground effect and ingestion effects. The possibility of analyzing the ground effect by modifying the analyses of Betz[2] and Knight, et al[3] should be studied.

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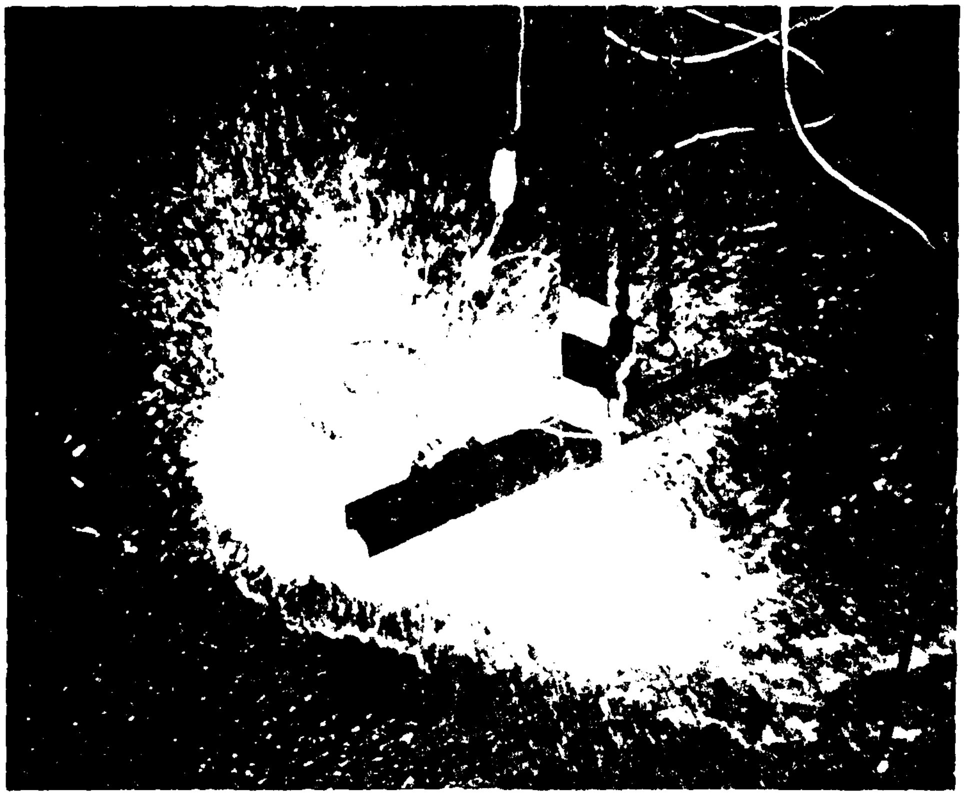


Figure 1

Photograph of the DTNSRDC Test Apparatus

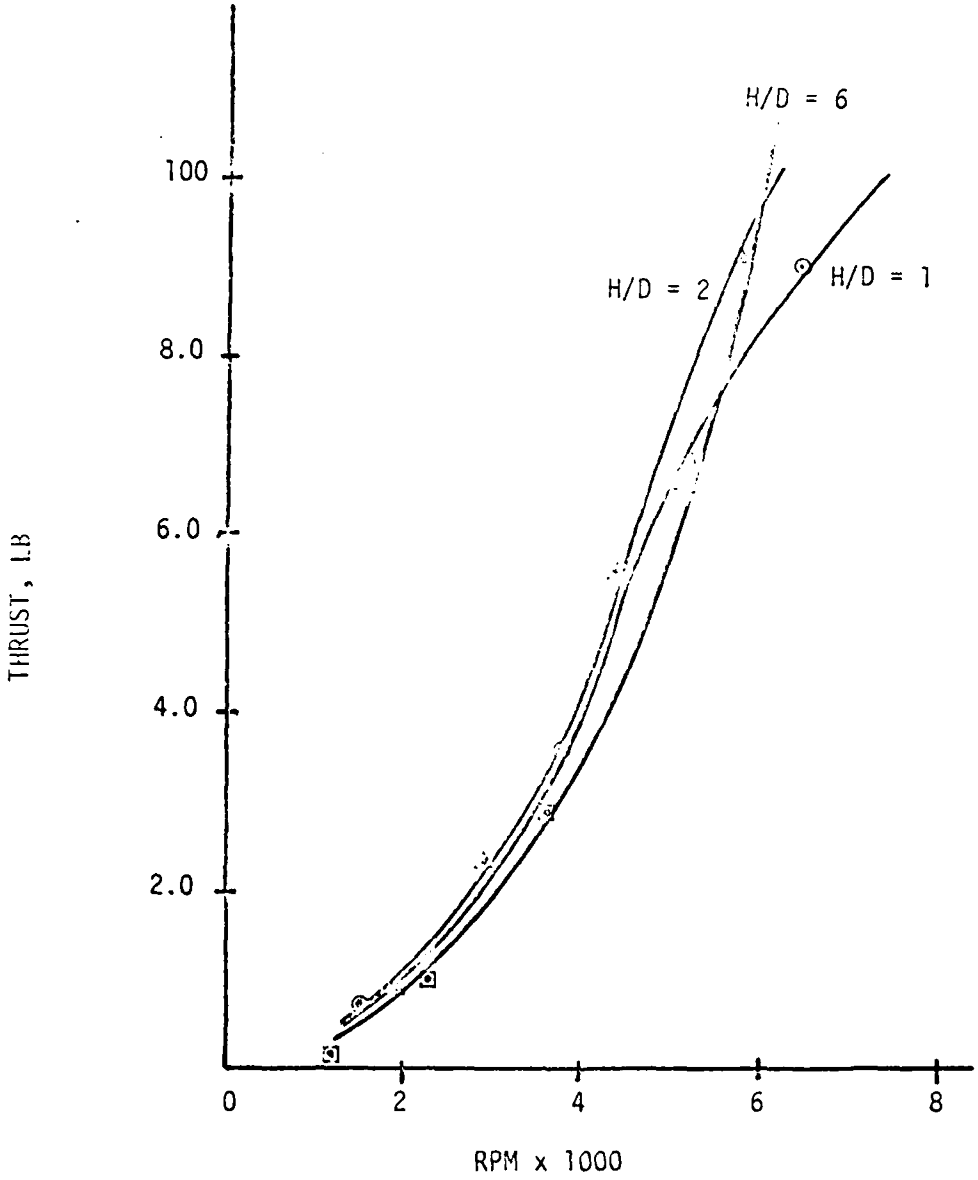


Fig. 2 Thrust vs RPM Curves For DTNSRDC Data

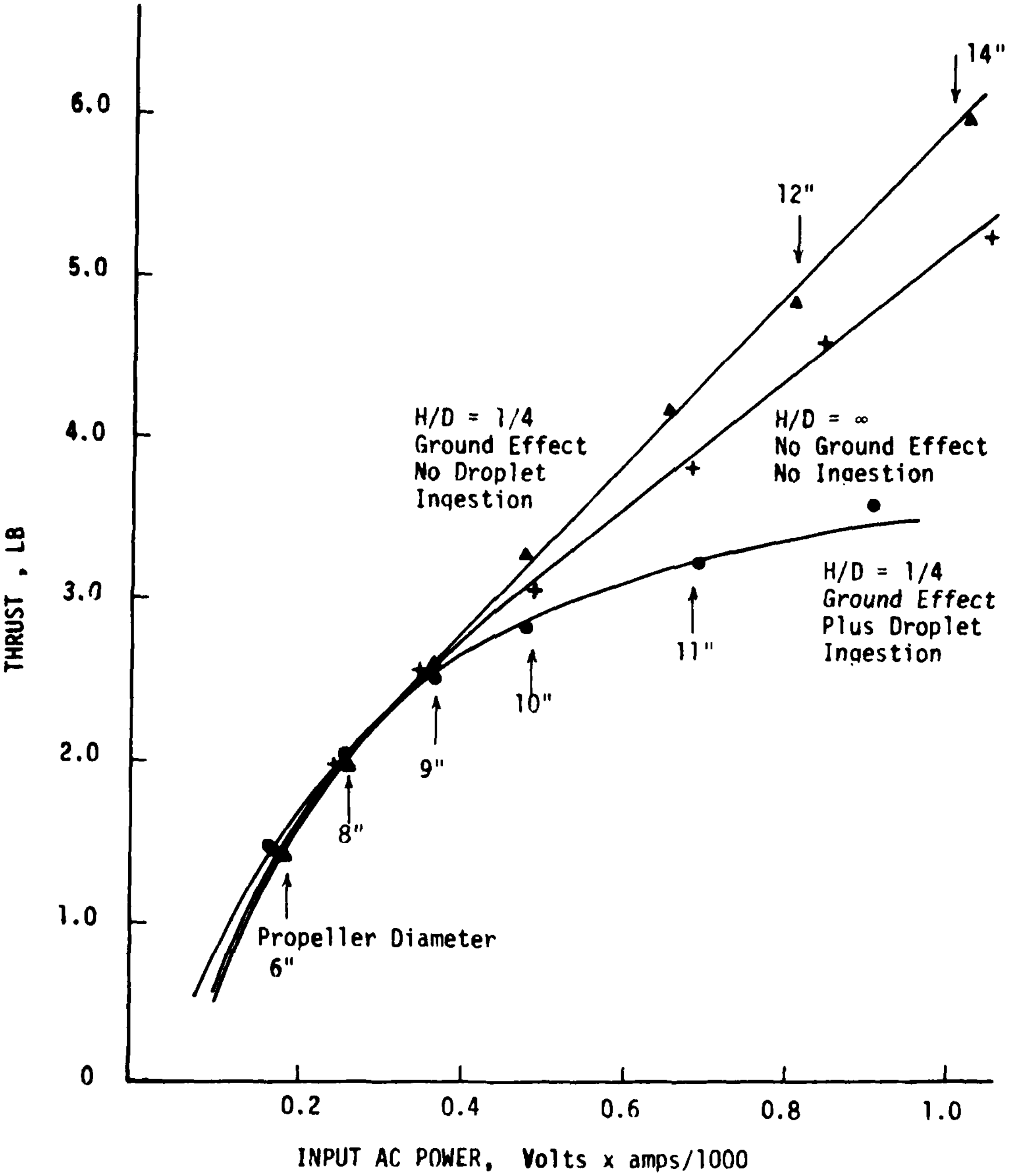


Fig. 3 Thrust Characteristics Including Ground Effect and Spray Ingestion (VPI&SU Test Data)

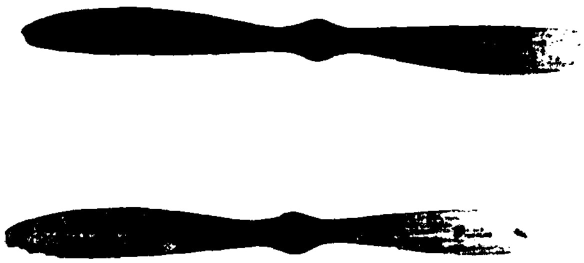


Figure 4

Erosion of Propeller Blades Due to Droplet Ingestion

3.0 PART II - THE MAIN VPI&SU TEST SERIES

3.1 Background

The main VPI&SU Test Series was planned on the basis of a Dimensional Analysis Study that delineated the primary groupings of variables and parameters of describe the droplet formation problem. This analysis is described in the first section of this part of the report. Next, the general experimental philosophy is outlined. This is followed by a description of the apparatus and then by a presentation of results.

3.2 Dimensional Analysis

For a very large diameter and sufficiently deep water tank, the parameters governing the physical drop formation process are:

1.	Thrust loading	$P = Th/D^2$	$= MLT^{-2}/L^2 = ML^{-3}T^{-2}$
2.	Surface tension of liquid	σ_ℓ	$= MT^{-2}$
3.	Liquid viscosity	μ_ℓ	$= ML^{-1}T^{-1}$
4.	Gas viscosity	μ	$= ML^{-1}T^{-1}$
5.	Liquid density	ρ_ℓ	$= ML^{-3}$
6.	Gas density	ρ	$= ML^{-3}$
7.	Propeller diameter	D	$= L$
8.	Height of Propeller above Water surface - H		L
9.	Characteristic dimension of spray "d"		L
10.	Gravitational Acceleration, g		LT^{-2}

An application of Buckingham π theorem and intuitive reasoning yields the following seven non-dimensional groups.

$$F\left(\frac{H}{D}, \frac{\rho}{\rho_\ell}, \frac{\mu}{\mu_\ell}, \frac{d}{H}, \frac{\sigma_\ell}{PD}, \frac{P}{\rho g D}, \frac{\mu}{\sqrt{\rho}\sqrt{P}\,D}\right) = 0$$

For water-air system, ρ/ρ_ℓ, μ/μ_ℓ are constant and the above function reduces to:

$$F\left(\frac{H}{D}, \frac{d}{H}, \frac{\sigma_\ell}{PD}, \frac{P}{\rho g D}, \frac{\mu}{\sqrt{\rho}\sqrt{P}\,D}\right) = 0$$

It is now recognized that

$$\frac{\sigma_\ell}{PD} = (W)^{-1} = (\text{Weber number})^{-1}$$

$$\frac{P}{\rho g D} = F = \text{Froude number}$$

$$\frac{\mu}{\sqrt{\rho P}\ D} = (R)^{-1} = (\text{Reynolds number})^{-1}$$

Thus we can write

$$\frac{d}{H} = G\left(\frac{H}{D}, W, F, R\right)$$

Thus for given values of W, F, R and H/D, the spray patterns for a model and a prototype will be geometrically similar. Simultaneous matching of W, F and R, however, presents conflicting requirements and we must choose the most important parameters. If we choose "d" as some "characteristic" droplet size then it seems logical to assume that surface tension effects will be predominant and hence W is the most important independent variable. It has been concluded from our earlier work that the spray generation process is intimately connected with the generation of surface wavelets inside the depression. Since wave generation is a Froude number effect, F seems to be the second most important parameter. In addition, we assume that Reynolds number effects (on spray) are negligible in an already highly turbulent flow. Finally,

$$\frac{d}{H} = g\left(\frac{H}{D}, W, F\right) \tag{1}$$

It is the purpose of the present investigation to evaluate the functional form of Equation 1 by conducting appropriate experiments.

3.3 Experimental Procedure

The process of droplet generation due to a jet of air impinging on a water surface is very complex and is governed by several parameters, such as, thrust loading, H/D, viscosity and surface tension of water, etc. Consequently, a purely analytical prediction of droplet size distribution is an impossible task and therefore an approach combining dimensional analysis and scaled experiments must be resorted to.

First of all, some assumptions need to be made about the droplet size distribution itself. Suppose that it is possible to take a picture of the entire droplet distribution at a particular instant. This would then enable one to obtain a size distribution in the form of the number of droplets versus diameter - let us call this a sample distribution. In principle, we need an infinity of such distributions (i.e.pictures of the spray at an infinitely large number of instances) which would form an ensemble (for a given set of experimental conditions). This is,of course,impossible in practice,and at this point we must introduce the assumption of an ergodic random distribution of droplets. This means that all sample distributions are the same,and hence it is efficient to consider only one "representative" distribution. Thus,the instant at which the distribution is obtained is immaterial.

The preceding discussion implies that a distribution contains <u>all</u> the droplets of the spray. However, in practice, it is quite impossible to obtain a photograph in which the entire depth of the spray is in focus. In an actual experiment it is possible to scan only a relatively short depth of field (due to requirements of sufficient light from the flash, the speed of the film used, etc.). However, in view of the statistical similarity of the distributions obtained at different instances (due to the ergodicity assumption), it is permissible to obtain an entire distribution by scanning the spray across its diameter (assuming that the entire height of the spray can be contained in every picture). This is illustrated in Figure 1.

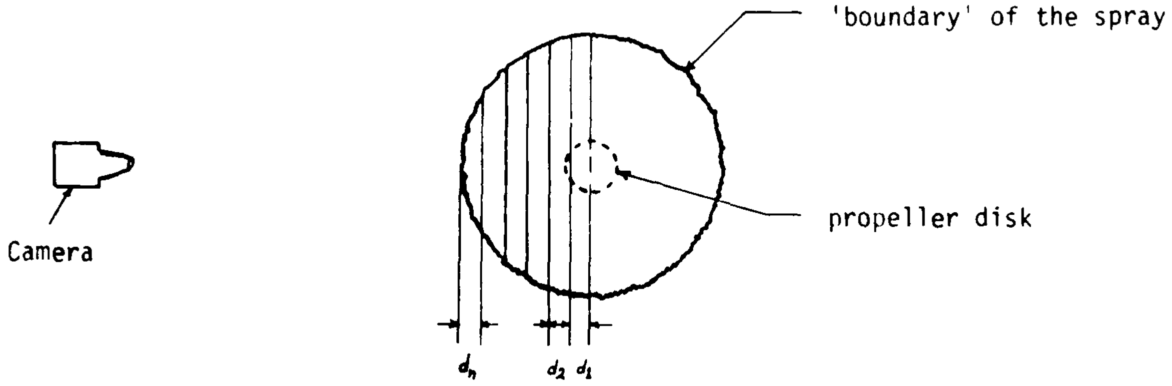


Figure 1

Picture of spray from top.

The aforementioned method implies that the spray is symmetric about the vertical axis and therefore it would be advisable to obtain distributions in 3 or 4 different radial directions and then take their mean. In view of the painstaking task of counting droplets from photographs, even the "simplified" procedure described above proves to be cumbersome. It was therefore decided to concentrate our attention only on a part of the spray - e.g. region d_2 just outside the depression in the surface which seems to have a dense population of droplets. Thus, in the present work the droplet distributions are really in one a section of the spray, and the object was to see the effect of various parameters of the experiment on these "sectional" distributions.

3.4 Apparatus

For the testing done at VPI&SU, unshrouded, two-bladed propellers were used instead of a turbine, and the propellers were driven by AC/DC electric motors. The purpose of these experiments was to study droplet formation and the effects of H/D and droplet ingestion on the thrust loading, and hence no provisions were made for wave action, forward velocity or tilt.

Two separate, but similar, arrangements were used depending upon the thrust level being studied. For lower thrust levels, the thruster was a single, 2 HP (@ 11000 rpm) motor suspended on a 7 1/2 feet long cantilever mount over a 15 feet diameter, 4 feet deep pool of water (Fig. 2a). Thrust measurements were taken using strain gauges mounted near the support of the cantilever. Several gauges were mounted two on the top surface of the cantilever (in tension) and two on the bottom (in compression) - connected in a bridge circuit. Three different two-bladed propellers, with diameters of 6 through 14 inches were used. The maximum thrust level varied depending on the propeller used and was of the order of 3 to 5 pounds. For each value of H/D, seven different values of thrust were obtained by varying the input power. Typical range of H/D values was 1/4 to 3. Strip chart recordings of the thrust, and stroboscopic measurements of the propeller rpm were recorded.

A similar arrangement was used for the higher thrust levels. Here, however, four motors were "ganged" in series to produce greater torque and thrust. This arrangement can be seen in Fig. 2b. Due to the greater weight of the system, it was supported by a beam which spanned the entire 15 ft. diam. pool. The strain gauge system was similar to that described above.

3.5 Test Plan

Recall that our goal here is to investigate the function:

$$\frac{d}{H} = g\left(\frac{H}{D}, W, F\right) \qquad (1)$$

where "d" is some characteristic droplet diameter and g( ) represents the functional dependence of the phenomena upon the dimensionless height, H/D, the Weber Number, W, and the Froude Number, F.

We choose first to hold H/D and F constant and vary W. The baseline case was taken as H/D = 1/4 and F_1 = .00194. Any varying Weber Number experiment, denoted here as sub 2 must be related to the baseline case, sub 1 , as

$$F_2 = F_1$$

or

$$\frac{P_2}{D_2} = \frac{P_1}{D_1}$$

and

$$\frac{Th_1}{Th_2} = \left(\frac{D_1}{D_2}\right)^3$$

Thus, if thrusts are matched according to this relation, then Weber Number varies as

$$W_2 = W_1\left(\frac{D_1}{D_2}\right)^3 \qquad (2)$$

The second main test series was run at constant H/D and W and variable F. The baseline case was H/D = 1/4 and W = 664. With

$$W_2 = W_1$$

or

$$P_2D_2 = P_1D_1$$

or

$$\frac{Th_2}{Th_1} = \frac{D_2}{D_1}$$

Thus, with thrust varied following this rule, we get

$$F_2 = F_1 \left(\frac{D_1}{D_2}\right)^2 \tag{3}$$

Two short test series were run to investigate the effect of varying H/D and the effect of varying W to a different baseline for the variable F case.

3.6 Results

The main,constant H/D and F, variable W test series was run at the conditions shown in Table I.

Table I

Variable Weber Number Test Series
H/D = 1/4, F = 0.00194

W	D, in	H, in	F
1255	8	2.0	.00194
992	9	2.25	"
803	10	2.5	"
644	11	2.75	"
558	12	3.0	"
410	14	3.5	"

A typical droplet size distribution obtained during this test series is shown in Fig. No. 3. On the basis of the shape of these distributions, the characteristic droplet size diameter was chosen as the "most probable" droplet size ≡ d.

Fig. No. 4 shows the variation of d/H vs. W obtained from this test series. It is worth note that a straight line seems to represent the data well.

The main constant H/D and W, variable F test series was run at the conditions shown in Table II.

Table II

Variable Froude Number Test Series
$H/D = 1/4$, $W = 664$

F	D, in.	H, in.	W
.00366	8	2.0	664
.00290	9	2.25	"
.00235	10	2.5	"
.00194	11	2.75	"
.00163	12	3.0	"
.00120	14	3.5	"

The results for d/H vs F obtained for this test series is shown in Fig. No. 5. Again a straight line represents the observations well.

We can return now to Eqn. (1) and write

$$d(d/H) = \left.\frac{\partial g}{\partial(H/D)}\right|_{F,W} d(H/D) + \left.\frac{\partial g}{\partial F}\right|_{H/D,\, W} dF$$

$$+ \left.\frac{\partial g}{\partial W}\right|_{H/D,F} dW \qquad (1a)$$

The results of our two main test series enable us to determine the last two differentials on the right hand side at specific values of the variables to be held constant. In particular, from Fig. No. 4, we find

$$\left.\frac{\partial g}{\partial W}\right|_{\substack{H/D = 1/4 \\ F = .00194}} = 1.29 \times 10^{-5}$$

Fig. No. 5 gives

$$\left.\frac{\partial g}{\partial F}\right|_{\substack{H/D = 1/4 \\ W = 664}} = 4.61$$

Since both differentials are constants, we can easily integrate to obtain

$$(d/H)_{H/D = 1/4} = .0175 + 4.61\ (F - .00194) + 1.29 \times 10^{-5}\ (W - 664) \qquad (5)$$

This derivation implicitly assumes that $\frac{\partial g}{\partial F}\Big|_{\substack{H/D \\ W}} \neq f_1(H/D, W)$

and $\frac{\partial g}{W}\Big|_{\substack{H/D \\ F}} \neq f_2\ (H/D,F)$. These assumptions will have to be tested by further experiment, and thus Eqn. (5) must be viewed as tentative at this time.

The predictions of this equation have been compared point by point with the data from the two main test series, and the average error in d/H was found to be less than 2%.

A brief investigation of the effect of varying H/D to 1/3 was made at F = .00194 and W = 558. The result is plotted in Fig. No. 4, where it can be seen that a smaller value of d/H was obtained.

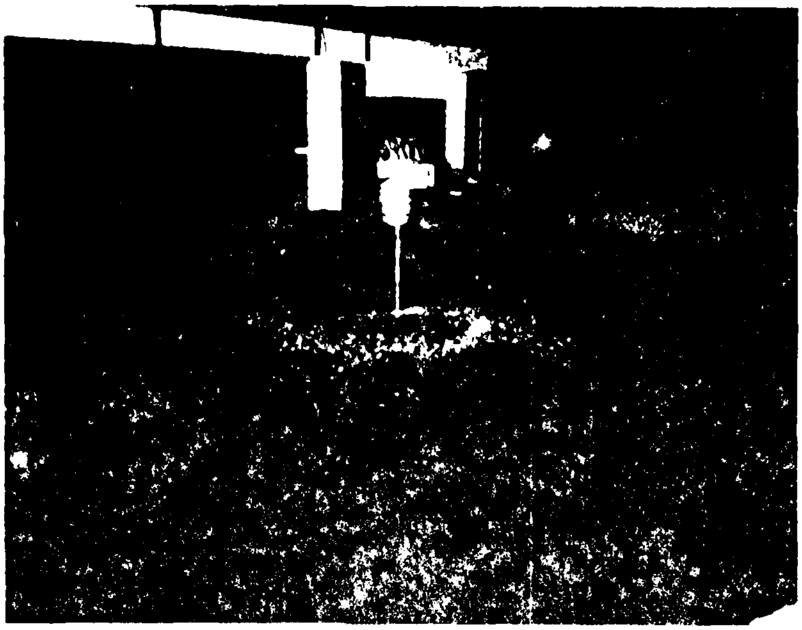
An additional brief study was undertaken to investigate the effect of both high F and W (higher thrust). The result is plotted on Fig. No. 5 where it can be seen that a higher value of d/H resulted. The prediction given by Eqn. (5) for this case, which was not used in the derivation of Eqn. (5), also showed excellent agreement when compared to the actual test data.

3.7 Discussion

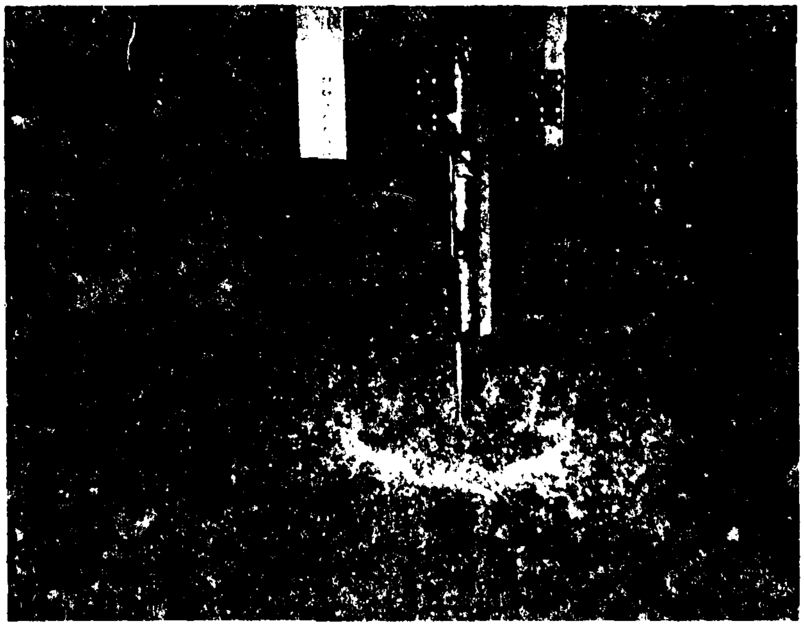
This investigation of droplet formation showed the dependence of the process on the main parameters: Weber Number, Froude Number and height to diameter ratio. A tentative correlation equation was determined based upon the restricted range investigated to date. Wider ranges of the parameters should be studied in the near future.

The method of droplet size determination was simple and inexpensive to set up, but it was very tedious. Direct methods based upon light scattering techniques should be adopted for future work.

Actual physical damage by droplet impingement to sturdy, wooden, model airplane propellers was observed repeatedly. This phenomena should be studied in depth.



(a) Single Motor Arrangement for Lower Range Loading Tests



(b) Four Motor in Series Arrangement for Higher Range Loading Tests

Figure 2

Photographs of the Two Vertical Thruster Arrangements
in Operation Over the Water Tank

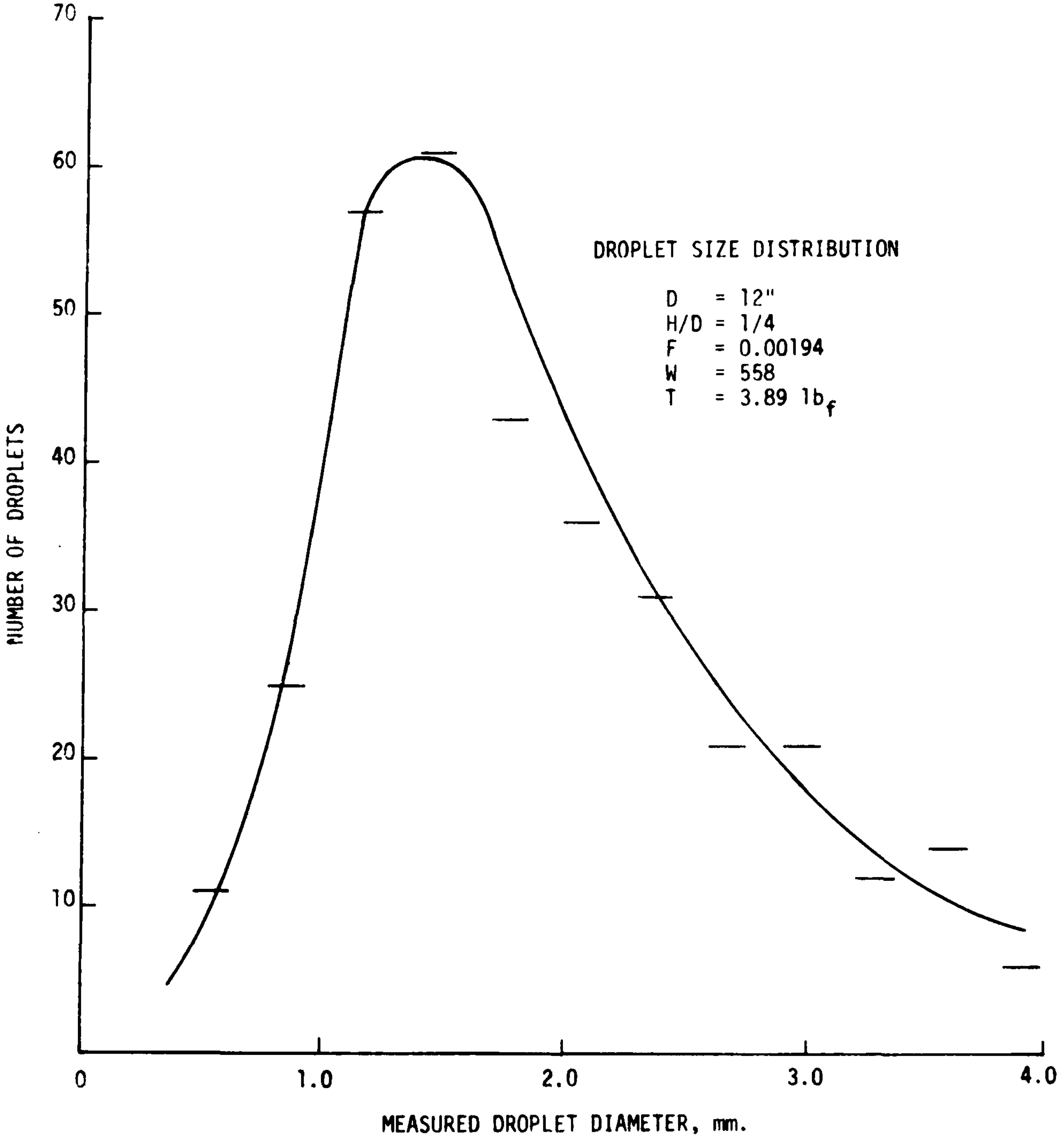


Figure 3

Typical Droplet Size Distribution

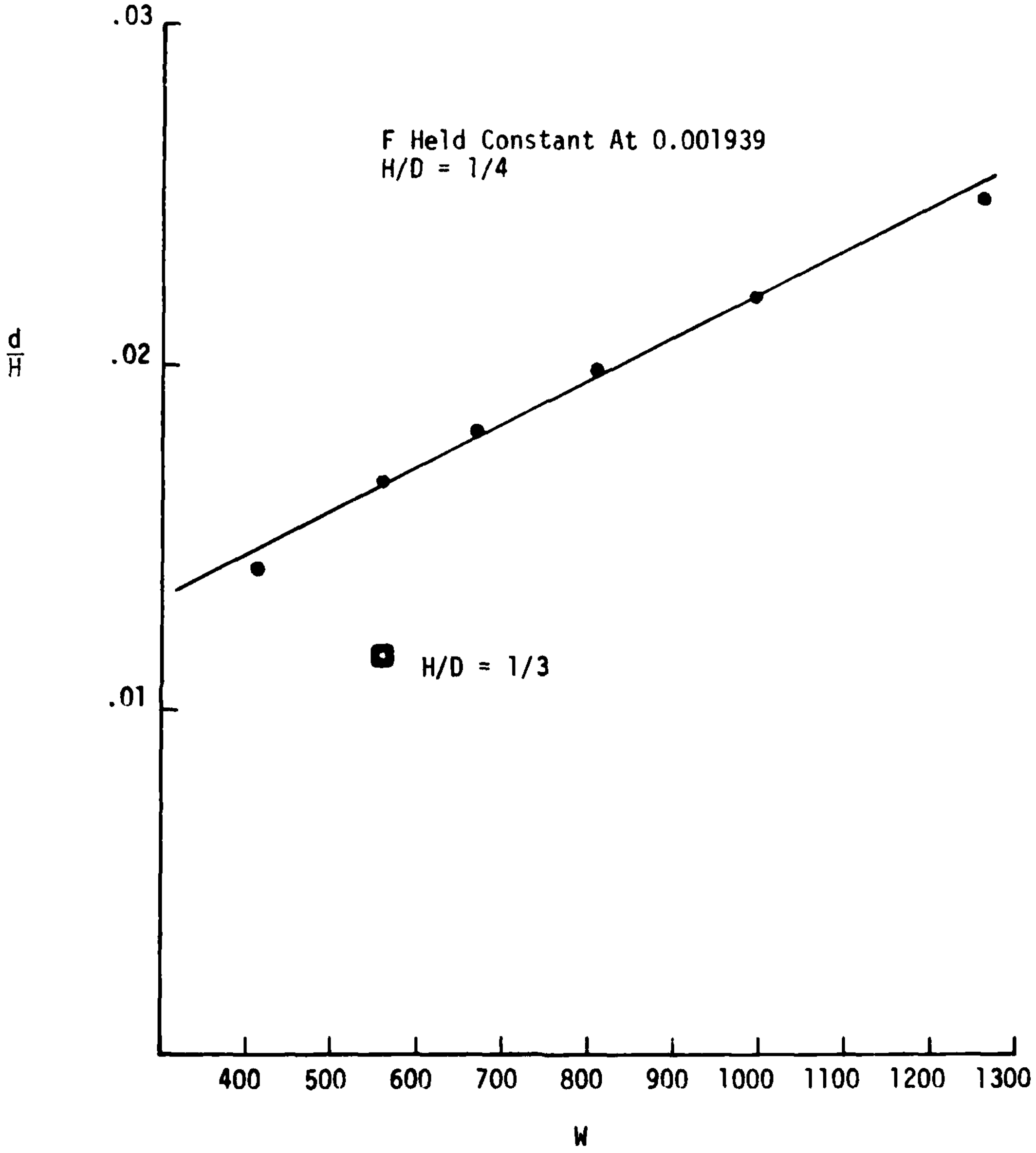


Figure 4

Variation of "Most Probable" Droplet Size vs. Weber Number for Constant H/D and Froude Number

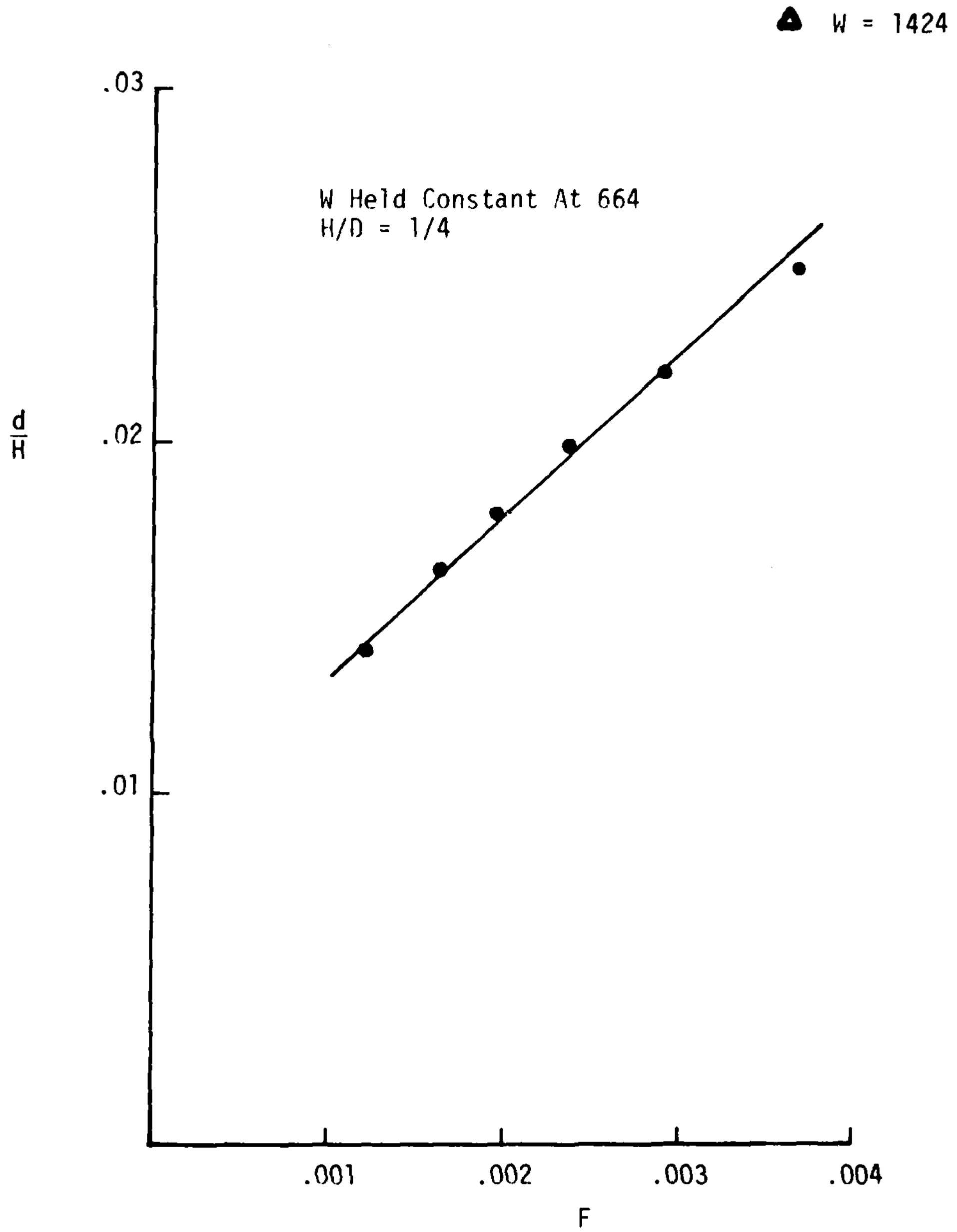


Figure 5

Variation of "Most Probable" Droplet
Size vs. Froude Number for
Constant H/D and Weber
Number