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(ANVCE) Standard Performance and
Weights for Propulsors

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This document presents methods of predicting propulsor efficiency and weight for preliminary design purposes. Knowing the thrust required, and taking the working area of the propulsor as an independent variable, the propulsive efficiency, and hence the power required, can be computed. The designer will then select a rotational tip speed (which, in air, largely defines his noise levels and, in water, is subject to cavitation and structural strength limitations) and so determine torque. For air propulsors, the accuracy of the performance method given in this document will

20. (cont.)

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This document presents methods of predicting propulsor efficiency and weight for preliminary design purposes. Knowing the thrust required, and taking the working area of the propulsor as an independant variable, the propulsive efficiency, and hence the power required, can be computed. The designer will then select a rotational tip speed (which, in air, largely defines his noise levels and, in water, is subject to cavitation and structural strength limitations) and so determine torque. For air propulsors, the accuracy of the performance method given in this document will degrade as the tip speed approaches the speed of sound, but such high tip speeds are, in any case, precluded by the need for reasonable noise levels.

PROPULSIVE EFFICIENCY

The finer points of propulsor technology are not particularly germaine to ANVCE; and particularly those problem areas which we may expect to see cleared up to some extent within the next two decades. Accordingly, it has been decided that all thrust and power requirement computations will be based upon one-dimensional, incompressible, flow momentum theory. This assumes that all propulsors will be variable pitch. In fact, at least some may be variable camber as well. This being so, it is anticipated that estimates based on momentum theory will be quite realistic throughout the speed range.

We define a thrust coefficient $C_T = \frac{T}{\frac{1}{2}\rho u^2 A}$

where

T = thrust

ρ = mass density of the working fluid

u = free stream velocity

A = swept disc area for an open propeller or the immersed area for a semi-submerged one

= duct exit area for a ducted propulsor, if the nozzle area change $dA/dx = 0$, or

= duct exit area times the vena contracta coefficient if $dA/dx \neq 0$

x = distance measured along the propulsor axis

The ideal efficiency is, for an open propeller

$$\eta_{iP} = \frac{2}{\phi + \sqrt{\phi^2 + C_T}} \tag{1}$$

and for a ducted propulsor

$$\eta_{iD} = \frac{4}{3\phi + \sqrt{\phi^2 + 2C_T}} \tag{2}$$

where the interference factor, ϕ, is defined by

$$\phi = \frac{u_{AV}}{u} = 1 + \frac{\Delta u}{u}$$

$$u_{AV} = 1 + \Delta u = \text{average velocity at the propulsor inlet}$$

Values of ϕ will generally be available from wind tunnel or tank tests. Very roughly, for an air propeller mounted above a hull

$$\phi = \sqrt{1 + C_L}$$

where C_L is the lift coefficient of the hull. (Typically $0.1 < C_L < 0.4$) Current values for the ratios

$$\frac{\eta}{\eta_i} = \frac{\text{actual efficiency in open flow}}{\text{ideal efficiency}}$$

and

$$M = \text{factor of merit} = \frac{\text{ideal static power requirement}}{\text{actual static power requirement}}$$

are given in Table 1, together with the values to be employed in ANVCE. Note that $M = \eta/\eta_i$ for the latter. For the reasons described in the Appendix the power loss due to the vertical separation of waterjet inlet and nozzle will not be accounted for.

WEIGHTS

The following standard weights will be used:

Air Propeller

$$\text{weight} = 3.5\ D^2 \quad \text{(lb)}$$

- when the diameter D is in feet. This figure includes blades and hub.

Shrouded Air Propeller or Fan (including Shroud)

$$\text{weight} = 11.0\ D^2 \quad \text{(lb)}$$

- when the diameter D of the fan or propeller is in feet. The maximum diameter of the duct will, in general, be larger than D.

This weight figure includes fan, hub, bearings and support plus the external duct.

Table 1. Values of $\frac{\eta}{\eta_i} = \frac{\text{open fluid efficiency}}{\text{ideal efficiency}}$ and Factor of Merit M.

	Design Point $\frac{\eta}{\eta_i}$	Static (M)	ANVCE Study
Air Propeller	0.82	0.75-0.8	0.82
Air Ducted Fan	0.85	---*	0.85
Subcavitating Water Screw	0.8	---*	0.82
Supercavitating Water Screw	0.76	---*	0.8
Surface Piercing Propeller	0.73	---*	0.78
Water Jet	0.85	0.85	0.85

*not known as of this writing

All appendage drags are charged separately.

Water Propellers; All Configurations

$$\text{weight} = 30.0\ D^3\ (\text{lb})$$

- when the diameter, D, is in feet.

Waterjets

As normally presented there is a very large spread in the specific weight of water jets; lb/bhp may vary by almost two orders of magnitude. The scatter is greatly reduced, however, if weight is correlated with static thrust, as shown in Figure 1. The weight figure to be employed in the ANVCE study is

$$\text{weight} = 0.4\ T_s^{0.86}$$

- where T_s is the rated static thrust in pounds. This figure includes the weight of diffuser, pump, nozzle and entrained water, but not the ducting or inlet.

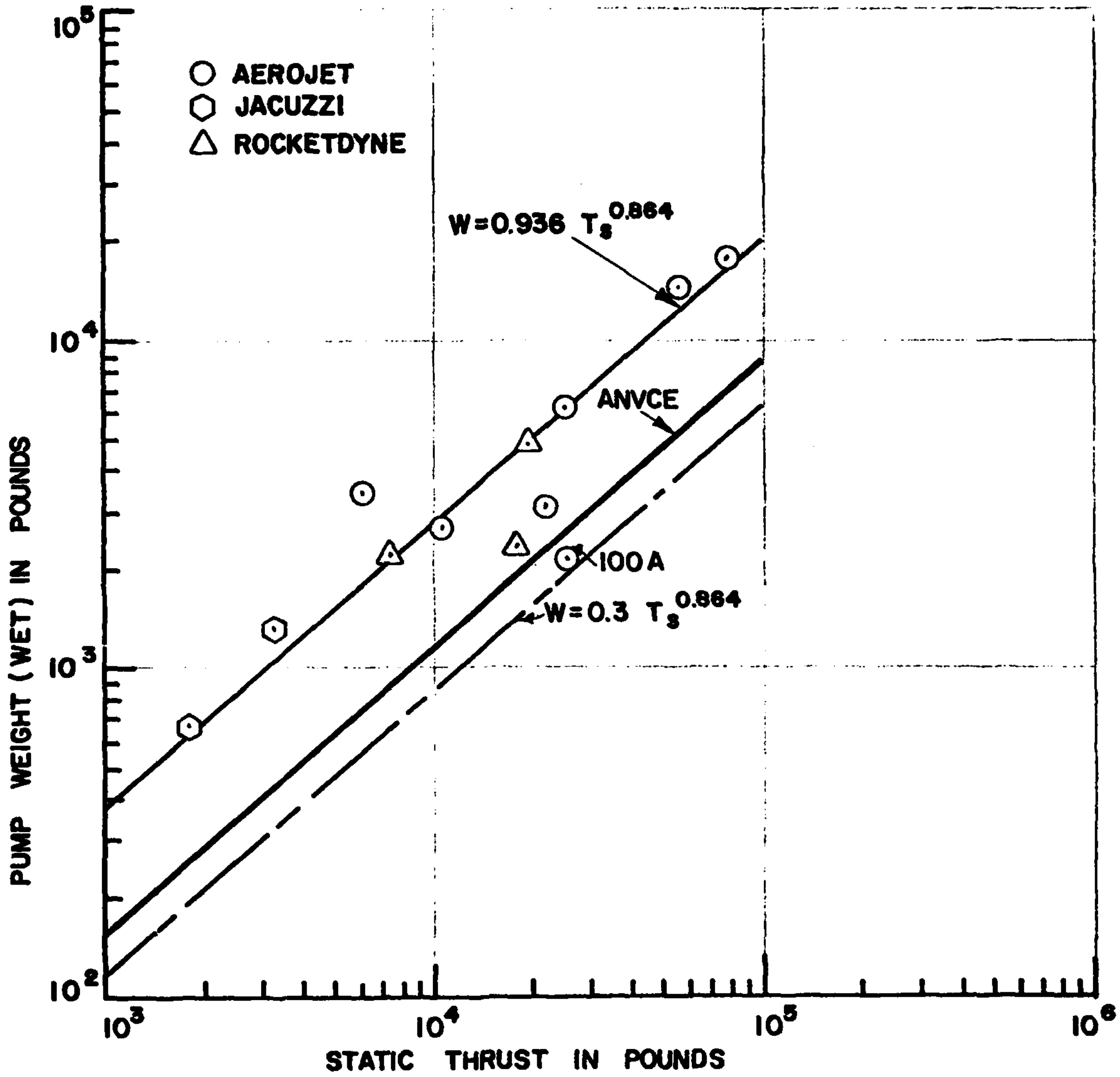

Figure 1. Correlation of Water Jet Weights.

APPENDIX I

Additional Notes

For an unshrouded propulsor, the power required under static thrust conditions is

$$\frac{P_s}{T_s} = \frac{1}{M}\sqrt{\frac{1}{2\rho}\left(\frac{T_s}{A}\right)} \qquad \text{(I-1)}$$

where M is the "factor of merit", equal to P_i/P_s

P_s is actual static power

T_s is static thrust

P_i is the ideal static power required to product static thrust T_s

The efficiency at forward speed is

$$\eta = \left(\frac{\eta}{\eta_i}\right)\left[\frac{2}{1 + \sqrt{1 + C_T}}\right] \qquad \text{(I-2)}$$

As $u \rightarrow 0$ $\quad C_T \rightarrow \infty$

$$\eta \rightarrow \left(\frac{\eta}{\eta_i}\right)\frac{2}{\sqrt{C_T}}$$

and

$$\frac{P}{T} = \frac{u}{\eta} \rightarrow \left(\frac{\eta_i}{\eta}\right)\frac{\sqrt{T/\tfrac{1}{2}\rho A}}{2} = \left(\frac{\eta_i}{\eta}\right)\sqrt{\frac{1}{2\rho}\ \frac{T}{A}}$$

Comparing (I-1) and (I-3) we see that M and η_i/η have identical meanings; are, in fact, the same ratio.

Another useful coefficient is

$$C_P = \frac{P}{\tfrac{1}{2}\rho u^3 A}$$

From which

$$\eta = \frac{Tu}{P} = \frac{C_T}{C_P} = \frac{\eta}{\eta_i}\left[\frac{2}{1 + \sqrt{1 + C_T}}\right]$$

Thus, for a fixed power, and hence known C_P, C_T may be obtained from the cubic

$$C_T^3 + 4\left(\frac{\eta}{\eta_i}\right)C_P C_T - 4\left(\frac{\eta}{\eta_i}\right)^2 C_P^2 = 0 \qquad \text{(I-4)}$$

For a ducted propulsor such as a waterjet, it is often convenient to think in terms of flow rate (Q) and thrust, rather than area. Thus if A is the nozzle area and Q_s the static flow, the static power required is given by

$$\frac{P_s}{T_s} = \frac{1}{M} \cdot \frac{\frac{1}{2}(\rho Q)}{T_s} \cdot \left(\frac{Q}{A}\right)^2 \qquad \text{(I-5)}$$

Also

$$T_s = (\rho Q_s) \left(\frac{Q_s}{A}\right)$$

$$\therefore \quad A = \frac{\rho Q_s^2}{T_s}$$

Substituting this in (I-5)

$$\frac{P_s}{T_s} = \frac{1}{M} \frac{T_s}{2\rho Q_s} \qquad \text{(I-6)}$$

As shown in Table I-1 M varies between 0.7 and 0.9. When the propulsor is moving forward at a speed u

$$\tfrac{1}{2}\rho \left(\frac{Q}{A}\right)^2 = \Delta H - K \tfrac{1}{2}\rho \left(\frac{Q}{A}\right)^2 + \eta_R \tfrac{1}{2}\rho u^2 \qquad \text{(I-7)}$$

here K is the system loss coefficient, referred to nozzle velocity

η_R is the ram recovery fraction of the free-stream dynamic head

ΔH is the pressure rise in the pump

$= P/Q\eta_P$

P is the power required by the pump

η_P is the pump efficiency

Solving equation (I-7) for Q

$$\left(\frac{Q}{A}\right)^2 = \frac{\frac{2}{\rho} \Delta H + \eta_R u_o^2}{1 + K} \qquad \text{(I-8)}$$

But

$$A = \rho Q_s^2/T_s$$

$$\therefore \quad \left(\frac{Q}{Q_s}\right)^2 = \frac{2\rho Q_s^2}{T_s^2}\left(\frac{\Delta H + \eta_R \tfrac{1}{2}\rho u_o^2}{1 + K}\right) \qquad \text{(I-9)}$$

Solving these equations for $u_o = 0$ we find

$$(1 + K)\eta_P = \frac{1}{M}$$

With forward speed

$$\Delta H = \frac{P}{Q\eta_P} = \frac{P}{\eta_P}\frac{T_s}{Q_s^2} \Bigg/ \sqrt{2\rho\left(\frac{\Delta H + \eta_R \tfrac{1}{2}\rho u_o^2}{1 + K}\right)}$$

Squaring

$$2\rho \Delta H^2 \left(\frac{\Delta H + \eta_R \tfrac{1}{2}\rho u_o^2}{1 + K}\right) = \left(\frac{PT_s}{\eta_P Q_s^2}\right)^2$$

$$\Delta H^3 + \eta_R \tfrac{1}{2}\rho u_o^2 \Delta H^2 = \frac{(1 + K)}{2\rho}\left(\frac{PT_s}{\eta_P Q_s^2}\right)^2 \qquad \text{(I-10)}$$

We can thus solve (I-10) for ΔH, and then obtain Q from (I-9)

Then the thrust

$$T = \rho Q\left(\frac{Q}{A} - u_o\right) \qquad \text{(I-11)}$$

and the propulsive efficiency

$$\eta = \frac{u_o T}{P} = \frac{\rho u_o Q^2}{AP} - \frac{\rho u_o^2 Q}{P}$$

$$= \frac{u_o T_s}{P}\left(\frac{Q}{Q_s}\right)^2 - \frac{\rho u_o^2 Q_s}{P}\left(\frac{Q}{Q_s}\right) \qquad \text{(I-12)}$$

The cubic for ΔH is conveniently solved by writing

$$\phi = \left(\frac{\eta_R \tfrac{1}{2}\rho u_o^{\,2}}{3\Delta H_s}\right) \quad \left(= \frac{\eta_P \eta_R q_o Q_s}{3P}\right)$$

- where $\Delta H_s = \dfrac{P_s}{\eta_P Q_s}$, the static value, and $q_o = \tfrac{1}{2}\rho u_o^{\,2}$

Then

$$\frac{\Delta H}{\Delta H_s} = \left\{\left[\tfrac{1}{2} - \phi^3 + \sqrt{\tfrac{1}{4} - \phi^3}\right]^{1/3} + \left[\tfrac{1}{2} - \phi^3 - \sqrt{\tfrac{1}{4} - \phi^3}\right]^{1/3} - \phi\right\}$$

(I-13)

Then in the same notation, from (I-9)

$$\left(\frac{Q}{Q_s}\right)^2 = \frac{\Delta H}{\Delta H_s} + 3\phi = F(\phi) \quad \text{say} \qquad \text{(I-14)}$$

$$\eta = \frac{u_o T_s}{P}\left(\frac{\Delta H}{\Delta H_s} + 3\phi\right) - \frac{6\phi}{\eta_P \eta_R}\sqrt{\frac{\Delta H}{\Delta H_s} + 3\phi}$$

$$= \frac{u_o T_s}{P} F(\phi) - \frac{6\phi}{\eta_P \eta_R}\sqrt{F(\phi)} \qquad \text{(I-15)}$$

As Figure I - 1 shows, this gives realistic results. The test data efficiency points are slightly higher than the theory because we have not allowed for the favorable effect (in these tests) of the boundary layer upstream of the pump inlet. It's also worth noting that, for the relatively high values used, ram recovery and pump efficiency do not have a very powerful effect on propulsive efficiency.

Table I - 1. Some Waterjets Currently in Production

	BHP	T_s	Q	M_{pump}	M	Wet Weight	$\frac{\text{Wet Weight}}{\text{BHP}}$	$\frac{T_s}{\text{BHP}}$	$\frac{\text{Wet Weight}}{T_s}$	$\frac{1}{y}\frac{\Delta P}{P}$ (4)
Aerojet AJW-400	400	6,070	63.27	0.71	0.662	3,350	8.375	15.175	0.552	0.0184
Aerojet AJW-800	790	10,450	68.40	0.90	0.919	2,660	3.367	13.228	0.255	0.0101
Aerojet AJW-3,000	2,960	25,000	133.67	0.84	0.718	6,170	2.084	8.446	0.247	0.0053
Aerojet AJW-4,500	4,440	22,000	56.14	0.866	0.883	3,090	0.696	4.955	0.140	0.0015
Aerojet AJW-8,000	7,890	25,600	45.67	0.87	0.827	2,150	0.272	3.245	0.084	0.00067
Aerojet AJW-12,000	11,800	56,000	149.27	0.87	0.809	14,330	1.214	4.746	0.256	0.0015
Aerojet AJW-18,000	16,000	79,000	209.42	0.87	0.847	17,640	1.103	4.938	0.223	0.0015
Aerojet 2KSES	40,000	145,300	282.72	0.831	0.849	--	--	3.633	--	0.00082
Rocketdyne Powerjet 16	1,500	7,400	40.55 (1)	--	--	2,200	1.467	4.933	0.297	--
Rocketdyne Powerjet 20	4,300	18,000	51.58 (2)	--	--	2,326	0.541	4.186	0.129	--
Rocketdyne Powerjet 24	5,000	19,500	100.25 (3)	--	--	4,800	0.96	3.900	0.246	--
Jacuzzi 14YJ	260	2,800	--	--	--	665	2.558	10.769	0.238	--
Jacuzzi 20J-HP	700	3,250	--	--	--	1,325	1.893	4.643	0.408	--

(1) at 200 RDM at 30 knots - maximum pump speed is 2,270 RPM

(2) at 3080 RDM at 30 knots - maximum pump speed is 2,250 RPM

(3) at 1640 RDM at 30 knots - maximum pump speed is 1,750 RPM

(4) Incremental power ratio per foot of lift between inlet and nozzle.

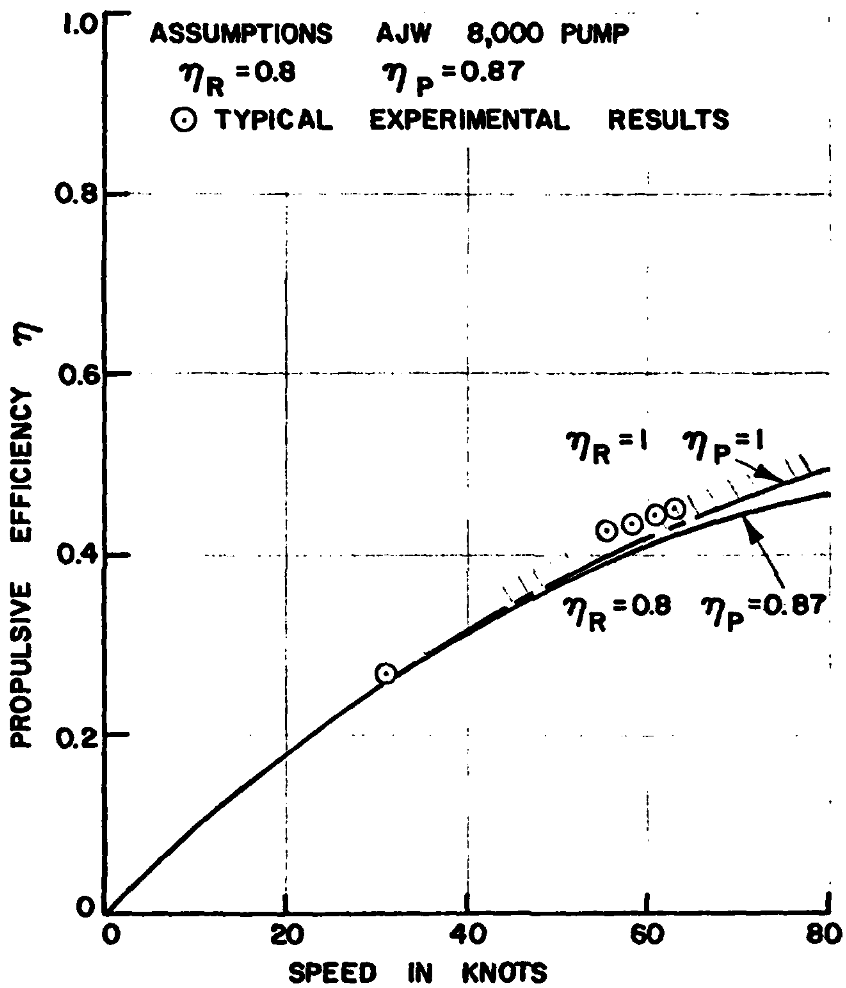

Figure I - 1. Equation I-15 as a Function of Speed for a Particular Example.

The foregoing calculations ignore the power loss due to the weight difference between the inlet and nozzle, which is

$$\Delta P = \rho g Q y \qquad \text{(I-16)}$$

As Table I - 1 and Figure I - 2 show, this correction is very small for modern water jets, and not worth accounting for unless a vehicle's propulsion configuration is very unusual. In such cases, the equation for propulsive efficiency should be multiplied by the factor

$$\frac{1}{(1 + \Delta P/P)} \qquad \text{(I-17)}$$

It should also be noted that in using the rated static thrust T_s, and associated flow and power, we are referring to a pump's performance when not limited by the inlet cavitation, which might actually occur in an actual installation.

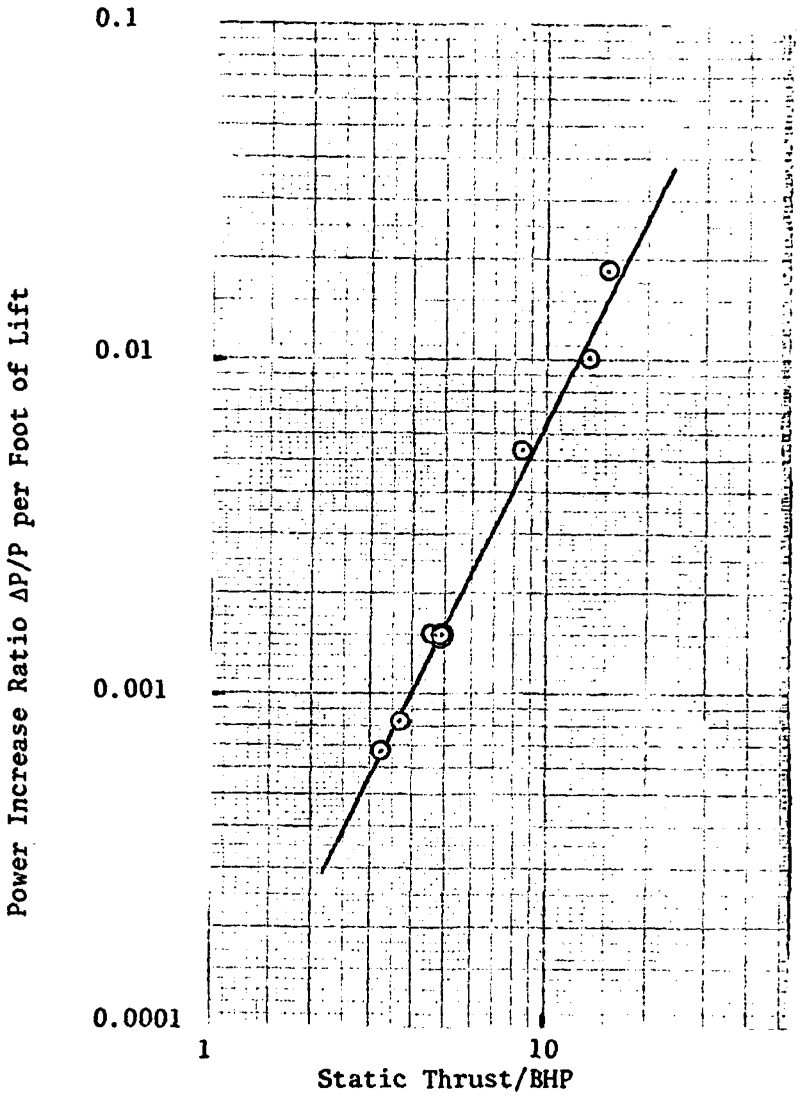

Figure I - 2. Water Jet Power Penalty per Foot of Lift Height, as a Function of Static Thrust per Unit Power.