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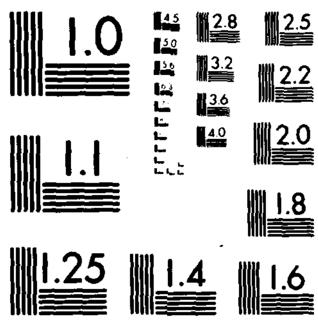

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LEVEL II

OVERLAND AND AMPHIBIOUS ACV DESIGN DATA RELATING TO PERFORMANCE

by
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Division of Mechanical Engineering

OTTAWA
APRIL 1979

NRC NO. 17423

MECHANICAL ENGINEERING REPORT
ME-245

(14) DME ME-245

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OVERLAND AND AMPHIBIOUS ACV DESIGN DATA RELATING TO PERFORMANCE

(DONNÉES TECHNIQUES RELATIVES AU RENDEMENT DE VCA TERRESTRES ET AMPHIBIES).

(11) Apr 79

by/par

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SUMMARY

This handbook of data endeavours to collect and present in practical form such design data relating to performance as are currently publicly available.

The art is at present in an early stage of its development, and many of the data given are tentative or incomplete, and are hedged around by ill-defined boundary conditions.

We shall attempt to keep up with the ever-shifting frontiers of ignorance by issuing amendments to this handbook as exploration proceeds.

Finally one must remember that he who lives strictly by the rules, stagnates. Progress is attained only by knowing the rules, and then living dangerously beyond them.

RÉSUMÉ

Ce manuel de données tente de faire la compilation et de présenter sous une forme pratique des données techniques relatives au rendement de véhicules à coussin d'air (VCA), dans la mesure où de telles données sont couramment disponibles pour le public.

Présentement, ce domaine n'en est encoure qu'aux toutes premières étapes de son développement, et nombreuses sont les données qui ne sont proposées qu'à titre provisoire ou qui sont incomplètes et dont les conditions limites sont plus ou moins bien définies.

Nous tenterons de rester à jour malgré le recul sans cesse constant des frontières de l'inconnu, en publiant des modificatifs au fur et à mesure des recherches.

Enfin, il y aurait lieu de ne pas oublier que la stagnation est le fruit de l'observance stricte des règles. Le progrès n'est possible qu'en tenant compte des règles puis en se risquant ensuite au delà des limites prescrites par ces mêmes règles.

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OVERLAND AND AMPHIBIOUS ACV DESIGN DATA RELATING TO PERFORMANCE

1.0 AIRSPEED

Basically, airspeed is calculated from the difference between static and total pressures, which equals dynamic (velocity) pressure. Frequently only one measurement need be taken, as one or other of total or static pressures is equal to atmospheric pressure, as shown below. This is possible since almost any pressure-measuring instrument measures the difference between the applied pressure and the atmosphere surrounding the instrument, unless specially connected in an unusual manner.

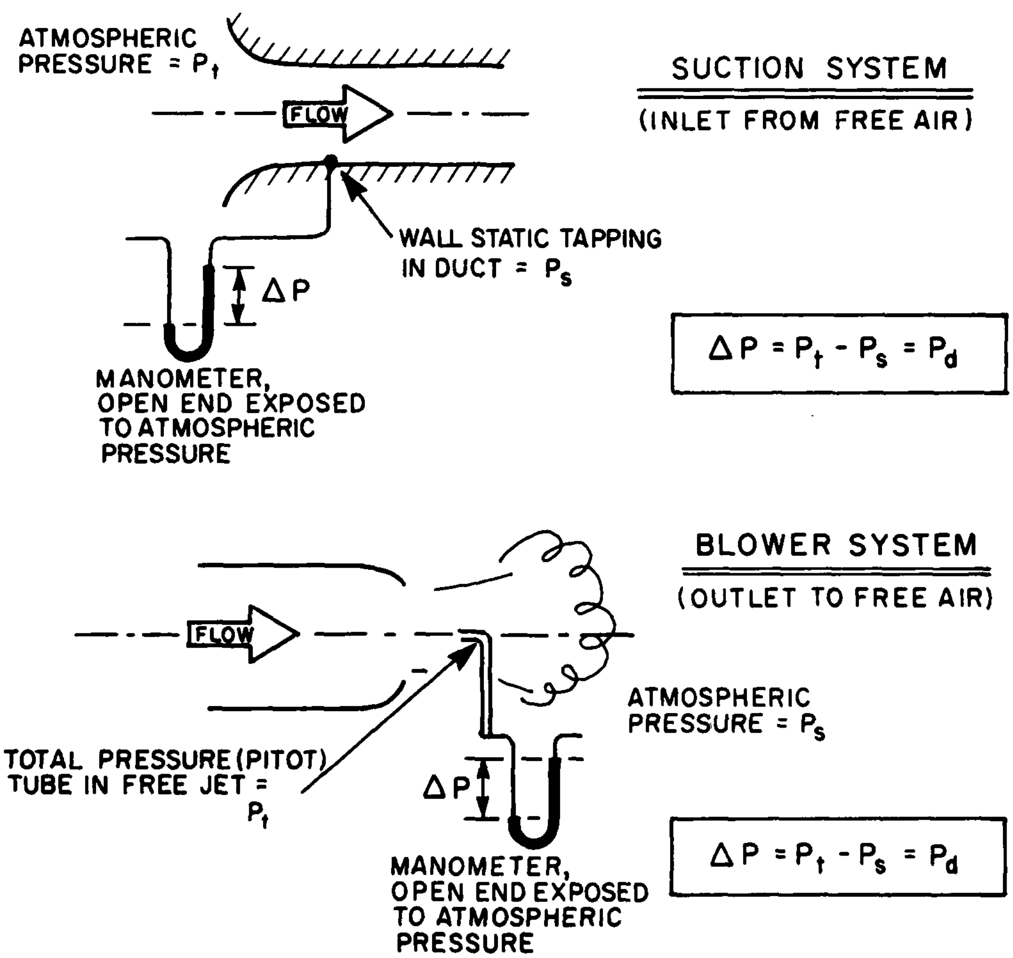


FIG. 1: SUCTION AND BLOWER SYSTEMS

where P_t = Total Pressure (Pa)

P_s = Static Pressure (Pa)

P_d = Dynamic Pressure (Pa)

From Bernouilli's equation, we have the fundamental relationship

$$P_d = \frac{1}{2}\rho V^2 \qquad (2)$$

where ρ = Air Density (Kg/m^3)

V = Air Velocity (m/s)

P_d = Dynamic Pressure (Pa)

The above equation may be rearranged to the form:

$$V = 0.756 \sqrt{\frac{Pd \times t^\circ K}{\text{Air Press. (kilopascals)}}} \qquad (3)$$

This calculation may be used up to about 150 m/s. Above this the flow must be assumed to be compressible, and calculated by iteration from the formula:

$$\frac{P_t}{P_s} = \left(1 + \frac{\gamma-1}{2} M_n^2\right)^{\frac{\gamma}{\gamma-1}} \qquad (4)$$

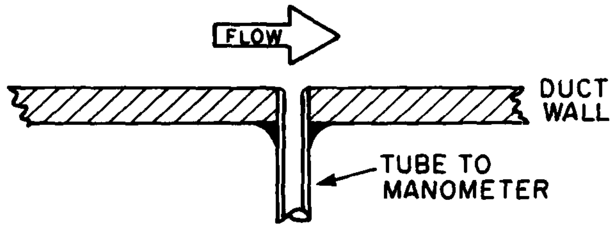
where γ = RATIO OF SPECIFIC HEATS (= 1.3984 for air)

M_n = Mach No.

(where Mach Number is defined as $\frac{\text{Velocity relative to gas}}{\text{Velocity of sound in gas}}$ (at local static temperature).

At standard sea level atmospheric conditions, this becomes $\frac{V}{340}$ (V in m/s).

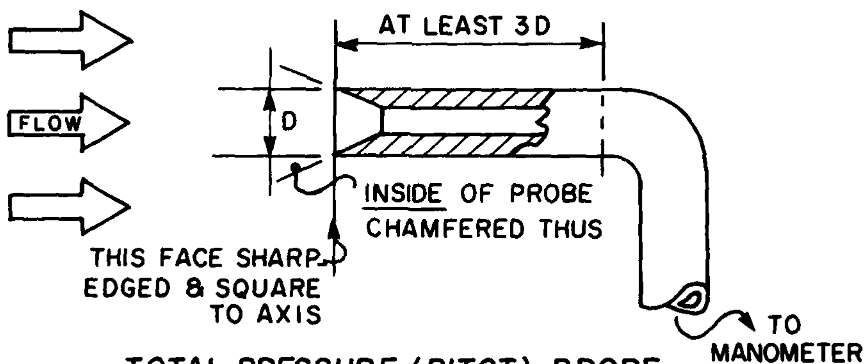
The function P_t/P_s is usually displayed on compressible flow curves or tables for easy reference.



STATIC PRESSURE WALL TAPPING

WALL SURFACE MUST BE DEAD SMOOTH AROUND TRULY FLUSH HOLE, WHOSE AXIS IS NORMAL TO SURFACE. NO RAGS, BURRS, OR COUNTERSINK.

HOLE DIAMETER = 1 mm. TO 4 mm.



TOTAL PRESSURE (PITOT) PROBE

THE INSIDE CHAMFERED NOSE MAKES THIS PROBE INSENSITIVE TO AIRFLOW DIRECTION UP TO $\pm 30°$

D = OUTSIDE DIAMETER = 2 mm. TO 7 mm.

FIG. 2: STATIC AND TOTAL PRESSURE PROBES

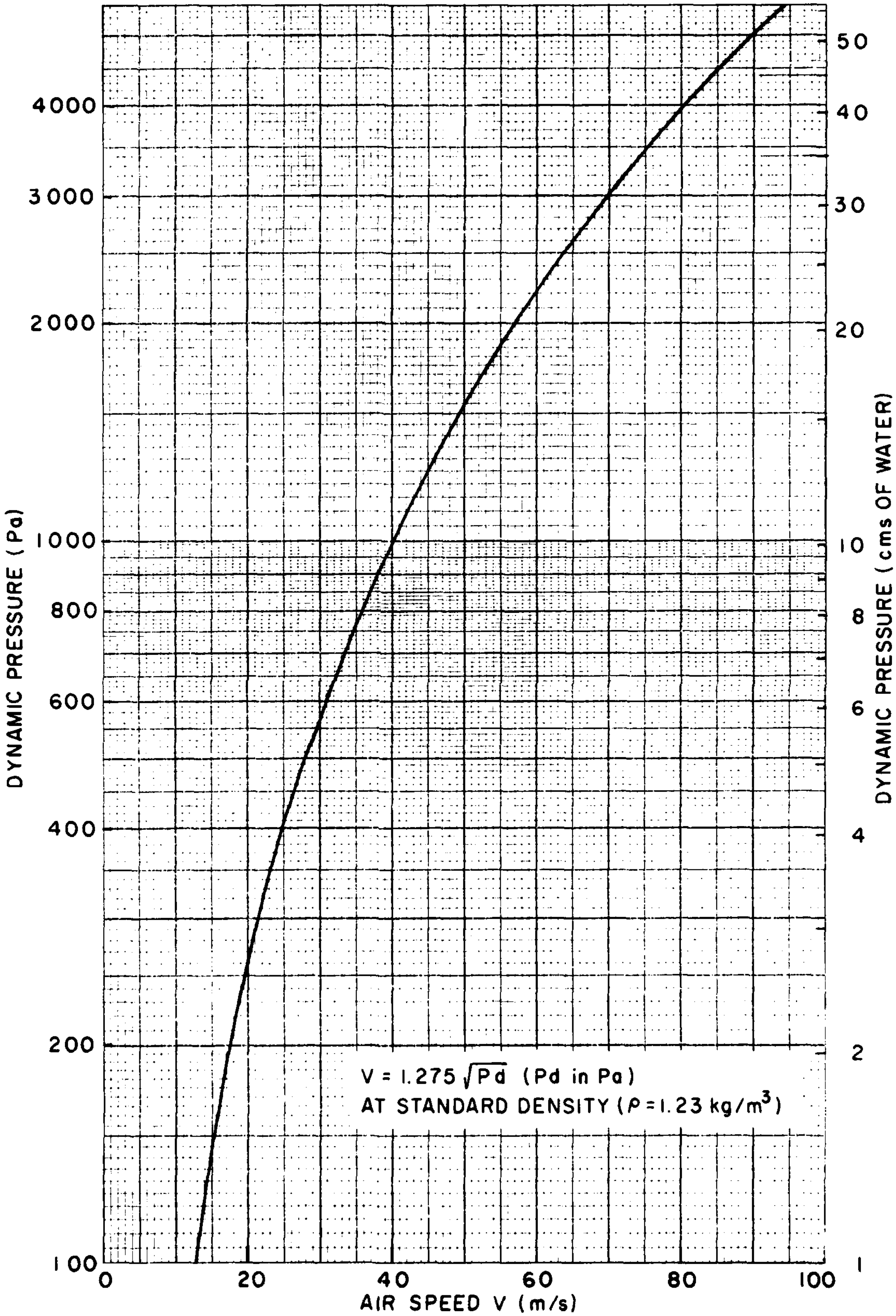


FIG. 3: AIRSPEED vs. DYNAMIC PRESSURE (LOW SPEED)

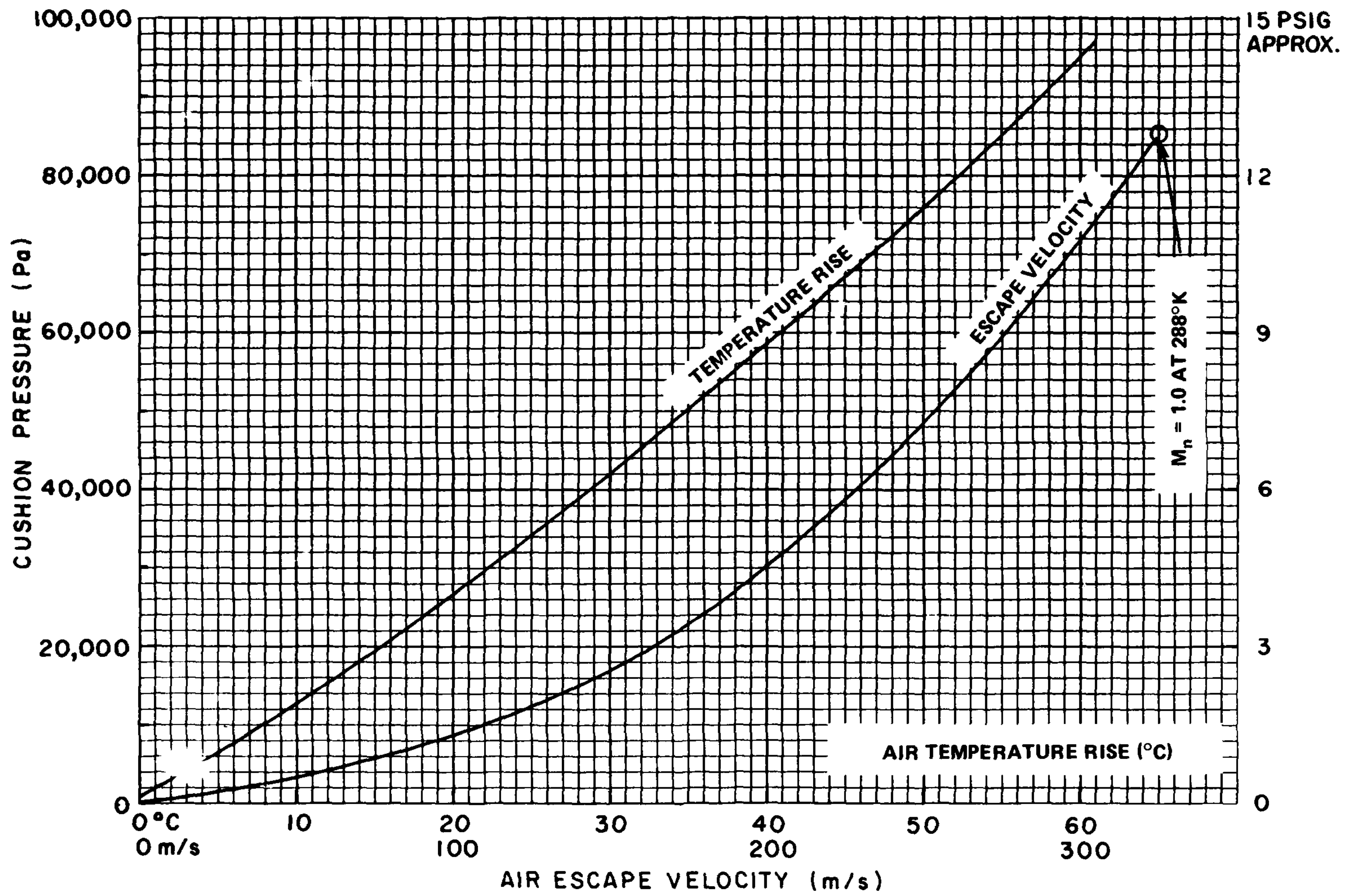


FIG. 4: HIGH PRESSURE CUSHION-AIR TEMPERATURE AND ESCAPE VELOCITY

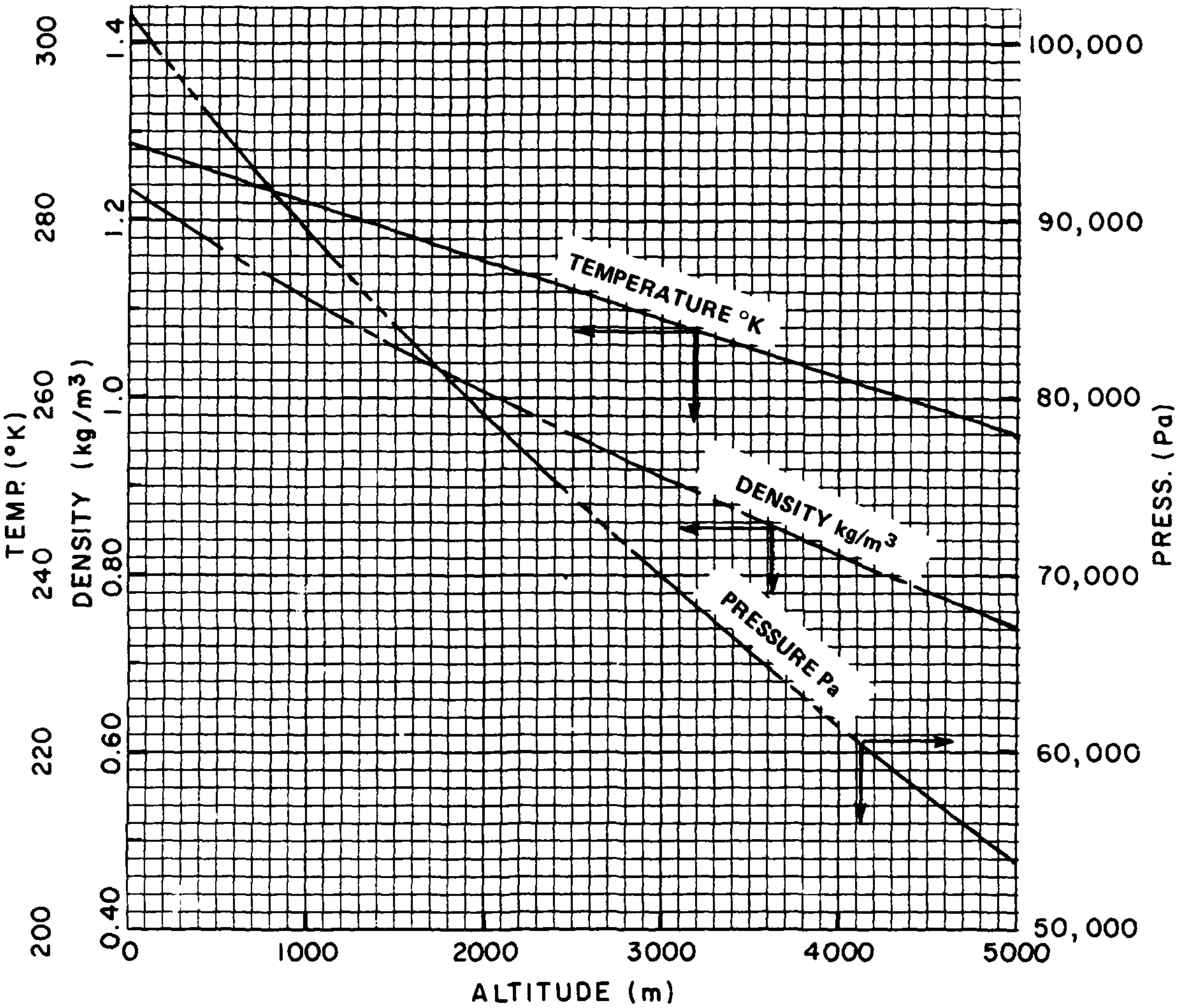


FIG. 5: AIR TEMPERATURE, PRESSURE AND DENSITY AT VARIOUS ALTITUDES

2.0 CENTRIFUGAL FAN LAWS

Pressure Rise

$$\Delta P_t = \rho(U^2\sigma)\eta \tag{5}$$

[for radial vane blowers]

where ΔP_t = Total Pressure Rise (Pa)

ρ = Air Density (kg/m^3)

U = Tip Speed of Impeller (m/s)

σ = Slip Factor (usually taken as 0.9)

η_c = Efficiency (between 0.65 and 0.75)

Note,

$$U = \frac{RPM}{60} \times \pi \times \text{Diam. (Diam. of rotor in metres).} \tag{6}$$

Or for impellers with **swept-back vanes**, whose exit direction is at $\theta°$ to the tangent to the impeller periphery:

$$\Delta P_t = \rho(\text{Tip Speed (Tip Speed} - V_r\cos\theta°)\sigma)\eta \tag{7}$$

where V_r = Calculated radial velocity at impeller exit — (m/s).

This formula gives approximate results only, since $\theta°$ and V_r are not easily estimated.

Fan Power

The power required to drive the fan (not accounting for drive, transmission, or bearing losses) is:

$$\text{Power} = \frac{\text{Volume Flow} \times \text{Pressure Rise}}{1000} \times \frac{1}{\eta_c} \text{ in kilowatts} \tag{8}$$

If duct losses are to be included in the calculation, a term η_d is used (for duct efficiency), which may vary from 0.9 for good fan volute delivering low-speed air directly into the cushion to 0.25 for a complex duct system.

Then,

$$\text{Power} = \frac{\text{Vol. Flow} \times \Delta P_t}{1000} \times \frac{1}{\eta_c} \times \frac{1}{\eta_d} = \text{power (kw)} \tag{9}$$

The so-called "Fan Laws" which permit predictions of the performance of the same fan at various conditions, or of geometrically similar fans, are as follows. These statements should be taken as approximate guides, and demand some experience for successful application.

(a) **For the same Impeller and Volute at a Range of Conditions**

$$\frac{Q_{v1}}{Q_{v2}} = \frac{RPM_1}{RPM_2} \quad \text{(1 and 2 are two running conditions)} \qquad (10)$$

$$\frac{\Delta P_{t1}}{\Delta P_{t2}} = \left(\frac{RPM_1}{RPM_2}\right)^2 \qquad (11)$$

$$\frac{HP_1}{HP_2} = \left(\frac{RPM_1}{RPM_2}\right)^3 \qquad (12)$$

(b) **For Geometrically similar Impellers and Volutes (NB Impeller width varies with tip diameter)**

$$\frac{\Delta P_{t1}}{\Delta P_{t2}} = \left(\frac{D_1}{D_2}\right)^2 \quad \text{(1 and 2 are similar impellers)} \qquad (13)$$

$$\frac{Q_{v1}}{Q_{v2}} = \left(\frac{D_1}{D_2}\right)^3 \qquad (14)$$

$$\frac{HP_1}{HP_2} = \left(\frac{D_1}{D_2}\right)^5 \qquad (15)$$

where Q_v = Volume Flow — (m^3/s)

ΔP_t = Rise of Total Pressure — (Pa)

HP = Power — (kw)

D = Tip Diameter — (m)

RPM = Revolutions/minute

Centrifugal Force (on a body of weight W(N) moving around a centre at radius R(m) at N (Revs/sec))

$$\text{CENT. FORCE (newtons)} = W\,R\,N^2 \times 4.024 \qquad (16)$$

or

$$\text{C.F. (N)} = \frac{W\,V^2}{Rg} \qquad (17)$$

where V = Tangential speed (m/s)

g = Accel. due to gravity (9.81 m/s^2)

3.0 LIFT FORCE AND LIFT AIRFLOW

The Lift Force being exerted on an ACV at any moment must equal its total weight at that time (dynamic effects excepted). Clearly also the lift force must equal the product of cushion pressure times footprint area. However, although cushion pressure can be measured with good accuracy, the footprint area of a flexible skirt is very difficult indeed to measure, so (pressure × area) is not an acceptable test method. The only useful method of measuring lift is to weigh the vehicle (including fuel, freight, crew, etc. to give total weight).

For a given vehicle total weight, Lift Airflow can vary widely according to terrain, skirt, and lift blower characteristics, and to the operating point which the driver chooses on the lift airflow/hoverheight/drag curve. This subject is discussed in detail in References 1, 2, and 3 which should be consulted.

It should be noted that this discussion relates only to the airflow blown into the cushion and used for lift. This includes leakage between segments, seals, etc., but does not include air "stolen" for engine flow, cooling, and other non-lift uses.

Following the argument of Reference 2, lift airflow is expressed by equation:

$$Q = \frac{L}{\sqrt{S_c}} \times \frac{h_f K}{\sqrt{S_c}} \times C_D \times \sqrt{\frac{2}{\rho}} \times \frac{w}{\sqrt{P_c}} \qquad (18)$$

where	Lift airflow = Q	(m^3/s)
	Skirt perimeter = L	(m)
	Efflux gap height = h or h_f	(m)
	Discharge coefficient = C_D	——
	Air density of day = ρ	(kg/m^3)
	Total vehicle weight = w	(N)
	Footprint area = S_c	(m^2)
	Cushion pressure = P_c	Pa (gauge)

The discharge coefficient C_D is that for flow between a skirt hem and flat ground, (0.61 according to standard text books such as Lamb's Hydraulics, sharp-edged orifice data, and NRC tests), h_f is the efflux gap height over flat nonporous ground at low speed, while a factor K (or possibly a group $K_1 K_2$ etc.) represents the increase of h required due to terrain porosity, uneveness, highspeed operation, wave pumping, etc. This factor will be discussed later; at present it will simply be included in the equation and the results presented in Figure 6, given in terms of the factored efflux gap height $h_f K$.

In the above equation it is clear that the various terms have real physical significance.

The term $\frac{L}{\sqrt{S_c}}$ is related to vehicle planform, or aspect ratio. The term $\sqrt{\frac{2}{\rho}}$ describes the atmospheric conditions, and is of surprising importance in designing and testing a vehicle for use in the arctic, or on a hot high-altitude plateau. $\frac{W}{\sqrt{P_c}}$ considers both the cushion pressure and the total weight of the vehicle, and might be called a "loading" term, while the term $\frac{h_f K}{\sqrt{S_c}}$ defines the efflux gap in a non-dimensional manner.

The convenience of the above equation to a designer is therefore apparent, since it enables him to see at a glance the effect of juggling the several variables open to him in meeting a particular requirement, and at the same time ensures that by using a value of $h_f K$ appropriate to the terrain and operational mode specified he will produce a vehicle with adequate hovering performance by currently accepted standards.

Returning now to reality, it is well known (and clearly demonstrated in Fig. 6) that various classes of air cushion vehicles operate at considerably different values of lift airflow, expressed here as values of $h_f K$.

In the high speed marine "hovercraft", the very high value of $h_f K$ is designed partly to reduce skirt drag and wear by minimizing (within practical limits) skirt/wave contact, and partly to offset the results of "wave pumping".

The low speed over-water/mud-flat A.C. ferry barge operates at an extremely low $h_f K$ since it has only small frictional and sealing demands to contend with.

Experiments with the CASPAR vehicles and other scattered clues lead us to believe that operation over notably rough ground or porous vegetation at low speed, or high speed operation over flat ground, will require larger values of $h_f K$ but still not up into the marine "hovercraft" range.

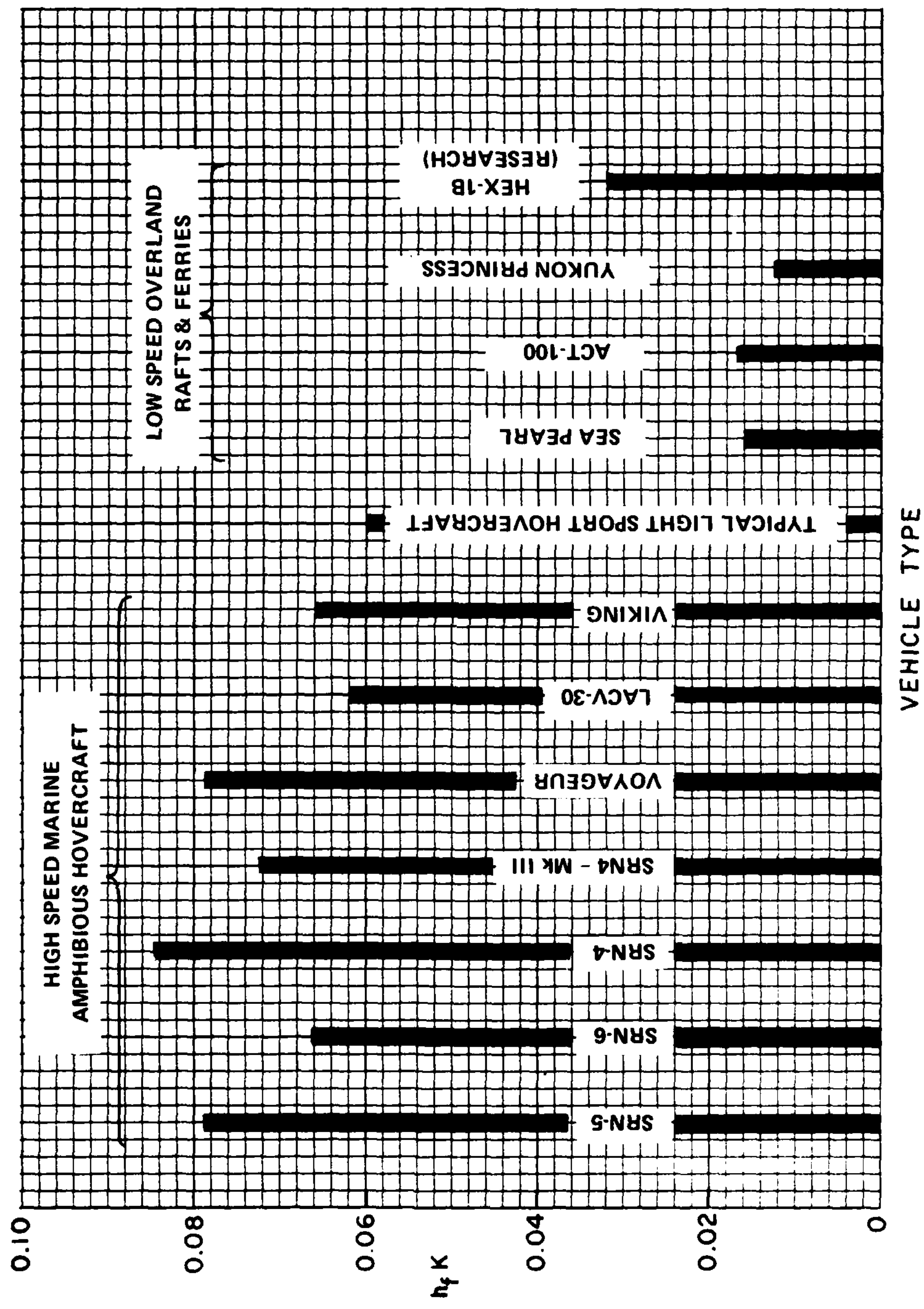


FIG. 6: LIFT AIR CAPACITY OF VARIOUS ACVs

4.0 THRUST

The thrust exerted on an ACV by its propulsion system can be generated in a number of ways — by aerodynamic means (propellers, fans, or other airjets) or by terrain contacting systems such as wheels, tracks or underwater screws.

4.1 Measurement

It is simple to measure the static thrust (i.e. the thrust generated while the vehicle is stationary and pulling at measuring device) but the measurement of thrust while moving is more difficult. The only reasonably direct method of measuring moving thrust is to make a series of runs on standard terrain at a series of speeds and engine RPM, and then repeat these runs while towing the ACV, with its thrust system inoperative, and measuring the tow force required at each speed. Even then, a number of sources of error (mainly concerned with the drag of the unpowered propulsion unit) make the results less than reliable.

Static thrust may be measured directly by the tension in a restraining cable while the ACV hovers over smooth ground forming its own frictionless bearing. As a matter of detail, the anchor (a truck or other heavy vehicle) should be at least two vehicle lengths behind the ACV, to ensure that there is no aerodynamic interference, and the cable should be horizontal, with the scale or strain gauge between cable and ACV, (not between anchor and cable) to eliminate errors due to cable weight. It is also necessary to run the experiment twice, facing in opposite directions with the ACV on the same spot so that the average value of thrust will eliminate the effect of any slight wind or slope in the ground. If this is impossible, then the slope of the ground must be checked with an accurate level at the actual place occupied by the ACV. Even a slope of 1 in 100, which is hardly perceptible to the eye, will introduce an error of 1% of the weight of the vehicle, which is a 10% error of the thrust commonly installed in ACVs.

Static thrust may also be measured, provided the ACV has a lift system completely separate from its thrust system, by hovering the vehicle on a slope (which pretensions the cable) and then generating thrust, which will equal the difference of gauge reading between slope only and slope plus thrust-on cases.

It is also necessary in all cases to see that the vehicle is trimmed level, as an unequal hovergap or tilted hull can generate thrust from the cushion which will upset the results.

Theoretically, aerodynamic thrust can be measured by measuring the velocity and quantity of air leaving the thrust duct or propeller disc. However, it is so difficult to measure this non-uniform jet and integrate these quantities successfully that this method should not be attemped for thrust measurement.

4.2 Calculation of Aerodynamic Thrust

This subject has been discussed in detail in Reference 4 which should be consulted.

Briefly, Thrust = Change of momentum of air passing through thruster.

= Mass flow/sec × increase of velocity.

Assuming zero inlet velocity to the thruster

∴ Thrust = mass flow/sec × exit velocity [Static thrust]

where Thrust — (newtons) = T

Mass flow — (kg/s) = Q_m

Exit Vel. — (m/s) = V

Converting to Volume Flow,

$$T = (V \times \rho \times A) \times V \times C_D.$$

$$\therefore T = V^2 \rho A\, C_D \text{ of the exit jet.} \tag{19}$$

where ρ = Air density (kg/m^3)

A = Nozzle area (m^2)

C_D = Discharge coefficient (varies from 0.95 from a good nozzle or thrust duct to 0.6 for a sharp edged flat plate and 0.5 for flow through an unducted propeller disc of area A).

This makes it clear that any aerodynamic thrust calculations must account for air density, with its considerable variation from summer to winter, and from sea level operation to work on a high plateau. One should note that even in the Canadian Prairies, at 1000 metres altitude, the air density is down to 1.10 kg/m^3 instead of sea level value of 1.23 kg/m^3, — a change of 10% for the worse!

For a standard aircraft-type propeller or fan the thrust is usually expressed as a Thrust Coefficient (T_c), which accounts for atmospheric conditions:

$$\text{Thrust} = T_c \times \rho \times (\text{Revs/sec})^2 \times (\text{Fan tip diam.})^4 \tag{20}$$

A very useful set of relationships for ducted fans or open propellers is shown in Figure 7. It is derived directly from momentum increase through the fan, for the lowspeed or static case. The derivation is discussed at length in Reference 4.

The relevant quantities are plotted in the following form.

(a) THRUST/POWER — (N/kw) — (Conversion N/kw $\times$ 0.168 = lbs/HP)

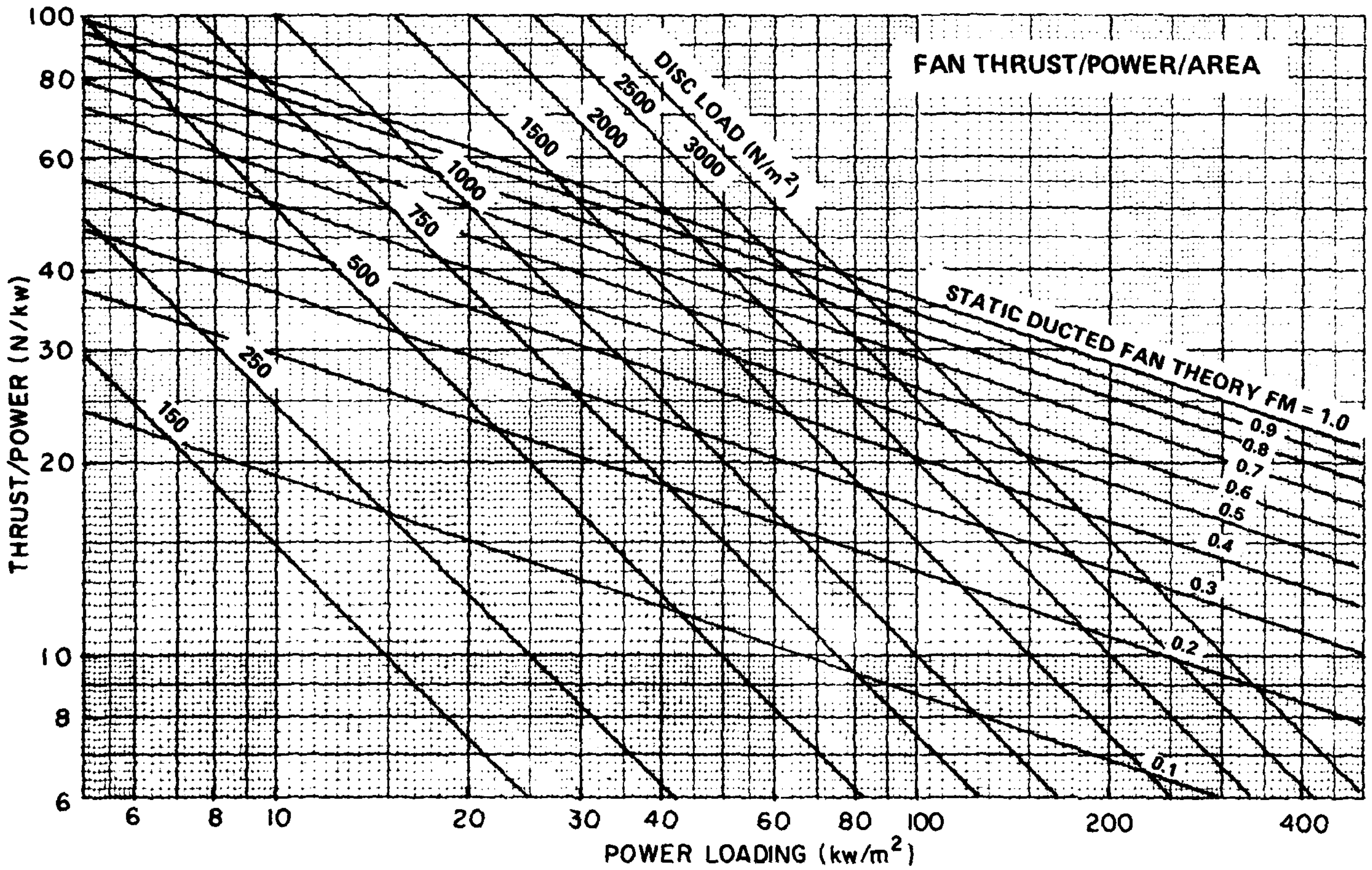
(b) POWER /FAN DISC AREA — (kw/m^2) — (kw/m^2 $\times$ 0.125 = HP/ft^2)

(c) THRUST/FAN DISC AREA — (N/m^2) — (N/m^2 $\times$ 0.0205 = lbs/ft^2)

F.M. is the "Figure of merit", and represents a fan efficiency. An FM = 1.0 implies that the thrust developed is the theoretical maximum under the circumstances.

A Figure of merit of 0.8 is good for a ducted fan with an aerodynamically clean intake, while 0.6 is not surprising in a practical installation. On the same calculation basis, a centrifugal fan blowing air out through a thrust nozzle, as installed on a number of smaller ACVs, is likely to have a F.M. of around 0.3 largely owing to bend losses in the blower and volute, and to the small high-speed nozzles usually employed in the absence of a large and clumsy diffuser. In these cases the "fan disc area" is of course the propulsion nozzle area.

It is frequently difficult to assess the thrust system, since valid engine power figures are very difficult to obtain. Those quoted are often attainable only for one or two minute bursts, while the reliable continuous power is far lower.



N.B. This curve is for **Ducted Fans**, where Fan Area = Jet Area
For ***Unducted Props.***, use Area = ½ Fan Disc Area

FIG. 7: FAN PERFORMANCE (THRUST/POWER/AREA)

5.0 DRAG

5.1 The drag of a highspeed over water ACV is fairly well understood, and is made up of five components, as itemized below, to which must be added the underwater drag of any submerged parts (keels, skegs, rudders, propellers, etc.) if present, as in non-amphibious craft. This latter is calculated according to standard marine practice. The analysis shown below follows the treatment given by Trillo (Ref. 5).

Total Drag	=	External Aerodynamic Drag	(A)	
	+	Lift Air Momentum Drag	(B)	
	+	Wavemaking Drag	(C)	
	+	Spray Momentum Drag	(D)	
	+	Skirt Friction Drag (in water contact)	(E)	(21)

5.1.1 (A) External Aerodynamic Drag ("Form Drag")

$$D_A = \frac{1}{2} \rho V^2 A C_{DA} \text{ in newtons} \quad (22)$$

where ρ = Air Density — (kg/m^3)

V = Craft Speed relative to the air — (m/s)

A = Frontal Area at max. section — (m^2)

C_{DA} = Drag Coefficient (Varies from 0.3 to 0.6, with 0.3 to 0.5 as most likely values. The value for an ACV could easily rise to 0.8 at 90° yaw. (See examples on page 16 — Fig. 8) (See Ref. 6).

5.1.2 (B) Lift Air Momentum Drag
(drag of lift air inhaled and accelerated to craft speed)

$$D_M = Q_m V \text{ in newtons} \quad (23)$$

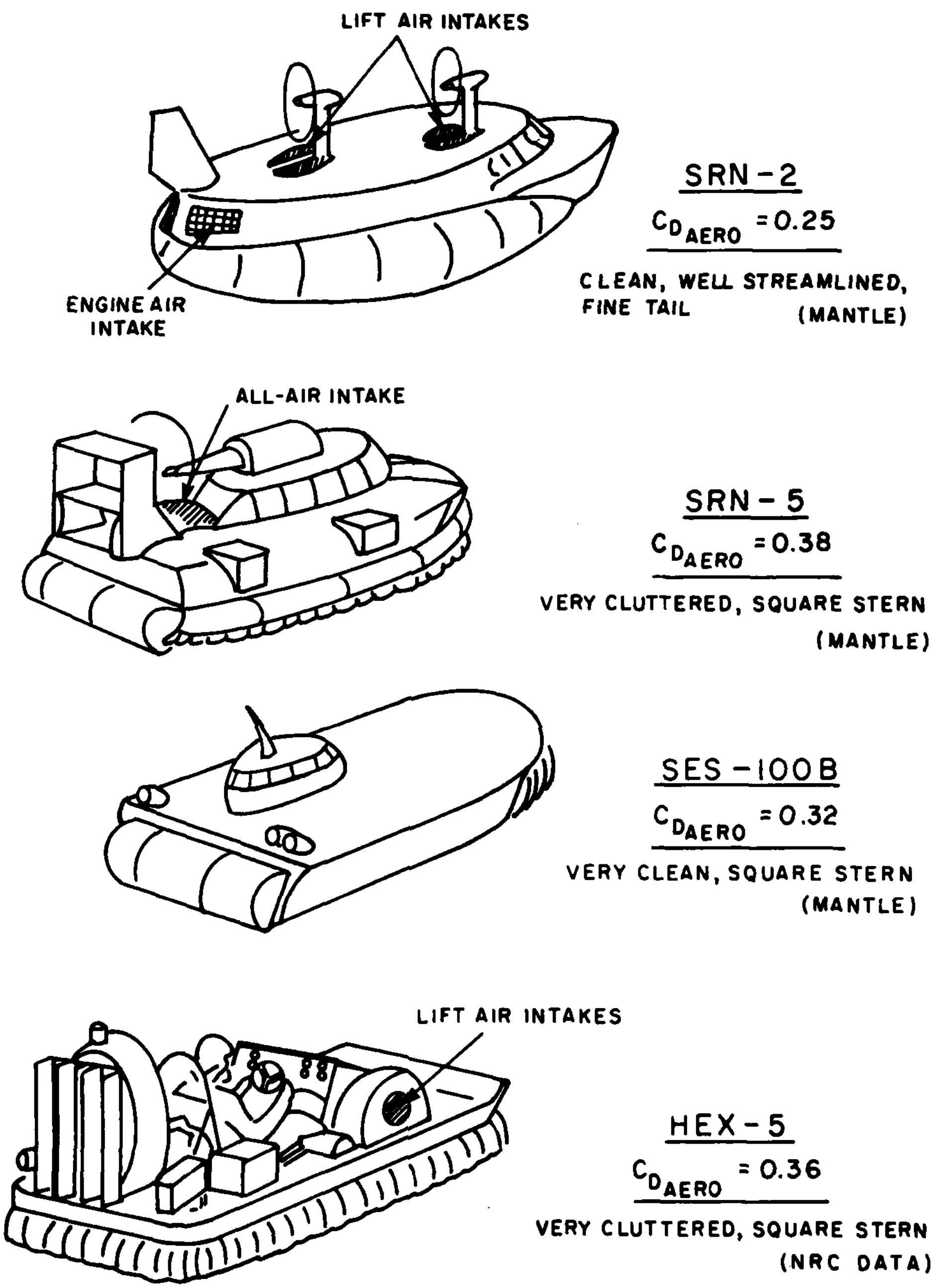
where Q_m = Mass flow of lift air — (kg/s)

V = Craft speed relative to air — (m/s).

5.1.3 (C) Wavemaking Drag

At low speed the ACV acts as a displacement boat, and raises a large wave system. At a critical speed ("Hump speed", so-called from the hump in the drag curve) the ACV rises above the water, and planes. The wave system almost vanishes and wave drag is sharply reduced. In order to pass the critical speed and perform satisfactorily in the planing mode, the craft needs a thrust equal to roughly 1.5 or 2 times the hump wavemaking drag (as a rough approximation).

$$\text{Hump Speed} = k\sqrt{\ell} \quad (24)$$



NRC WIND-TUNNEL TESTS ON HEX-5 SHOW NO CHANGE OF C_D WITH R_N OVER (FULL SCALE) SPEED RANGE 2-20 m/s.

FIG. 8: TYPICAL AERODYNAMIC DRAG COEFFICIENTS (AT ZERO YAW)

where Speed = Craft speed relative to water — (m/s)

ℓ = Cushion length — (m)

k = a constant between 1.4 and 1.8 (theoretically 1.76)

Wavemaking drag at hump speed is known as Hump Drag (D_H) and

$$D_H = \frac{0.03 \times M^2}{S_c \times \ell} \times \text{Factor (in newtons)} \tag{25}$$

where M = Craft Mass — (kg)

S_c = Cushion footprint area — (m^2)

ℓ = Cushion footprint length — (m)

and the Factor depends on the water. Approximate values given by R.G. Wade are:

Smooth deep water = 1

Rough deep water = 2

Shallow water = 3

These factors apply to a cushion planform aspect ratio of 2:1.

5.1.4 (D) Spray Momentum Drag

This accounts for the acceleration up to craft speed of spray taken on board or thrown up beneath the skirt, and includes a very empirical constant.

It obviously depends also on the sea state

$$D_{SP} = \frac{6.5}{1{,}000{,}000} \times S_c \times P_c \times \frac{\ell}{h} \times V \text{ in newtons} \tag{26}$$

where S_c = Cushion area — (m^2)

P_c = Cushion pressure — (Pa)

ℓ = Cushion footprint length — (m)

h = hovergap — (m)

V = Craft speed relative to water — (m/s)

5.1.5 (E) Skirt Friction Drag (Wave contact)

$$D_{SF} = 4.2 \times S_c \times a \times V^2 \text{ in newtons} \tag{27}$$

where S_c = Cushion area — (m^2)

a = Wave height — (m)

V = Craft speed relative to water — (m/s)

This term can be very large.

These drags combine to form the total drag of an overwater ACV. Their relative proportions in a typical case have been shown diagrammatically in various sources (Ref. 7 etc.) by the figure (Fig. 9).

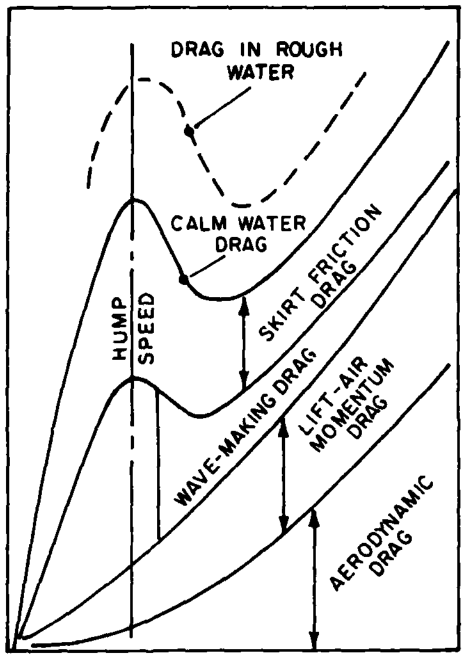


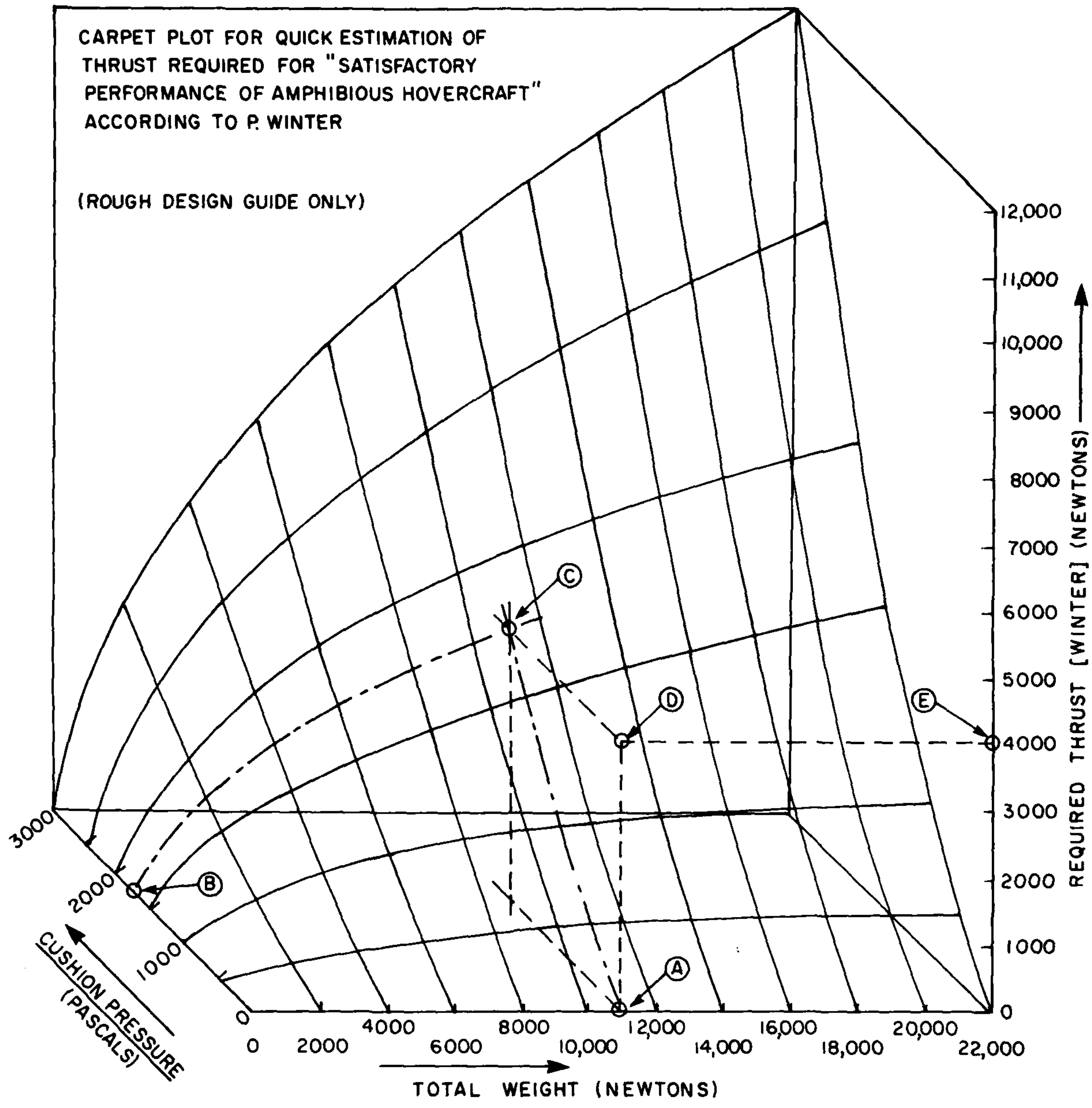
FIG. 9: OVERWATER DRAG
(After Elsely & Devereux)

The full lines represent a calm-water situation, and a dotted line suggests the additional drag in a rough sea (wave height approximately equal to skirt height).

While on this subject, one may quote Winter, who remarks in a report that "for satisfactory performance (of a light ACV, of say up to 25,000 N total weight) the installed thrust should be about 2.5 times the calm-water hump wavemaking drag". For very approximate estimating purposes, Figure 10 sets out this thrust requirement.

5.2 Drag Overwater at 'Low' Speed

It appears that at present there is a great lack of reliable published data for predicting overwater drag of ACVs at low speed. Until better data and methods are available, the following approach is suggested.



EXAMPLE: VEHICLE OF 11,000 NEWTONS TOTAL WEIGHT & 1750 PASCALS CUSHION PRESSURE. INTERPOLATE WEIGHT CURVE (A-C) AND PRESSURE CURVE (B-C). VEHICLE STANDS AT POINT C. DRAW C-D, PARALLEL TO PRESSURE AXIS (I.E. AT CONSTANT THRUST LINE) TO (D), VERTICALLY ABOVE (A). DRAW D-E, PARALLEL TO WEIGHT AXIS. (E) REPRESENTS THE REQUIRED THRUST (4000 NEWTONS).

FIG. 10: THRUST REQUIREMENT FOR AMPHIBIOUS HOVERCRAFT

At low speeds the following simplifying assumptions may be made:

(a) In the range up to 0.5 × hump speed, Aerodynamic and Momentum drags are negligible, and can be accounted for under total drag without serious error.

(b) In this range wavemaking is observed to be small, and wave drag can also be neglected.

(c) To define this range, the standard theoretical value that Hump Speed = $1.76\sqrt{\text{cushion length}}$ (speed in m/s, length in m) may be used.

In this speed range, the total drag would appear to be substantially the form-drag of a bluff body towed under water, and defined by the area of skirt below water across the bow of the craft. This is clearly equal to the product of (cushion beam × cushion pressure in height of water gauge units).

Form drag is calculated from the standard formula:

$$D = \frac{1}{2} \rho V^2 A C_D \qquad (28)$$

where D = Drag (newtons)

ρ = Density (of water = 1000 kg/m^3)

V = Craft Speed relative to water (m/s)

A = Opposed area (of skirt) = $b \times P_c$ (m^2)

C_D = Drag Coefficient (see following argument).

The drag coefficient C_D must be found experimentally, and the attached curve (Fig. 11) gives an opportunity to estimate it for vehicle HEX-5.

Using the method stated above, a curve of C_D vs. speed derived from the speed vs. drag curve is shown in Figure 12.

The procedure for calculating the drag of any similar vehicle is therefore as follows:

1. Hump speed is calculated, as $V_H = 1.76\sqrt{\ell}$.

2. The method may be used up to $V = V_H/2$.

3. Vehicle speeds in m/s are calculated, corresponding to a series of percentages of V_H up to $V_H/2$.

4. From Figure 12 the C_D values at each of these percentages of V_H are read off.

5. Using the C_D values appropriate to each speed, the equation $D = C_D A \frac{\rho}{2} V^2$ has the series of speeds substituted in it, and values of the drag D may be read off.

Drag measurements on HEX-5 while carrying a heavy load of ballast have fallen on a curve predicted from this data, and future experiments on HEX-1B, (geometrically similar but approximately twice the size) will be made at the earliest opportunity to further confirm the validity of this approach.

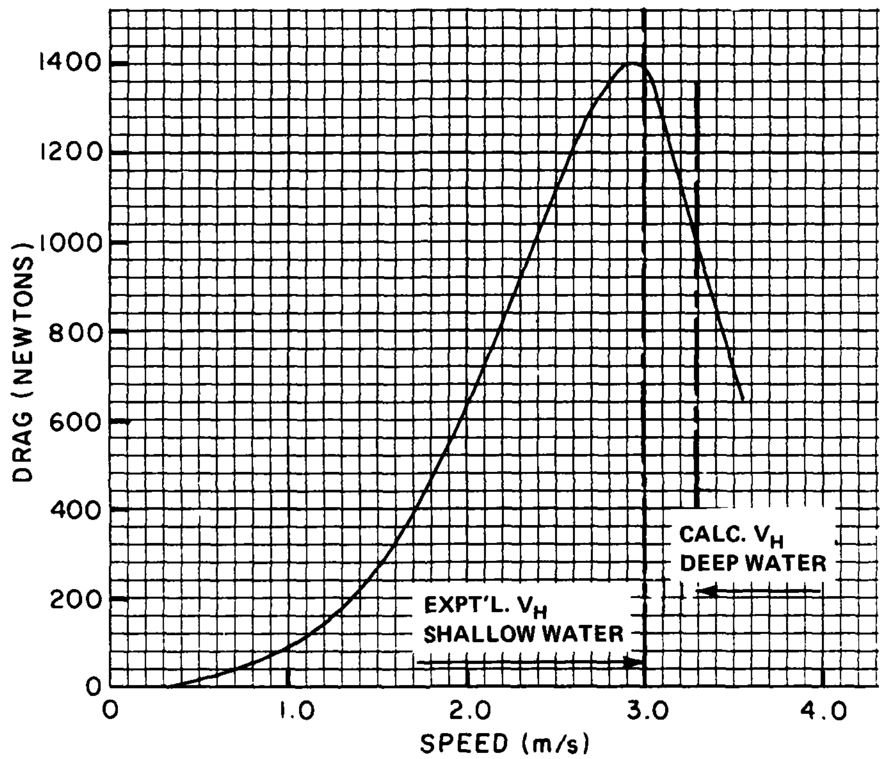


FIG. 11: LOW-SPEED OVERWATER DRAG OF HEX-5

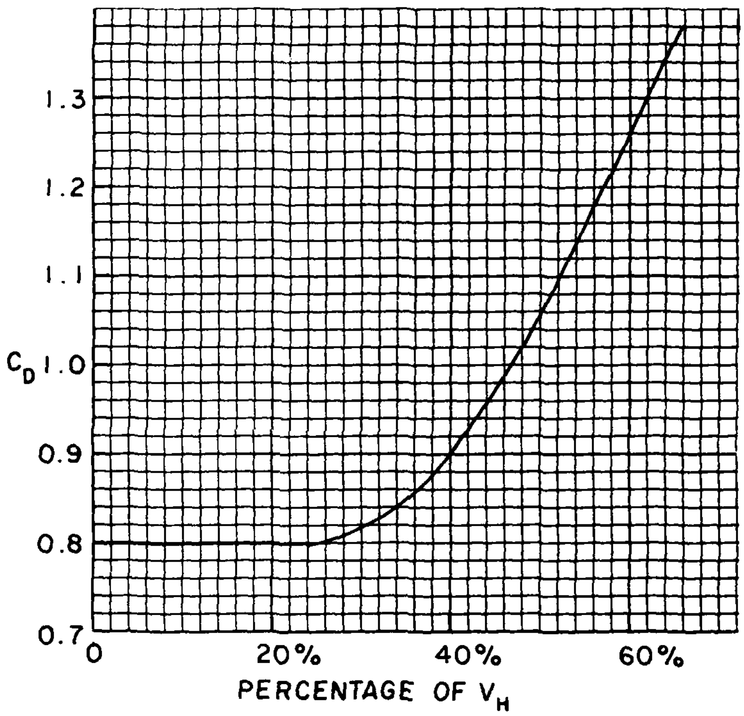


FIG. 12: DERIVED DRAG COEFFICIENT FOR HEX-5

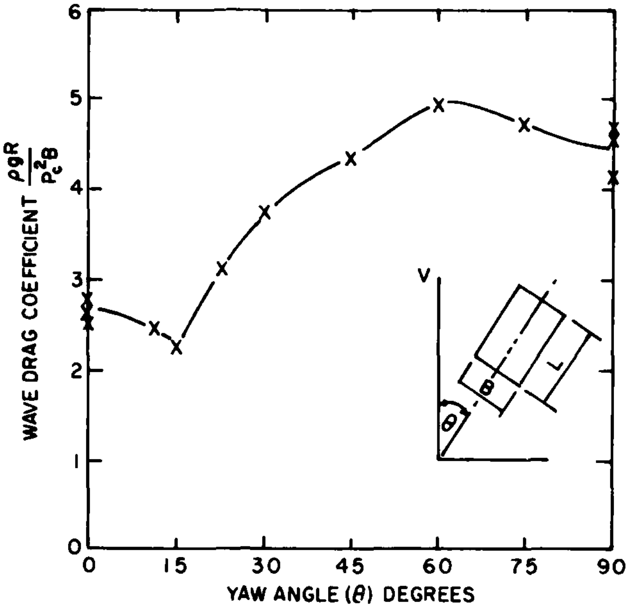


FIG. 13: MEASURED WAVE DRAG OF YAWED ACV

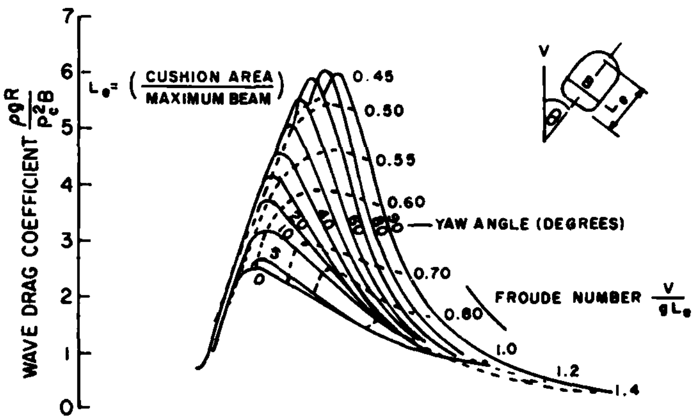


FIG. 14: VARIATION OF WAVE DRAG WITH YAW AND FROUDE NO.

Two curves showing the influence of yawed motion on wave drag. Reproduced from N.P.L. Hovercraft Unit Report No. 7, Feb. 1969, "A Review of Hovercraft Research in Britain", by A. Silverleaf.

5.3 The drag of overland ACVs is under intensive study, and is being treated under the same headings as that of the overwater craft, but the values of the skirt/terrain component are not yet well-established.

By analogy with Section 6.1 (high speed overwater drag) the drag is composed of:

Total Drag = External Aerodynamic Drag — (A)

+ Lift Air Momentum Drag — (B)
(Wavemaking Drag (C) is not present)

+ Spray (Debris) Momentum Drag — (D)

+ Skirt/Terrain Interaction Drag — (E)

+ Slope Drag — (F) (29)

Items (A) and (B) are calculated exactly as in Section 6.1.

Item (D) can usually be neglected.

Item (E) is not yet susceptible to calculation, but some empirical coefficients are being obtained.

This subject is discussed at length in References 1, 2, 3, and 8.

It is clear that the Skirt/Terrain Interaction Drag is very strongly sensitive to lift airflow and it appears likely that it is sensitive to $(\text{speed})^2$. It is also very sensitive to the nature of the terrain, both in porosity and in density of vegetation cover.

The best guidance which can be given at the present time is a few curves for tow coefficient at various lift airflows, from tests on research vehicles HEX-1B, -4 and -5. The lift airflows are given as Efflux Gap Heights while the Interaction Drag is defined as Tow Force/Vehicle Total Weight (given as a percentage). The results are all at low speed (2- m/s) and are specifically for Skirt/Terrain Interaction Drag only, other components having been subtracted before plotting. (Fig. 15).

The effect of speed is plotted separately (Fig. 16). Again the picture is very hazy at present, but at least up to 10 m/s data can be presented with some confidence. Above this speed, testing becomes more difficult and there is at present some confusion.

It should be noted that skirt wear appears to increase as $(\text{speed})^2$ or worse, at any rate over abrasive surfaces such as concrete or gravel road.

In passing through dense vegetation, the drag may be divided into two portions — frictional drag which is more or less constant, and "bush-bashing" drag which decreases greatly with successive passes. A plot showing the decrease of drag due to the reduction of the bush-bashing component over a series of passes is given in Figure 17.

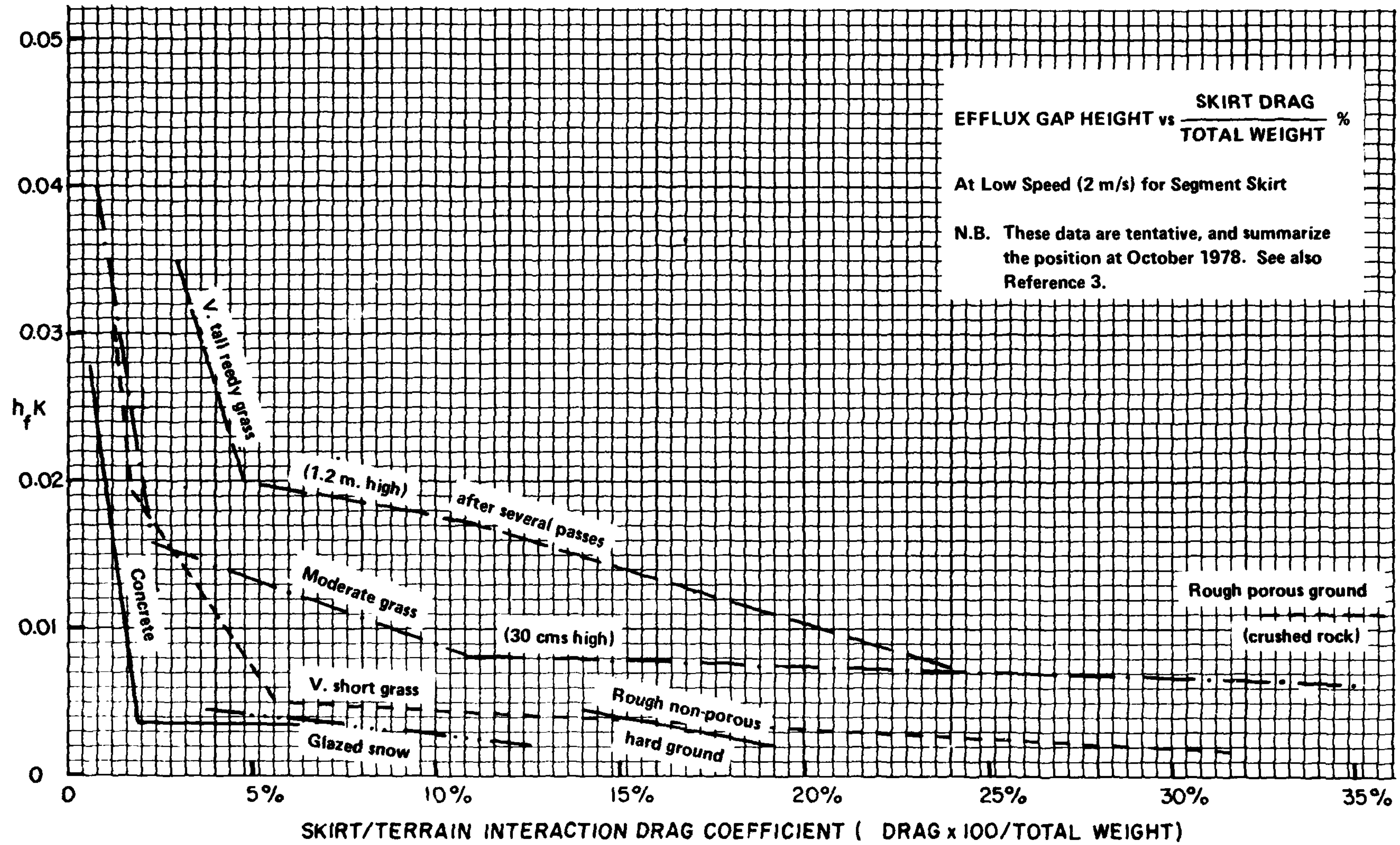


FIG. 15: EFFLUX GAP HEIGHT vs. SKIRT DRAG COEFFICIENT

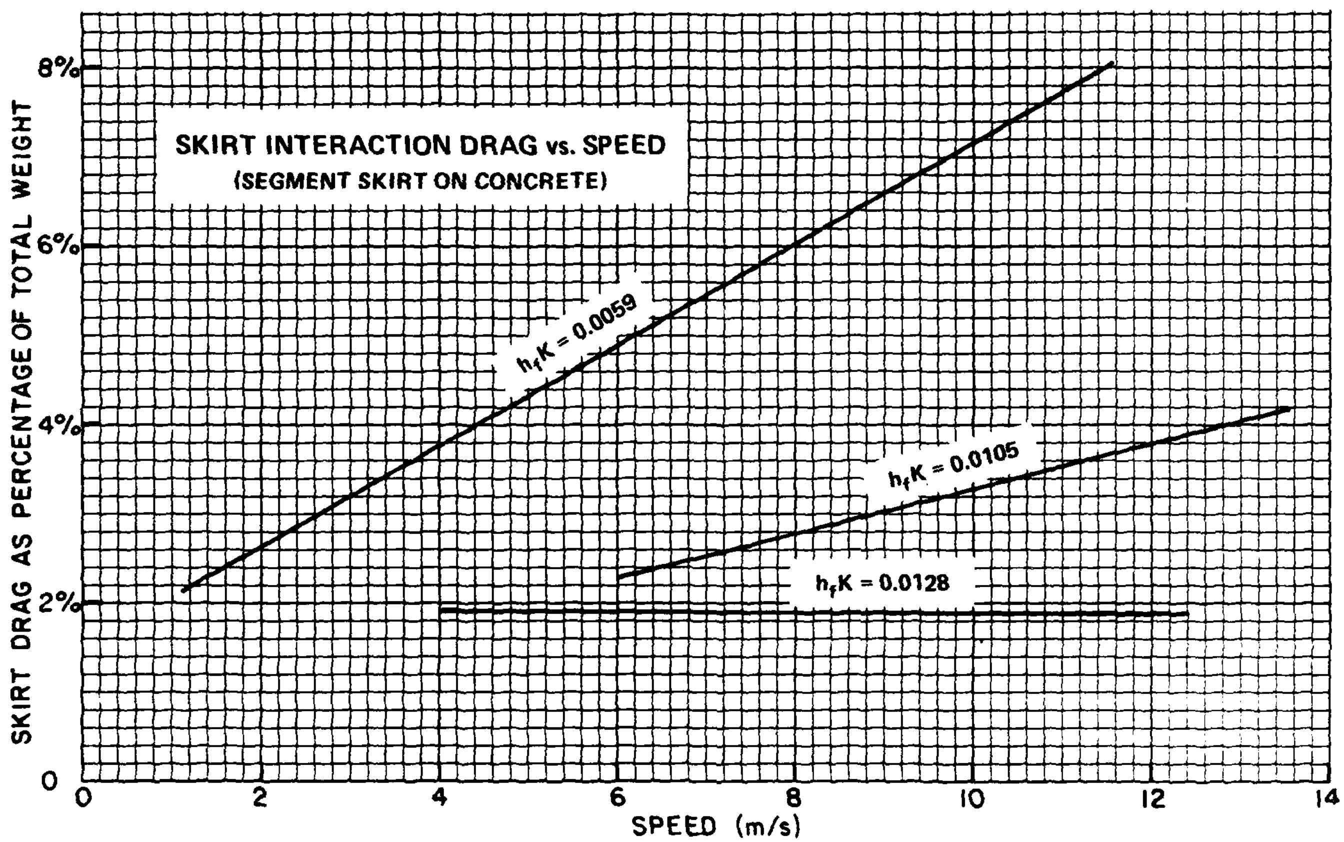


FIG. 16: SKIRT DRAG vs. SPEED AT VARIOUS EFFLUX GAP HEIGHT

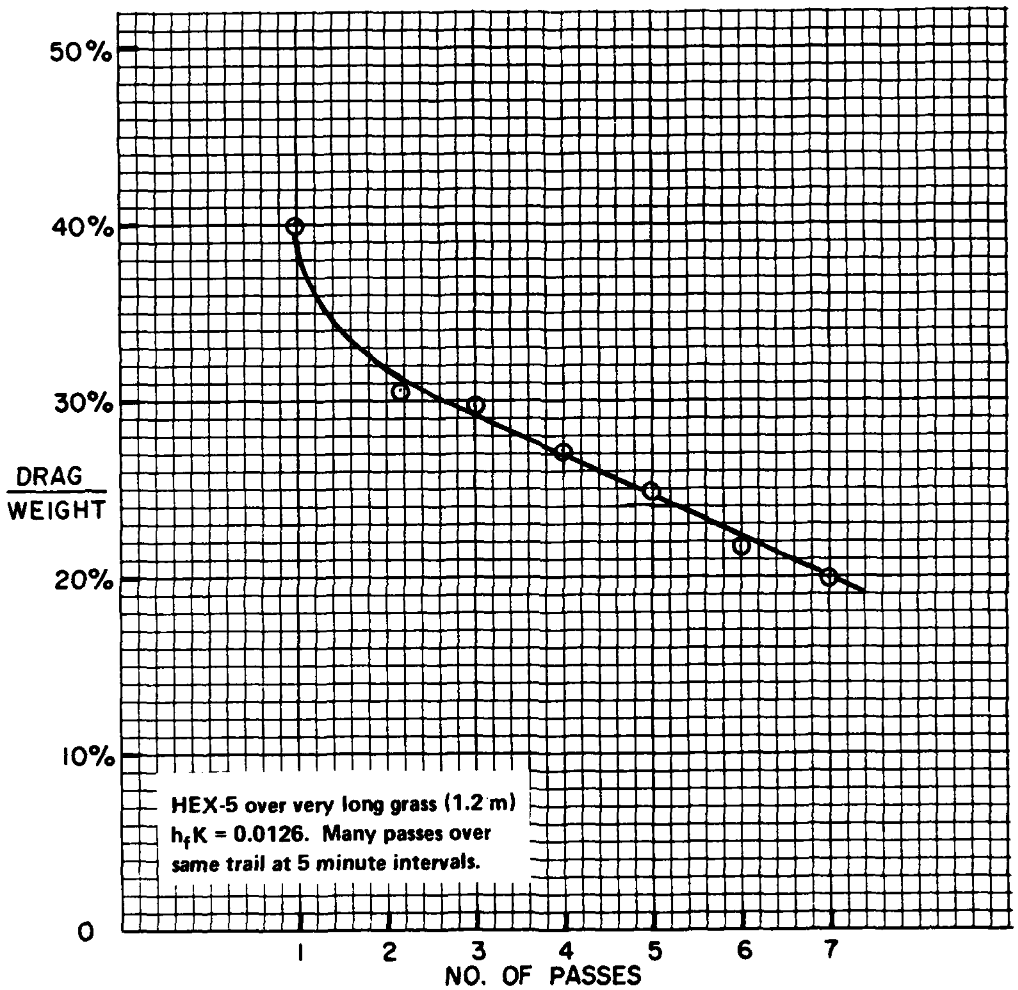


FIG. 17: CHANGE OF DRAG WITH REPEATED PASSES THROUGH DEEP GRASS

6.0 ROLL AND PITCH

Roll and pitch stability are required for three reasons:

(a) to permit acceptably steady ride across uneven terrain,

(b) to permit some latitude in loading cargo or passengers, and

(c) to permit changes in thrust or drag without causing excessive trim changes.

On the other hand, excessive stiffness in roll, pitch or heave can result in an unacceptably hard ride over an uneven surface.

It is therefore necessary in the vehicle requirement to specify what CG and thrust changes are to be permitted without exceeding given roll or pitch angles, and then design for a stiffness which will satisfy this requirement, without giving a stiffness too great for comfort.

So far, it has been the practice to calculate and measure only the static stiffness, relating this to stiffness while in motion by experience. It appears likely that 'moving' stiffness is different to static stiffness.

The calculable stiffness is in the relatively "small-displacement" range, where the skirt is behaving as an elastic inflated structure. However, at some critical value, this structure buckles and collapses. This critical point is difficult to predict, and with some types of skirt may occur without warning. Recovery from the collapsed condition may not follow when the disturbing force is removed.

In general, roll and pitch stiffness of a skirt are exactly similar, and if the appropriate length (cushion beam for roll or length for pitch) is used, are calculated in the same way.

Typical curves for three well-known skirt types are shown in Figure 18.

It is important to understand that the skirt is not a pure inflated membrane, but possesses some inherent structural strength due to the actual material. This shows up more strongly, as the scale of a model is reduced, unless very special thin material is used for a model skirt. Roll tests on model skirts have been shown to give increasingly optimistic results as the scale is reduced, showing stiffness up to 50% higher than in the full scale case. The buckling and collapse point is probably also delayed in a model with a stiffer-than-scale skirt.

The whole subject of roll/pitch stability is being studied by Sullivan at UTIAS, and reports are available from that source.

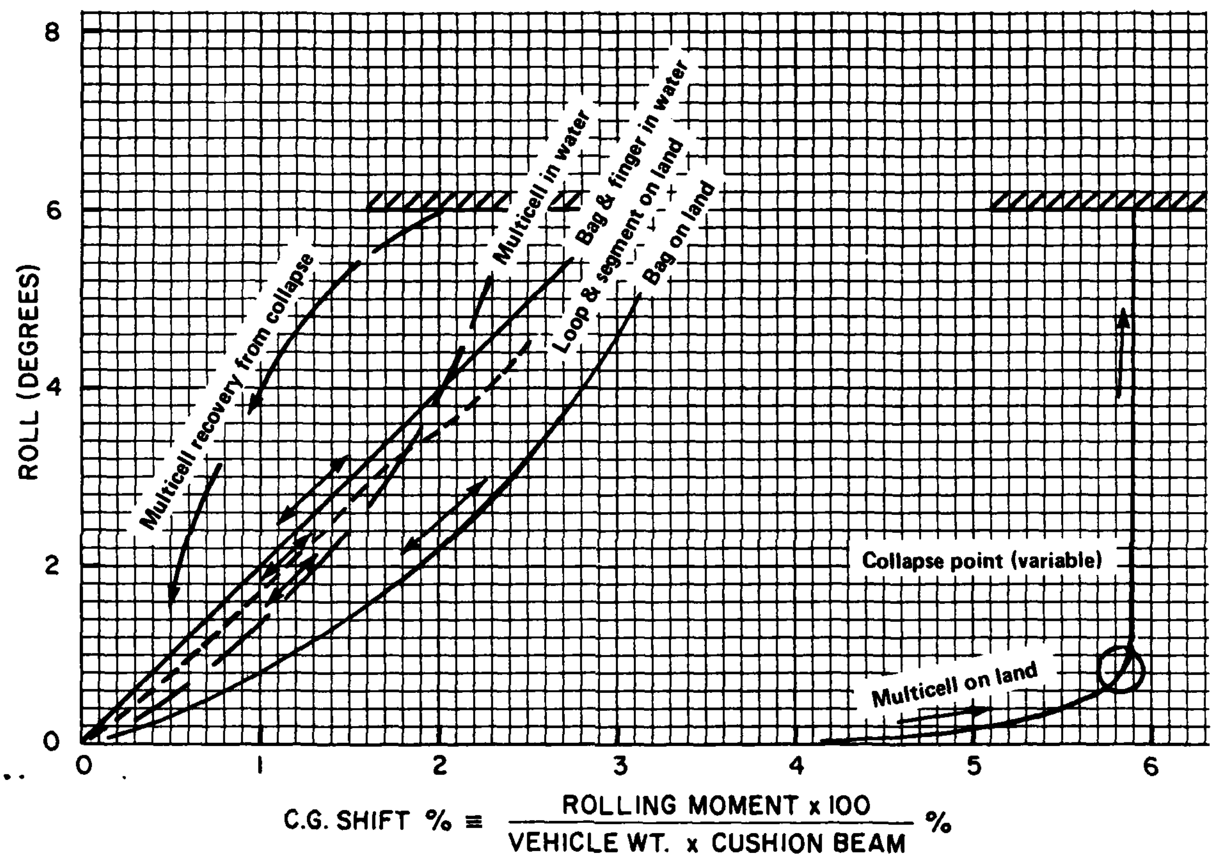


FIG. 18: ROLL STIFFNESS OF TYPICAL SKIRTS

7.0 HEAVE STABILITY

Heave instability is a well known fact, but its analysis is complex, and so far in an early stage. It has been established that the instability can have several different causes, and these are under intensive study by Sullivan and Hinchey at UTIAS.

In practice, the instability varies from a mild tremble of the vehicle to a $\frac{1}{2}$ — 5 Hertz bouncing of up to 10 cms amplitude of vehicles of up to 2,000,000 newtons weight. This instability is more serious over hard flat ground. Rough ground or vegetation often reduces it considerably, whether from increased skirt friction and damping or from the effect of a porous wall on the resonating cushion cavity is not yet clear. If the bounce is detected promptly, it can usually be stopped by throttling back the lift system slightly. Vehicles designed for high cushion pressure appear to be more prone to it, and it may even prevent them ever reaching design point. Various possible remedies are being studied for such cases.

It should be added that a similar vertical bounce may be experienced on any vehicle at very low lift power, just before it rises to hover. This is probably in fact the lift blower surging (perhaps with duct resonance) while no air is escaping under the crumpled skirt, before lift-off establishes a hovergap. This is not a cause for alarm, and is merely a condition which is easily avoided.

As a simple guide to the factors involved in the heave stability problem, Wingate Hill (Ref. 9) suggest that the criterion for stability is that:

$$H<\gamma h\left(\frac{P_c}{P_c-P_a} + B - \frac{1}{\gamma}\right) \qquad (30)$$

where H = Height of cushion plenum cavity

γ = Ratio of specific Heats of Air (CP/CV)

h = Hovergap (height of exit gap under skirt hem)

P_c = Absolute Cushion Pressure

P_a = Barometric Pressure

B = Slope of fan characteristic curve (usually negative).

He adds that: "In practical situation this could imply, for example, that for a given air exit gap height an unstable heave motion can be avoided by making the plenum chamber height small, the cushion pressure low, and choosing a blower which produces a large change in mass flow for a small change in delivery pressure." (i.e. a "flat" characteristic is required). (See also References 10 and 11 and note Hill's unusual definition of B in Reference 9).

8.0 A SIMPLE LOW-SPEED ANEMOMETER

A simple anemometer for measuring airspeeds of up to about 15 m/s has been devised and reported by the Von Karman Institute in Brussels, (Ref. 12). It depends on the drag of a sphere, which is well known, and on the fact that an ordinary table-tennis ball is a sphere of very closely controlled weight, diameter, and sphericity. Such a ball is hung on about 25 cms of fine flexible thread, and will attain steady equilibrium in a light wind as shown in the attached diagram. It is held well away from the observer, in line with a protractor levelled by a spirit level, and the wind-speed may be read off at once.

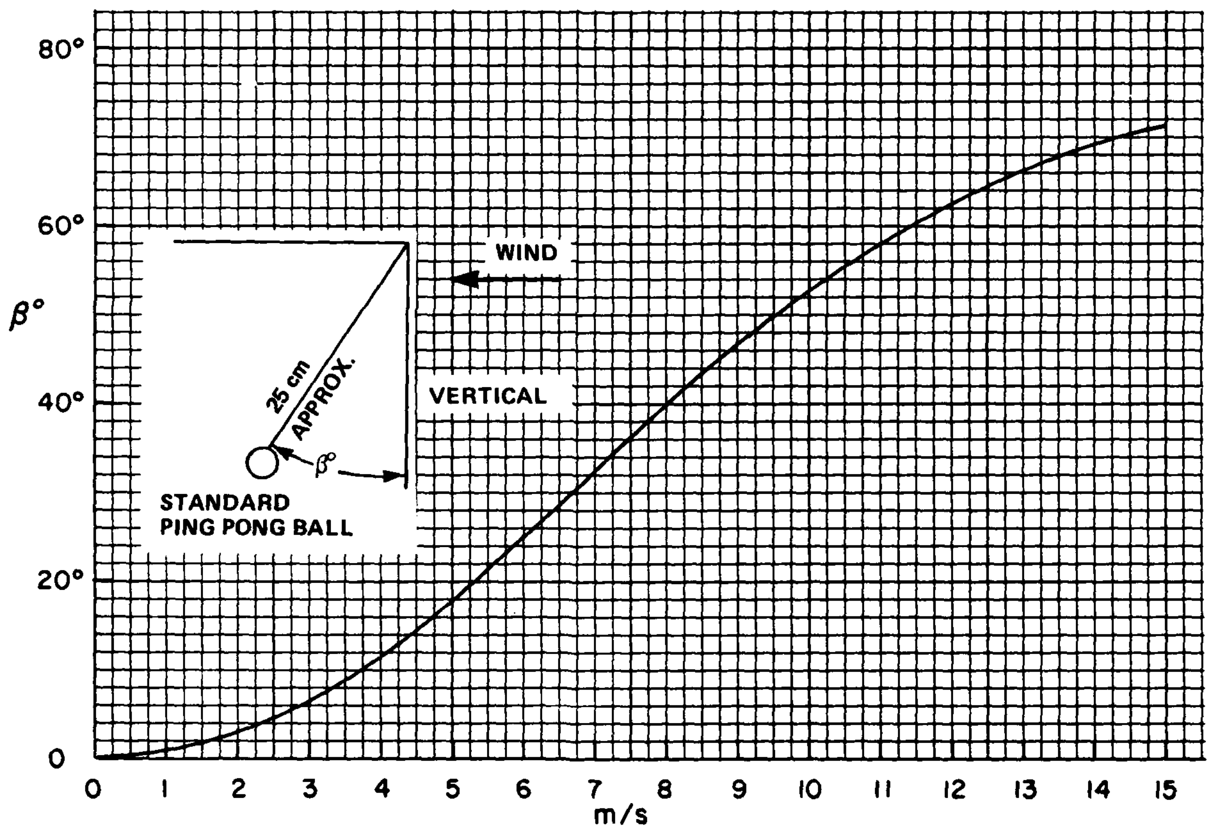


FIG. 19: V.K.I. LOW-SPEED ANEMOMETER

9.0 RATE OF FALL OF SPHERICAL PARTICLES

In connection with calculations on dust clouds generated by ACVs, and the inertia-separation of particles in air intakes, it is useful to know the terminal velocity of small particles in air. In clouds, the "downward acceleration" is that due to gravity, while in a centrifugal separator the local centrifugal acceleration should be used. The attached nomogram is drawn for the gravity case, at standard air density (288°K, 101.3 kPa), but other cases may be calculated from the formula. The particles are assumed to be spherical. Particles of other forms are likely to fall at lower speeds, with flat thin plate particles having a much lower rate of fall, as low as perhaps $\frac{1}{3}$ the rate of the spherical particle.

RATE OF FALL OF SPHERICAL PARTICLES IN AIR

Stokes Law

$$V = \frac{1}{18} \frac{gd^2 (Wp - Wa)}{S} \qquad (31)$$

V = Velocity of fall cms/sec

g = 981 cms/sec^2

d = Particle diam. cm

Wp = Sp. Gr. particle

Wa = Sp. Gr. air

S = Viscosity of air
181 X 10^{-6} centipoise

(1 Micron = 0.001 cm)

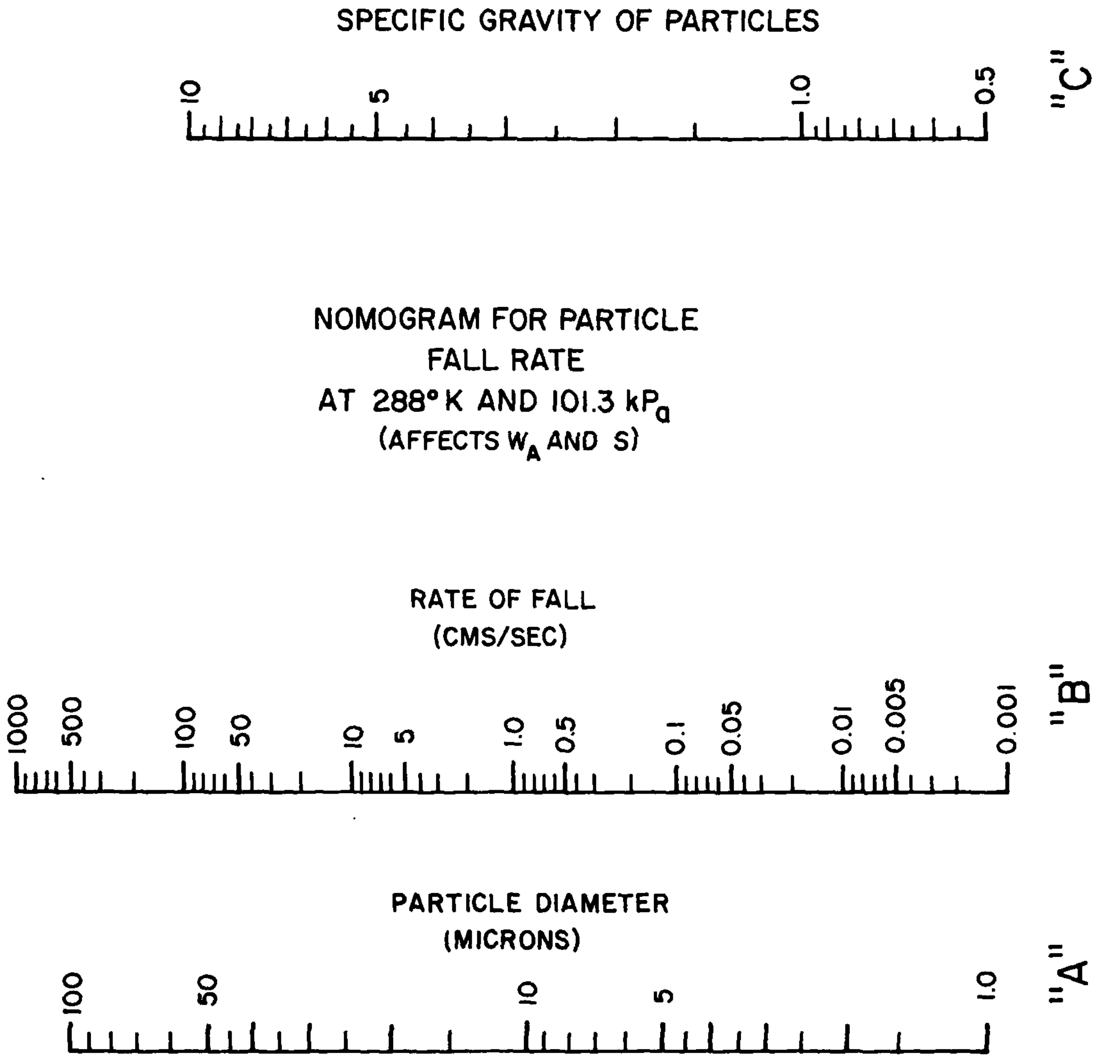


FIG. 20: RATE OF FALL OF SMALL SPHERICAL PARTICLES IN AIR

10.0 EFFECT OF ALTITUDE AND TEMPERATURE ON PERFORMANCE

In order to focus attention on the importance of accounting for the atmospheric conditions of actual operation in design calculations, the performance of an ACV at standard-day sea level conditions, sea level arctic conditions, and at hot-day prairie ground-level altitude has been calculated. A summary of calculations follows, assuming the same engine and fans in each case.

The vehicle is as follows:
Total Weight = 100,000 N (W)
Cushion Press. = 4000 Pa (P_c)

Cushion Areas = 25 m^2 (S_c)

Aspect Ratio = 2:1 (A.R.)
$\therefore \ell$ = 7.072 m
b = 3.536 m
L = 21.216 m
Lift Air Escape C_D = 0.61

Lift Airflow = Qm^3/s (Q)
Hoverheight (Standard day) = 0.03 m(h)
Frontal Area = 10.5 m^2(A_f)

10.1 Standard Day, Sea Level

$\rho = 1.23\ kg/m^3$, $t^\circ = 288^\circ K$, Bar = 101.3 kPa.

Lift air exit velocity (from $V_e = 0.756 \sqrt{\dfrac{P_d \times t^\circ K}{Bar}}$

where P_d = Exit dynamic pressure, equal to P_c, in pascals,

t° = Atmospheric temp. in $^\circ$K

Bar = Barometric press., in kilopascals

$\therefore V_e = 80.0$ m/s

Hence, for 0.03 m hovergap, 21.3 m perimeter, $C_D = 0.61$.

Lift air flow Q = 31.16 m^3/s

Compressor Power to supply this air, at 70% compressor efficiency and 80% duct efficiency:

$$\text{Power} = \frac{Q\,\Delta p}{1000\,\eta_c\,\eta_d} = 223 \text{ kw}$$

This is assumed to be full power at this condition from the lift engine.

The Total Drag at 20 m/s over smooth deep water, calculated in the standard manner, using an aerodynamic drag coefficient of 0.36 is

$$D = D_{aero} + D_{mom} + D_{wave} + D_{spray} + D_{skirt}$$

$$= 1300\text{ N} + 460\text{ N} + 17000\text{ N} + 3100\text{ N} + 4200\text{ N} = 26060\text{ N}.$$

To drive this at 20 m/s would require (at 100% propulsion efficiency)

$$\text{Power} = \frac{26000 \times 20}{100} = 520 \text{ kw}$$

Using a 3 m diam. ducted propeller, of disc area 7.07 m^2, $\therefore$ Disc loading = Thrust/Area = 3677 N/m^2 at which about 28 N/kw might be expected (from the chart in the section on Thrust).

Therefore $\frac{26000}{28}$ = 930 kw would be required at the prop. shaft. This is assumed to be full engine power from the thrust engine at this condition.

10.2 Recalculation for Arctic Sea Level Condition

$t = -40°C$ (= 233°K) Bar = 101.3 kPa
Hence $\rho = 1.52 \text{ kg/m}^3$
$\therefore V_e$ is recalculated (owing to new air density) at 72.5 m/s
However, Lift Engine Power is proportional to air density, at constant RPM.
$\therefore$ Available Lift Power = 275 kw
$\therefore$ Lift Airflow Q (at same efficiency) = 39.0 m^3/s
Therefore Hovergap = 0.0414 m
i.e. the hovergap has increased from 3 cms to 4.14 cms.

For a given propeller, thrust is proportional to air density, and engine power will rise in the same ratio to drive it, both being considered at constant RPM, so that thrust will rise in the ratio $\frac{288}{233} = 1.236$.

Drag, as itemized above will be sensitive to density^2 for the aerodynamic drag, density^1 for momentum drag, and not sensitive for the other components. Since these drags are relatively small, and since the rise of hoverheight will probably reduce skirt drag, the craft speed might be expected to rise a little.

10.3 Recalculation for Hot-Day at 1067 m Altitude (= 3500 ft. = Calgary)

$t° = +35°C$ (= 308°K) $\therefore$ with altitude effect, $\rho = 1.01 \text{ kg/m}^3$
$\therefore V_{exit} = 89$ m/s
$\therefore$ Lift Engine Power = 183 kw
and Lift Q = 24.4 m^3/s
$\therefore$ Hovergap = 0.021 m
i.e. Hovergap has reduced from 3 cms standard to 2.1 cms.

For a given propeller, the thrust will fall (at const. RPM) to some 0.82 of standard value, and while the drag will fall slightly, the speed will probably fall off to an appreciable extent.

In a Low Speed Overland Case, where the total drag is believed to be proportional to the hovergap, the drag and engine power will change in opposite senses, so that the Arctic case will show reduced drag and higher power, while the Hot Highlevel case will show increased drag and reduced power, which will certainly reflect on slope-climbing ability, even with wheel or track propulsion. It is also likely that there will be a noticeable change in stability of the ACV due to the changes in hovergap and lift airflow.

11.0 TERMINOLOGY AND NOTATION

11.1 Terminology Peculiar to ACVs, Primarily Overland or Amphibious

Term	Definition
apron	A sheet of flexible material external to all other skirt components to suppress spray or dust.
aerodynamic yaw angle	Angle in the horizontal plane between the craft ℄ and relative air direction.
air gap (local)	Distance below the local skirt hem and the surface when on its cushion.
bounce	An instability in heave which may be involuntary due to an internal aerodynamic problem, or which may be induced by increasing lift air supply excessively. Sometimes called tramping.
buzz	An involuntary stable oscillation of a bag skirt due to resonance. May be eliminated by adjusting the mass distribution of the skirt material.
anti-bounce web	Tensioned skirt membrane connected between upper and lower bag points to restrain self-sustained vibration, i.e. "bounce".
bag	An enclosed inflatable flexible structure supplied with air essentially direct from the lift fan. May be used for several purposes. **Peripheral bag** — a bag attached to the periphery of the vehicle. May be used as a single skirt component or in conjunction with stern bags (q.v.) to contain and feed the cushion, and also in combination with fingers (q.v.). **Keel bag** — a bag dividing the cushion in a fore and aft direction to provide stability in roll. **Stability bag** — a bag dividing the cushion in an athwartships direction to provide stability in pitch. **Stern bag** — a bag used to seal the cushion at the stern of a vehicle; used in conjunction with a peripheral bag. May be used in combination with cones. **Chip bag** — a segment usually at the rear of a craft having an additional wall on the cushion side to prevent water scooping.
beam-on	Beam-on implies that the craft is travelling sideways, i.e. at a 90° angle of yaw to the long axis.
boating	Expression used to describe a hovercraft when operating in the wholly displacement condition, i.e. well below hump speed.
centre of pressure	Point through which cushion pressure acts vertically to support vehicle.

Term	Definition
clearance	Distance between the hard structure and the terrain surface.
click instability	A small roll attitude which may be either positive or negative and of equal magnitude assumed by a vehicle when hovering. Associated with incorrect keel depth in compartmented cushions.
cone	A truncated conical flexible structure attached to the base of a stern bag to seal the cushion at the stern of the vehicle. Used when the peripheral bag has fingers. May also be used on keel bags and stability bags.
control (puff, yaw) ports	Controllable apertures in the cushion supply ducting or skirt system which enable jet reaction forces to be generated.
CP shifter	A control which moves the centre of pressure of the supporting cushion(s) relative to the centre of gravity of a hovercraft.
CG height	Height of the CG of the craft above flat terrain in the designed static hover (or other as stated) case.
cushion	A volume of air under pressure enclosed between the bottom of a hovercraft and the supporting surface by rigid structure, curtains, skirts or any combination thereof.
cushion footprint area	Planform area of the cushion at the terrain (land or water) surface. In the displacement mode over water, the footprint area is taken at the undisturbed water surface. In any case, it is likely to vary with lift airflow, and hence cause a small variation of P_c even at constant weight.
cushion length	Length of the cushion planform.
cushion footprint	The footprint made by the skirt hemline on the supporting surface at a specified lift airflow.
drag	The horizontal component along the instantaneous direction of motion of the resultant of all external forces acting on a hovercraft due to its motion.
drift angle or yaw angle	The angle between the track of a craft and its centreline.
efflux gap height	A design parameter used to determine cushion air mass flow requirements.
escape area	The total leakage area from cushions.
heave	Displacement along the vertical (Oz) axis.
heave stiffness	Rate of change of restoring force in the heave direction with displacement in that direction.
hemline	The lowest peripheral edge of the hovercraft skirt.
hinge spacing (horizontal) (x_H)	Horizontal distance between inner and outer "hinges" or attachment points of skirt to structure.

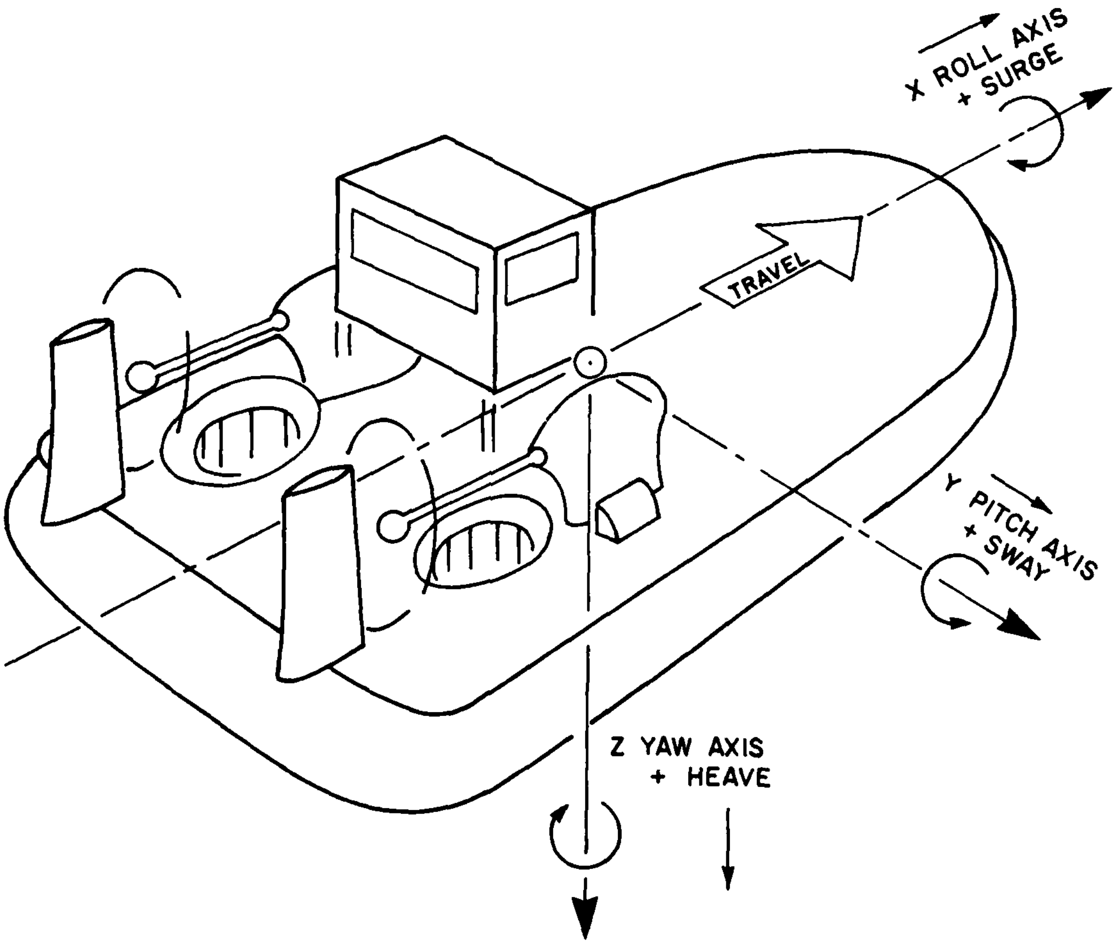
Term	Definition
hinge spacing (vertical) (z_H)	Vertical distance between inner and outer "hinges" or attachment points of skirt to structure.
hump speed	A speed over water at which there is a peak value of the wave-making drag. In general there will be several hump speeds, the highest being known as the "primary hump speed".
hydrodynamic yaw angle	The angle, in the horizontal plane, between the longitudinal axis of a hovercraft and the instantaneous direction of motion relative to the local water surface.
loop	An abbreviated form of bag having large openings over the segments so that there is little pressure difference between the loop and the cushion. A loop may or may not include a sheet of material inboard of the segment inner attachments. N.B. There is no definitive demarcation as to when a bag becomes a loop.
mean bag or loop pressure	Mean pressure in bag or loop, relative to atmospheric pressure.
nibbling	The action describing the catching of the skirt, usually the bow fingers, on the surface being traversed. Nibbling is one indication of a possible plough-in situation developing.
pitch attitude (roll attitude)	Instantaneous angle between the surface traversed and the longitudinal (lateral) datum of the craft.
pitch stiffness	Rate of change of restoring pitching moment with pitch angle.
plenum	Space or air chamber beneath or surrounding a lift fan or fans (not to be confused with "cushion").
plough-in	A divergent pitching motion involving an increase in drag and nose-down pitch attitude.
propeller fin effect	The propeller lateral force (normal to the axis of rotation) which results from a side gust.
puff ports	See "control ports".
hoverheight or rise height	The distance which a hovercraft rises from flat hard ground to being fully cushion-borne.
roll stiffness	Rate of change of restoring rolling moment with roll angle.
rough water drag increment	The increment in the hydrodynamic drag during operation in rough water over the drag (under otherwise identical conditions) in calm water, taken as a time average.

SKIRT SYSTEMS

Term	Definition
bag	A skirt system in which cushion containment is effected only by a bag or bags. Generally restricted to small recreational vehicles.

Term	Definition
bag-and-finger	A skirt system in which cushion containment is effected by a bag or bags with fingers attached. This system is occasionally referred to as the "BHC system" since it is the commonly used system on BHC-designed vehicles. The cushion contained by this system generally requires keel and stability bags for stability. The cushion is fed through feed holes from the bags, and from the fingers.
Bertin	A skirt system employing an array of jupes to supply cushion air and stabilize the vehicle. This jupe is often enclosed within a peripheral skirt. So called due to its origin with the French designer Jean Bertin, whose vehicle designs use it exclusively.
loop/segment	A skirt system in which the cushion containment is effected by a loop and segments. This system is occasionally referred to as the "HDL system" since it originated and was developed by Hovercraft Development Ltd. (HDL). The cushion is generally a simple plenum with no compartmentation.
peri-cell	A peripheral array of small diameter jupes used to contain a cushion. Sometimes referred to as peri-jupe.
flexi-cell	An array of shallow jupes attached to a horizontal flexible diaphragm which forms the base of a plenum beneath the vehicle.
feed hole	A hole, usually circular, cut in bag or segment to allow flow of cushion air. May be used in peripheral and stern bags, or in segments. May also be used in keel and stability bags to stabilize their inflated shape.
finger	A sheet of flexible material attached to the lower surface of a peripheral bag to seal the cushion. Fingers are generally open on the inboard side, and are fed with air from feed holes in the bag; they are generally closed at the top by the bag.
jupes	Truncated conical inflated flexible structures, generally used in multiplicity to feed air into the cushion of a vehicle using a Bertin skirt system.
segment	One of a series of sheets of flexible material attached to a loop and the underside of the vehicle to seal the cushion. A segment is open at the top, fed with air either from the loop or the cushion plenum, and may be open or closed on the inner face. Feed holes are sometimes cut in the inner face if this is closed.
segment angle	The angle between the outer face of a segment and the surface of the ground.
skirt height (H_{SK})	Designed vertical distance from the craft hard structure to finger tip. See Figure 31.
stability skirt (trunk)	A skirt used to divide a cushion to increase the pitch or roll stability by preventing or restricting cross flow.
surge	Displacement along the longitudinal (Ox) axis.

Term	Definition
sway	Displacement along the lateral (Oy) axis.
tip flip	Turning-under of the lower tip of a segment or finger.
track	The direction of the path of the craft over the earth.
trim angle (longitudinal) (lateral)	The pitch or roll angle which results under steady running conditions.
tuck-under	The action of the skirt being pulled back under the structure as a result of local drag forces.



CO-ORDINATE SYSTEM

N.B. POSITIVE DIRECTIONS OF MOTION AS FOLLOWS:

TRAVEL	–	FORWARD	= +
SURGE	–	FORWARD	= +
SWAY	–	TO STARBOARD (RIGHT)	= +
HEAVE	–	DOWNWARD	= +
ROLL	–	STARBOARD DOWN	= +
PITCH	–	STERN DOWN	= +
YAW	–	BOW TO STARBOARD	= +

FIG. 21: ACV CO-ORDINATE SYSTEM

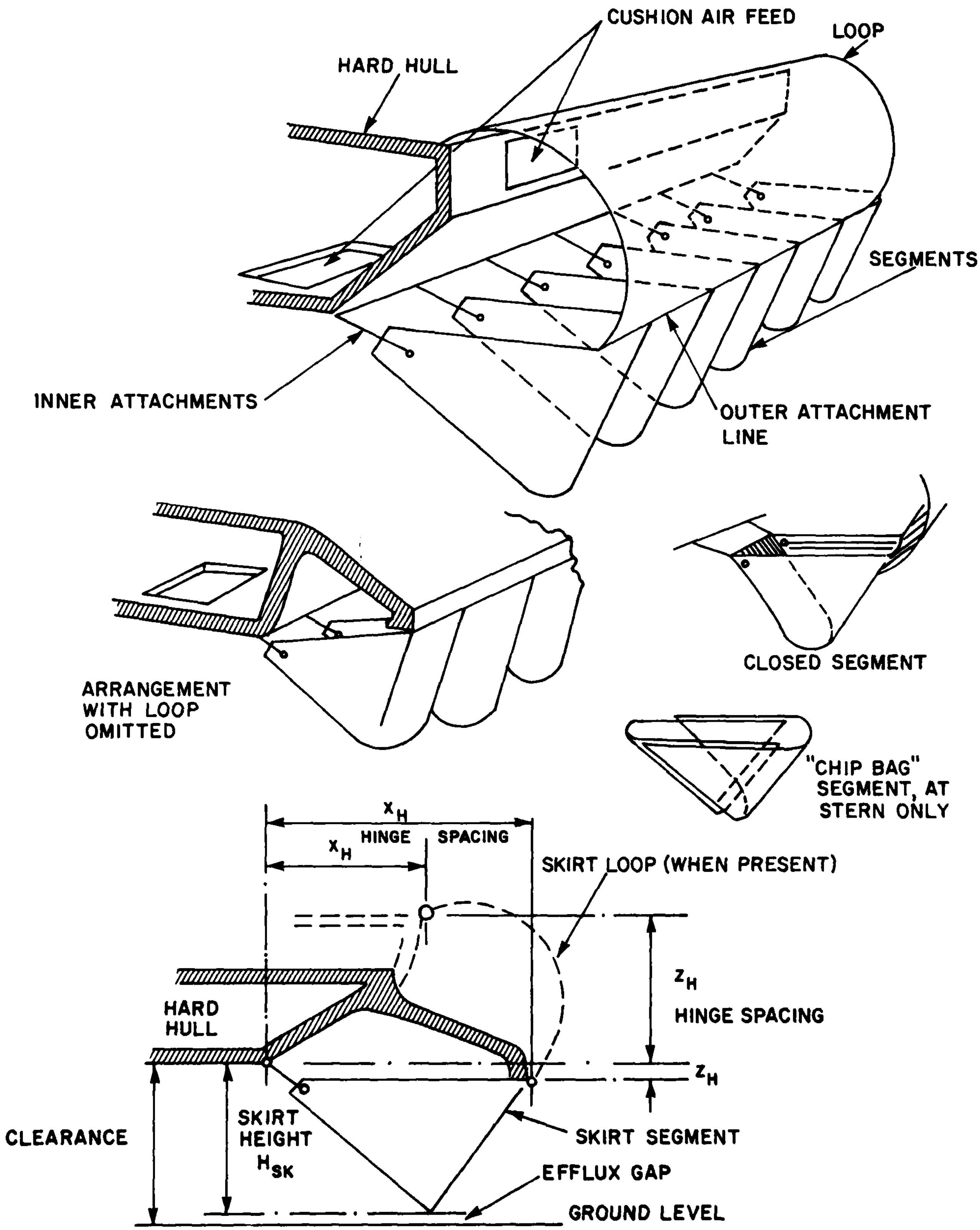


FIG. 22: FEATURES OF SEGMENTED (HDL) SKIRT SYSTEM

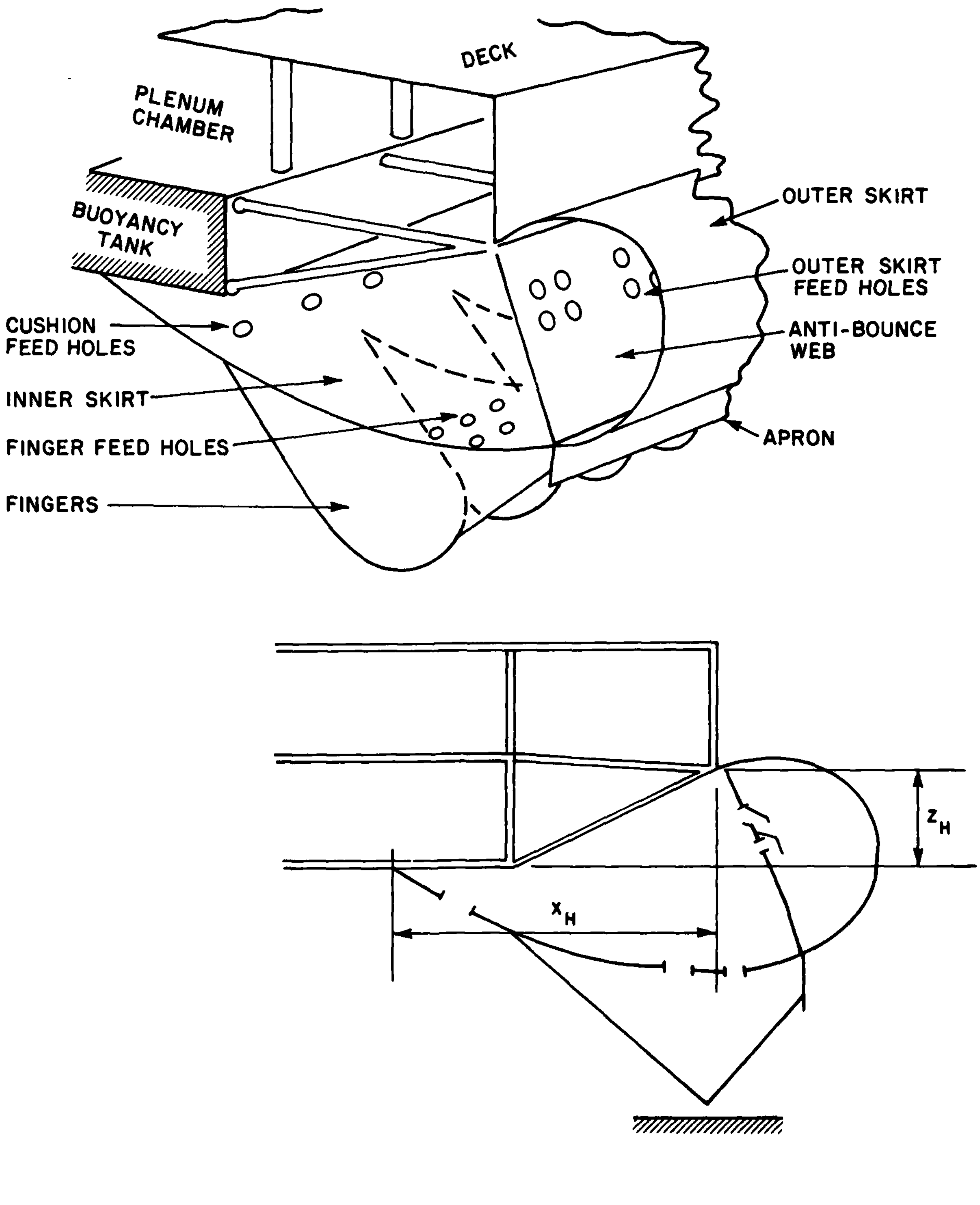


FIG. 23: FEATURES OF FLEXIBLE TRUNK AND FINGER (BHC) SKIRT SYSTEM

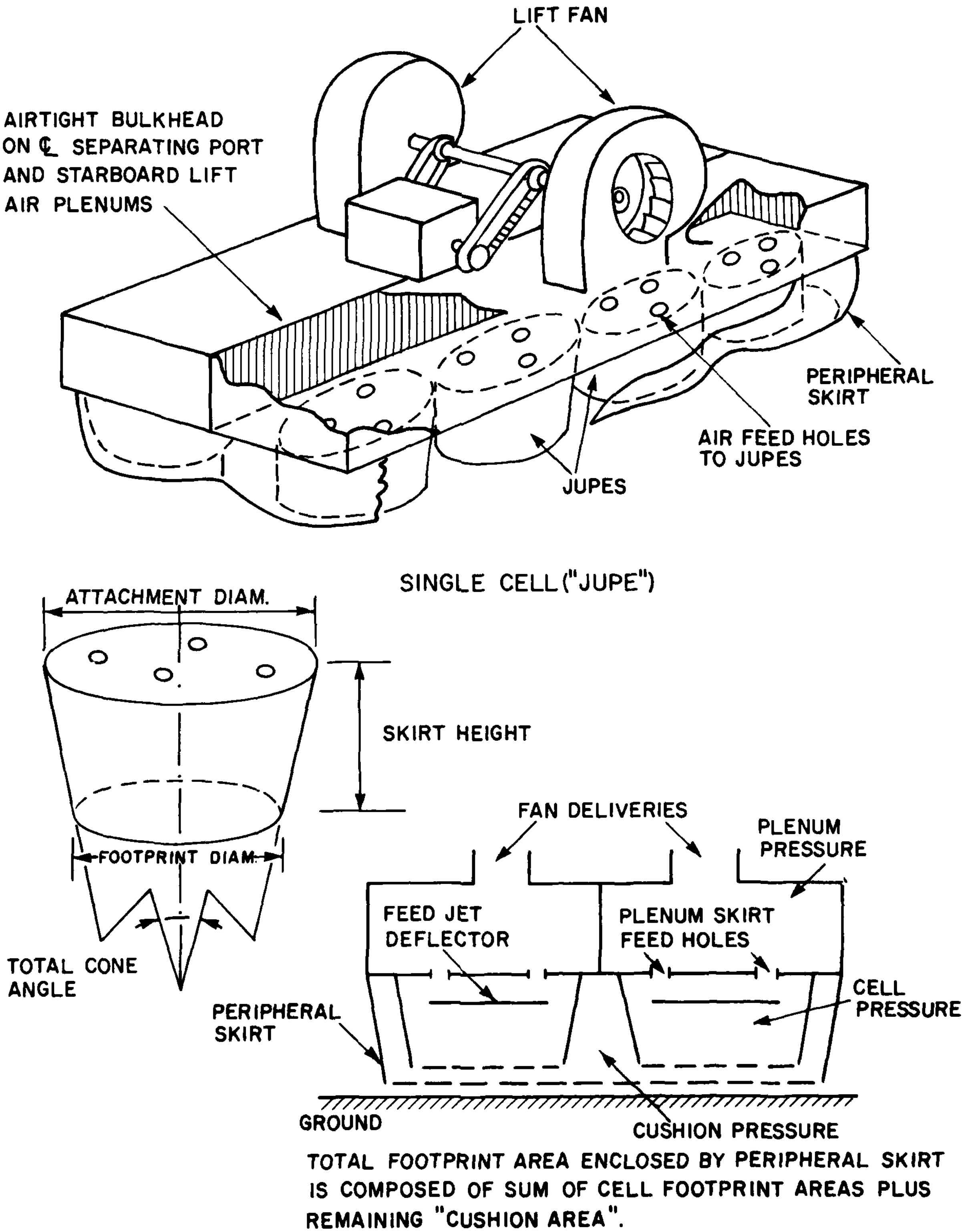


FIG. 24: FEATURES OF BASIC MULTICELL (BERTIN) SKIRT SYSTEM

11.2 Notation

Symbol	Quantity	Dimensions
A	Frontal area	m^2
A_e	Escape area (=Efflux gap height × cushion perimeter)	m^2
b	Cushion footprint beam	m
C_D	Coefficient of discharge	—
C_{DA}	Aerodynamic drag coefficient	—
D	Diameter	m
D_A	Aerodynamic drag	N
D_H	Wavemaking drag at hump speed	N
D_M	Inhaled-air momentum drag	N
D_{SF}	Skirt-friction drag	N
D_{ST}	Skirt-terrain interaction drag	N
D_{SP}	Spray drag	N
D_W	Wavemaking drag	N
F_N	Froude number $V/\sqrt{g\ell}$	—
g	Acceleration due to gravity (9.81 m/s^2)	m/s^2
h	Efflux gap height ("Hovergap")	m
h_f	Efflux gap height over flat nonporous ground at low speed	m
H	Hoverheight (Vertical rise of vehicle from rest to hovering position (Approx. equal to skirt height + efflux gap height)	m
K	Efflux gap height Terrain and Operational factor	—
L	Cushion footprint perimeter, $= 2(\ell+b)$	m
ℓ	Cushion footprint length	m
ℓ_c	Cushion footprint effective length, $= S_c/b$	m
M_n	Mach number (V/V_{sound})	—
M	Mass	kg
P_A	Barometric pressure (101.3 kPa standard)	Pa
P_b	Bag pressure	Pa

Symbol	Quantity	Dimensions
P_c	Cushion pressure	Pa
P_d	Dynamic (velocity) pressure	Pa
P_s	Static pressure	Pa
P_t	Total pressure, $P_s + P_d$	Pa
Q_m	Mass flow	kg/s
Q_v	Volume flow	m^3/s
R	Radius	m
S_c	Cushion footprint area	m^2
t	Temperature (288°K standard atmosphere)	°C or °K
T	Thrust	N
T_c	Thrust coefficient	—
T_s	Static thrust	N
U	Rotor tip speed	m/s
V	Velocity	m/s
V_H	Hump speed	m/s
W	Weight	N
η_c	Fan efficiency	—
η_d	Duct efficiency	—
ρ_a	Air density (1.23 standard atmosphere)	kg/m^3
ρ_w	Water density (1000 fresh water)	kg/m^3
γ	Ratio of specific heats (1.4 for air)	—
σ	Centrifugal fan slip factor (approx. 0.9)	—

12.0 REFERENCES

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13.0 SI UNITS AND IMPERIAL EQUIVALENTS

In the following pages, the SI units for quantities most often used in ACV technology are stated, and their Imperial equivalents are given to normal engineering standards of accuracy. In most cases a graph is also given for quick approximate conversion.

Note on the Relation Between Mass, Weight and Force

The common confusion between the terms "Mass" (of an object, measured in **kilograms**) and "Weight" (the downward force exerted on the same object in the earth's gravitational field, measured in **newtons**) has caused engineers trouble ever since Newton invented gravity. These pages, dealing with an unfamiliar system of units, therefore seem a good place to remark on the relation between the units of Mass and Force in this system.

The quantity of matter in an object is the measure of the force necessary to give it a stated acceleration. This quantity of matter in an object, i.e. the **mass** of the object, is measured in **kilograms** in SI units.

The **force** needed to generate a stated acceleration in the object is measured in **newtons** in SI units.

When an object is held in the hand, the downward force exerted by it under the influence of the earth's gravitational field, is called its **weight**, but being a force it must properly be expressed in **newtons**.

The newton is defined as the force required to give a mass of 1 kilogram an acceleration of 1 metre per second per second. Since the earth's gravitational field produces an acceleration of 9.81 m/s^2 at standard seal level conditions, the **weight** of an object whose **mass** is 1 kilogram is equal to **9.81 newtons.**

In ACV calculations the mass of the vehicle and its components must often be specified, when concerned with its acceleration in various directions under various forces. The vehicle total mass, and component masses, are therefore specified in **kilograms**.

However, the vertical downward force exerted by the vehicle on its air cushion, commonly known as its "weight", being a true force, must be expressed in **newtons**. The value of this "weight" in newtons will be numerically equal to 9.81 times its mass in kilograms.

It then becomes simple to equate the downward force (weight) of the vehicle in newtons, to the upward supporting force of the air cushion in units of pressure × area, $(\text{newtons}/\text{metres}^2) \times \text{metres}^2$, which is clearly a force in newtons.

Any other force experienced by the vehicle in a turn or in transient motion is equally properly expressed in newtons, provided the mass in kilograms is known, and that the acceleration can be specified in m/s^2. The commonly used acceleration stated as so many "g" must therefore be expressed as so many times 9.81 m/s^2 (e.g. 5g becomes $5 \times 9.81 = 49.1$ m/s^2).

Units of Pressure

The standard SI unit of pressure is the pascal — which equals one newton per square metre, in conformity with the discussion above. However, an optional unit which is more convenient to the pressures used in ACV technology is the water-gauge pressure, stated in cm of water. The equivalence is approximately 1 cm water = 100 pascals.

Units of Power

Since Work = Force × Distance Moved

∴ Work unit = 1 newton × 1 metre = 1 watt second = 1 joule

And since Power $= \dfrac{\text{Work}}{\text{Time}}$,

$$\therefore \text{the power unit} = \frac{\text{newton metres}}{\text{seconds}} = \text{watts.}$$

Or, more conveniently,

$$\frac{\text{newtons} \times \text{metres}}{\text{seconds} \times 1000} = \text{kilowatts}$$

[in conversion, 0.746 kw = 1 Horse Power, or 1 kw = 1.34 HP.]

14.0 ACKNOWLEDGEMENT

These data have been compiled, and in some cases generated, under the CASPAR program, operated by the National Research Council of Canada, and partially supported by grants from Transport Canada, (Transportation Development Centre and ACV Division, Canadian Coast Guard), and from the Defence Research Board. The writer also wishes to acknowledge the generous assistance in compiling this handbook given by Mr. R. Dyke, Dr. P.A. Sullivan, and Mr. R.G. Wade.

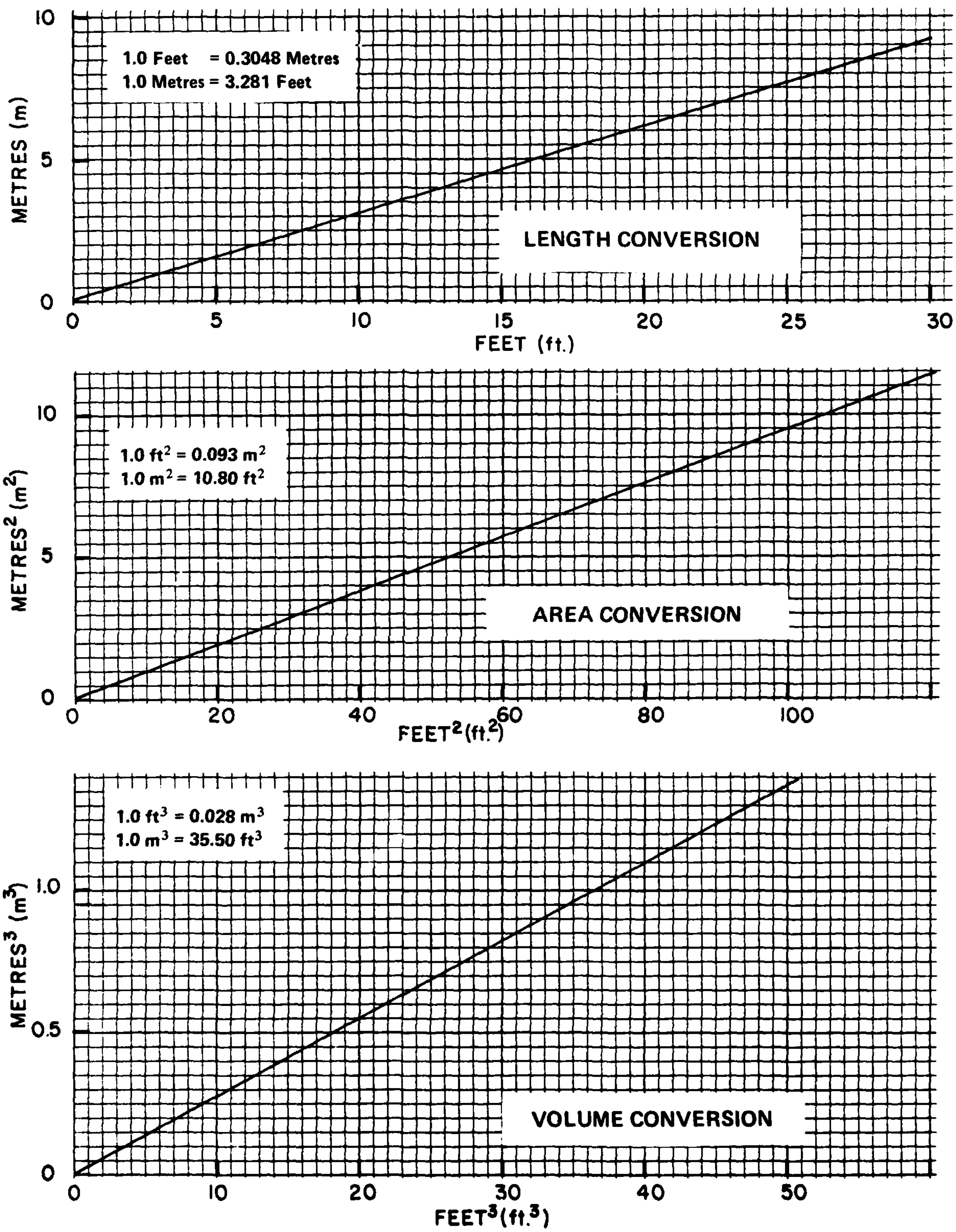
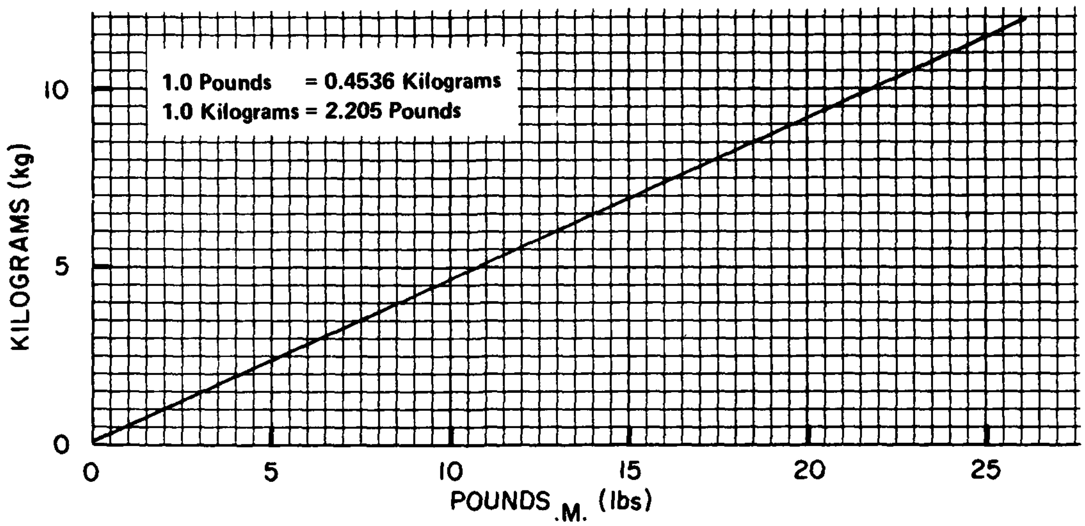


FIG. 25: LENGTH, AREA, AND VOLUME CONVERSION



Pounds (Mass) x g = Pounds (Force)
Kilograms x g = newtons
Standard value of g = 9.81 m/s^2
32.2 f/sec^2

FIG. 26: MASS CONVERSION

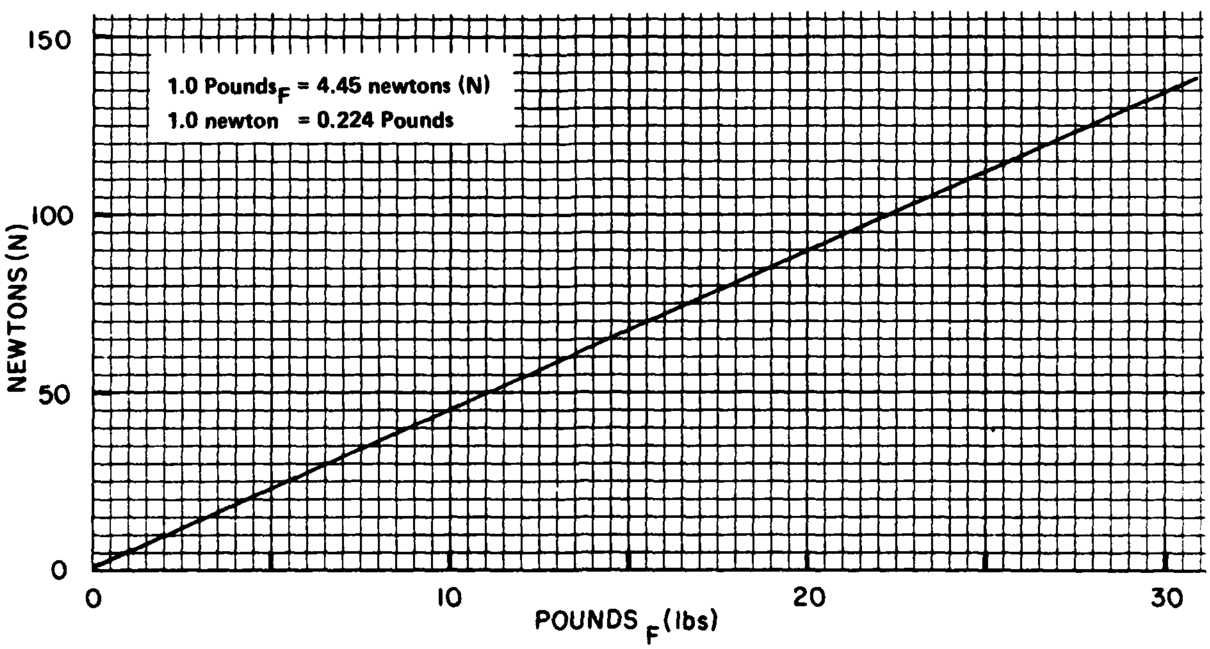


FIG. 27: FORCE (INCLUDING WEIGHT) CONVERSION

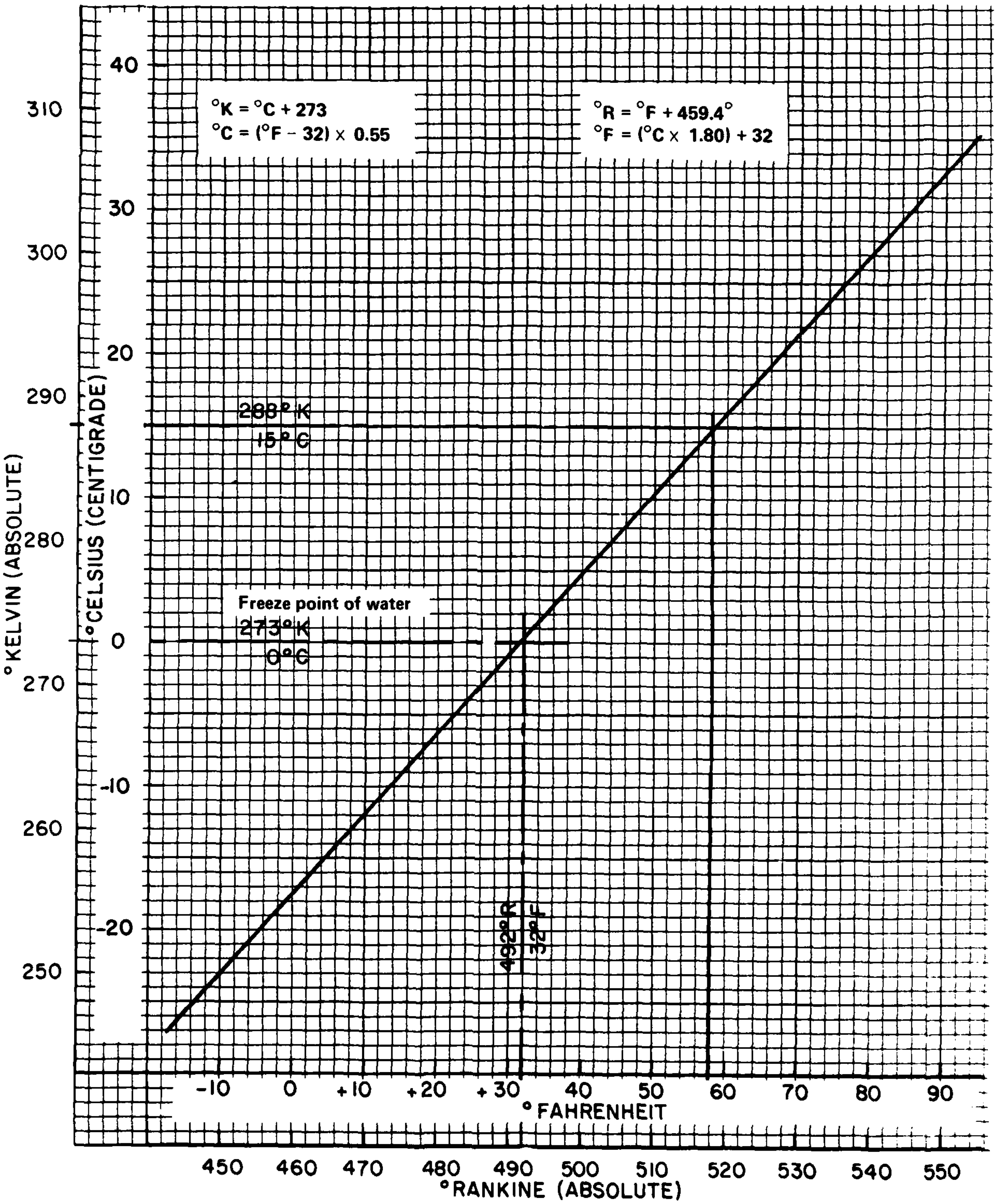
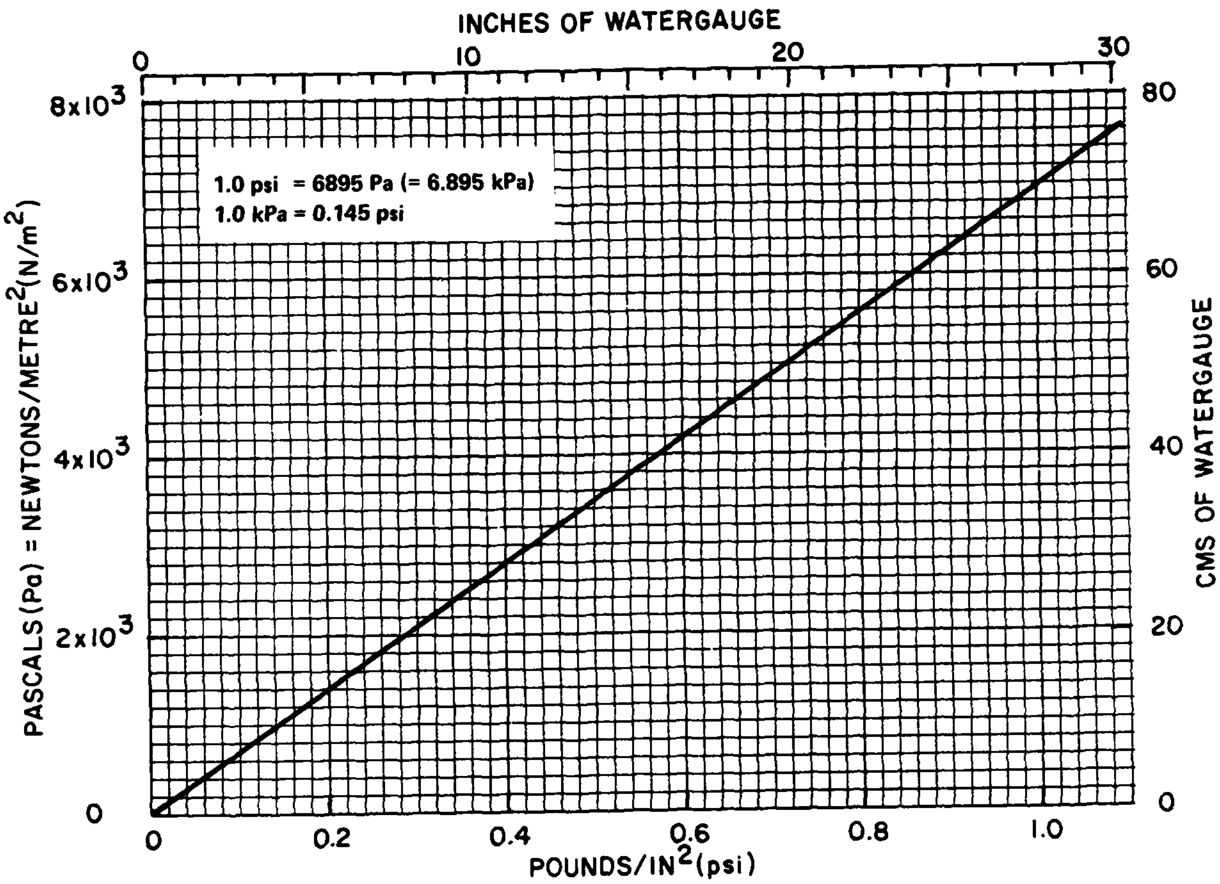


FIG. 28: TEMPERATURE CONVERSION



PSI × 6890 = Pascals
INS Water × 249 = Pa
CMS Water × 98 = Pa
INS Mercury × 3386 = Pa
mm Mercury × 133.3 = Pa
PSF × 47.88 = Pa
Millibars × 100 = Pa

Standard Atmosphere = 101.3×10^3 Pa = 1013.0 mb
= 760 mm Mercury
= 14.696 psi
= 29.92 inches Mercury = 406.9 inches water
= 1033.55 cms water.

FIG. 29: PRESSURE CONVERSION

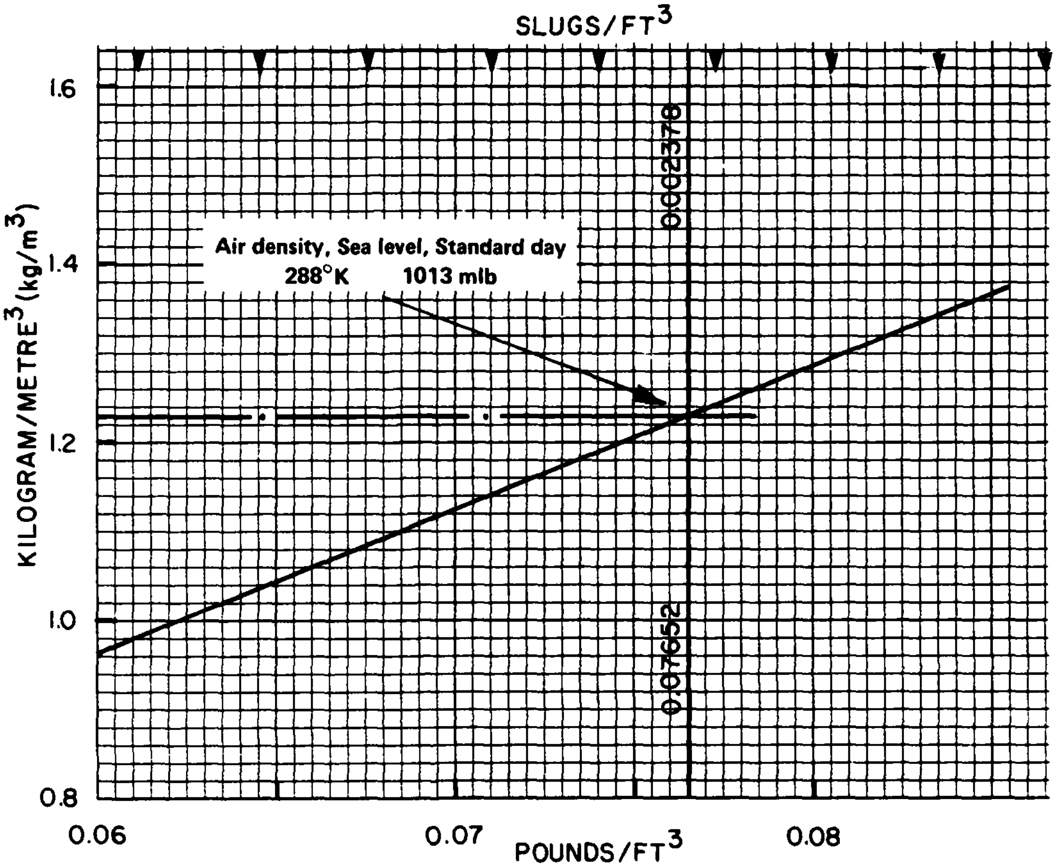


FIG. 30: AIR DENSITY VALUES AND CONVERSION

AIR DENSITY AT STANDARD SEA LEVEL ATMOSPHERE [288°K, 1013 mb]

$= 1.230\ \text{kg/m}^3 = 0.07652\ \text{lbs/ft}^3 = 0.00238\ \text{slugs/ft}^3$

AIR DENSITY AT OTHER TEMPERATURE AND PRESSURE t°K and P mb

$$= 1.230 \times \frac{288}{t} \times \frac{P}{1013}$$

$$= 0.350\ \frac{P}{t} \times\ \text{kg/m}^3.$$

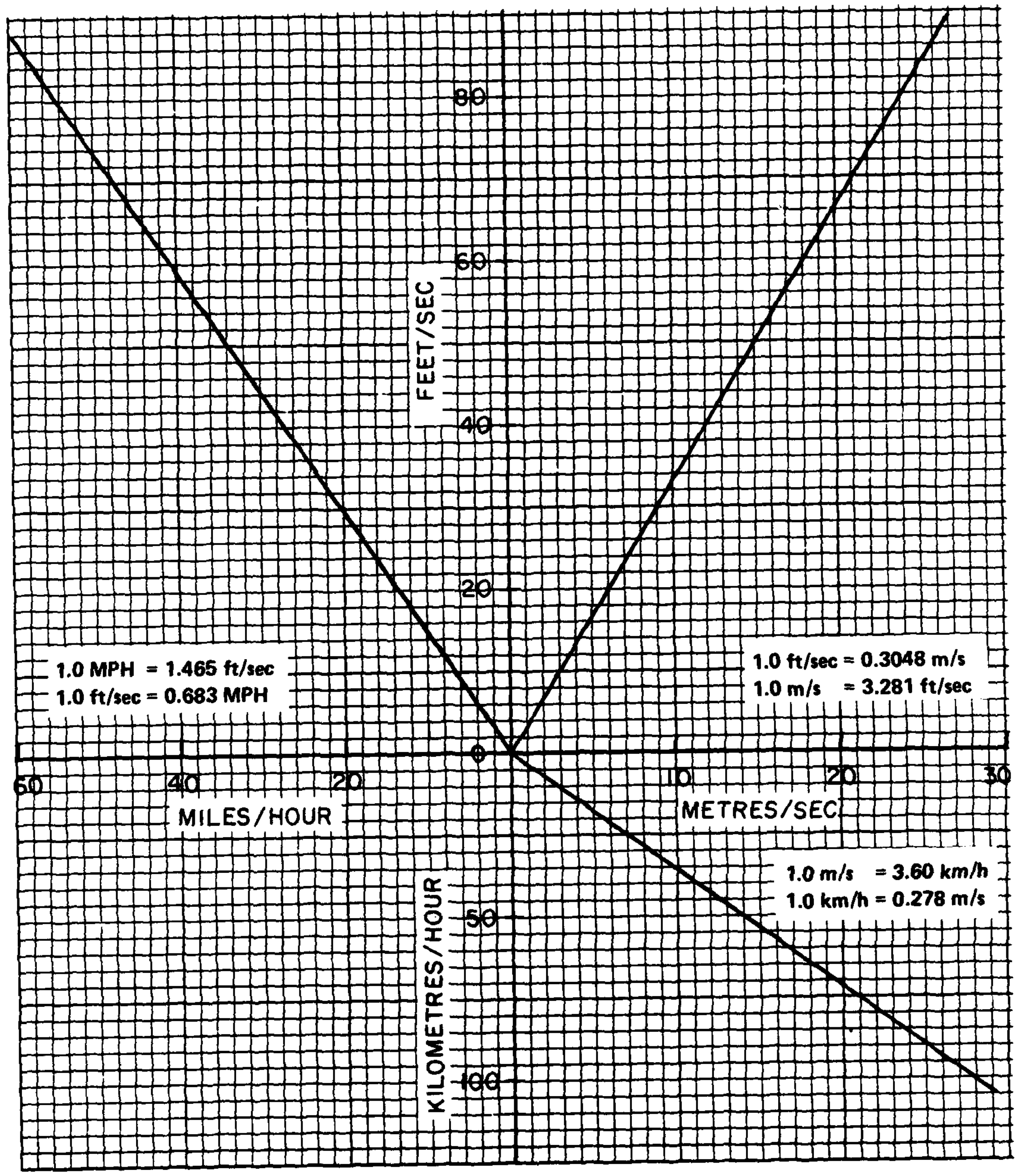
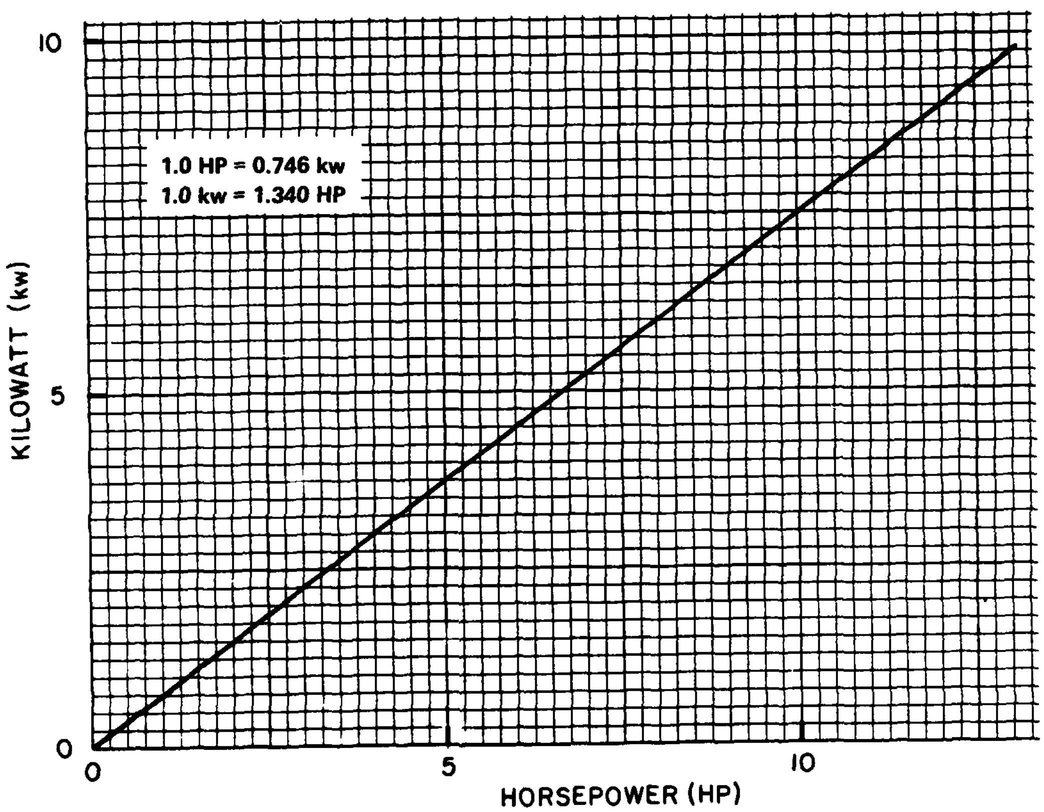


FIG. 31: SPEED CONVERSION



$$\frac{\text{newtons} \times \text{metres}}{1000 \times \text{seconds}} = \text{kilowatts.}$$

FIG. 32: POWER CONVERSION

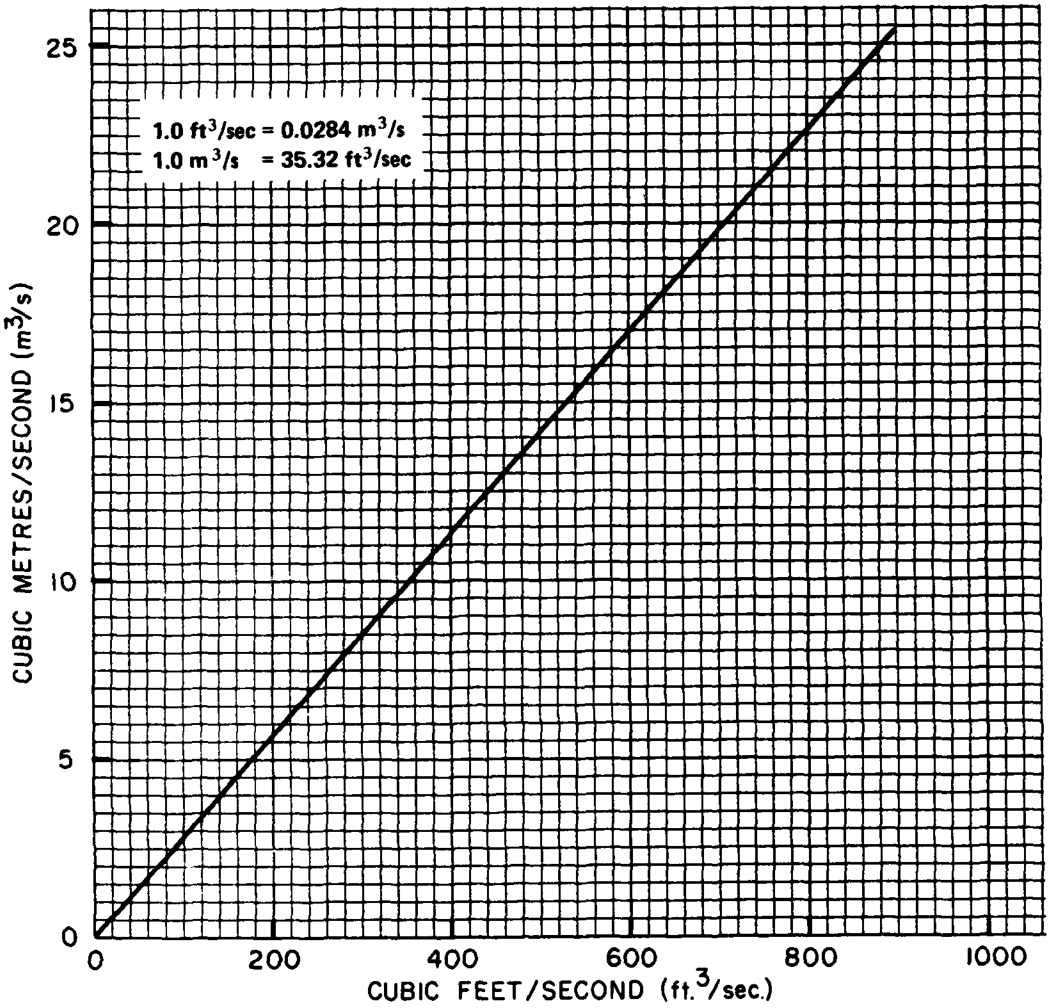


FIG. 33: FLOW CONVERSION AND DISCHARGE COEFFICIENTS

APPROXIMATE DISCHARGE COEFFICIENTS:

(a) SHARP EDGED ORIFICE $C_D = 0.61$

(ALSO BETWEEN BHC, HDL AND BERTIN TYPE SKIRT HEMS AND FLAT SMOOTH GROUND)

(b) BELL MOUTH $C_D = 0.98$

(INHALING FROM LARGE VOLUME OF STILL AIR)

(c) BAG SKIRT EFFLUX OVER SMOOTH FLAT GROUND (ESTIMATED). $C_D = 0.9$

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This handbook of data endeavours to collect and present in practical form such design data relating to performance as are currently publicly available.

The art is at present in an early stage of its development, and many of the data given are tentative or incomplete, and are hedged around by ill-defined boundary conditions.

We shall attempt to keep up with the ever-shifting frontiers of ignorance by issuing amendments to this handbook as exploration proceeds.

Finally one must remember that he who lives strictly by the rules, stagnates. Progress is attained only by knowing the rules, and then living dangerously beyond them.

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