CONFIDENTIAL

JOHN H. CARL & SONS, INC.
150 MERRICK ROAD
ROCKVILLE CENTRE, NEW YORK

FINAL REPORT COMPARATIVE STUDY OF PROPULSION SYSTEMS FOR HYDROFOIL BOAT

BY

JOSEPH V. CHARYK
and
WILLIAM P. CARL

PREPARED FOR THE
OFFICE OF NAVAL RESEARCH
NAVY DEPARTMENT
WASHINGTON, D. C.
CONTRACT NO. N onr-587(00)

JANUARY 1954

COPY NO. 8

CONFIDENTIAL

NOTICE: THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C., SECTIONS 793 and 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW.

JOHN H. CARL & SONS, INC.

150 MERRICK ROAD

ROCKVILLE CENTRE, NEW YORK

FINAL REPORT

COMPARATIVE STUDY OF PROPULSION SYSTEMS
For
HYDROFOIL BOAT

By

JOSEPH V. CHARYK

WILLIAM P. CARL

PREPARED FOR THE
OFFICE OF NAVAL RESEARCH
NAVY DEPARTMENT
WASHINGTON, D. C.
CONTRACT NO. N onr-587(00)

JANUARY 1954

COPY NO.

Distribution List for Final Report, Contract N onr-587(00)

Office of Naval Research, Code 466	10
" 429	1
" 438	1
Bureau of Ships, Code 300	1
" 362 (Library)	2
" 430	1
" 420	1
" 554	1
" 516	1
ONR Branch Office, London	1
New York	1
Chicago	1
Pasadena	1
San Francisco	1
David Taylor Model Basin	2
Naval Research Laboratory (Technical Information Office)	1
Naval Ordnance Test Station	2
Propulsion Research Corporation 1860 Franklin Street Santa Monica, California (Attn: Mr. W. D. Crater) VIA: ONR, Pasadena	1
Fairchild Engine Division Fairchild Engine & Airplane Corp. Farmingdale, L.I., New York (Attn: Mr. A. Gregory) VIA: ONR, New York	1
Gibbs & Cox, Inc. 21 West Street New York, N. Y. (Attn Mr. E. O. Smith) VIA: Sup Ship & NIO, New York	1
Total copies	32

COMPARATIVE STUDY OF PROPULSION SYSTEMS

For

HYDROFOIL BOAT

SUMMARY

This report evaluates the comparative performance of various propulsion systems considered for the propulsion of a 53-foot hydrofoil vehicle designed and constructed by John H. Carl & Sons, Inc. under U. S. Navy Cont. N7 onr-312.

These systems have been compared on a basis of payload to total gross weight versus range calculated for two types of operation. The first considers motion at constant velocity throughout the course of a run. Since certain potentialities of such a vehicle may well depend on its acceleration characteristics, a comparative study has also been made assuming various values of constant acceleration up to a given cruise speed followed by constant speed operation to a point of fuel exhaustion.

Comparative performance data is presented graphically. For a rigorous calculation of this type, it is essential to know the complete characteristics of the power plant at each velocity, including efficiencies of the various components of the system. These, in turn, are also functions of the velocity. Such a calculation can only be made for a specific design and entails the use of a step-by-step integration method.

INTRODUCTION

A proposal to evaluate various propulsion schemes for hydrofoil vehicles was submitted to the Office of Naval Research in July 1951. Cont. No. N onr-587(00) was issued in October 1951 to cover such studies.

The original proposal included the following suggested propulsion schemes:

1. Water pump-jet
2. Gasoline-air hydropulse
3. Conventional propeller with "V" drive
4. Conventional propeller with right angle gear drive
5. Conventional and variable pitch propeller
6. Voith-Schneider propeller
7. Kort nozzle
8. Schnitger propeller

The inadequacy or inappropriateness of several of these schemes for the application in question was discussed in a conference at the Office of Naval Research on December 10, 1951 (Ref. 1). Paragraph 3 of the report of this meeting states:

"Thus, the work is then reduced to the water pump-jet system, the gasoline-air hydropulse and the open stream propeller. As mentioned above, the first two items are already under study and the remaining conventional propeller work will be done by the Bureau of Ships in co-operation with John H. Carl & Sons, Inc."

In order to provide all interested parties with common basic weight and hydrodynamics data for the specific hydrofoil craft in question, a report summarizing this information was issued in January 1951 (Ref. 2).

Specific design studies leading to a recommendation for a water pump-jet system applicable to this vehicle were published in March 1952 (Ref. 3) and corresponding studies pertinent to a high speed underwater propeller system were made available in July 1952 (Refs. 4 & 5). A double-ducted hydropulse engine was built by Aerojet General Corporation in February 1952 but performance data pertinent to this form of propulsion has not been obtained and such information is not anticipated in the near future (Ref. 6). Accordingly it was felt desirable to exclude the latter system in the present studies and prepare the present report without formal treatment of the gasoline-air hydropulse system.

It was felt, however, that a more representative picture of the characteristics and potentialities of this type of vehicle might be forthcoming by including in the present study certain systems which would permit high accelerations. Also, the actual reciprocating engine-air propeller combination at present in use on this craft is compared with the other suggested systems, as are certain modifications of the present system. These include a more efficient propeller design for the particular application as well as a ducted air propeller arrangement. In summary, therefore, the following systems are included in the present system:

1. Reciprocating engine-air propeller #1 (System being employed at present in studies of characteristics of 53-foot hydrofoil vehicle)
2. Reciprocating engine-air propeller #2 (Practical optimization of propeller efficiency)
3. Reciprocating engine-ducted air propeller
4. Reciprocating engine-underwater propeller
5. Reciprocating engine-water pump-jet
6. Air turbo-jet
7. Liquid propellant rocket motor

SUMMARY OF DATA

WEIGHT BREAKDOWN OF SYSTEMS

1. Reciprocating Engine-Air Propeller (System presently installed): Ref. 9.

1.	Engines (Dry weight)(Pratt & Whitney R-985 AN-1 includes carburetors, magnetos, ignition and priming systems)	1,364.0
2.	Propellers	320.0
3.	Air-cooling fans	78.0
4.	Lub. oil system	102.0
5.	Exhaust system	30.0
6.	Starter system	52.0
7.	Fire wall assembly	40.0
8.	Controls	18.0
9.	Instrumentation	28.0
10.	Cowling	160.0
11.	Fuel system	145.0
*12.	Electrical system	184.0
	Total	2,521.0 lbs.

*Electrical system shown in Ref. 9 is 264 lbs. This is reduced in in this report as an extra battery was included in this figure to be used for the experimental instrumentation system.

2. Reciprocating Engine-Air Propeller (Practical optimization of propeller efficiency) Total 2,500.0 lbs.

3. Reciprocating Engine-Ducted Air Propeller estimated 300 lbs. for shrouds Total 2,800.0 lbs.

4. Reciprocating Engine-Underwater Propeller (Ref. 4)

1.	Allison 1710 engine	1,560.0
2.	Heat exchanger & accessories	310.0
3.	"V" drive & coupling	350.0
4.	Exhaust system	100.0
5.	Cooling water	215.0
6.	Lub. oil system	200.0
*7.	Starter system	52.0
*8.	Fire wall assembly	40.0
*9.	Controls	18.0
*10.	Instrumentation	28.0
*11.	Fuel system	145.0
*12.	Electrical system	184.0
**13.	Clutch & reverse	300.0
14.	Propeller shaft & strut	425.0
	Total	3,927.0 lbs.

*Assumed same as System No. 1
**Estimated

5. Reciprocating Engine-Water Pump-jet (Refs. 3 & 10)

1.	Allison 1710 engine	1,560.0
*2.	Heat exchanger & accessories	310.0
*3.	Exhaust system	100.0
*4.	Cooling water	215.0
*5.	Lub. oil system	200.0
*6.	Starter system	52.0
*7.	Fire wall assembly	40.0
*8.	Controls	18.0
*9.	Instrumentation	28.0
*10.	Fuel system	145.0
*11.	Electrical system	184.0
12.	Clutch & reverse	300.0
13.	Strut, pump & gears	620.0
	Total	3,772.0 lbs.

*Assumed same as System No. 4

6. Air Turbo-jet

The average weight of existing engines on a pound/pound of thrust basis is used. A 3,000 lb. thrust engine is assumed Total 1,000.0 lbs.

7. Liquid Propellant Rocket Motor

The average weight of existing units on a pound/pound of thrust basis is used. A 3,000 lb. thrust unit is assumed Total 600.0 lbs.

The aircraft Allison engine was used in System No. 4 rather than the Packard marine engine in order to make the comparison of the two underwater systems on a common basis.

A summary of the comparative horsepowers or thrust, total weights of propulsion systems, and specific fuel consumptions is shown in Table I.

TABLE I

System Number	Horsepower or Thrust	Weight	Specific Fuel Consumption 25 m.p.h.	45 m.p.h.	65 m.p.h.
1	Max. 900 H. P. Cont. 900 H. P.	2,500.0	See Figure 1.		
2	Max. 900 H. P. Cont. 900 H. P.	2,500.0	See Figure 1.		
3	Max. 900 H. P. Cont. 900 H. P.	2,800.0	See Figure 1.		
4	*Max. 2250 H. P. Cont. 1600 H. P.	3,900.0	See Figure 1.		
5	*Max. 2250 H. P. Cont. 1600 H. P.	3,800.0	See Figure 1.		
6	Max. 3000 lbs.T. Cont. 3000 lbs.T.	1,000.0	**1.00	1.00	1.00
7	Max. 3000 lbs.T. Cont. 3000 lbs.T.	600.0	**15.65	15.65	15.65

*With water injection **Expressed in lbs. fuel/hr./lb. thrust

Max. = Maximum
Cont. = Continuous

EFFICIENCIES

The efficiencies used over the speed range for the various systems studied are shown in graphical form in Fig. 2.

In case of System No. 1 the variation of thrust with speed was furnished by Hamilton Standard. In the case of System No. 2 the value of 84% at 65 m.p.h. was obtained from the Curtiss Propeller Co., Caldwell, N. J., as being the efficiency of their C432S-C2/634-3C2-6 propeller currently in use on the U. S. Navy Blimps. The variation of efficiency was assumed parallel to the existing propeller. In the case of System No. 3 the points shown were from Ref. 8.

In the case of System No. 4 the point taken at 65 m.p.h. was from Ref. 5. An earlier estimation of efficiency at this speed was 62.5%. Since this was not realized at 65 m.p.h. it was assumed that it was realized at 40 m.p.h. and that the efficiency starting at 0 at 0 m.p.h. would vary linearly as:
$\eta = 3.182\ v$, with v in ft./sec.

The efficiency for System No. 5 was given in Ref. 3 as being constant in speed range under consideration (25 m.p.h.- 65 m.p.h.).

No efficiency curves are presented for Systems Nos. 6 & 7 as they are constant thrust devices.

BASIC ASSUMPTIONS

1. Maximum gross weight: 15,000 lbs.
2. Empty weight, exclusive of power plant: 7,500 lbs.
3. Range is one way.
4. The speed range is 25 m.p.h. to 65 m.p.h.
5. The L/D is assumed constant over the speed range at a value of 5 for the range calculations.
6. The weight variation due to fuel consumption and hence the variation of the rate of fuel consumption due to reduced power requirements during each run is taken into account.
7. The variation in specific fuel consumption during any one run is also taken into account.

METHOD OF ANALYSIS

The present studies have been designed to compare the various power plant systems on an optimum range basis under constant velocity conditions and also to assess certain aspects of the acceleration problem. If high accelerations are demanded, the fuel consumption in the acceleration portion of the operation may be appreciable and thus the ultimate range may be affected.

For constant velocity operation the comparison of the various power plant systems is made on the basis of the ratio of payload to gross weight as a function of range.

For the acceleration case the thrust requirement as a function of speed to maintain constant acceleration is calculated and the effect of such operation on range is assessed. For power plant systems limited to low accelerations, the range is not significantly affected by the acceleration phase.

The power plant systems studied fall into broad types, the first being those of the jet or rocket type where the specific fuel consumption is expressed in terms of the thrust delivered, and the second being those utilizing a reciprocating engine as the power source where the specific fuel consumption is normally expressed in terms of the brake horsepower output of the engine. Since the analysis will normally be slightly different for each of these two types, the distinction in the following material will be made by referring to power plants of type 1 or type 2 respectively.

a) Constant Velocity

1. Type 1

The calculations in this case can be carried out in straightforward fashion. The general equation of motion is written in the form:

$$\frac{W}{g} a = F - \left(\frac{D}{L}\right) W \text{ - - - - - - - - - - - - - - - - - (1)}$$

where
W = weight of boat at any time, lbs.
F = thrust, lbs.
D/L = drag/lift ratio = constant
a = acceleration, ft./sec.^{2}

can be simplified to give:

$$F = \left(\frac{D}{L}\right) W \text{ - (2)}$$

now,

$$W = W_1 - \int_0^t c.\ F\, dt \text{ - - - - - - - - - - - - - (3)}$$

where
W_1 = initial weight, lbs
c = specific fuel consumption (lbs.fuel/sec./lb. thrust)

hence,

$$\frac{dW}{dt} = c\ F$$

or

$$\frac{dW}{dt} = -c \left(\frac{D}{L}\right) W \text{ - - - - - - - - - - - - - - - - - (4)}$$

by virtue of equation (2)
The range, R, is given as:

$$R = \int_0^t v_o\, dt \text{ - - - - - - - - - - - - - - - - - - - (5)}$$

where v_o is the steady velocity of the craft.

Combining equations (4) and (5), the simple range formula is obtained:

$$\frac{dW}{W} = -c \left(\frac{D}{L}\right) \frac{dR}{v_o}$$

or

$$l_n \frac{W}{W_1} = -c \left(\frac{D}{L}\right) \frac{R}{v_o}$$

or

$$\frac{W}{W_1} = e^{-c \left(\frac{D}{L}\right) \frac{R}{v_o}} \text{ - - - - - - - - - - - - - - (6)}$$

The initial weight, W_i, consists of the empty weight, W_e, plus fuel weight, W_f, plus payload, W_p.

Since the weight, W, in formula (6) is simply equal to the empty weight plus payload for maximum range, the plots shown in Figs. 3-6 are obtained directly. The empty weight includes the power plant weight as well as the structural weight and the former varies from power plant to power plant.

2. Type 2

In this case, equation (3) can be better written in the form:

$$W = W_i - \int_0^t f\,P\,dt \qquad (3')$$

where f = specific fuel consumption (lbs./BHP/hr.)
P = power output

If we assume f to be a constant and relate the power output to the thrust via the efficiency as follows:

$$T\,v_o = P\,\eta$$

the range formula is immediately deduced to be:

$$\frac{W}{W_i} = e^{-\left(\frac{D}{L}\right)\left(\frac{f}{\eta}\right)R} \qquad (6')$$

This, however, tacitly assumes that the specific fuel consumption expressed in fuel consumed per brake horsepower per unit time is a constant. The more complex but more realistic situation where this quantity varies with the horsepower output of the engine can also be considered analytically.

We assume a linear variation as follows:

where $f = c_1 P + f_o$
P = power output of engine
f = specific fuel consumption

Since,

$$\frac{dW}{dt} = -fP$$

[illegible] $\frac{\ldots P + f_o)}{v_o}$

$$= -f_o\left(\frac{D}{L}\right)\frac{W}{\eta\,(v_o)} - c_1\left(\frac{D}{L}\right)^2\left(\frac{W}{\eta}\right)^2 v_o$$

where R = distance travelled
W = weight at any time

This differential equation can be integrated to yield:

$$\frac{W}{W_i} = \frac{1}{e^{(\frac{D}{L})(\frac{f_o}{\eta})R} - W_i c_1 (\frac{D}{L}) \frac{v_o}{f_o \eta} \left[1 - e^{\frac{D}{L} \frac{f_o}{\eta} R}\right]} \quad \text{- - - -(6")}$$

It is easily seen that if $c_1 = o$, i.e. if the specific fuel consumption itself is independent of the power output of the engine, the above equation reduces to:

$$\frac{W}{W_i} = e^{-(\frac{D}{L})(\frac{f_o}{\eta})R}$$

or

$$l_n \frac{W}{W_i} = -(\frac{D}{L})(\frac{f_o}{\eta}) R$$

which is the weight-distance expression derived earlier.

This integration can also be carried out in closed form for more complex variations of f with P than the linear one used here. The present assumption, however, seems to fit the given data to a sufficient accuracy for the present investigation. By the use of equations 6' and 6", the comparative performance data for the various power plant systems can now be presented as shown in Figs. 3-5.

b) <u>Constant Acceleration</u>

The range calculations in this case are based on the hypothesis of a constant acceleration up to a velocity, v_o, followed by constant velocity motion at v_o until complete consumption of fuel. The second phase of this calculation is, of course, identical with the constant velocity case above but with an initial weight value that must be determined from the constant acceleration phase.

For a rigorous calculation of this type, it is essential to know the complete characteristics of the power plant at each velocity, including efficiencies of the various components of the system. These, in turn, are also functions of the velocity. Such a calculation can only be made for a specific design and entails the use of a step-by-step integration method.

A semi-quantitative analysis can, however, be carried out to yield a rough comparison between the various propulsion systems if certain simplifying assumptions are made.

1. Type 1

From equation (1) we have that:

$$W\left[\frac{a}{g}+\frac{D}{L}\right] = F \quad \text{- - - - - - - - - - - - - - - - - - (7)}$$

For constant acceleration, the time rate of change of the weight can be written as:

$$\frac{dW}{dt} = -cF = \frac{dW}{dv}a \quad \text{- - - - - - - - - - - - - - - (8)}$$

where we assume c, the specific fuel consumption expressed in terms of the thrust to be constant:

$$W\left[\frac{a}{g}+\frac{D}{L}\right] = -\frac{a}{c}\frac{dW}{dv} \quad \text{- - - - - - - - - - - - - - - (9)}$$

or

$$\frac{dW}{W} = -dv\left[\frac{a}{g}+\frac{D}{L}\right]\frac{c}{a} \quad \text{- - - - - - - - - - - - - - (10)}$$

The L/D curve for the hydrofoil boat can be represented approximately by an expression of the type:

$$L/D = a_1 + \frac{a_2}{v} \quad \text{- - - - - - - - - - - - - - - - - - - -(11)}$$

where the two constants, a_1 and a_2, are obtained by fitting the actual curve at two points. With this assumption,

$$\frac{dW}{W} = -\frac{c}{g}dv - \frac{c}{a}\frac{v}{a_2\left[1+\frac{a_1}{a_2}v\right]} \quad \text{- - - - - - - - (12)}$$

and hence, the weight, W_o, when the steady velocity, v_o, is reached, is expressable in the form:

$$\frac{W_o}{W_i} = e^{-\frac{c}{g}\left[v_o+\frac{g}{aa_1}\left\{v_o-\frac{a_2}{a_1}\ln\left(1+\frac{a_1}{a_2}v_o\right)\right\}\right]} \quad \text{- - - (13)}$$

The thrust variation with velocity associated with this constant acceleration phase is immediately determined by use of equation (8):

$$\frac{F}{F_i} = \frac{\frac{a}{g}+\frac{v}{a_1 v+a_2}}{\frac{a}{g}}\, e^{-\frac{c}{g}\left[v_o+\frac{g}{aa_1}\left\{v_o-\frac{a_2}{a_1}\ln\left(1+\frac{a_1}{a_2}v_o\right)\right\}\right]} \quad (14)$$

where $F_i = W_i\frac{a}{g}$

This variation of thrust with velocity is shown graphically in Fig. 6.

The payload to gross weight ratio is plotted versus range for various values of the acceleration, a, for the turbo-jet and rocket in Figs. 7 and 8 respectively.

The effect on range as depicted by these two sets of curves is due to two reasons. One reason is the higher fuel consumption associated with the demands of a high acceleration. The second is due to the higher initial weight of the power plant in order that it be capable of delivering the required thrust to achieve the specified accelerations.

2. Type 2

For cases where the fuel consumption is normally expressed in terms of the brake horsepower of the engine:

$$W = W_1 - \int_0^t f\,P\,dt \qquad (15)$$

where

P = brake horsepower
f = specific fuel consumption

Replacing equation (10) in this case, we have:

$$\frac{dW}{W} = -dv \; \frac{a}{g} \; \frac{D}{L} \; \frac{vf}{a.\eta(v)} \qquad (16)$$

where η = efficiency factor relating engine BHP to power output of the power plant.

The integration of this equation depends on a knowledge of the efficiency factor variation with velocity.

If this can be expressed as a function of v, equation (16) can be integrated and the weight variation with speed determined. The total range is then determined, using the method outlined under (a) for the steady state phase of the dalculation. The actual variation of η with v is dependent on the specific power plant being treated. It is clear that a linear variation of η with velocity yields the same result as that obtained in the case of a constant specific fuel consumption based on thrust.

The systems as chosen in the Type 2 category are incapable of very high accelerations except at very low velocities and are also low specific fuel consumption devices. Hence, the effect, in this case, of the acceleration phase on the comparative results given in Figs. 3-5 is negligible and accordingly the conclusions indicated there are unchanged.

c) Calculation of Time to Reach Specified Velocity

For certain applications, the ability of the 53-foot hydrofoil craft to reach design speed in a short period of time may be of considerable importance. Accordingly, it is desirable to consider a method of analyzing the time required to reach design speed through a consideration of the thrust versus speed characteristics of each type of power plant treated in these studies. The previous analysis of the effect of acceleration on overall range has been limited for simplicity to the case of constant acceleration. The following analysis considers the actual acceleration capabilities of each type of power plant:

Since,

$$\frac{a}{g} = \frac{F}{W} - \frac{D}{L}$$

$$dt = \frac{dv}{\frac{F}{W} - \frac{D}{L}}$$

1. Type 1

For rocket and turbo-jet power plants, the thrust F, can be considered as a constant, independent of velocity. Also, if we neglect the effect of the weight variation during the acceleration period, the above equation can be simply integrated for the prescribed variation of (D/L) with velocity to yield the following result:

$$t = \left(\frac{1}{g}\right)\left(\frac{W}{F}\right)\left(\frac{a_1}{a_2}\right)\left(\frac{a_2}{a_1 - \frac{W}{F}}\right)\left\{v - \left[\left(\frac{a_2}{a_1 - \frac{W}{F}}\right) - \left(\frac{a_2}{a_1}\right)\right] \ln\left(\frac{a_1 - \frac{W}{F}}{a_2} v + 1\right)\right\} \quad (17)$$

2. Type 2

In the case of power plants employing a constant horsepower engine to drive the various propeller combinations, the thrust output will vary with velocity in a manner dependent on the variation of the overall efficiency with speed. Hence,

$$dt = \frac{dv}{\frac{F\eta}{Wv} - \frac{D}{L}}$$

If, for simplicity, the actual variation of η with speed can be approximated by a linear relation, whose form, however, will vary from one part of the speed range to another, the integration can again be simply carried out.

If, we assume

$$\eta = k_1 v \qquad \text{for } o < v < v_1$$

$$\eta = k_2 v + k_3 \qquad v_1 < v$$

then the following result is obtained:

$$t = \frac{W}{k_1 P_g}\left\{\frac{a_1}{a_2}\left[\frac{a_2\, v}{\left(a_1 - \frac{W}{k_1 P}\right)} - \frac{a_2^2}{\left(a_1 - \frac{W}{k_1 P}\right)^2}\, l_n\left(\frac{a_1 - \frac{W}{k_1 P}}{a_2}\, v + 1\right)\right] + \left(\frac{a_2}{a_1 - \frac{W}{k_1 P}}\right) l_n\left(\frac{a_1 - \frac{W}{k_1 P}}{a_2}\, v + 1\right)\right\} \quad (18)$$

$$t - t_1 = \frac{W}{P_g}\left\{\int_{v_1}^{v} \frac{\frac{a_1}{a_2} v^2\, dv}{\left(\frac{a_1}{a_2} k_2 - \frac{W}{a_2 P}\right) v^2 \left(\frac{a_1}{a_2} k_3 + k_2\right) v + k_3} \quad o < v < v_1\right.$$

$$\left. + \int_{v_1}^{v} \frac{v\, dv}{\frac{a_1}{a_2} k_2 - \frac{W}{a_2 P}\; v^2\; \frac{a_1}{a_2} k_3 + k_2\; v + k_2}\right\} v_1 < v \quad (18')$$

where the actual form of the integrated expression depends on the relative values of:

$$a = \left(\frac{a_1}{a_2} k_2 - \frac{W}{a_2 P}\right)$$

$$b = \left(\frac{a_1}{a_2} k_3 + k_2\right)$$

$$c = k_3$$

It is most important to keep in mind that the validity of the equations become inaccurate for long times because of the assumption of essentially constant weight. This, however, is not too objectionable in that acceleration characteristics are ordinarily of interest only for reasonably low values of t. Although the form of relations (17), (18) and (18') is seen to be relatively simple, the complexity of the integrated expressions in the general case and the uncertainty of the important relationship between η and v in the low speed range, seriously questions the desirability of making a complete general analysis. The equations, however, will be of use in checking specific performance calculations where the variation of η with v is accurately known in the low speed range.

DISCUSSION

Power Plant System Total Weight

The importance of the all up weight of the power plant system to be used in a craft of this type becomes most evident in this type of an analysis. In Figs. 3-5 note the variation of the Payload/Gross Weight ratio for the 0 range condition. The lighter the power plant system the greater the Payload/Gross Weight ratio at 0 range.

The reason for choosing power plants with more horsepower than is actually required by the drag of the bare vehicle is evidently to take care of the increased drag of the underwater components, the losses in the "V" drives and gear trains and lack of availability of medium power liquid cooled engines.

Efficiency

The efficiency curves of the various systems (Fig. 2) show that, neglecting the all up weight of the power plant systems in question, the underwater propeller has a superiority over the practically optimized air screw up to about 35 m.p.h. and over the pump-jet up to about 40 m.p.h. The pump-jet shows a superiority over the air screw up to about 30 m.p.h. However, it should again be pointed out that the efficiencies are not as great a factor as the weights of the systems. It should be noted that in the case of System No. 1 an "off-the-shelf" propeller, which was designed for a much higher operating speed than 65, was used in the interest of economy on the experimental craft. This accounts for the poor efficiency of System No. 1. System No. 2 is an example of the practical optimization of the air propeller as exemplified by the Curtiss propeller used on the U. S. Navy blimps. This propeller has an efficiency of 84% at 65 m.p.h. and is 11'6" in diameter. The reason it was not used on this particular craft is that it was designed and built for the next size larger engine i.e. 600 H.P. and the hub will not fit on the 450 H.P. engine. No known adapters from a 40 spline shaft to a 30 spline shaft were available. This particular propeller would be very interesting for a production model for several reasons. It is made of steel, which would help the erosion problem and is reversible, which would answer the maneuverability question of air propellers.

System No. 3 shows the gain to be realized by shrouding an air propeller--i.e. greater efficiency for the same diameter. The shrouding also increases the safety of the air propeller.

General

The lightness, low drag and simplicity of the air screw are important advantages. Air screws are not as vulnerable as underwater methods of propulsion. The vulnerability of the underwater systems is best attested to by the carrying aboard of spare propellers and diving gear by the PT class boats. They also offer a gain in less draft and the fact that they do not have to be retracted with the foils.

Their disadvantages are the high level of noise, which, however, is acceptable in commercial aircraft; their element of danger to the crew; their high center of gravity which decreases the maneuverability somewhat; and the problem of leading edge erosion by spray. This latter problem is being worked on and the Hamilton Standard Propeller Div. of the United Aircraft Corp. has developed a method of rubber coating and then nickel plating the blades. This has reportedly increased the life of the propellers on the Martin P5M by a factor of 3.

The reason for the displacement of the 65 m.p.h. curve of System No. 1 in Fig. 5 is that for the assumed L/D of 5 @ 65 m.p.h. the efficiency of this particular propeller is so low that it doesn't produce 3000 lbs. of thrust @ 65 and so enough fuel had to be taken out at the beginning to bring the drag and thrust in balance. This of course, would not be the case with a practically optimized propeller. In actuality the boat has an L/D of 8 at this speed so that this is not the case. The range is lower at the high speed for the underwater propeller and greater for the rocket, turbo-jet, air propellers and ducted-air propellers due to the efficiency being less at the high speed for the underwater propeller. The slope of the curves of Figs. 3-5 reflects the specific fuel consumption and propulsive efficiencies of the various systems.

The calculated results, as summarized in Figs. 3-5, clearly show the relative proficiency of the low weight, high thrust per unit area engines as exemplified by the rocket and turbo-jet for very short range, high payload applications and conversely the overwhelming importance of low specific fuel consumption for longer range performance.

For ranges below about 40 miles, the turbo-jet engine provides the optimum payload/gross weight ratio for all the power plants considered, but beyond this point the air screw with its combination of low engine weight and high propulsive efficiency is the best choice. In the case of the pump-jet the invariance in propulsive efficiency together with the constancy of the L/D with speed yields a single curve independent of speed. The pump-jet --Allison engine combination shows up clearly as the best of the underwater systems.

The very large influence of power plant weight in the hydrofoil boat application is most graphically depicted in the cases of the underwater propulsive schemes where the engine selected has a very high weight as compared to the other engines used in the study. The reduction of the propulsive efficiency with speed is actually a relatively minor influence compared to the restriction imposed by the very heavy engine weight.

For a more refined optimal study, it would be necessary to utilize a more accurate efficiency versus velocity curve and to seek in each case the most efficient engine to deliver the horsepower required for the specific application in mind.

Acceleration Study

For reasonable values of initial acceleration, the analysis indicates that with the exception of the very short range power plants, i.e. the rocket and the turbo-jet, the overall range is affected in negligible fashion by the acceleration phase of the operation. The effect on range of various initial accelerations is illustrated graphically in Figs. 7 and 8 for the rocket and the turbo-jet. The influence is seen to be significant.

The thrust variation to maintain a constant acceleration is shown as a function of velocity in Fig. 6. If a specific power plant is considered, the acceleration will, therefore, drop off with speed since none of the available power plants possess a thrust characteristic of the type required for constant acceleration if operated at constant power.

The methods outlined for calculating time required to reach a given speed imply a decreasing acceleration with speed, the exact form of which depends on the characteristics of the power plant in question.

CONCLUSIONS

1. The Type 1 power plants are of interest for heavily loaded, short range, high speed and high acceleration applications.

2. In the Type 2 class the most significant factor is the weight of the power plant in question for the reason that the efficiencies and fuel consumptions are not widely diverse. Assuming that through detail design and future development, equal power plant installation weights can be achieved, the selection would be made on the basis of some practical design consideration in the specific application except in the very lightly loaded ultimate range cases.

3. The air propeller is limited to the application where the design cruising speeds are in excess of 40 m.p.h. In this range it is possible to achieve larger efficiencies than underwater systems with reasonable diameters (10-11'6"). Below 40 m.p.h. the underwater propulsion methods appear optimum.

4. Of the underwater systems the pump-jet appears to be most favorable in the high speed range due to its cavitation delaying characteristics.

5. A requirement of high accelerations (over 1/30 over the take-off range, 0 - 30 m.p.h.) results in significant range penalty in any system.

--- REFERENCES ---

1. Conference Report on Hydrofoil Propulsion Systems, Feasibility Study. Office of Naval Research, December 10, 1951.

2. John H. Carl & Sons, Inc.: "Hydrodynamic and Weight Data Employed in 50 Foot Hydrofoil Vehicle Propulsion Study." Memorandum No. 1, January 2, 1951.

3. Propulsion Research Corporation: "Design Study for Pump-jet Application for Carl Company Hydrofoil Boat." March 19, 1952.

4. Bureau of Ships: "Feasibility Study of Hydrofoil Propulsion." July 22, 1952.

5. Communication from Bureau of Ships: "Cont. N onr-587(00) (420) Serial 420-235, 6 October 1953.

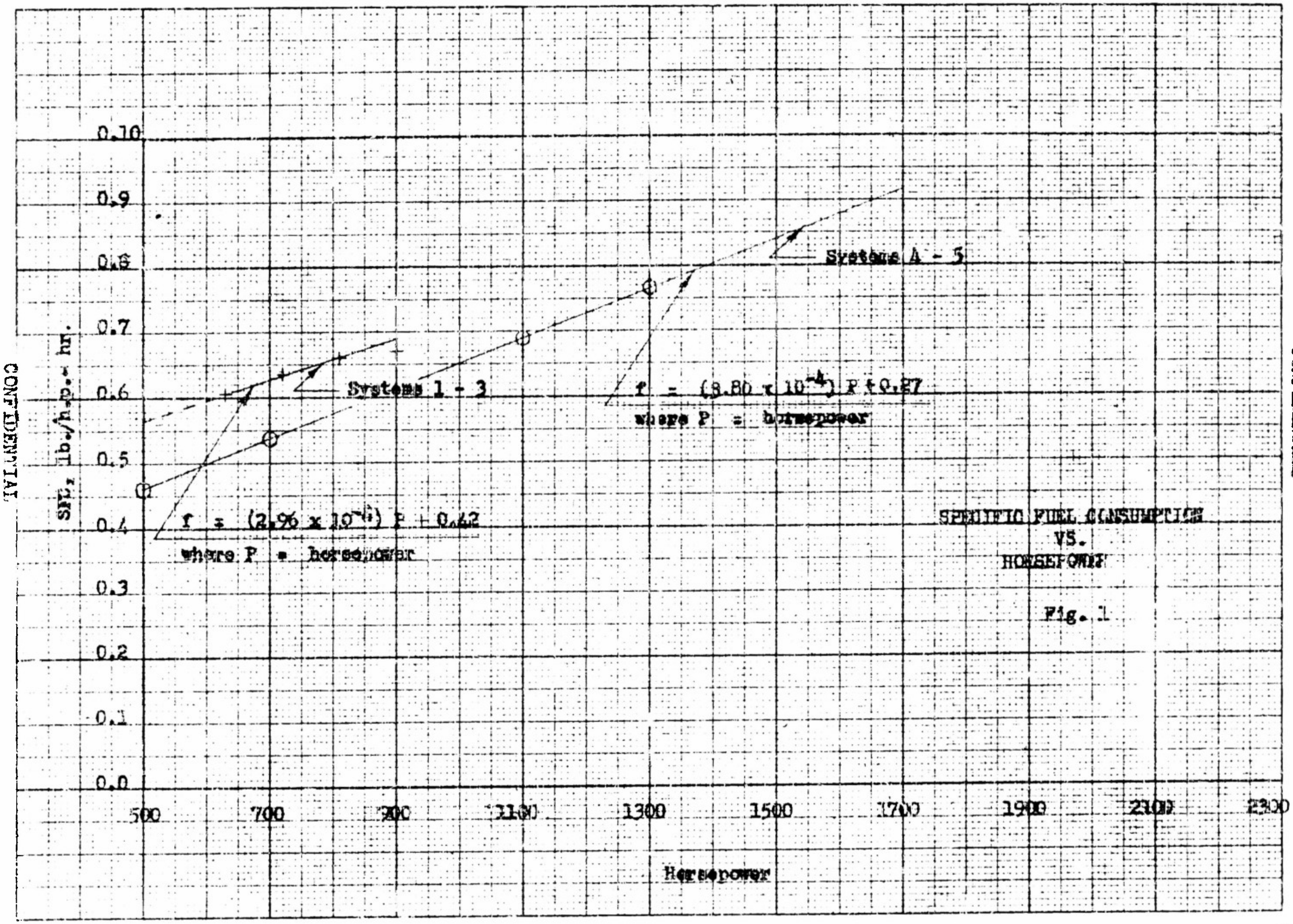
6. Communication from Aerojet General Corporation to John H. Carl & Sons, Inc., July 7, 1953.

7. Communication from Bureau of Ships to Chief of Naval Research for distribution: "Feasibility Study for Hydrofoil Propulsion; forwarding of Bureau of Ships study covering conventional propeller." July 22, 1952.

8. Kuchemann & Weber: "Aerodynamics of Propulsion." McGraw-Hill, 1952.

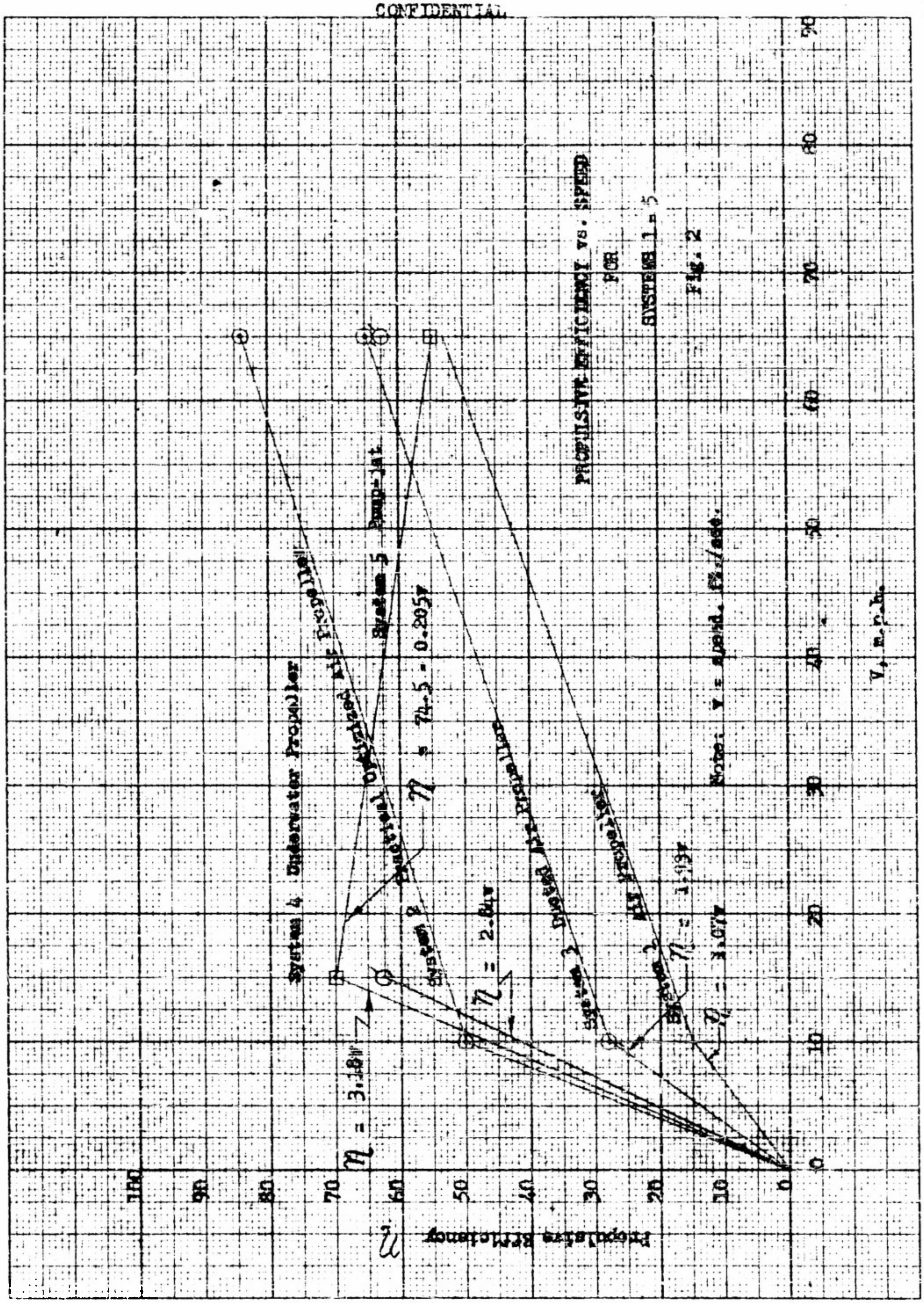
9. John H. Carl & Sons, Inc.: "Weight and Center of Gravity Calculations for 53-Foot Hydrofoil Vehicle." Report No. 10, July 1953.

10. Wilkinson, Paul: (Aircraft Engines of the World - 1951). Paul Wilkinson, 225 Varick Street, New York, N. Y.



SPECIFIC FUEL CONSUMPTION
VS.
HORSEPOWER

Fig. 1


PROPULSIVE EFFICIENCY vs. SPEED
FOR
SYSTEMS 1 - 5
Fig. 2
Propulsive Efficiency η
V, m.p.h.
Note: V = speed, ft./sec.
System 4 Underwater Propeller
Air Propeller
System 5 Pump-Jet
System 2
System 3 Ducted Air Propeller
System 1 Air Propeller
η = 3.18v
η = 2.8v
η = 74.5 - 0.205v
η = 1.93v
0
10
20
30
40
50
60
70
80
90
100

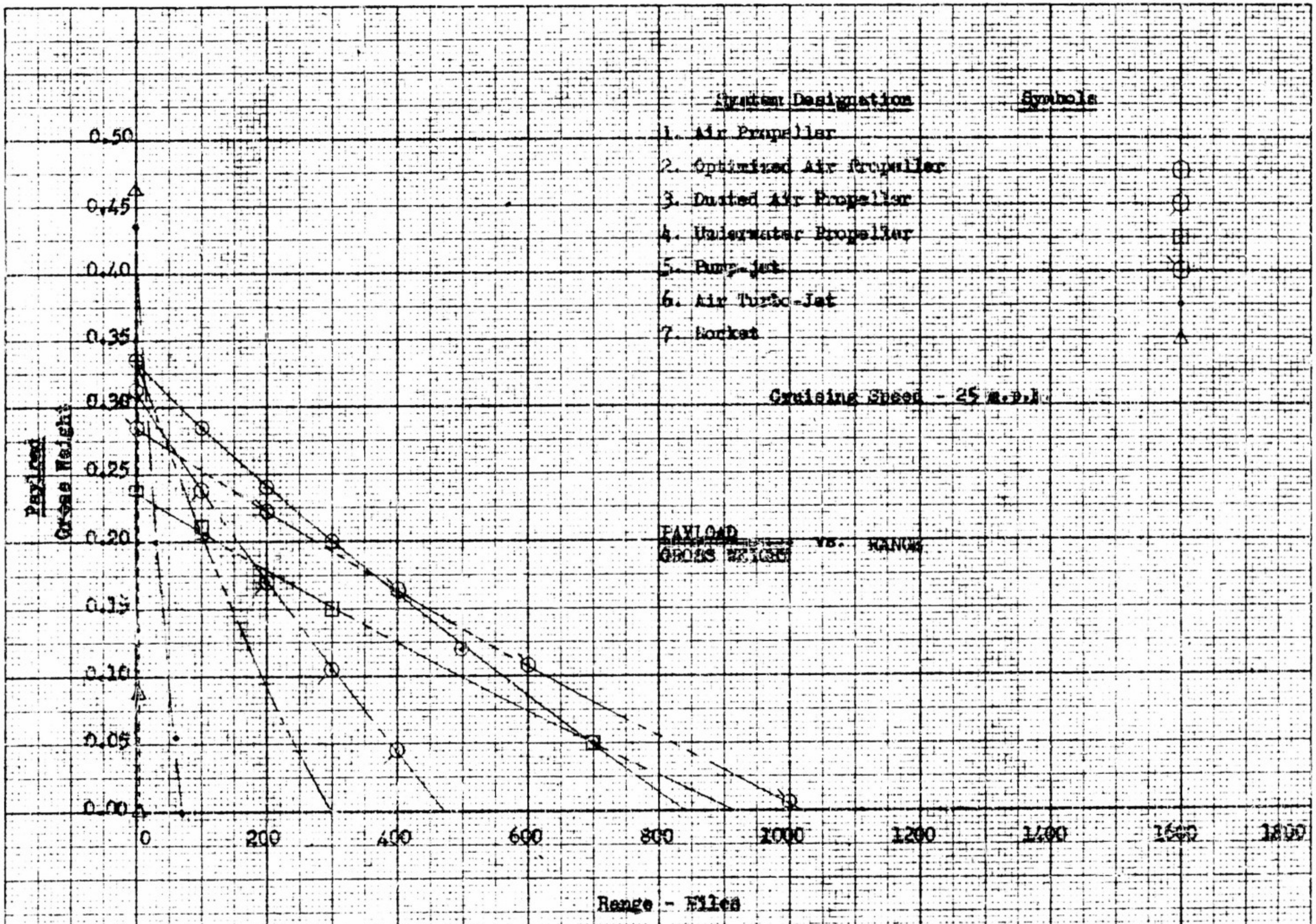

System Designation
Symbols
1. Air Propeller
2. Optimized Air Propeller
3. Ducted Air Propeller
4. Underwater Propeller
5. Pump-Jet
6. Air Turbo-Jet
7. Rocket
Cruising Speed - 25 m.p.h.
PAYLOAD / GROSS WEIGHT vs. RANGE
Payload / Gross Weight
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
200
400
600
800
1000
1200
1400
1600
1800
Range - Miles

Fig. 3

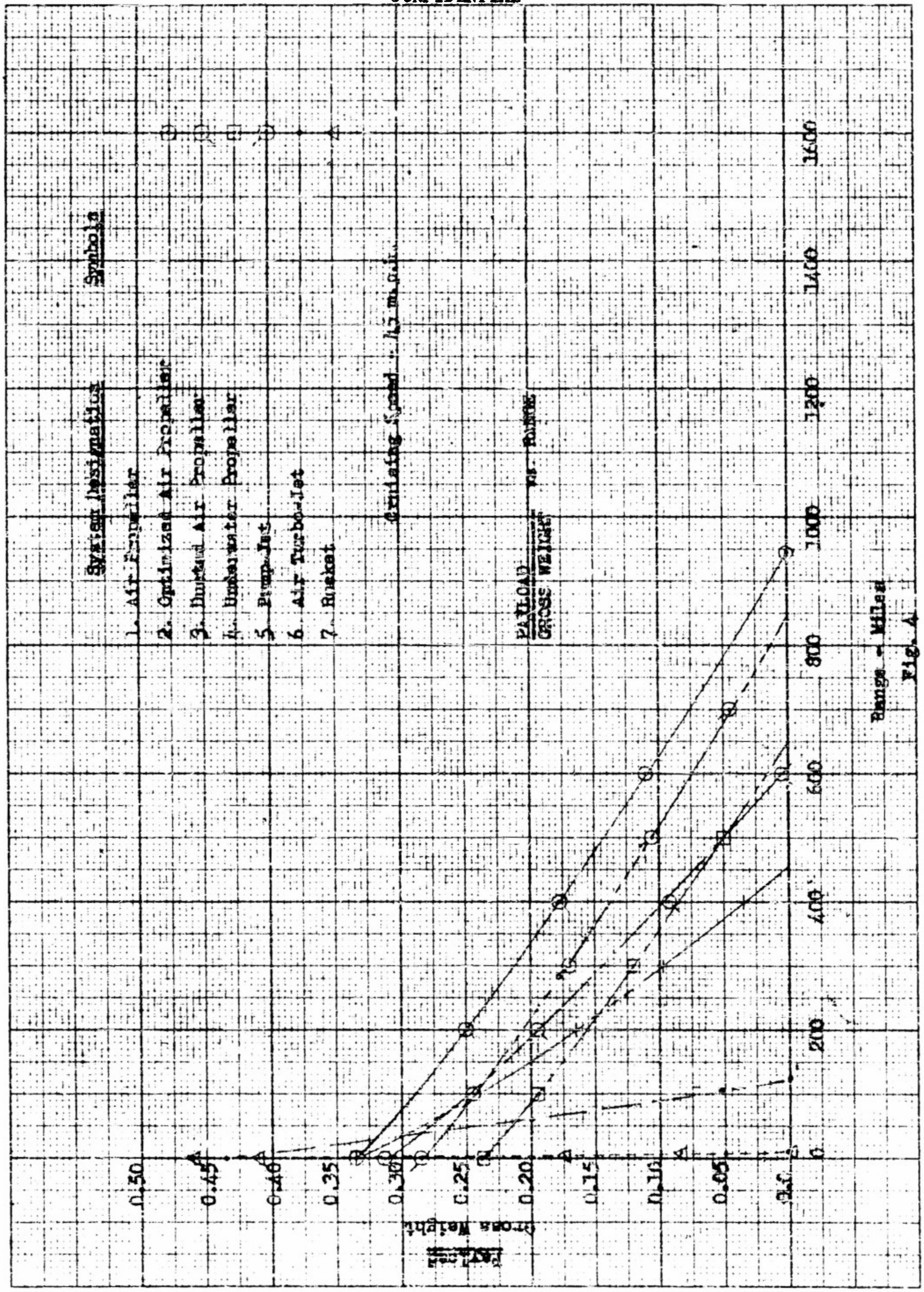

System Designation
Symbols
1. Air Propeller
2. Optimized Air Propeller
3. Ducted Air Propeller
4. Underwater Propeller
5. Pump Jet
6. Air Turbo-Jet
7. Rocket
Cruising Speed - 45 m.p.h.
PAYLOAD / GROSS WEIGHT vs. RANGE
Payload / Gross Weight
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.0
Range - Miles
0
200
400
600
800
1000
1200
1400
1600

Fig. 4

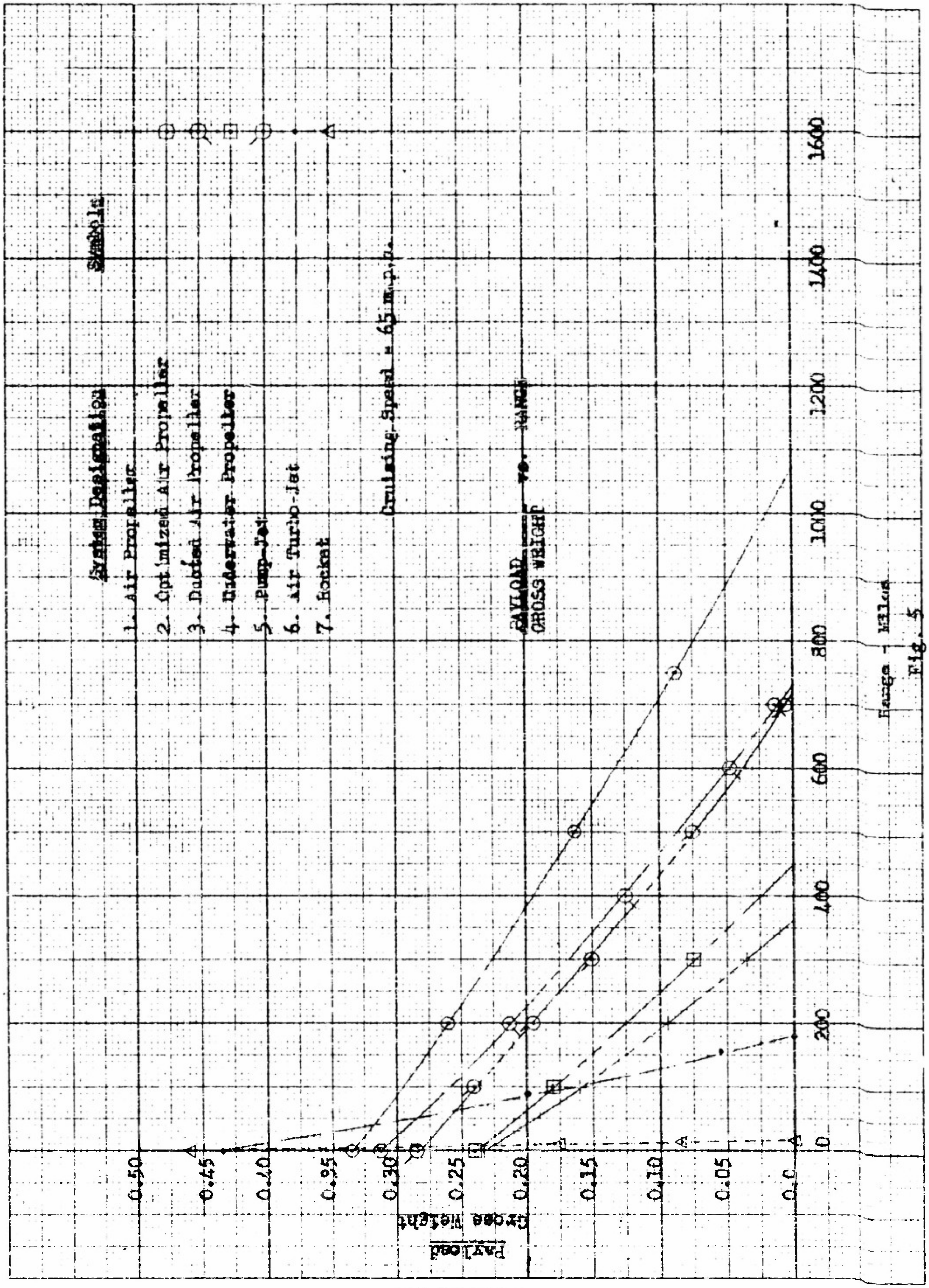

System Designation
1. Air Propeller
2. Optimized Air Propeller
3. Ducted Air Propeller
4. Underwater Propeller
5. Pump-Jet
6. Air Turbo-Jet
7. Rocket
Symbols
Cruising Speed = 65 m.p.h.
PAYLOAD / GROSS WEIGHT vs. RANGE
Payload / Gross Weight
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.0
0
200
400
600
800
1000
1200
1400
1600
Range - Miles

Fig. 5

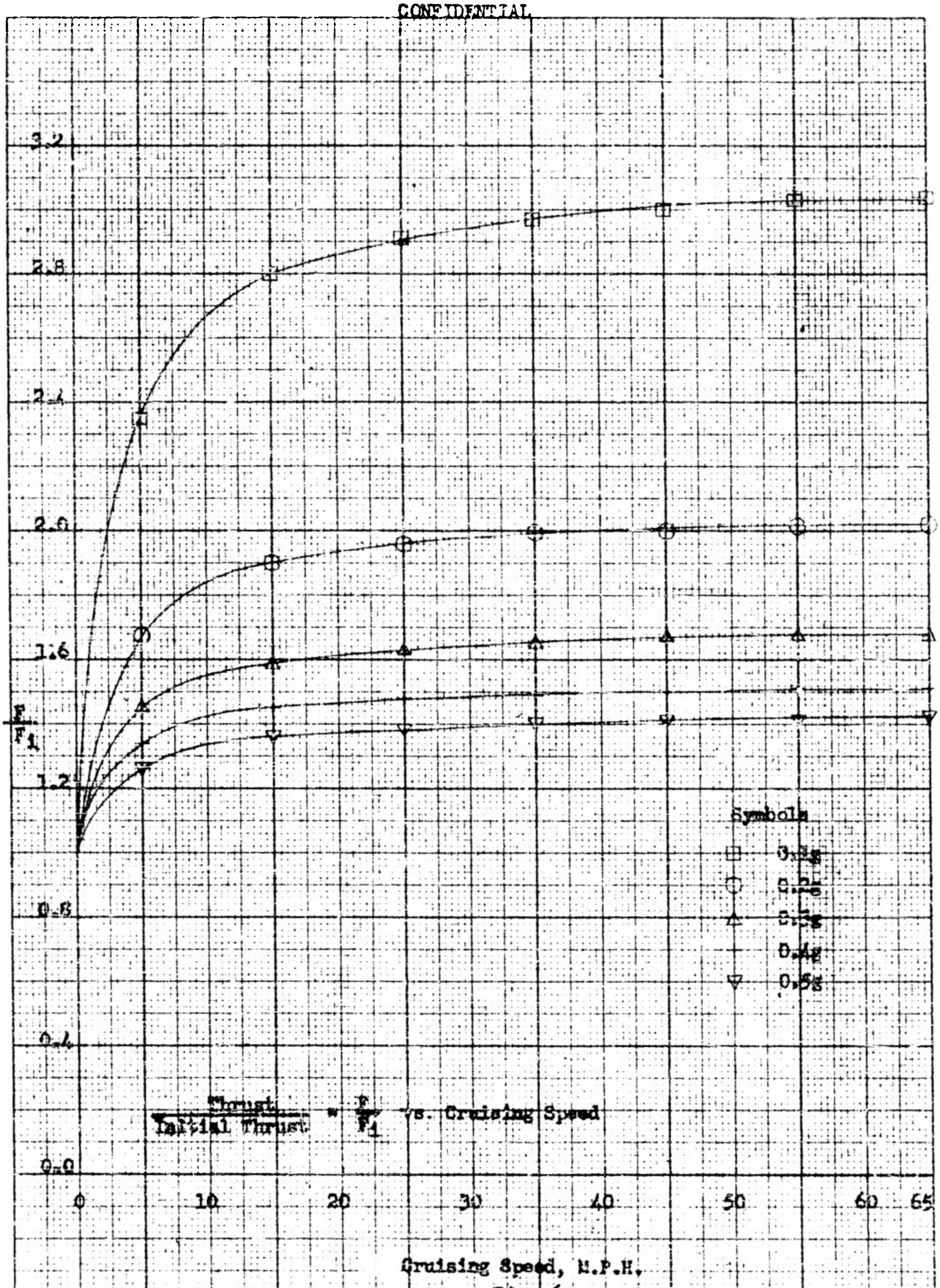
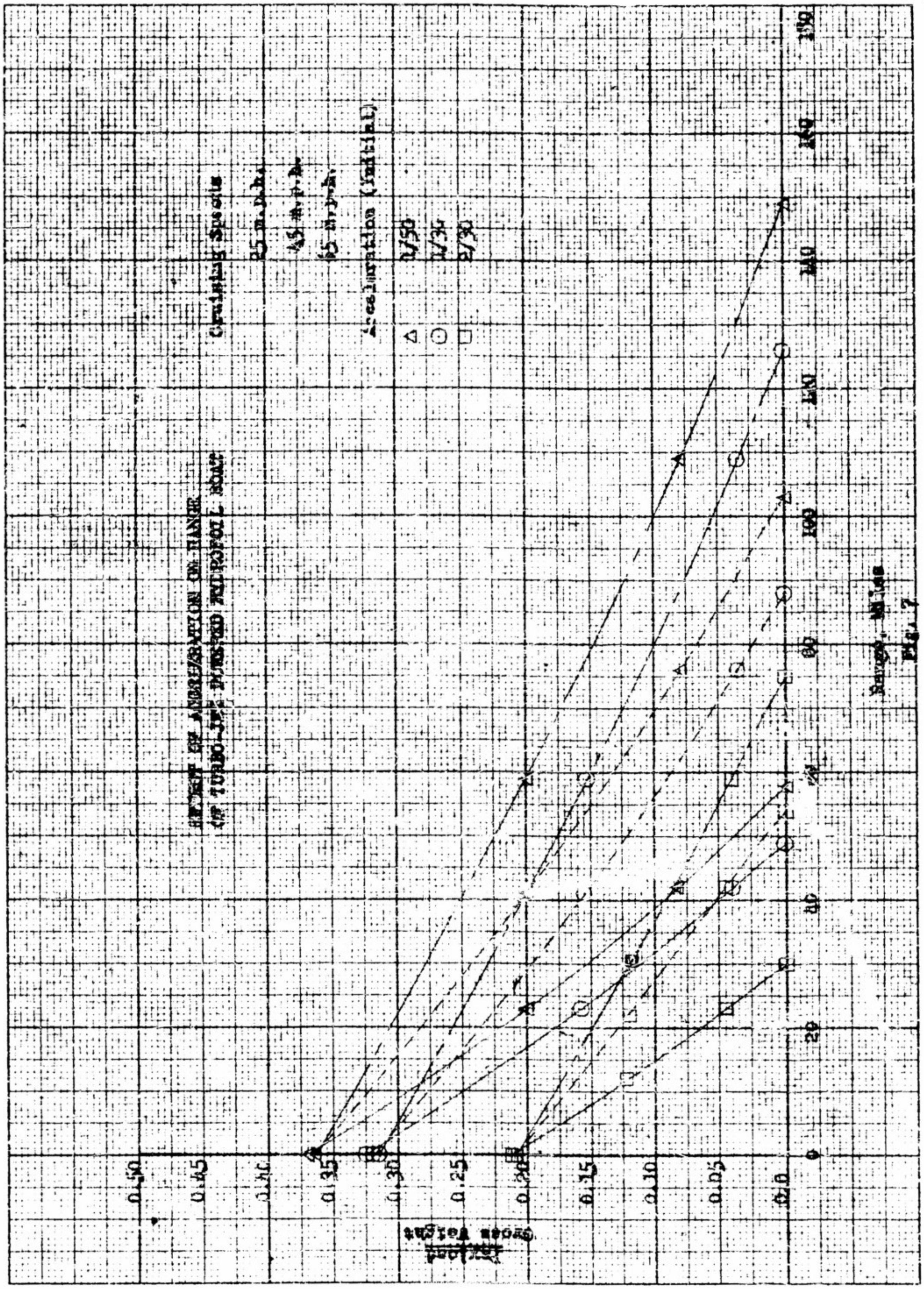

3.2
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0.0
$\frac{F}{F_1}$
0
10
20
30
40
50
60
65
Symbols
0.1g
0.2g
0.3g
0.4g
0.5g
$\frac{\text{Thrust}}{\text{Initial Thrust}} = \frac{F}{F_1}$ vs. Cruising Speed
Cruising Speed, M.P.H.

Fig. 6


OF TURBO-JET POWERED HYDROFOIL BOAT
Cruising Speeds
25 m.p.h.
45 m.p.h.
65 m.p.h.
Acceleration (Initial)
1/50
1/30
2/30
0.0
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0
20
40
60
80
100
120
140
150
Range, Miles
Fig. 7

CONFIDENTIAL

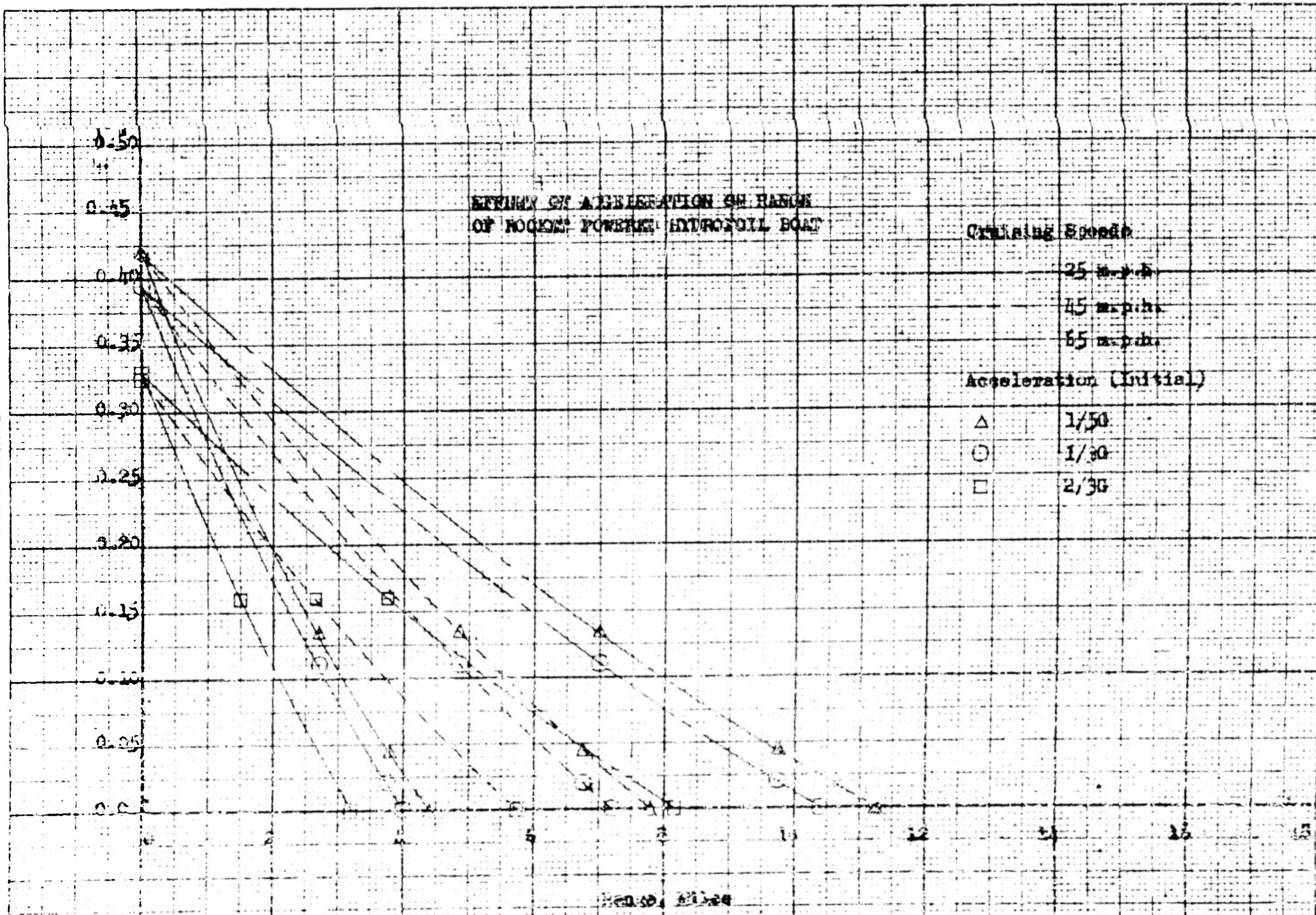


Fig. 8

CONFIDENTIAL