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HUGHES TOOL COMPANY · AIRCRAFT DIVISION
Culver City, California

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Report X-424

INTRODUCTION TO THE HUGHES HYDROSTREAK CONCEPT

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CONTENTS

I. SUMMARY

~~This report presents and discusses~~ the basis of the Hughes Hydrostreak design concept of water-wall vehicles is discussed. The fundamental theory is given, comparisons are made with air-wall vehicles, and preliminary test data are presented. A typical design study is shown, illustrating the advantages of the Hydrostreak concept over the air-wall system and demonstrating the high over-water speeds attainable with moderate power inputs.

II. INTRODUCTION

The present interest and the state of the art of ground-effect machines are illustrated thoroughly by Reference 1. It is becoming apparent that the power requirements of these vehicles are such that they will be restricted to operation over fairly smooth surfaces. Further, if operated at high speeds, their turning and braking ability restricts them to low accelerations and fairly straight paths. These considerations lead directly to the conclusion that ground-effect vehicles are best suited to over-water operation.

If the ground-effect vehicle is to prove successful in over-water operation, it must show superiority to aircraft and three types of water vehicles: (1) Displacement vessels, (2) planing craft, and (3) hydrofoil craft.

Each of these three types of water craft has its own regime of superiority, as shown in Reference 2, for example. While it might seem that hydrofoil craft would have very high speed capability even in typical ocean waves, there are serious practical limitations to their operation, as discussed in Reference 3. It does not appear that any existing type can operate at speeds above 50 knots in average ocean conditions at reasonable efficiency.

The ground-effect, or air cushion vehicle, by reducing friction and wave drag can presumably operate at very high speeds over the water if it can clear the waves. As shown below, the air-wall ground-effect vehicle loses efficiency rapidly as its height above the surface is increased. In order to operate at reasonable heights (several feet) the air-wall vehicle must be very large in surface area or very inefficient.

In considering the basic momentum flux problem, engineers of Hughes Tool Company--Aircraft Division saw that the use of water (instead of air) to form the bubble-containing wall would result in a very large performance gain. This concept, the Hughes Hydrostreak water-wall vehicle, has since been intensively studied experimentally and analytically by HTC-AD. Preliminary results have borne out expectations to a large degree. A number of design studies have shown the concept useful for landing craft, ASW craft, high-speed cargo ships, missile launchers, aircraft carriers, and a variety of other vehicles. Analytical and experimental efforts are continuing, while the fundamentals of the problem and its status are presented below.

III. NOTATION

The notation used in this report is shown in the sketch of Figure 1.

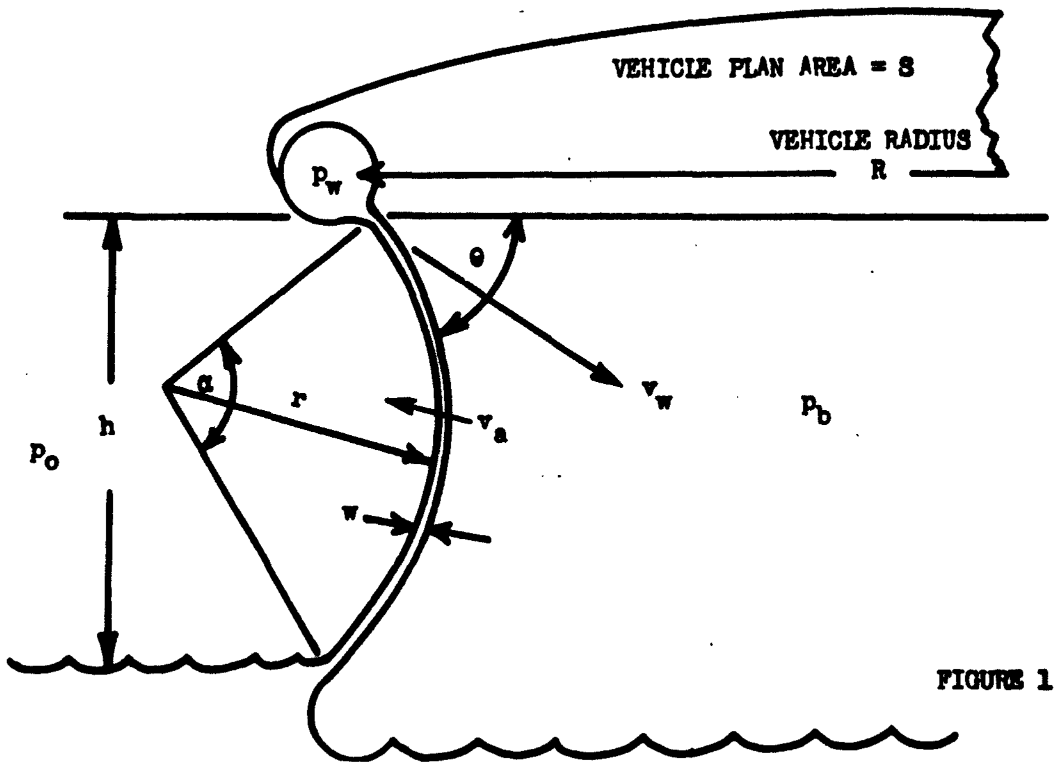


FIGURE 1

D_c	Discharge coefficient for air flow through wall	
h	Height of vehicle above water	ft
ℓ	Peripheral length of wall	ft
P	Power	ft-lb/sec or HP
p_b	Bubble pressure	psf
p_o	Ambient pressure	psf
p_w	Water pressure at nozzle	psf
Q	Volume flow	cu ft/sec
q	Dynamic pressure	psf
R	Radius of circular vehicles	ft
r	Radius of curvature of water wall	ft

S	Planform area of vehicle	sq ft
v_a	Air leakage velocity through wall	fps
V_o	Forward speed	fps
v_w	Spouting velocity of wall	fps
w	Water wall thickness	ft
Δp_w	$p_w - p_o$, nozzle pressure drop	psf
Δp_a	$p_b - p_o$, bubble pressure differential	psf
α	Wall turning angle	degrees
θ	Initial spouting angle	degrees

IV. DISCUSSION

A. Fluid-Wall Theory

1. In Hovering. The means of containing a bubble of high-pressure air under a vehicle with a dynamic wall of fluid can be derived easily if certain simplifying assumptions are made. These are:

a. The wall section is two-dimensional

b. The wall thickness is small compared to its radius of curvature

c. The velocity of the wall is constant along its length and across its width

d. The shear forces between the wall and the ambient fluid can be neglected

It follows directly from the above assumptions that the shape of the wall is a circular arc. It will be shown below that the above assumptions are fairly realistic in the case of a water wall. The equations derived subsequently do not depend on the fluid considered, but the assumptions are not so realistic if an air wall is used. Most of the existing air vehicles use relatively thick air walls with small radii of curvature.

Consider the sketch of Figure 1. The balance of forces normal to the wall, acting on a fluid element, is:

$$\Delta p_a dA = \rho \frac{w\, v_w^2}{r} \; dA \tag{1}$$

if the nozzle efficiency is 100 per cent, then

$$1/2 \; \rho \, v_w^2 = \Delta p_w$$

so that

$$\frac{r}{w} = 2 \frac{\Delta p_w}{\Delta p_a} \tag{2}$$

A convenient assumption in making design studies is that the wall turning is symmetrical, in which case

$$h = 2r \cos \theta \text{ and } \alpha = 2(\pi - \theta)$$

then

$$\frac{h}{w} = 4 \cos \theta \frac{\Delta p_w}{\Delta p_a} \tag{3}$$

The lifting effectiveness of fluid-wall vehicles can now be derived, in terms of the lift/horsepower ratio, $\frac{L}{P}$.

The total lift is the sum of the pressure force plus the jet reaction:

$$L = \Delta p_a S + \rho \, \ell \, w \, v_w^2 \sin \theta \tag{4}$$

The total power is the sum of the power put into the fluid pumps. In the case of the water wall vehicle operating at moderate bubble pressure, both the air and water may be considered as incompressible. Then

$$P = \frac{1}{550} \left[\frac{\ell w \; v_w \Delta p_w}{\eta_w} + \frac{\ell h \; v_a \Delta p_a}{\eta_a} \right]$$

where η_w and η_a are the efficiencies of the water and air pumps, respectively.

The lift-power ratio is then

$$\frac{L}{P} = \frac{(\Delta p_a/\Delta p_w)}{(\ell_w/S)}\ \frac{550\eta_w}{v_w}\left[\frac{1+2\left(\frac{\ell_w}{S}\right)\left(\frac{\Delta p_w}{\Delta p_a}\right)\ \sin\theta}{1+4\ \frac{\eta_w}{\eta_a}\ \ \frac{v_a}{v_w}\ \cos\theta}\right] \tag{5}$$

In the case of circular planforms,

$$\frac{\ell_w}{S} = \frac{2w}{R} \qquad \text{and}$$

$$\frac{L}{P} = 1100\ \frac{R}{h}\ \ \frac{\eta_w}{v_w}\cos\theta\left[\frac{1+\left(\frac{\eta}{R}\right)\ \tan\theta}{1+4\left(\frac{\eta_w}{\eta_a}\right)\left(\frac{v_a}{v_w}\right)\ \cos\theta}\right] \tag{6}$$

If the wall does not leak,

$$\frac{L}{P} = 1100\ \frac{\eta_w}{v_w}\left[\left(\frac{R}{h}\right)\ \cos\theta + \sin\theta\right] \tag{7}$$

The optimum spouting angle can be derived from (7) and is:

$$\theta_{opt} = \tan^{-1}\left(\frac{h}{R}\right) \tag{8}$$

for any given set of $\frac{R}{h}$, v_w, η_w.

Equation (7) is plotted in Figure 2 for the conditions noted on the figure. It will be noted that the effect of spouting velocity, v_w, is very important. This is precisely what makes the water wall superior to the air wall. The air bubble is contained by the momentum flux of the wall, and sea water has a density about 840 times that of air. The wall must have a dynamic pressure significantly higher than the bubble pressure if it is to contain the bubble. Since the dynamic pressure of water is 840 times higher than that of air at the same velocity, far lower spouting velocities can be used with a resultant large increase in the lift/power ratio. The regime of operation of water-wall and air-wall craft are indicated in Figure 2.

2. In Forward Flight. The drag of ground-effect vehicles is negligible at low speeds; this is their principal feature. At high speeds there are important drag forces, however, In the case of the water-wall vehicle, there are three forces to consider:

a. Adrodynamic drag

b. Hydrodynamic drag of water scoops, propeller supports, rudder, etc.

c. Momentum "drag" of water taken on board.

The last quantity seems to be the most serious for high-speed water craft. The hydrodynamic drag can be quite high in some cases, since the dynamic pressures encountered are extremely high, e.g., 10,000 psf at 100 fps (about 60 knots). It is possible, however, to obtain low hydrodynamic drag through proper design. Examples are shown in Part C, below.

A simple expression can be obtained for the lift/power ratio in forward flight if the air and water drag terms are neglected. Thus,

$$P = Q\left(\frac{\Delta P_w}{\eta_w} - q\right) + 2Q\,q$$

$$= Q\left(\frac{\Delta p_w}{\eta_w} + q\right) = P_o + Q\,q$$

where P_o is the power required at the hovering condition. In the case of circular vehicles, with P_w = 2(sea water)

$$P = P_o + 4\pi R\, w\, v_w\, v_o^2$$

Again assuming no air leakage and 100 per cent nozzle efficiency,

$$\left(\frac{L}{P}\right)_{FF} = \frac{\left(\frac{L}{P}\right)_o}{1 + \eta_w \left(\frac{v_o}{v_w}\right)^2} \tag{9}$$

If v_w is varied with v_o to give optimum performance,

$$(\frac{L}{P})_{FF} = \frac{(\frac{L}{P})_o}{2} \tag{10}$$

where $(\frac{L}{P})_o$ is calculated for the appropriate value of v_w, which is:

$$v_{w_{opt}} = v_o \sqrt{\eta_w} \tag{11}$$

Thus, if the pumping system were ideal, ($\eta_w = 1$) the best spouting velocity would be the same as the free stream velocity (with zero piping losses, no pump would be required), and the lift-power ratio would be just half that obtained in hovering flight at the same spouting velocity. The lift-power ratio for forward flight is given in Figure 3.

There is one more effect that occurs at high speeds. As the flight speed increases, the dynamic pressure of the air may increase to the value of the bubble pressure. This may affect operation in several ways:

a. Since the water wall along the front of the vehicle supports a lower pressure differential (lower by q_o), the power input to the front portion may be decreased.

b. The air leakage through the front wall will decrease, and at the point where $q_o = \Delta p_a$, no air pumping at all will be required since all necessary air can enter at the vehicle nose.

c. The bubble pressures considered in the design studies to date have ranged from 30 to 50 pounds per square foot. At 95 knots a dynamic pressure of 30 pounds per square foot is obtained, and 50 psf is reached at 122 knots. The question of altitude stability occurs when the dynamic pressure is higher than the bubble pressure. It is evident, however, that reduction of the water-wall strength can increase leakage easily enough to produce altitude control and that any increase in altitude, even at constant wall velocity, will provide altitude stability.

B. Fluid-Wall Experiments

Initial water-wall tests at HTC-AD were performed in a simple facility using whatever equipment was available. The results obtained were promising enough to justify a better facility, shown in the photographs of Figures 4 and 5. Here, the inner (high pressure) side of the wall is observed, the air being pumped out of the plenum chamber. Color movies, both 8mm and 16mm, are available showing the setup in operation.

Data taken to date indicate that practical water-wall vehicles can be designed, and that they will operate far more efficiently than their air-wall counterparts.

A typical set of test data is shown in Figure 6, which gives the discharge coefficient of the wall for various spouting velocities as a function of the bubble pressure.

Experimental data on power required are summarized in Figure 7, giving the horsepower required per square foot of wall area as a function of bubble pressure. Data points from the literature on air-wall vehicles are included.

It will be noted that the power required is far less for the water wall. However, the water-wall power is still higher than necessary due to the air leakage through the wall. The present experimental effort, therefore, is concentrated on producing a water wall of higher integrity.

C. Design Studies

A wide variety of design studies has been performed, covering designs from small test vehicles to large aircraft carriers. Over-water speeds of more than 100 knots and hull over-water heights of 20 feet have been considered and seem attainable. Rather than present all of these data in a general fashion, a more detailed presentation of one specific design is made here.

The-design considered is that of a multi-purpose vehicle of moderate size. Its specifications are:

MULTI-PURPOSE HYDROSTREAK VEHICLE	
Size	40 ft diameter
Gross Weight	37,500 lb
Maximum Speed	65 knots
Cruising Height	4 ft
Maximum Hovering Height	5.6 ft
Payload	19,000 lb
Horsepower	2500

Sketches of an ASW version of the vehicle are shown in Figures 8 and 9.

Details of the calculation procedure are too lengthy to present here, but one condition is given below, with some discussion:

Flight Speed	50 knots (84.5 fps)
Dynamic pressure of air	8.47 psf
Dynamic pressure of water	7120 psf

1. Air Drag. The drag coefficient of the vehicle may be taken as .005 (Reference 2) based on "wetted" area and allowing for roughness and some separation at the base. The air drag is then

$$D_A = .005\ (8.47)(1260) = 53.3 \text{ lb}$$

2. <u>Water Drag</u>. The drags of the surface-piercing scoop and propeller struts will be composed of four parts: (a) Spray drag, (b) friction drag, (c) base drag, and (d) wave drag. Since we are concerned with wave drag, the Froude number must be used for similarity estimates. It is:

$$F = \frac{V}{\sqrt{g\ell}}$$

Under the present conditions, the Froude number will be about 15. This is so high that the wave drag becomes of minor importance (see Reference 2, Section 10-13, Figure 24).

The total drag of a surface-piercing strut of good design is given in Reference 2, Section 10-15, Figure 29. Using these data, the drag of the propeller support strut, which is about one foot in chord and about one foot deep, will be

$$D = 0.012\ (1)(7120) = 85.5 \text{ lb}$$

The scoop struts are designed (Figures 8 and 9) so that the strut proper does not pierce the water surface. A plate, tangent to the water surface, prevents spray drag and provides a fairing between the scoop and the strut. The scoops are designed to ventilate at their bases; the resultant base drag is negligible according to the reference cited above.

The drag of each of the scoops is then primarily friction drag. This is estimated as

$$D_{scoop} = .005\ (7120)(2) = 71.2 \text{ lb}$$

3. <u>Momentum or "Ram" Drag</u>. The ram drag may be written:

$$D_{ram} = m\ v_o = \rho \ell w\ v_o = \frac{2Q\ q}{v_o}$$

where Q is the volume flow of water through the system and q is the "free stream" dynamic pressure of the water.

Assume, for example, that the pressure losses through the plumbing amount to 20 per cent of the free stream q, or about 10 psi. This can be obtained with careful piping design. Assume further that no pumping power is added at this condition. Then the spouting velocity is

$$v_w = v_o \sqrt{8} = 75.5 \text{ fps}$$

As shown above, the lift-power ratio (zero drag) will then be:

$$\left(\frac{L}{P}\right)_{FF} = \frac{\left(\frac{L}{P}\right)_o}{2} = 550 \frac{(.8)}{(75.5)} \left[\frac{20}{4} \cos \theta + \sin \theta\right]$$

taking $\theta = 37°$,

$$\left(\frac{L}{P}\right)_{FF} = 26.8 \text{ lb/horsepower}$$

For a gross weight of 37,500 pounds, the water pumping horsepower is then

$$HP_{pump} = \frac{37,500}{26.8} = 1400 \text{ HP}$$

4. <u>Air Pumping Power</u>. Data taken to date indicate that a leakage velocity of 10 fps through the wall may be anticipated with further development. The air pumping power will then be:

$$P = Q\left[\frac{\Delta p_a}{\eta_a} + q\right] = \frac{(4)(2\pi R)(10)}{550}\left[\frac{37,500}{0.8\ \pi\ R^2} + 8.47\right]$$

$$P = 420 \text{ horsepower}$$

The total power required is then

Air Drag Power (HP)	8
Water Drag Power	
Propeller Strut	13
Two Scoops	22
Ram Drag (Pumping)	1400 *)
Air Pumping	420
TOTAL POWER	1863

In the presence of waves, the power will be increased by additional friction and spray drag on the struts. Since this drag accounts for only 2 per cent of the total power, waves will not decrease the performance noticeably. This is in sharp contrast to hydrofoil or planing craft, as pointed out in Reference 3. Operation over waves higher than four feet will be possible depending on wave length and vehicle dynamics. These problems are being studied, and preliminary analysis has not revealed any very serious difficulties.

V. CONCLUSIONS

Preliminary analysis and experiments have shown:

1. The water wall is an effective means of supporting the pressure bubble for ground-effect vehicles
2. Speeds in the 60 to 70 knot range are possible with reasonable power input, and speeds of more than 100 knots can be attained
3. Two serious problem areas exist:
   a. The rate of air leakage through the wall must be minimized, and
   b. The momentum drag of the water taken on board must be kept to a minimum for economic high-speed operation.

VI. LIST OF REFERENCES

1. Princeton University Conference on Ground-Effect Vehicles, Oct 1959.
2. Hoerner, S. F., "Fluid Dynamic Drag." 1958.
3. Hoerner, S. F., "Consideration of Size-Speed-Power in Hydrofoil Craft." ASTIA AD 214011, Nov 1958.

FIGURE 2. HOVERING PERFORMANCE

$$\frac{L}{HP_{Pump}} = \frac{1100\left(\frac{R}{h}\cos\theta + \sin\theta\right)\eta}{v_w}$$

HP_{Pump} = HORSEPOWER REQUIRED TO DRIVE PUMP

η = OVER-ALL PUMPING EFFICIENCY, INCLUDING PIPING LOSSES

BASED ON:

$\eta = 0.7$

$\cos\theta = 0.8$

$\sin\theta = 0.6$

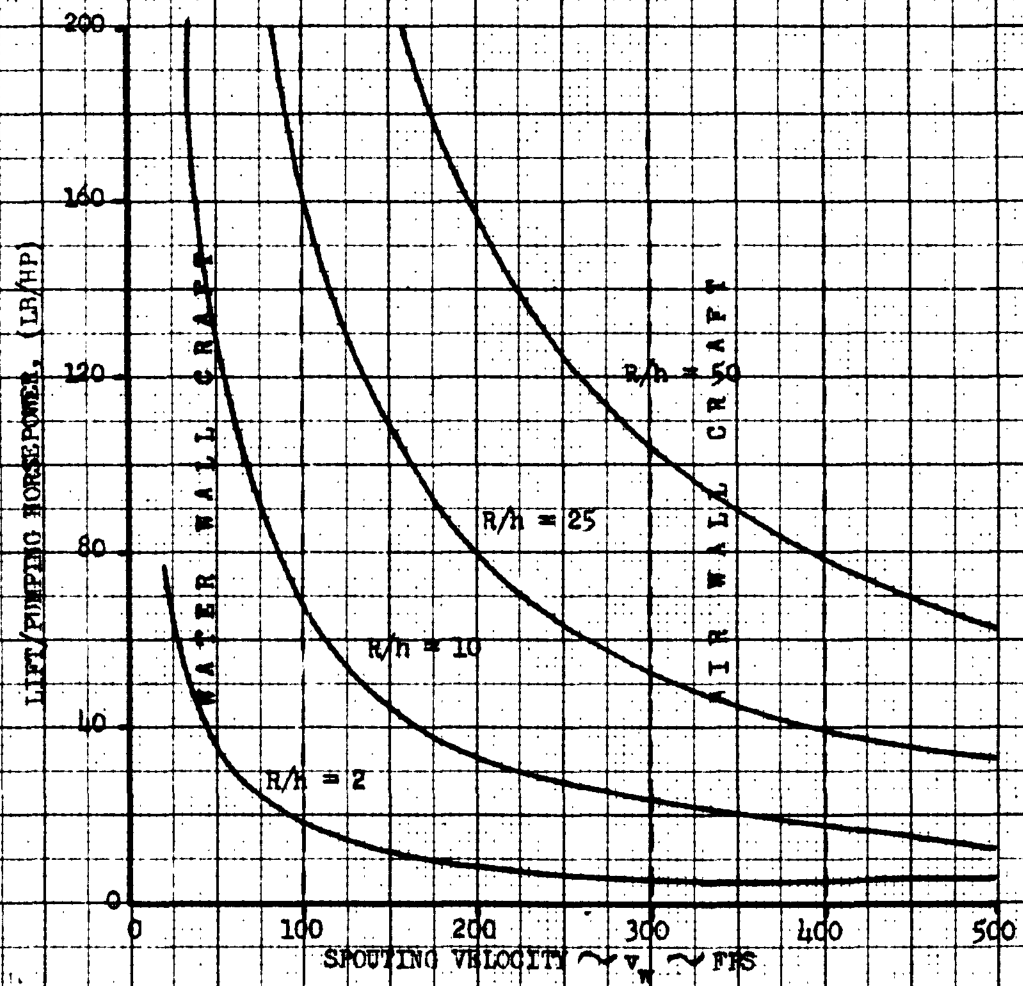
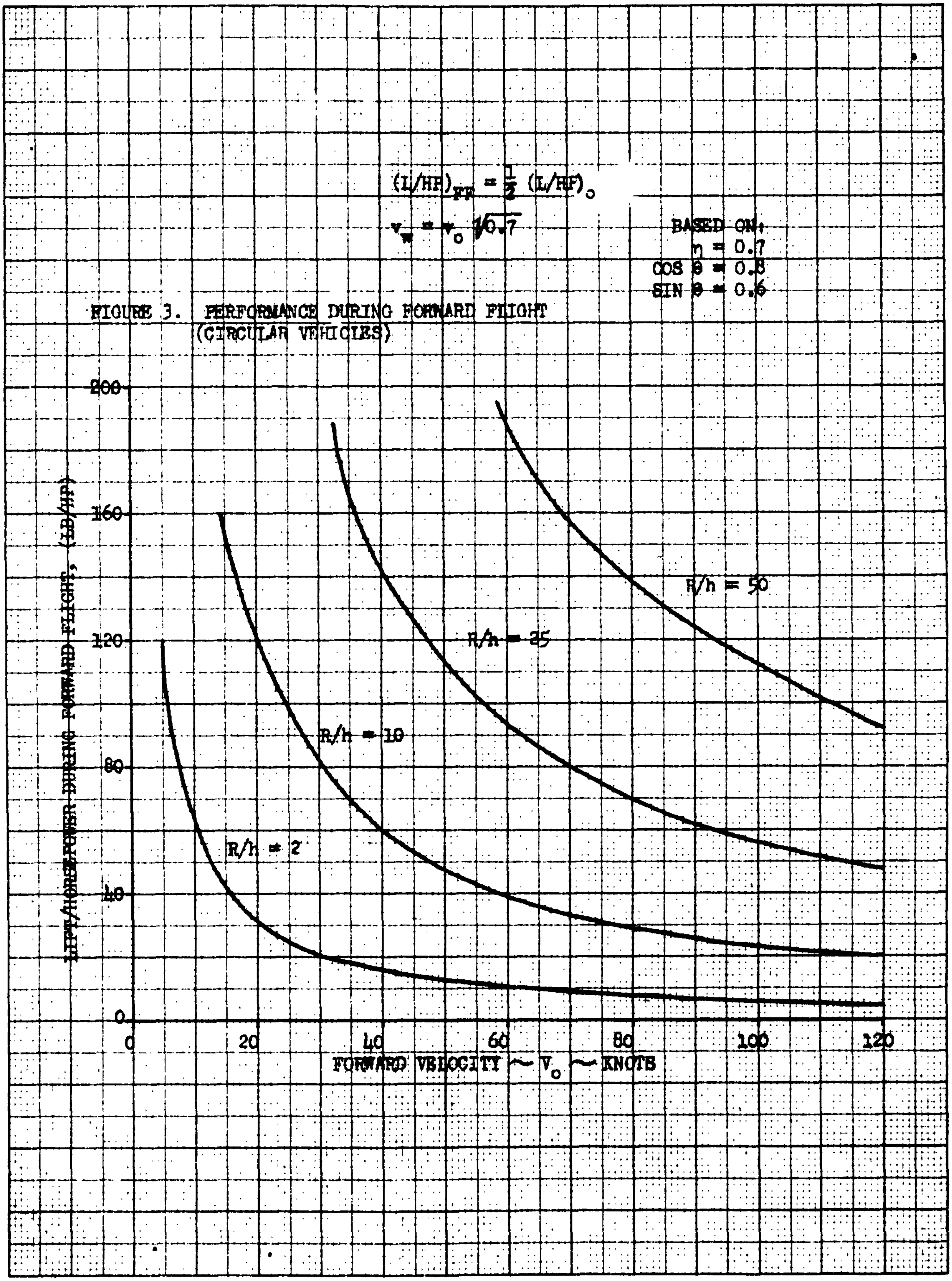


FIGURE 3. PERFORMANCE DURING FORWARD FLIGHT (CIRCULAR VEHICLES)



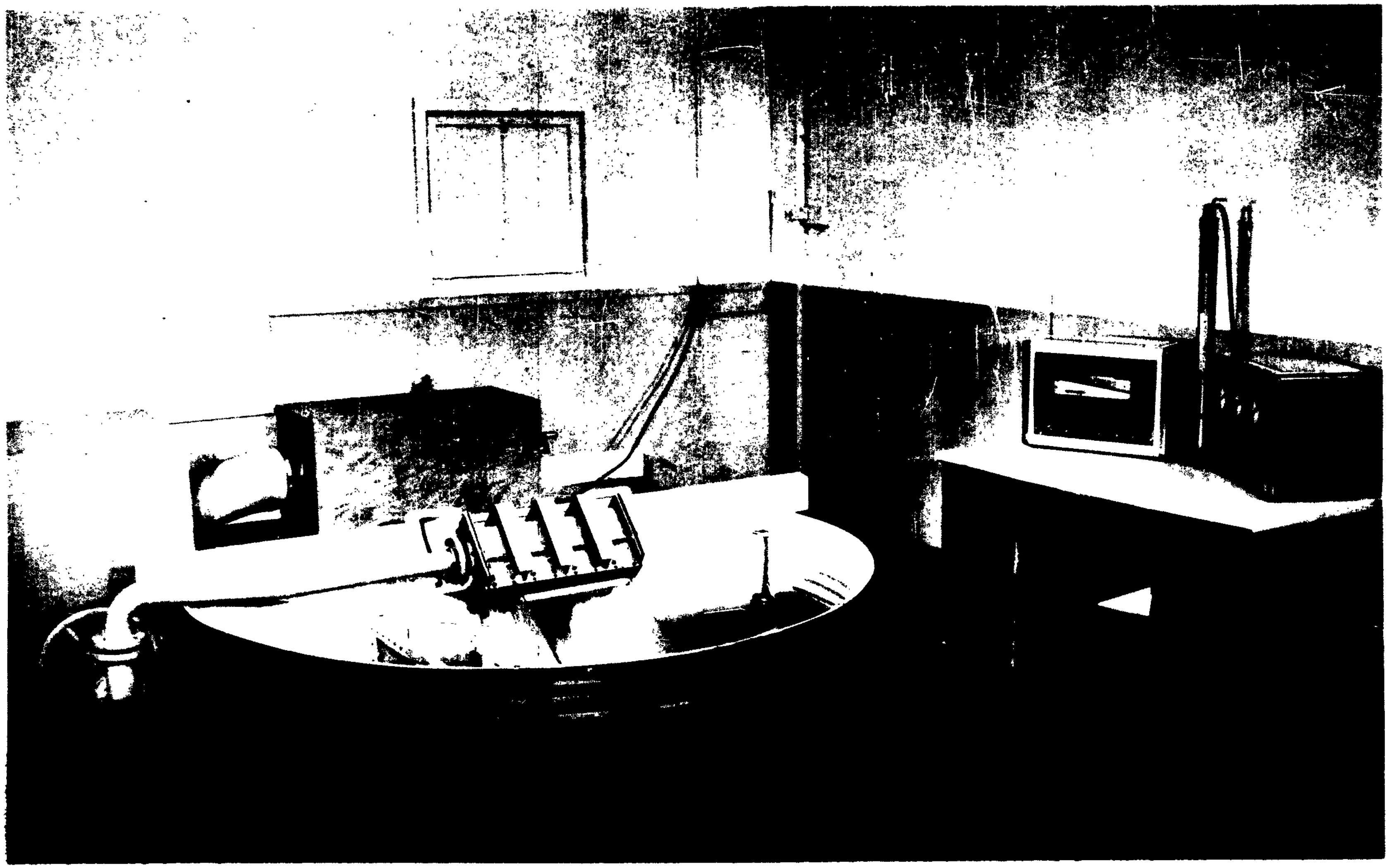


Figure 4

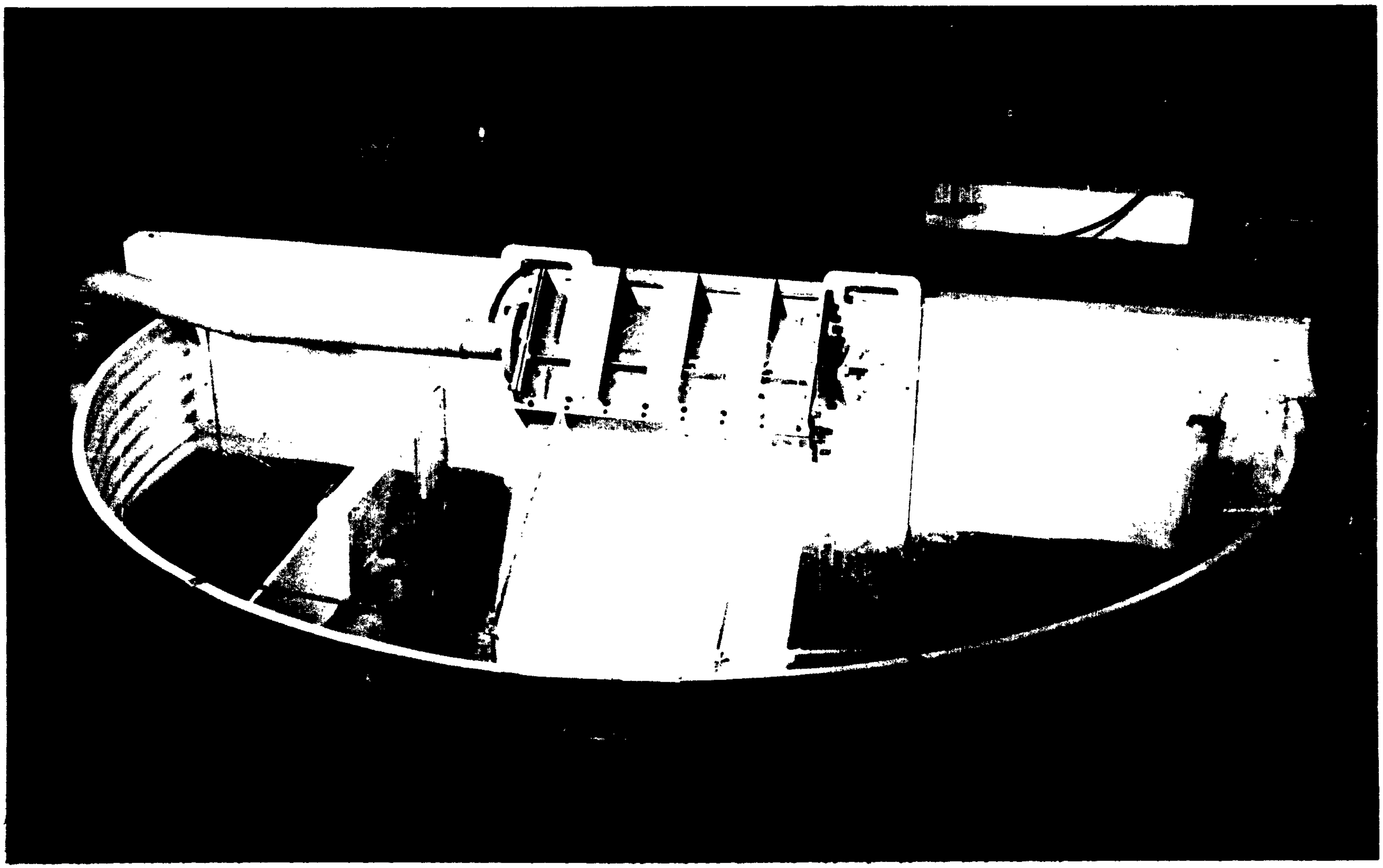
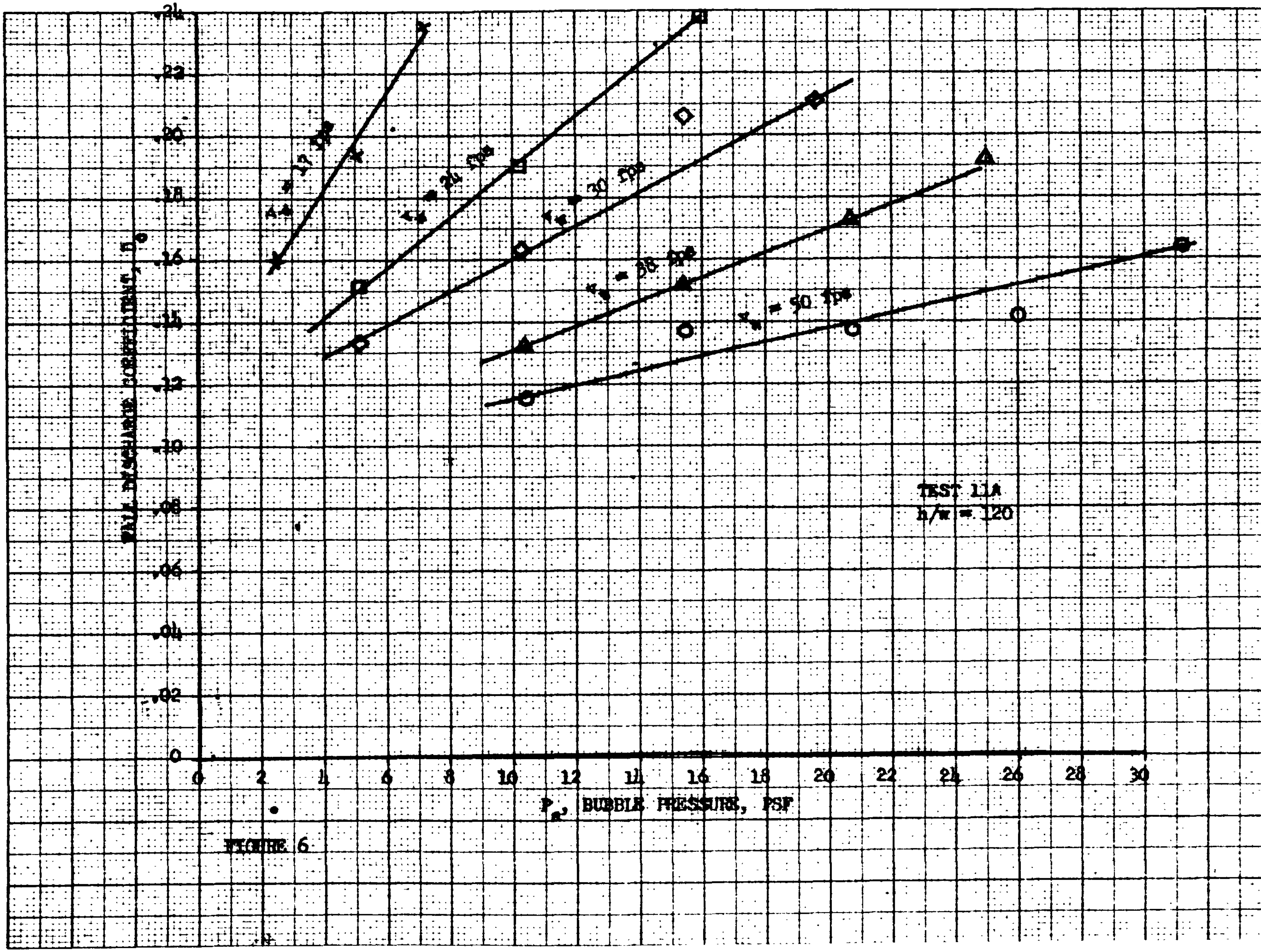


Figure 5



TEST 11A
h/w = 120
P_s, BUBBLE PRESSURE, PSF
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
.24
.22
.20
.18
.16
.14
.12
.10
.08
.06
.04
.02
0

FIGURE 6

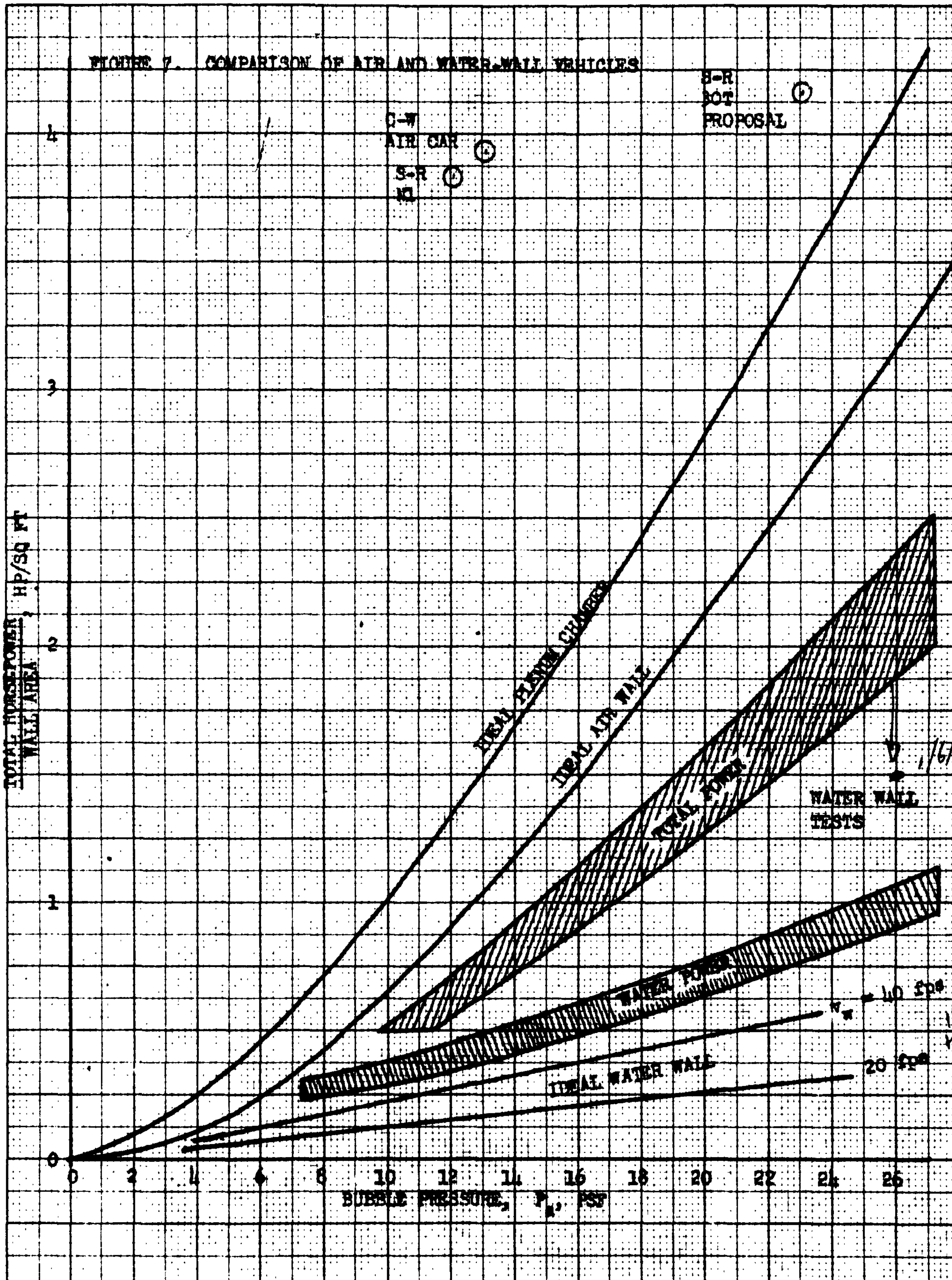


FIGURE 7. COMPARISON OF AIR AND WATER-WALL VEHICLES

MULTI-PURPOSE VEHICLE-ASW CONFIGURATION

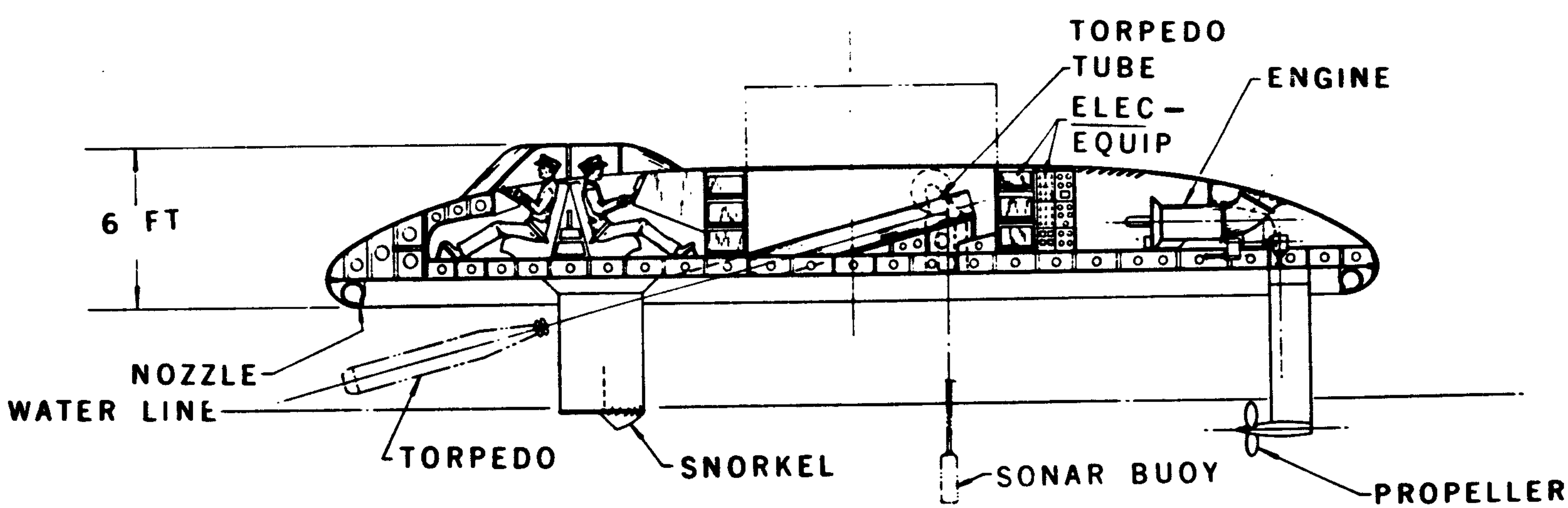


Figure 8

MULTI-PURPOSE VEHICLE-ASW CONFIGURATION

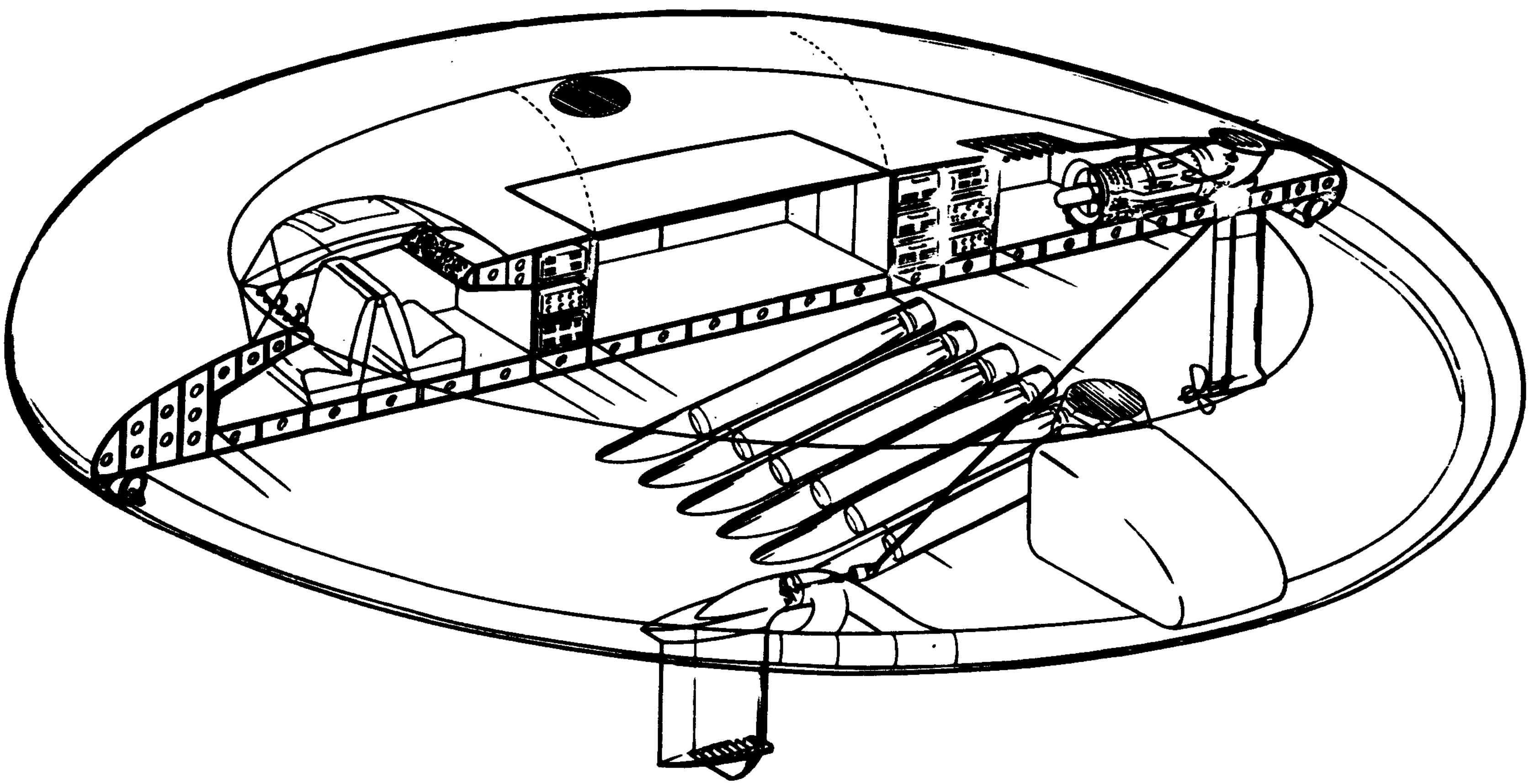


Figure 9

EXMONT 8-2711
UPTON 0-7111

HUGHES TOOL COMPANY
Aircraft Division
CULVER CITY
CALIFORNIA

16 February 1960

In reply refer to:
T-5021

Dr. V. J. Berinati
Institute for Defense Analyses
Advanced Research Projects Division
The Pendagon
Washington 25, D.C.

Dear Dr. Berinati:

Harvey Nay has asked me to answer your request for up-to-date performance estimates on Hydrostreak vehicles.

Attached hereto are three curves giving our present best estimates of performance for the Hydrostreak Research Vehicle (HRV). The following points should be observed in using these data:

1. Hydrostreak performance analysis is still in a state of flux, not because of any difficulties in predicting performance of a specific configuration, but because an optimum configuration has not been found as yet.

2. There seem to be at least 15 independent variables to consider in each case. Any set of these will produce a certain vehicle performance. Lack of agreement between different estimates of vehicle performance is usually due to different assumptions. The number of variables can be reduced in many cases, but the task of finding close-to-optimum solutions is still very large.

3. The curves of Figures 1 and 2 show, respectively, HRV performance based on present data and on "design objective" data. The "design objective" performance was set up as a reasonable development goal. It will be noted, however, that the "present data" estimate approaches the design objective curve at speeds above 70 kts. This is due to a recent data correlation which indicates a favorable effect of spouting velocity on wall performance. Some extrapolation of present data is needed to produce performance points above 50 kts, so the "present data" curves are shown as dashed lines at high speeds.

4. Recent performance analysis has considered the effect of adding a rearward velocity component to the water wall, thus obtaining some thrust at the expense of more air leakage. It has been found that the increase in air leakage was small, and that significant power reductions were possible. This advantage is shown in the comparison curves of Figure 3. This power reduction can be considered as coming out of the water ram drag terms of Figures 1 and 2.

5. An air-wall estimate curve is shown in Figure 3. Since the HRV cruising height, 3 ft, is rather large, compared to the vehicle size, and compared

to the height commonly used in air-wall vehicle designs, it was felt interesting to include this estimate. The air-wall performance analysis used the same state-of-the-art as the water-wall performance and included stability walls for the hovering condition, as did the water-wall analysis. The hovering point agrees with H. R. Chaplin's analysis, except that an additional 80% efficiency factor has been used here to account for the efficiency of the wall in producing the bubble pressure required.

We would like to give you a less complicated and more concise picture of Hydrostreak performance, but the plain fact is that any simple analysis cannot be realistic. We hope to be able to work out more relations between the independent variables to reduce the cumbersome nature of the analysis. In the meantime, we hope the enclosed data will answer your present needs.

Yours very truly,

HUGHES TOOL COMPANY
AIRCRAFT DIVISION

R T DeVault

Robert T. DeVault
Aerodynamics Staff Engineer

RTD:ma

S = 1296 C = 132

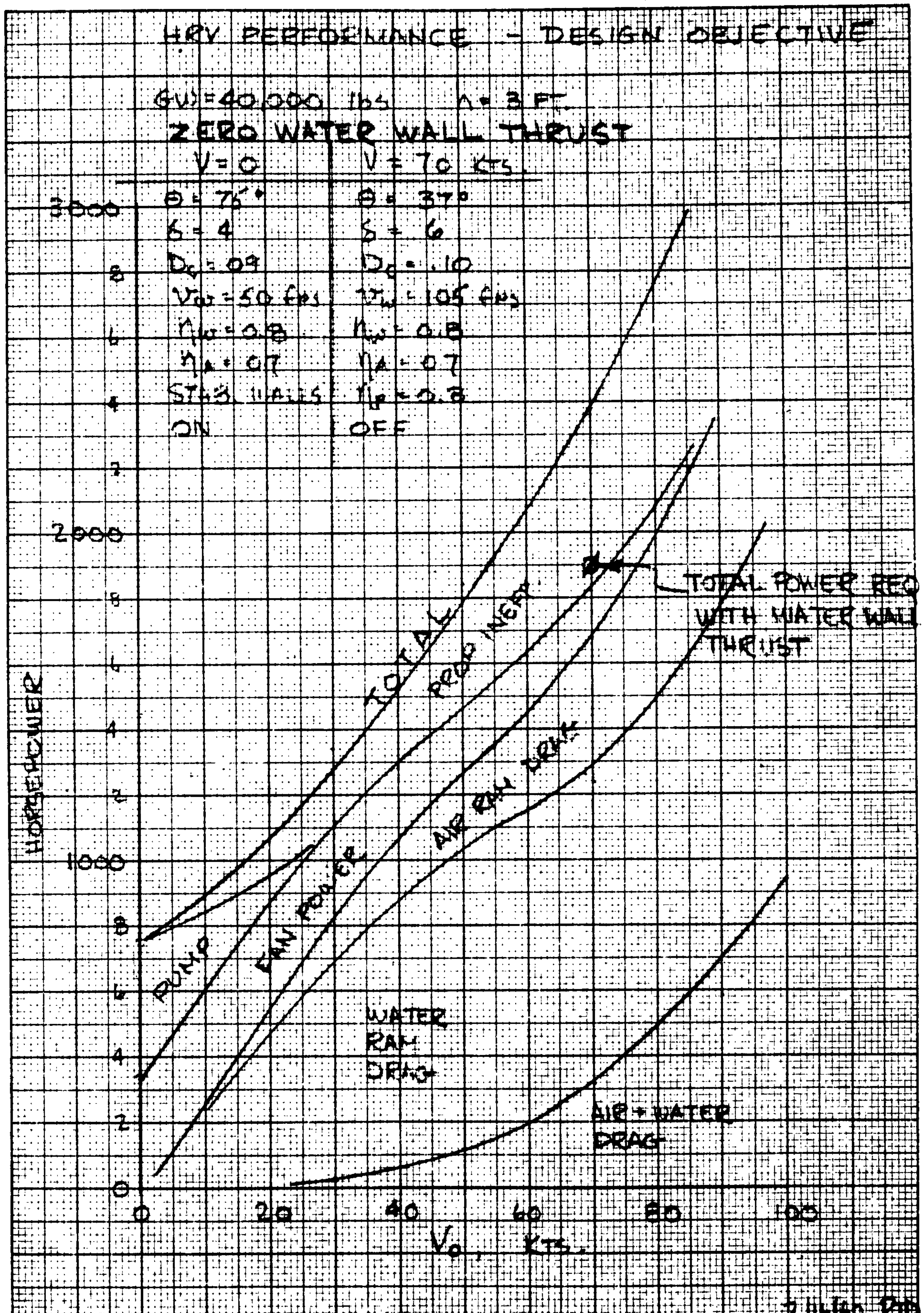
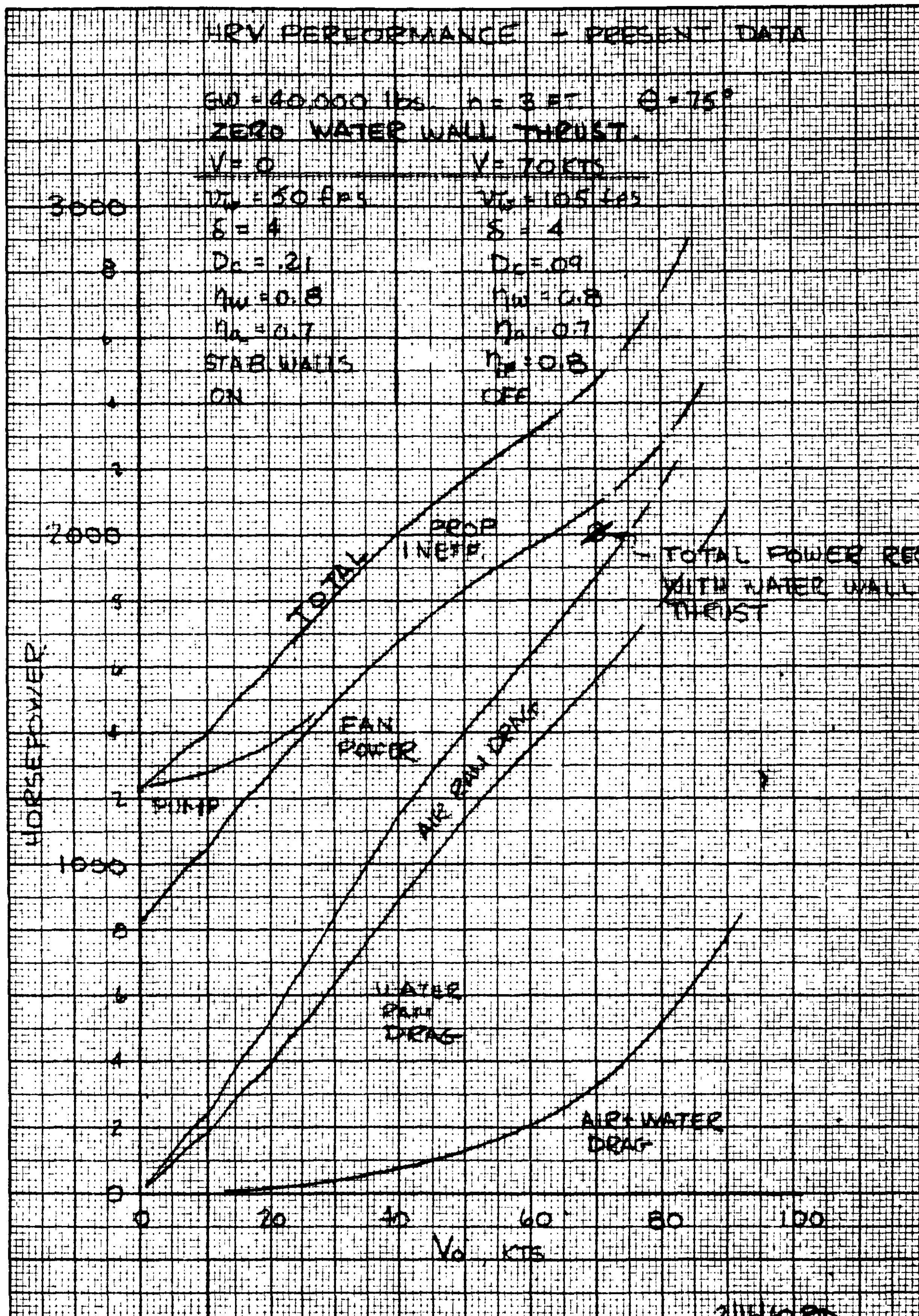


FIGURE 2



HRV PERFORMANCE - PRESENT DATA
GW = 40,000 lbs. h = 3 FT Θ = 75°
ZERO WATER WALL THRUST
V = 0
V = 70 KTS
Vw = 50 fps
Vw = 105 fps
S = 4
S = 4
Dc = .21
Dc = .09
ηw = 0.8
ηw = 0.8
ηa = 0.7
ηa = 0.7
STAB. WALLS ON
ηp = 0.8
OFF
HORSEPOWER
Vo KTS
TOTAL
PROP INEFF.
FAN POWER
PUMP
AIR PAN DRAG
WATER PAN DRAG
AIR + WATER DRAG
TOTAL POWER REQ WITH WATER WALL THRUST
3000
2000
1000
0
20
40
60
80
100

FIGURE 1

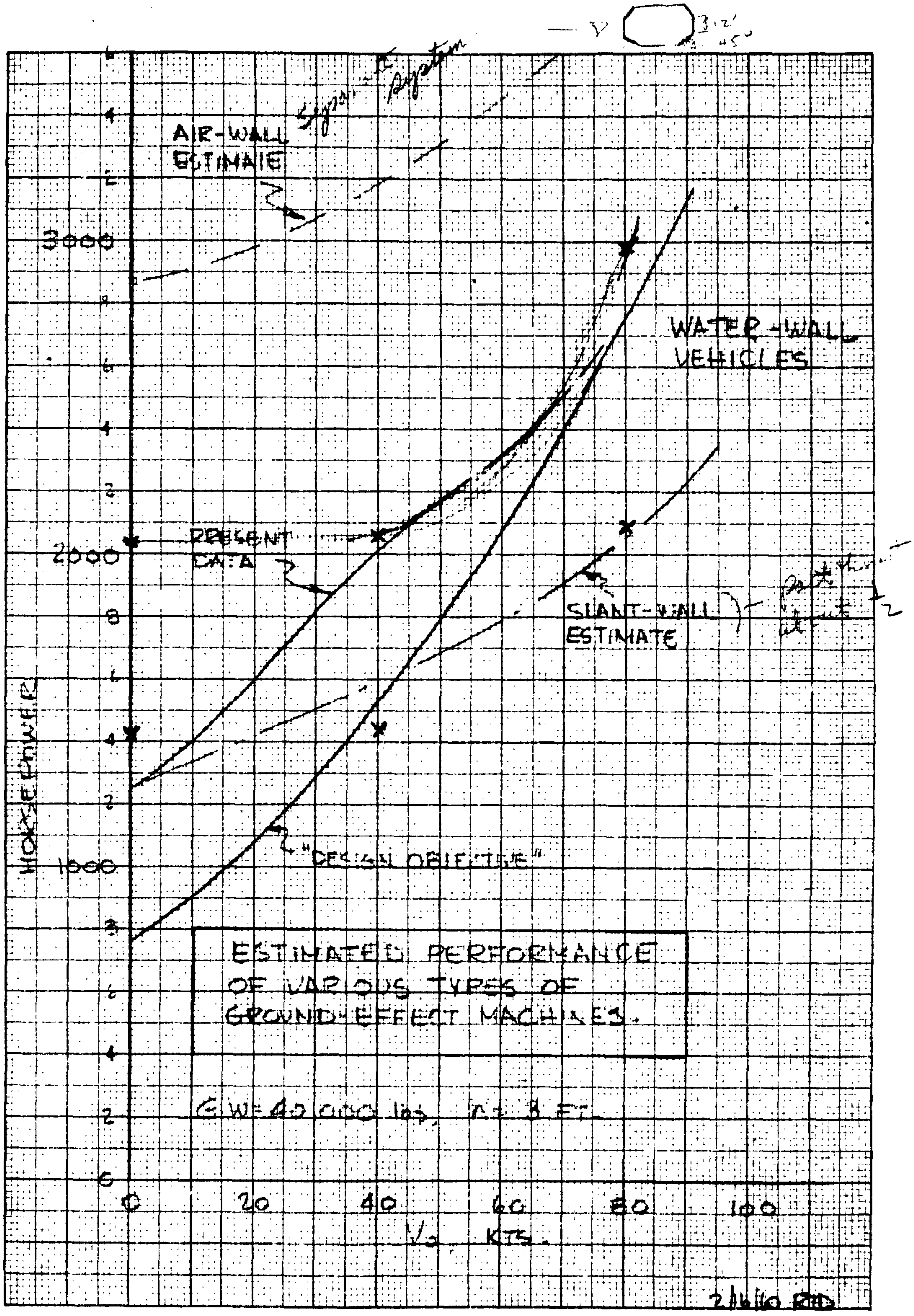
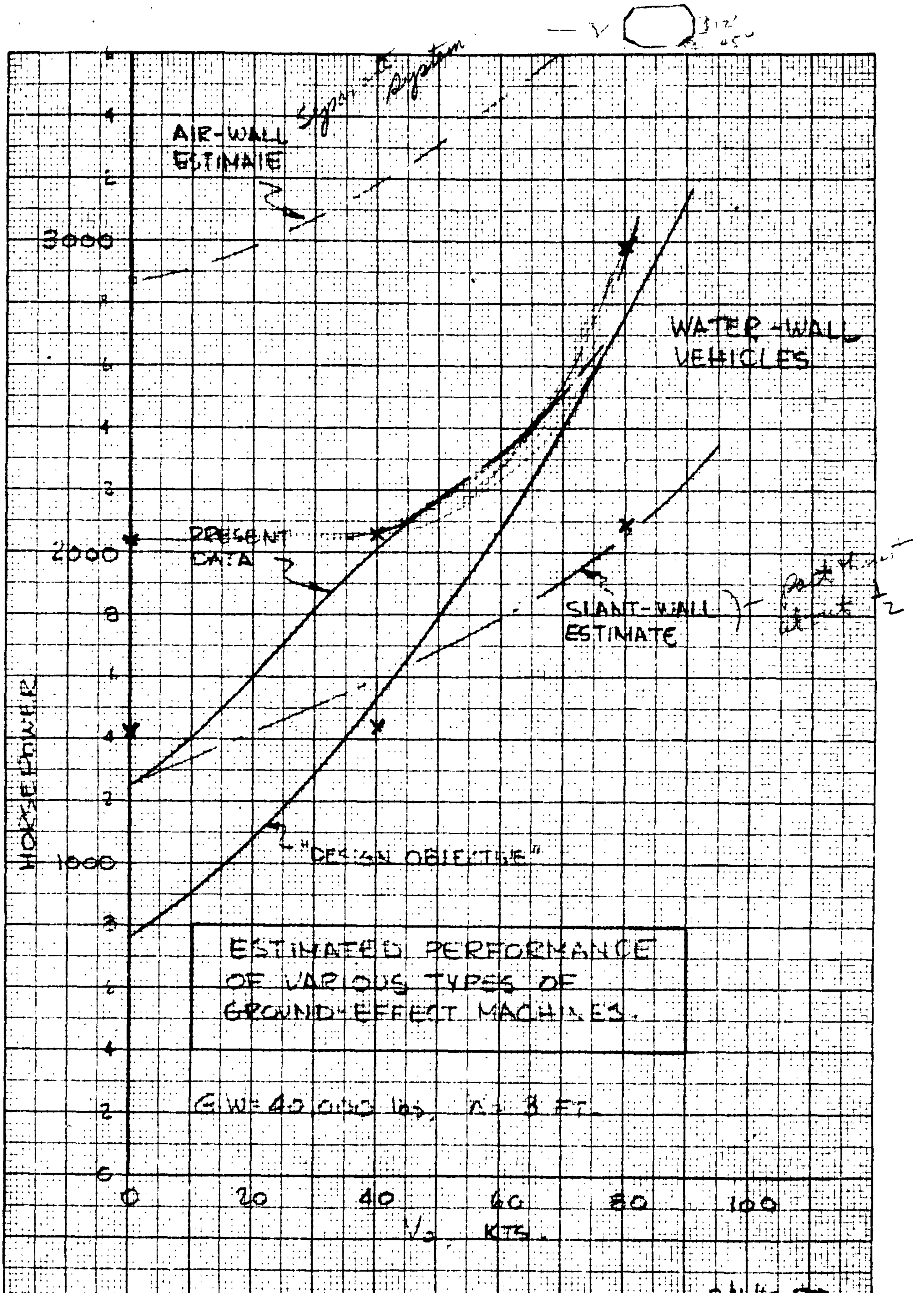

AIR-WALL ESTIMATE
WATER-WALL VEHICLES
PRESENT DATA
SLANT-WALL ESTIMATE
"DESIGN OBJECTIVE"
ESTIMATED PERFORMANCE OF VARIOUS TYPES OF GROUND-EFFECT MACHINES.
GW=40,000 lbs
HORSEPOWER
3000
2000
1000
0
20
40
60
80
100
KTS.

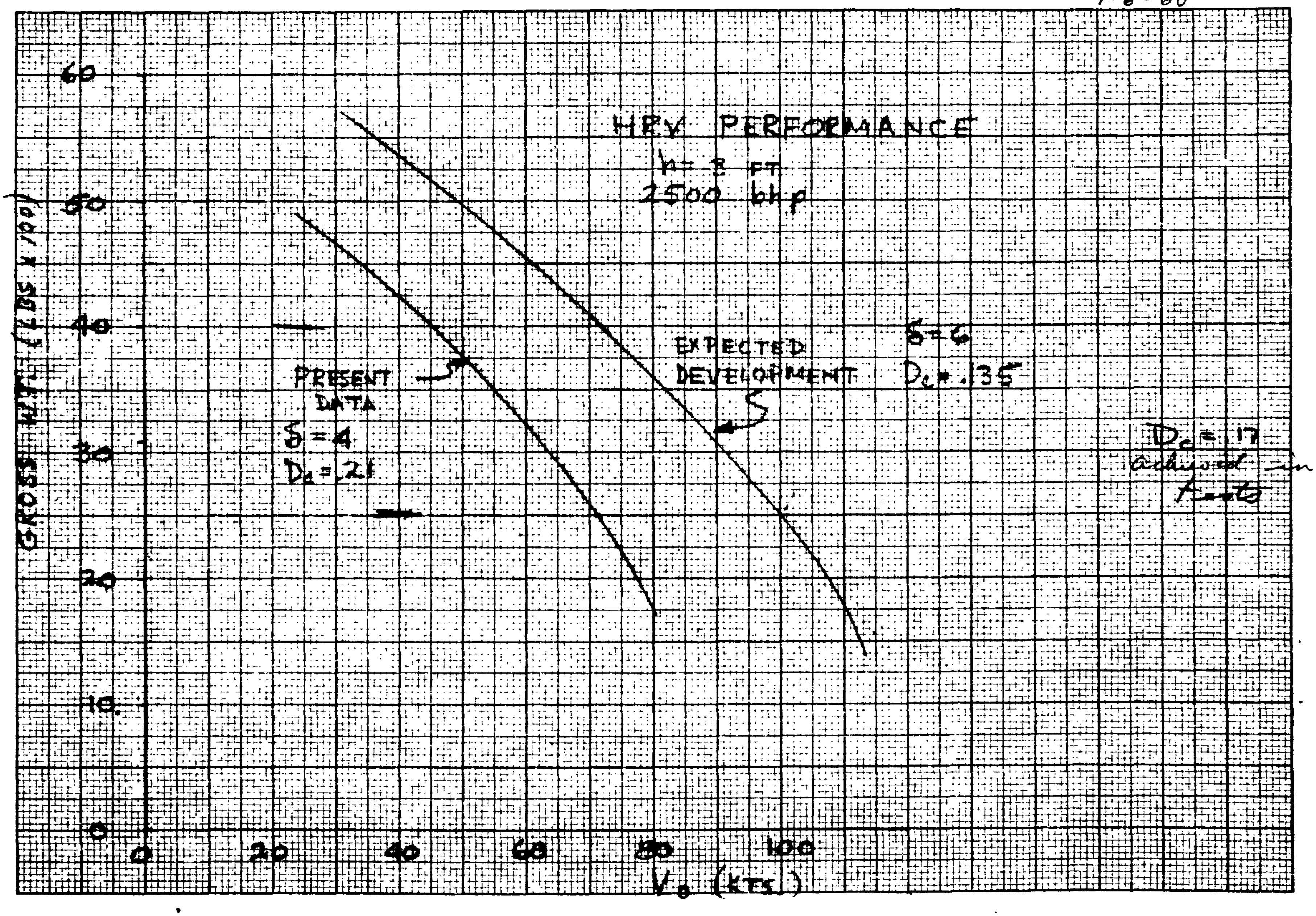
FIGURE 3



AIR-WALL ESTIMATE
3000
WATER-WALL VEHICLES
PRESENT DATA
2000
SLANT-WALL ESTIMATE
HORSEPOWER
"DESIGN OBJECTIVE"
1000
ESTIMATED PERFORMANCE OF VARIOUS TYPES OF GROUND-EFFECT MACHINES.
GW=40,000 lbs, h=3 FT
0
20
40
60
80
100
V0 KTS
21660 RD

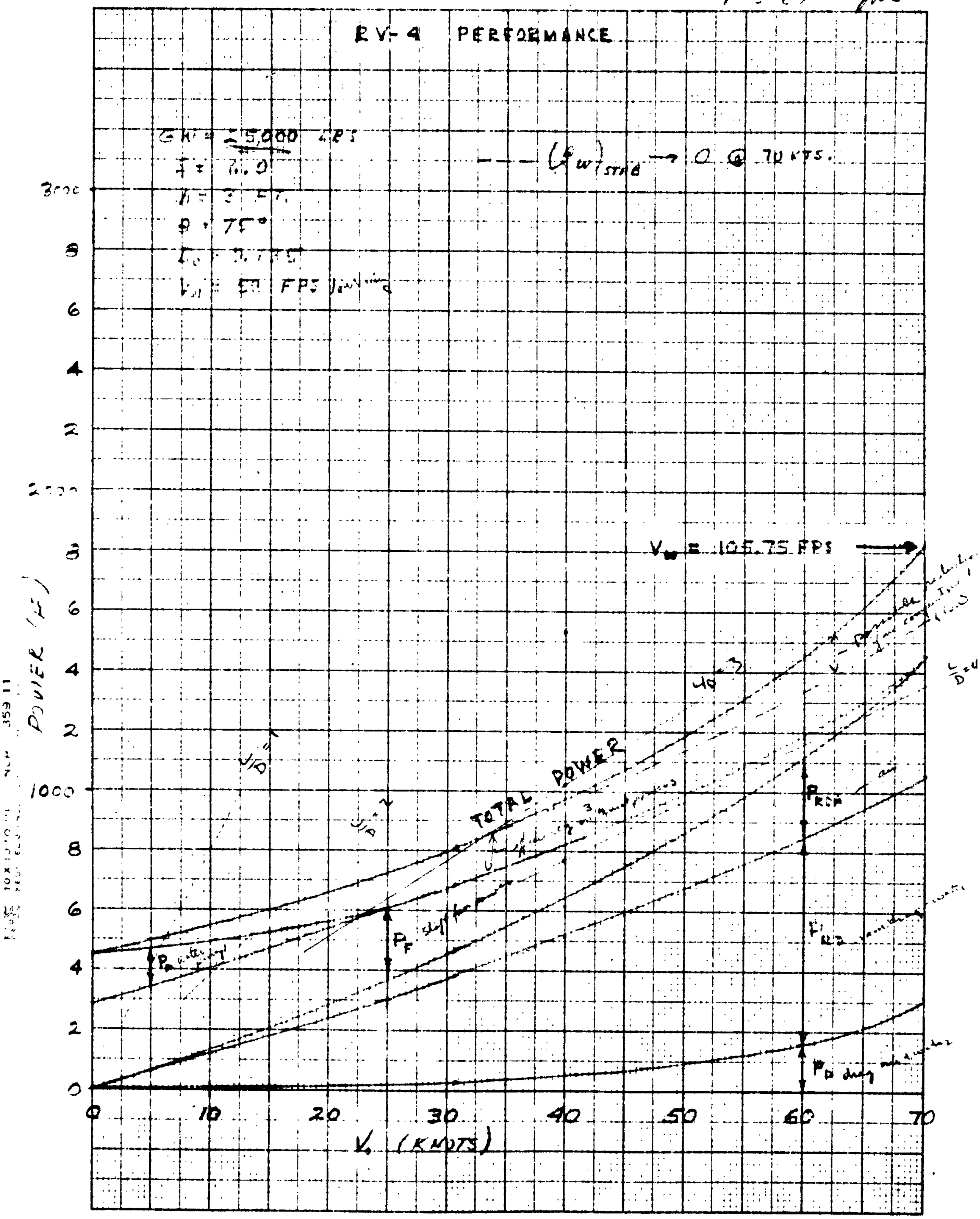
FIGURE 3

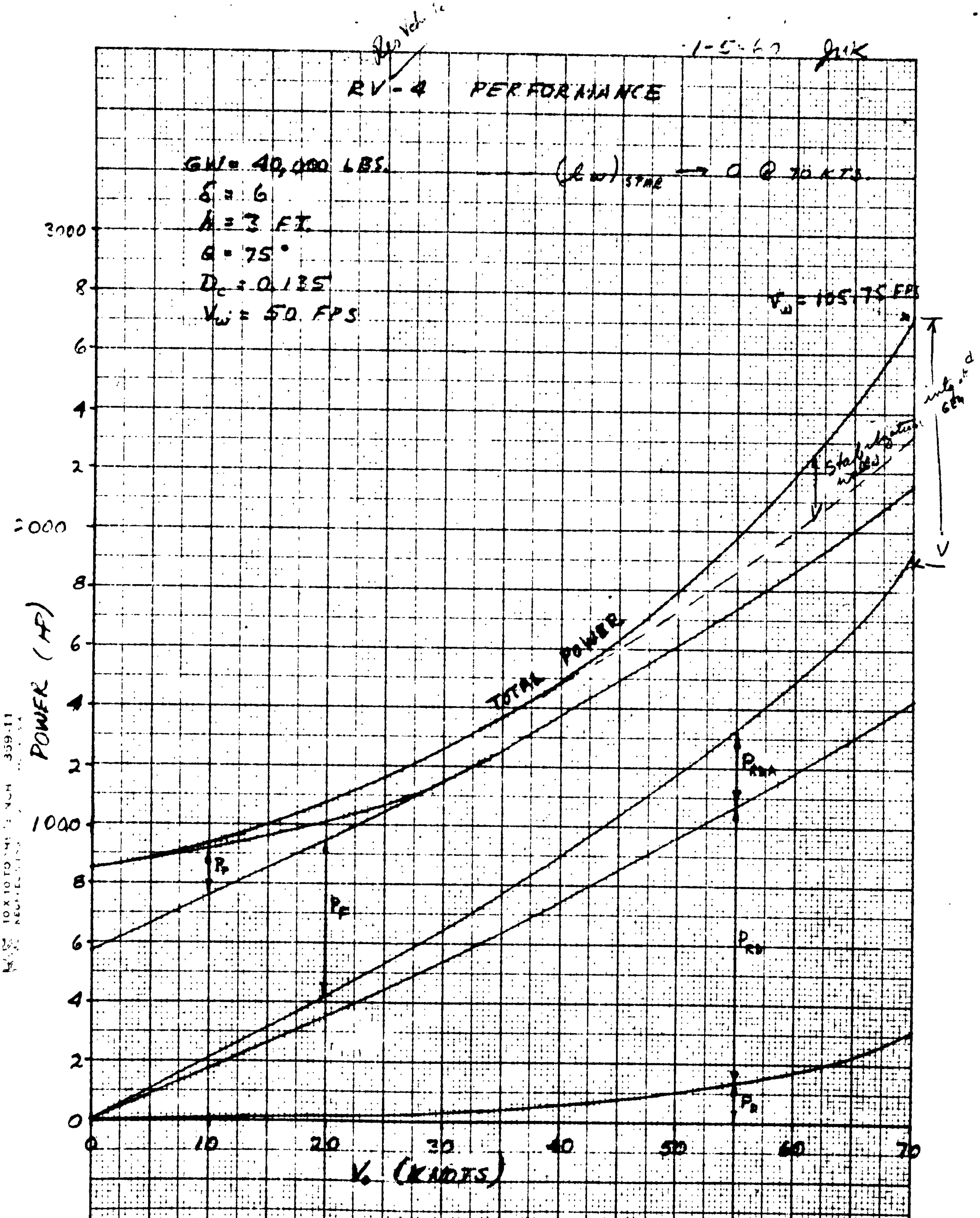
1-6-60

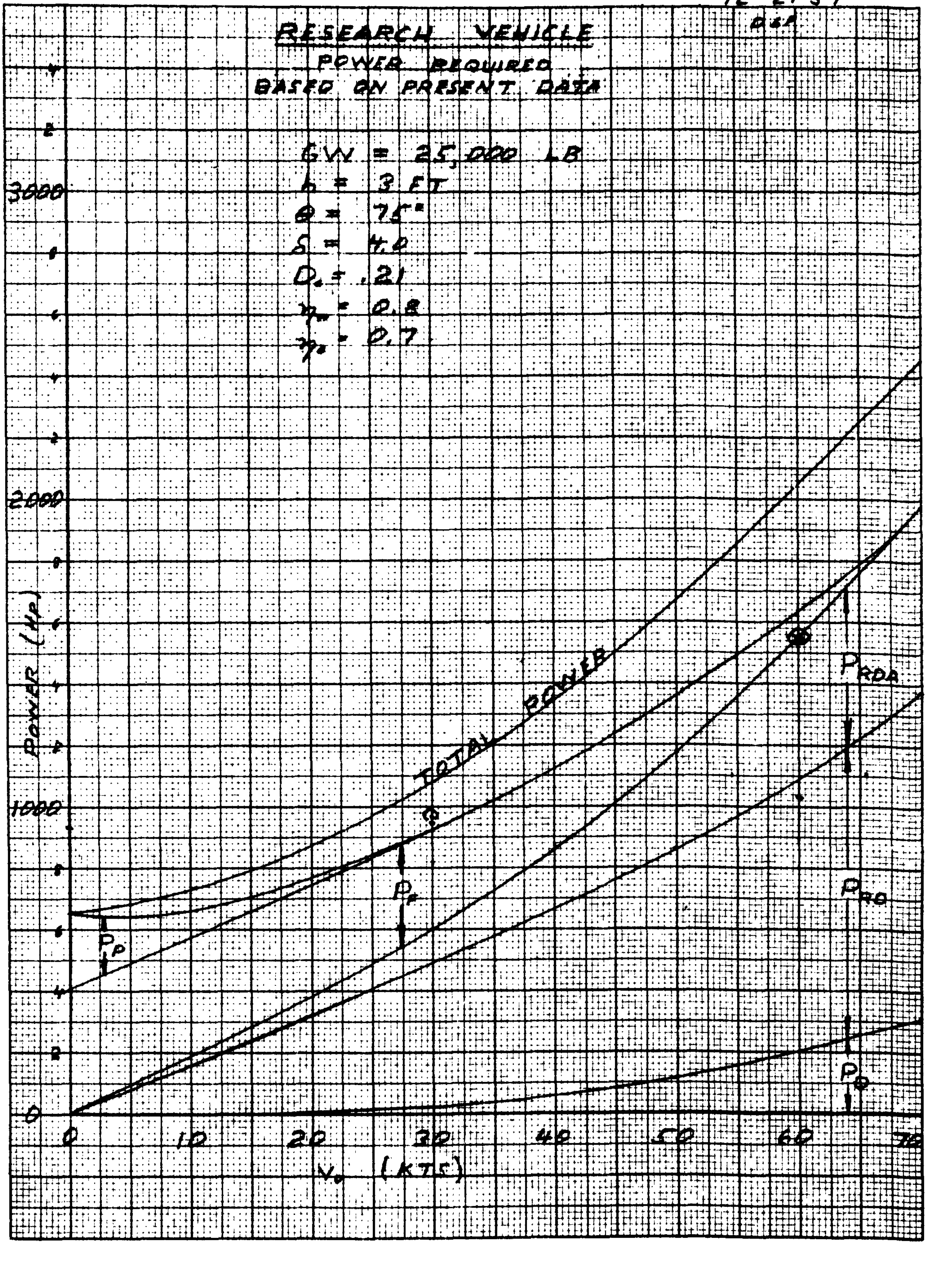


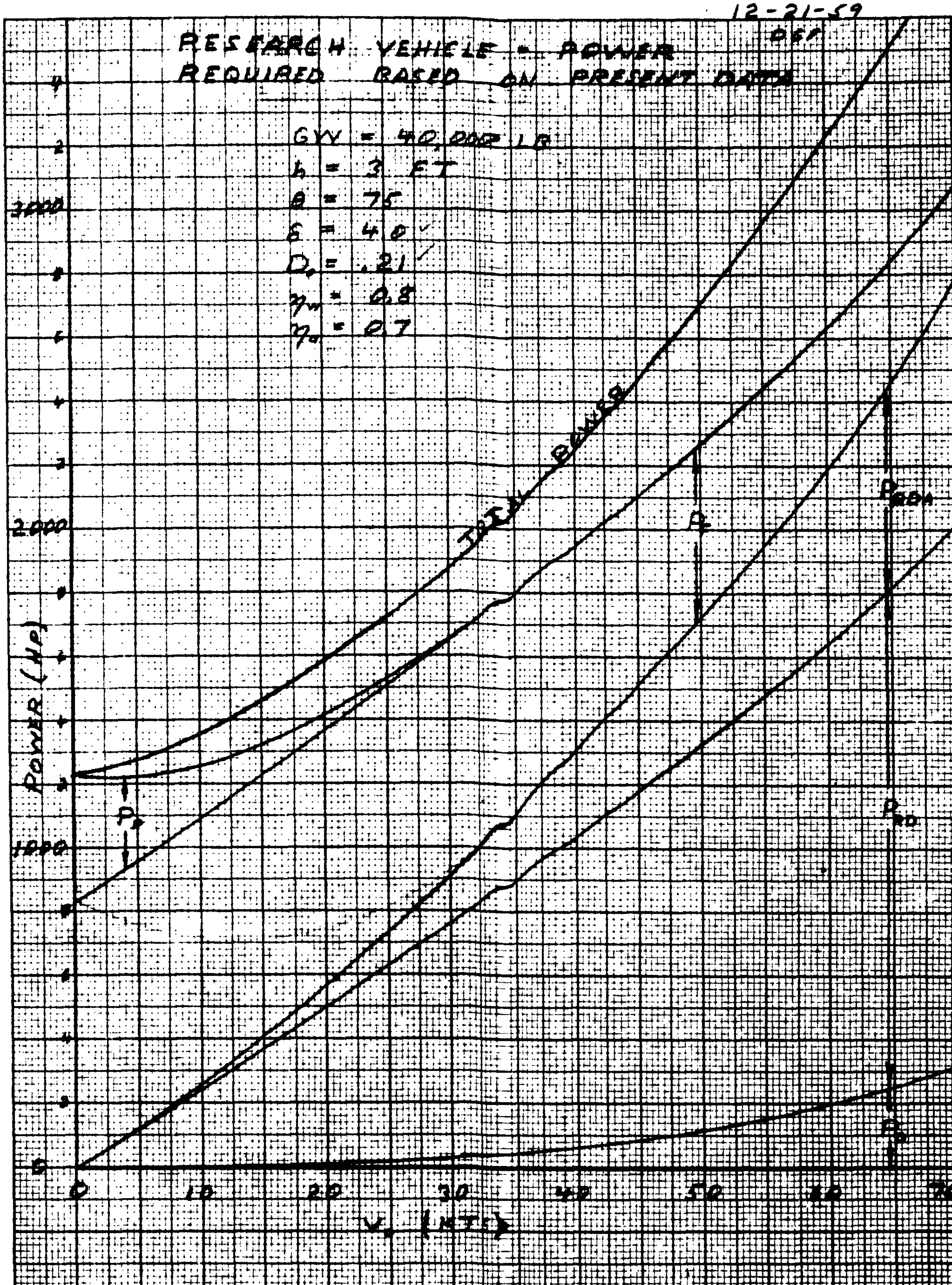
HRV PERFORMANCE
h = 8 FT
2500 bhp
PRESENT DATA
δ = 4
Dc = .21
EXPECTED DEVELOPMENT
δ = 6
Dc = .135
Dc = .17 achieved in Aeroto
GROSS WT. (LBS x 100)
V0 (KTS.)
60
50
40
30
20
10
0
0
20
40
60
80
100

1-5-60 JUK


RV-4 PERFORMANCE
GW = 25,000 LBS
TOTAL POWER
V = 105.75 FPS
POWER (HP)
V (KNOTS)
3000
2000
1000
0
10
20
30
40
50
60
70


1-5-62
RV-4 PERFORMANCE
GW = 40,000 LBS.
δ = 6
h = 3 FT.
θ = 75°
Dc = 0.135
Vw = 50 FPS
Vw = 105.75 FPS
TOTAL POWER
POWER (HP)
V0 (KNOTS)
PP
PF
PRDA
PRD
PB
3000
2000
1000
0
10
20
30
40
50
60
70


RESEARCH VEHICLE
POWER REQUIRED
BASED ON PRESENT DATA
GW = 25,000 LB
h = 3 FT
θ = 75°
S = 4.0
D = .21
η = 0.8
η = 0.7
TOTAL POWER
POWER (HP)
3000
2000
1000
0
0
10
20
30
40
50
60
70
V (KTS)
P_P
P_F
P_ROA
P_RO
P_θ


12-21-59
RESEARCH VEHICLE - POWER REQUIRED BASED ON PRESENT DATA
GW = 40,000 LB
h = 3 FT
θ = 75
ε = 40
D_o = .21
η_m = 0.8
η_o = 0.7
TOTAL POWER
POWER (HP)
3000
2000
1000
0
10
20
30
40
50
60
70
V_o (KTS)