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THE CONTROL AND GUIDANCE OF LIGHT AIR CUSHION VEHICLES

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THE CONTROL AND GUIDANCE OF LIGHT AIR-CUSHION VEHICLES

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SUMMARY

This study examines the control and guidance of light air-cushion vehicles, primarily below a weight of 5000 lb (2270 kg). The relatively small amount of data produced on the subject, since the operation of the first ACV, has been reviewed and presented in this study where appropriate. The nature of the control problem and the primary forces affecting directional control are discussed and illustrated, in particular, the turning and braking of ACVs. Very little measurement of control and handling behaviour of small ACVs has been carried out, so much of the data for this study has been drawn from tests on larger craft but is equally applicable in non-dimensional terms to smaller craft. A detailed review has been made of existing control methods applicable to light ACVs and data on these is presented.

Control standards were considered at some length but it was found difficult to advance this idea without first setting up "standard environmental conditions" for control assessment. A proposed set of such standard conditions is given in this study and tentative ideas are put forward for the type of control standards that might eventually be considered.

As a practical example of the development of a control system to meet the special needs of the ACV, a discussion is given on the Jones, Kirwan, Canive Industries range of craft in which specific attention has been given to control.

A number of new ideas for control devices and improvements are included in the report and recommendations are made for further work aimed at improving the controllability and safety of air-cushion vehicles.

CONTENTS

1.0 INTRODUCTION

This study was commissioned by the National Research Council of Canada and the contract awarded to German and Milne in association with Robert Trillo Limited. An additional contract was awarded to Jones, Kirwan and Associates on the merits and drawbacks of various systems tested in their research vehicles and this work has been incorporated as Section 13 of this report.

The subject of control and guidance of air-cushion vehicles (ACVs) is relatively unexplored in the literature which has been produced since 1959. With the small amphibious ACVs with which this study is concerned, (craft not exceeding 5000 lb (2270 kg) gross weight), very little technology has been applied to the design of their controls. This study has been undertaken with the object of reviewing data currently available from Canada, America and Europe; working towards the determination of control standards; identifying the forces required and means for generating these forces; outlining the ergonomics of the control situation and illustrating, where possible, the practical solutions to the particularly and uniquely difficult control problem of air-cushion vehicles.

The unique aspect of ACV control is that the craft must be steered in relation to surface routes and features but must seemingly derive its steering forces from the ambient airflow, whether these be powered-thrusting forces or free-stream derived aerodynamic forces.

Hence the ACV is extremely sensitive to wind speed and direction when trying to pursue a particular surface track. To obtain rather more positive steering forces, having some independence of prevailing wind conditions, suggests making contact with the surface over which the craft is operating. This is an area which has been rather neglected to date with only a very few instances of relatively crude systems having been tried. The nature of the control problem is discussed in this report, together with the basic aerodynamic characteristics of ACV-shaped bodies. Various control devices which have already been used on ACVs have then been reviewed and, where possible, data of control forces achievable has been presented. Turning and braking performance of current ACVs shows that considerable distances are required, particularly over ice, and illustrates well the need for improved control devices. It would be convenient if such devices could be designed against a set of control standards and this possibility has been looked at during the course of the work on which this study is based. It has become clear, however, that before actual control standards can be set up, environmental conditions must be defined. A proposed set of standard conditions for control assessment is put forward for consideration in this study, combining what appear to be primary surface conditions (e.g. horizontal or sloping land, shallow water, deep water, waves) with wind conditions and straight and turning craft motion. Assuming agreement can be reached on these standard conditions or something similar, then the behaviour of craft against such conditions may be examined and a picture built up of satisfactory and unsatisfactory areas of control. From that point on the requirements for controls can be sharpened and, hopefully, the safety of craft improved.

At the time of writing several basic control needs for ACVs have been recognised in general terms. The allocation of power for control, in one form or another, is essential. Control power must not deprive the thrust or cushion systems except when to do so is the deliberate intention. In braking conditions, directional control must be fully maintained. In downwind conditions when wind speed is equal to ground speed, directional control must be fully maintained. These requirements may seem to be obvious but they are difficult to achieve and have not been achieved on many ACVs, especially the smaller ones. The work by Canive Industries Ltd. in Canada on solutions to the control problem (in association with Jones, Kirwan) (Section 13), is of considerable interest because it highlights the difficulties in providing a control solution for the small ACV.

Suggestions for new control devices or developments of existing devices are given in this study and recommendations are made for further work aimed at improving the control and guidance of light ACVs.

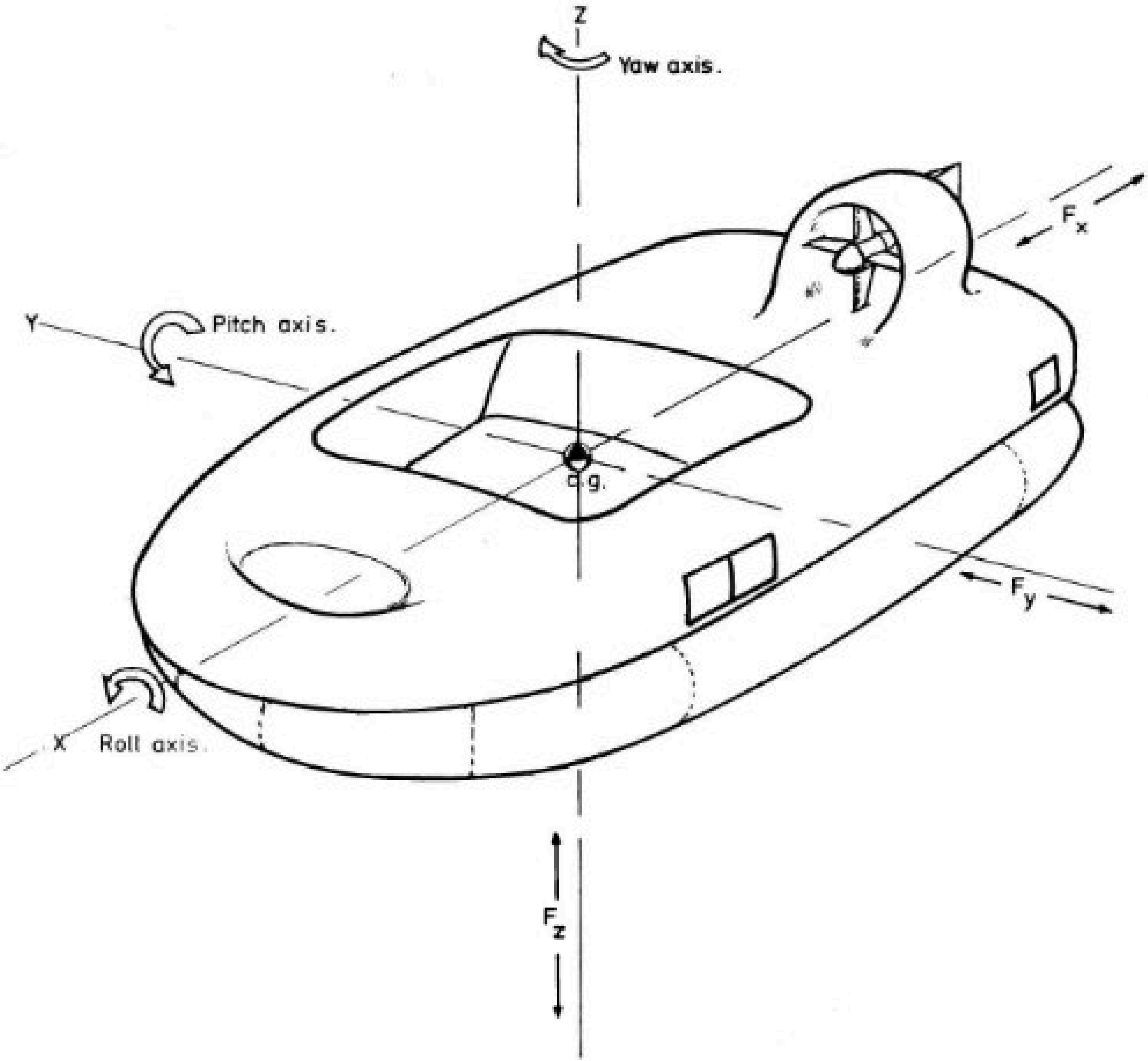
Where systems and devices have been described in this report, it should be noted that these may be subject to patent rights.

2.0 DEFINITION OF SYMBOLS

Symbol	Definition	Units
C_{D_A}	Aerodynamic drag coefficient	dimensionless
C_{D_H}	Hydrodynamic drag coefficient (based on frontal area)	dimensionless
C_L	Lift coefficient	dimensionless
$C_{L_{max}}$	Maximum lift coefficient	dimensionless
C_{N_A}	Aerodynamic yawing moment coefficient $= \frac{2N_A}{\rho_A . V_A^2 S_p . b}$	dimensionless
C_Y	Side force coefficient	dimensionless
C_{Y_A}	Aerodynamic side force coefficient $= \frac{2\ SF_A}{\rho_A\ V_A^2 S_p}$	dimensionless
C_{Y_H}	Hydrodynamic side force coefficient $= \frac{SF_H}{\frac{1}{2} . \rho_{WA}\ V_H^{\ 2} . S_p}$	dimensionless
D	Propeller diameter	ft, m
D_A	Aerodynamic drag	lb, kg
D_H	Hydrodynamic drag	lb, kg
J	Propeller advance ratio $= \frac{V}{nD}$	dimensionless
N_A	Aerodynamic yawing moment	lb.ft., kg.m.
N	Revolutions per minute	revs/min.
N_p	Propeller normal force	lb, kg.

Symbol	Definition	Units
R_A	Resultant of aerodynamic side force and drag	lb, kg
R_{AH}	Resultant of R_A and R_H	lb, kg
R_H	Resultant of hydrodynamic side force and drag	lb, kg
R_{NT}	Component of R_{AH} normal to track	lb, kg
R_T	Component of R_{AH} along track	lb, kg
S	Area	ft^2, m^2
SF	Side force	lb, kg
S_c	Cushion area	ft^2, m^2
S_f	Frontal area	ft^2, m^2
S_F	Fin area	ft^2, m^2
SF_A	Aerodynamic side force, normal to resultant flow velocity	lb, kg
SF_H	Hydrodynamic side force, normal to resultant flow velocity	lb, kg
T_c	Propeller thrust coefficient $= \frac{4T}{\Pi . D^2 q}$	dimensionless
$\bar{T_c}$	Propeller/duct thrust coefficient $= \frac{\text{Thrust at } \alpha = 0^\circ}{q.S}$	dimensionless
TM	Turning moment	lb.ft., kg.m.
V	Velocity	ft/s, m/s
V_A	Resultant of wind speed and vehicle ground speed, giving vehicle true aerodynamic velocity	ft/s, m/s

Symbol	Definition	Units
V_G	Vehicle speed relative to ground and along vehicle track	ft/s, m.p.h. knots, km/hr.
V_H	Resultant of water surface speed and vehicle ground speed (sea bed) along craft track, giving vehicle true hydrodynamic velocity	ft/s, m/s
V_s	Slipstream velocity	ft/s, m/s
V_{WA}	Water surface velocity, dependent upon wave and current velocities	ft/s, knots m/s
V_{WI}	Wind speed	ft/s, knots km/hr
V_{10}	Wind speed measured at 10 meters above surface	knots, km/hr
W	Weight	lb, kg
q	Dynamic pressure = $\frac{1}{2}\rho V^2$	lb/ft^2, kg/m^2
α	Angle of attack	degrees
$\beta_{0.75}$	Propeller blade angle at 0.75 radius	degrees
ρ_A	Density of air	$slugs/ft^3$
ρ_{WA}	Density of water (assume 1.99 $slugs/ft^3$)	$slugs/ft^3$
ψ_A	Angle between V_A and vehicle longitudinal axis (X) = aerodynamic yaw angle	degrees
ψ_H	Angle between V_H and vehicle longitudinal axis (X) = hydrodynamic yaw angle	degrees
ψ_T	Angle between vehicle longitudinal axis (X) and vehicle track	degrees



AIR CUSHION VEHICLE AXIS SYSTEM.

3.0 CHARACTERISTICS OF LIGHT AIR-CUSHION VEHICLES

The trends of the characteristics of a representative selection of existing light air-cushion vehicles in the weight range up to 5000 lb (2270 kg) are given in this Section by a series of charts, Figs. 1 to 9. For the purpose of this study, light ACVs are interpreted as those not exceeding 5000 lb (2270 kg) in gross weight, as opposed to 3000 lb (1365 kg) which the Department of Transport use for definition purposes. Descriptive information on light ACVs and their applications is given in Ref. 1 "Air-Cushion Vehicles - their potential for Canada", NRCC 10820, December 1969. The characteristics given in Figs. 1 to 9 are overall length and height, total installed power, installed lift power, installed thrust power, cushion pressure, cushion density (p_c/l_c) and the ratio of thrust b.h.p. to gross weight plotted against Froude Number.

The above Figures help to define the properties of the existing ACV types in the weight range being considered but the trends should not be considered as being very firmly established since the technology of small ACVs is still in an extremely unrefined state. Even some of the larger craft in the range do not reflect much input of currently available technology in the ACV field.

Other factors having a bearing on some of the characteristics considered include the environment in which the craft is designed to operate. High altitude operations (three small ACVs recently operated successfully in the Himalayan rivers at heights around 6000 ft (1800 m) with small reciprocating engines can incur power losses of around 4% per 1000 ft (303 m) and hence rather higher installed powers are called for than for sea-level operating craft. If craft are to operate only over land, then higher cushion pressures may be used since the induced wave drag thrust requirement no longer exists. On the other hand, operation in loose snow sets up a "wave" of snow in front of the craft which must be overcome in a similar way to induced waves when operating over water. The cushion does not blow away the snow. There is evidence also from SRN5 tests over land and over water (Ref. 2) that a one-third higher propeller power requirement is necessary over wet sand (rippled surface) than over water with 3 inch (7.6 cm) waves. Hence, it is apparent that very large differences may exist in powering and cushion characteristics depending upon the application of the craft. Similarly, large differences in control requirements and solutions are likely even when the technology is more advanced, especially when substantial differences in craft size are involved.

The craft referred to in Figs. 1 to 9 are identified by numbers in the following list, Table 1, on the next page.

TABLE 1

LIST OF CRAFT COVERED IN FIGURES NOS. 1 TO 9

(Details extracted from Ref. 3 or from manufacturers)

1. Hovermarine Hovercat Mk.2
2. Bruzzone Job 2.
3. Hovergem G-2E
4. Taylorcraft Transport Pty. Ltd. Skimaire 1
5. Canive Industries Ltd. BV 104
6. Flylo Corp. Ltd. Caliban
7. H.I.L. Industries Ltd. Hovertrek
8. Horn Bonny 1
9. Hoverjet HJ-100
10. Komar Engineering Ltd. Aquaterra
11. Modern Hover Vehicles Ltd. Spectra I
12. Modern Hover Vehicles Ltd. Spectra II
13. Gooch J-4
14. Club Francais de Aeroglisseurs Motoglisseur DSB II
15. Sedam Naviplane N 102 C
16. Israel American Motor Corporation Ltd. N-2 Lady Bird 2
17. ACVS Italiana Idria
18. Hovercraft Italiana SRL BT 3 Titan
19. Nihon University Pastoral 1 (2-seat)
20. N.V. Luchtkussenvoertuigenfabriek Industrieterrain B2 (5-seat)

21. Hover Vehicles (N-Z) Ltd. H.V.4.

22. Air Vehicles Ltd. AV2 (5-6 seat)

23. Ajax Hovercraft Ltd. AH2 (4-6 seat)

24. Daily Express. Air Rider

25. Light Hovercraft Co. Cyclone 274 (2-seat)

26. Pindair Ltd. Skima

27. Sealand Hovercraft Ltd. SH-2

28. Air Cushion Vehicles, Inc. Air Cycle

29. Air Kinetics Inc. Smuggler

30. Bertelsen Mfg. Co. Inc. Aeromobile 13

31. Curtis Dyna-Products Division. Hoverpacer Mk.I

32. Dobson Products Co. Air Car Model F

33. Eglen Hovercraft Inc. Hoverbug

34. Gluhareff Helicopters Inc. MEG-1H Yellow Jacket

35. Fishlock/Howe. Mistral

36. Cushioncraft Ltd. CC7

37. Hovermarine Canada Ltd. Sandpiper

4.0 INTRODUCTION TO THE CONTROL PROBLEM

The control of ACVs is often referred to as a problem because of the unique combination of the six degrees of freedom possessed by the concept and the infinite number of environmental conditions encountered in the air-to-operating surface interface. A lunar module has six degrees of freedom too but does not have imposed on it the irregular, sometimes unpredictable and infinitely variable effects of wind, surface roughness (whether fluid waves, ice formations, tarmac or tundra) that an ACV does. The extreme operating surface capability of the ACV is thus obtained at the expense of an unusual and difficult control problem.

The basic requirement of any transport vehicle is the carriage of a payload at an appropriate speed. Hence, the payload must be lifted and partially or wholly contained and then coupled to a device to propel it. The basic lift method of an ACV payload is the air-cushion, and the hull containing the payload is normally placed on top of the cushion. A platform-shaped craft usually results, but in the smaller craft sizes with which this study is concerned, the shape can be highly irregular for the reasons previously discussed. This aspect adds further difficulty since as a result the variation of forces and moments in the plane of directional control, the yaw plane, can become highly irregular due to flow separations and flow reattachments. Reference to the photographs, Figs. 10 to 15, of various light ACVs will quickly show the great variation between craft forms. In general then, the hull of a small

ACV will be considered in this report to be an irregular-shaped object and roughly oval in planform. As discussed in the next Section, the basic hull form will be assumed to be directionally unstable.

The above discussion has assumed that the ACV is free of contact with the surface over which it is operating. One of the main difficulties in controlling an ACV is unwanted sideways movement, often referred to as sway, drift or sideslip. This movement can be restricted or eliminated by surface contact, or, in the case of over-water operations, surface penetration. With the latter method, a retractable device is obviously required if amphibious capability is to be maintained. By such means, the quality of control can be considerably improved. Such a device can assist in yaw and sideslip control.

With large ACVs, swivelling propellers, pylon-mounted, can be used to obtain a high degree of control through providing direct thrust sideforce but are difficult to employ on small ACVs because of mechanical complexity although small-diameter swivelling ducted propellers could prove practicable for some craft. In general then, for small ACVs the craft will be yawed to execute turns and to resist beam wind components by using an opposing thrust vector. The velocity, forces and moments acting are illustrated for definition purposes in Figs. 16 and 17. Two main sources of disturbing forces are shown in these figures, natural wind forces and natural water forces as may arise from currents or waves, assuming here some degree of surface contact.

To maintain a particular track the ACV must be able to provide controlling forces and moments as well as thrust to achieve an equilibrium state against the forces and moments imposed on it by its environment and by its own motion. The make-up of the principal quantities is as follows:

Aerodynamic forces:

Hull profile drag (including inflated skirt)

Cushion airflow momentum drag

Hull side force (including inflated skirt)

Hull upper surface aerodynamic lift

Aerodynamic moments:

Hull pitching moment

Hull yawing moment

Hull rolling moment

Yawing moment due to fan intake momentum drag

Hydrodynamic forces (sea state effects included)

Induced wave drag

Water contact drag including skirt drag

Spray drag

Skirt/cushion sideforce

Hydrodynamic moments (sea state effects included)

Induced wave drag pitching moment

Skirt contact pitching moment

Skirt contact yawing moment

Rolling moment due to hydrodynamic drag when side-slipping

Terrain forces:

Sloping surface, component of weight acting parallel to surface (thrust, drag or sideforce)

Frictional resistance resulting from skirt contact

Stiction of skirt when moving off from hover

Terrain moments:

Rolling moment on sloping surface

Pitching moment on sloping surface

Rolling moment due to skirt contact when side-slipping

Skirt contact pitching moment

Skirt contact yawing moment.

The well-designed ACV should be able to contend with all the above forces and moments, within the limits of its design operating environment.

Numerous control devices and methods have been used and it seems probable that many further developments will take place in this field before a narrowing down occurs on really effective practical systems. Most methods to date fall under the following headings:

Group 1. Aerodynamic free stream control surfaces

" 2. Propulsive system including control surfaces in airstream

" 3. Cushion air manipulation

" 4. Surface contacting or penetrating devices

" 5. Separately powered air jets

" 6. Centre of gravity shift

" 7. Centre of pressure shift

Systems under headings 1 to 5 are capable of control in yaw, roll and pitch, lift, drag and sideforce, while 6 and 7 can be used to achieve results through pitch and roll. Particular examples will be shown in the next Section. Group 1 devices were used on some early craft such as the Cushioncraft CC2-001 and the MARAD test vehicle Columbia, but in combination with other controls. The hull of an ACV acts as a free stream control surface when yawed to produce centripedal force in a turn. A fixed fin at the stern of the vehicle can provide directional stability. In both circumstances the ability of the surface to provide a controlling force and moment is totally dependent upon a relative air velocity existing past the surface. This condition disappears when an ACV is travelling downwind at a ground speed equal to wind speed. Fig. 18 illustrates this situation and perhaps helps to bring out the unusual nature of the ACV control problem. A point to note with special reference to small ACVs below 5000 lb (2270 kg) gross weight is that their design cruising speeds are appreciably closer to typical average wind speeds and, as a result, they will in operation tend to spend rather more time in tailwind situations than will higher-speed larger craft. This condition is, however, somewhat offset by the fact that the wind speed existing at the typical centre of pressure height of small ACVs is only some 35% to 75% of the typically measured wind values at a height of 10 metres. See Figs. 3 and 54.

From the conditions illustrated in Fig. 18 it is clear that the effectiveness of free stream control surfaces can be reduced to zero and therefore even partial dependence upon such surfaces for control could prove disastrous in some situations. For instance, a craft turning downwind at a ground speed of 20 knots (36 km/hr) would find all free stream dependent control forces and moments disappearing, if the wind was also 20 knots (36 km/hr), as it became aligned with the wind direction. If reliance was usually placed on these controls being available, their absence could prove dangerous if sudden avoiding action was required.

By shifting the centre of gravity of the craft or centre of pressure, roll and pitch changes can be secured leading to skirt-to-surface contacting to produce yaw, sideforce, or improve directional control by means of drag and cushion air forces. In either instance power will be absorbed and speed will decrease. One way or another power will be absorbed in providing control. This fact is not always recognised. The allocation of power for control will be discussed in Section 6 against various methods covered by the headings previously listed.

Before coming to descriptions and results of particular control devices, it is worth noting some of the findings from ACV experience since 1959. Standing out more than anything is the need for higher controlling forces and moments. In particular, the provision of sideforce approaching the level of the thrust force would greatly improve the manoeuverability of ACVs. Low control forces tend to lead to overlong application causing overswing and zig-zag behaviour. Many control devices used cause secondary effects and cross-coupling effects.

Controls should not, upon operation, induce unwanted craft attitude changes or force and/or moment increments which have to be cancelled by another system. For example, high-mounted rudders can produce a rolling-out moment in a turn, leading to skirt contact drag forces opposing the turn. Puff ports fed from the cushion air supply can cause a drop in cushion depth, thereby impairing over-wave capabilities and possibly leading to the risk of ploughing in. Rolling in a turn to produce side force and/or asymmetric surface contact drag unavoidably uses up clearance height and may not be acceptable in rough terrain areas. If a high degree of directional stability is provided by means of a stern-mounted fin, not only will the weathercocking tendency in a tailwind situation prove difficult to handle but also response times in turning will be greater, offsetting to some extent the greater side area and force provided, except of course when turning into wind. Some form of variable-effectiveness fin seems to be required, either retractable or perhaps employing boundary layer control. For craft in the 3000 lb to 5000 lb (1350 kg to 2270 kg) weight range, such devices would not seem impracticable.

High yaw angles, if used to obtain high side forces, may be in the range of irregular yawing moment and sideforce variations with

with yaw angle and this would cause difficulty in control. Such variations are most likely with the very small ACVs where little streamlining is possible.

Speeds over smooth land surfaces tend to be considerably higher than over water and this is especially true over smooth ice. With most of the controls available on craft built to date the general experience has been that control and handling is more difficult over land than over water. Basically this finding is simply a reflection of the lack of surface contacting devices in overland use, while over water waves are nearly always present and there is little reluctance on the part of ACV drivers to allow the skirt to touch water in order to generate useful forces for control, the wear rate being less severe than when abraded over land.

In many of the past ACV designs it is clear that little consideration has been given to directional control, a good percentage of craft possessing only a rudder. Power has to be expended in providing control forces and moments, whether these are generated by a powered thrust system, such as a swivelling ducted propeller, or simply by aerofoil surfaces moving with the craft through the air. The use of puff ports, drawing upon cushion air is not an entirely satisfactory arrangement because for many craft a restriction is placed on their use at high speed because they deprive the cushion of some of its airflow. The cushion is the fundamental form of support for the ACV and unless alternative forms of lift are provided (on very large craft aerodynamic lift could be appreciable at high speed), it does not seem to be good practice to take air from the cushion unless a surplus is provided for in the initial design of the craft.

Summing up, the present control situation applied to small ACVs suggests that two main themes should be explored, firstly, that adequate power must be installed for control and, secondly, that surface contacting devices should be developed.

The provision of adequate directional control is an essential feature of any practical ACV. An extreme directional control could be considered as an instantaneous application of yaw, turning the craft until full thrust is vectored sideways. This would enable a maximum rate of turn to be initiated but is of course impracticable from the point of view of the accelerations involved. Some craft indeed may be quite satisfactory with only moderate control forces and slow responses, depending upon the use to which they are to be put. A craft operating in congested areas, however, or many light craft operating together, require fairly precise and responsive controls for safety. Opinions differ widely on the handling and controllability of various light hovercraft and this is not really surprising because the response of people to movement and accelerations, noise and outside stimuli also varies widely.

Because the ACV has extreme flexibility as far as the surfaces over which it may operate are concerned, it does not follow that controls should be capable of handling all situations regardless of speed, wind, waves, etc. In particular, ACVs should not be required to accomplish tight U-turns at high speed any more than cars do. It is obviously desirable to provide maximum manoeuvering and control capability at any speed but very often reduction of speed can enable manoeuvres to be carried out which would otherwise be dangerous or impossible at higher speeds.

With a number of ACVs in the range up to SRN6 size, there is a distinct feeling of lack of control below hump when moving forward at steady speed. In these conditions the thrust level is low and slip-stream-dependent control systems will not be generating their maximum forces. It is felt by some experienced operators that strong sideforce systems could be usefully employed in this speed regime.

Although fundamental to the performance of the ACV, the thrust/weight ratio is also important in relation to the control and handling of the craft, especially in difficult situations, for instance, where there is a large amount of ground friction.

The problem of braking ACVs effectively over ice is still outstanding and points to solutions using ground contact rather than aerodynamic means.

Another unique aspect of ACV control is that the response of the craft to control movements by the pilot depends upon the 180° range of craft headings which are possible in relation to the relative air velocity vector and, similarly, with the ground or surface velocity vector. For example, full application of rudder when the craft is proceeding forwards relative to the surrounding airstream will produce an entirely different result from that obtained when the craft is travelling sideways.

The number of combinations of craft motion, control and environmental conditions which may be encountered by an ACV is infinite. To establish the degree of manoeuverability possessed by a craft, however, certain basic manoeuvres may be carried out and the differences between craft and craft control devices noted. Fig. 19 from Ref. 4 is a good example of what can be done on these lines, showing the track of a 3200 lb (1455 kg) ACV when attempting to go round a square course.

Finally, in this introduction to the control problem it is instructive to read an extract of a paper by Crewe and Eggington (Ref. 5) describing the control problem and its solution on the world's first air-cushion vehicle, the Saunders Roe SRN1:

> "The choice of control systems was dictated by a desire to provide means which were reasonably simple, would not prejudice the demonstration of the cushion principle in its basic form, and would not involve hydrodynamic appendages since, although the latter could be efficient over water, they could not be used over land. However, the craft has considerable side and frontal area, and travels operationally at speeds ranging down to very low values at which straight-forward aerodynamic control surfaces, operating in the free

"air stream past the craft, will provide very little moment unless their area is quite excessive. Furthermore, one of the main purposes for which the SRN1 was constructed was to make experiments on control and stability since, like nearly all new craft, the 'feel' of piloting needs to be experienced at first hand before the requirements of the control system are fully appreciated.

"In these circumstances a combination of control devices was used. These comprise gate valves in the propulsion ducts, fore and aft rudders placed just ahead of and just behind the fore and aft ends respectively of the propulsion ducts, and 'lift' valves located in segments of the main cushion lift air ducts.

"The gate valves split the propulsion air in any desired ratio and direct it fore and aft enabling the craft to hover without forward motion, or move backwards or forwards. The propulsion jet system provided on the SRN1 does not give asymmetric thrust for directional control or lateral thrust to check sideslip, but the small rudders deflect the propulsion air and give some directional control whenever the craft is airborne, whatever its forward speed may be. The aft rudders are extended above the ducts into the free air stream, by tall high-efficiency, high-aspect-ratio aerodynamic surfaces, which provide directional control at speed.

"The 'lift' valves allow limited application of pitch and heel by dropping the sector of the craft on which the airflow is reduced and raising the remainder slightly. This allows the pilot to augment the thrust or braking power available from the propulsion ducts, or to move the craft sideways, since any tilt of the platform results in a thrust component in the direction of tilt down, due to the effective total cushion pressure, which acts perpendicular to the base, being deflected from the vertical in the same direction, by an angle equal to the tilt.

"It will have been apparent to many who have seen the SRN1 demonstrated that both asymmetric thrust and side thrust are necessary for completely easy control of a hovercraft, and further work is continuing to achieve this with a minimum requirement for additional power.

"The control devices of the SRN1 are operated by two levers and a rudder bar, located in the control cabin, and linked to the propulsion duct gate valves, the 'lift' valves and the rudders respectively."

5.0 AERODYNAMIC FORCE AND MOMENT CHARACTERISTICS OF THE ACV HULL

As previously discussed, the hull shapes of craft below 5000 lb (2270 kg) gross weight will tend to be rather more irregular in shape than those of very much larger ACVs. Most test data, however, has been obtained for larger craft and although in most instances the trends of the non-dimensional coefficients may be safely carried over in considerations of smaller craft, care should be taken in cases where large departures of shape are involved.

Although, as will be shown later, the hull aerodynamic forces and moments may often be assisting in the control of the craft, it has been considered convenient for the purposes of this study to look at them separately from the specific control devices which will be appraised. In this Section, therefore, the hull and its aerodynamic characteristics will be looked upon as the "body" which has to be controlled. It is generally agreed that control of ACVs is easier over water because more sources of controlling forces are available.

This study is fundamentally concerned with directional control, and three aerodynamic characteristics are of major concern:

1. Drag coefficient variation with yaw angle
2. Sideforce coefficient variation with yaw angle
3. Yawing moment coefficient variation with yaw angle

Drag coefficient

$$C_{D_A} = \frac{2D_A}{\rho_A \cdot V_A^2 \cdot S_f}$$ (S_c or S_p is used in some work instead of S_f)

In both examples from Refs. 6 and 7 shown in Fig. 20, drag coefficient begins to increase rapidly for yaw angles above 10° to 15°. When yaw as high as 40° is employed in a turn, drag along the track of the craft would, at unchanged speed, be approximately trebled for semi-rectangular planforms. In practice, speed falls off while turning due to increases in a number of drag components, as well as a reduction of thrust due to yaw. It seems probable that with small craft the level of C_{D_A} at zero yaw would be higher than for the examples shown, and for single-seat open cockpit ACVs a C_{D_A} at zero yaw of around 1.0 is quite possible. Towed craft drag measurements in a number of Jones Kirwan ACVs have given C_{D_A} values of around 0.7. Circular-shaped craft do not show any significant variation of C_{D_A} with yaw angle if the fan intake is amidships.

Sideforce coefficient

$$C_{Y_A} = \frac{2\ SF_A}{\rho_A \cdot V_A^2 \cdot S_p}$$

Three examples of the variation of sideforce coefficient with yaw angle are shown in Fig. 21. The characteristic variation is of approximately sinuisodal form. For yaw angles in the 20° to 40° range useful sideforces are generated by these particular body shapes which can assist in turning. On the other hand, in beam wind conditions with a relative airflow approaching the craft at, say, 45° of yaw, there is a large sideforce generated, a component of which, normal to the craft longitudinal axis, must be opposed to maintain track.

Yawing moment coefficient

$$C_{N_A} = \frac{2N_A}{\rho_A . V_A^2 . S_p . b}$$

Examples from Refs. 7 and 8 in Fig. 22 show the general characteristic variation of yawing moment with yaw angle and in conjunction with Fig. 21 the variation reflects the movement of the sideforce centre of pressure along the axis of the hull. The characteristics show a hull having directional instability, i.e. as the craft is deflected away from a heading aligned with the oncoming airstream, the moment acting on the hull arising from the pressure distribution around it, will act to increase the yaw.

Pitch and roll characteristics of the hull on cushion

Pitch and roll are expressed either as pitching and rolling moments versus pitch and roll angle respectively or as percentage centre of pressure shifts per degree of relevant angle. For an ACV to be controllable it must be statically and dynamically stable on its supporting means, the cushion. Angular movements in pitch and roll are required in order to optimise the craft attitude in various operating conditions and therefore stability must exist over the useable angular range. Different skirt systems are capable of producing different ranges of cushion stiffness (static stability) and hull centre of gravity height will also affect the final value. This study will not examine the effects of cushion stiffness on control and guidance since, assuming inherent cushion stability, the degree of stiffness provided will primarily affect the dynamic response of the system in roll and pitch rather than the directional control capability.

Typical characteristics for a segmented skirt system are shown in Fig. 23 extracted from Ref. 8.

6.0 CONTROL DEVICES AND METHODS

This Section describes and discusses a number of existing control devices and methods which can be applied to craft up to 5000 lb (2270 kg) in weight. Braking devices are mainly discussed in Section 8. The following list is considered in this Section and principally in relation to directional control:

1. Free-stream aerofoil surfaces
    - 1.1 Fixed fin
    - 1.2 All-movable surfaces (rotatable)
    - 1.3 Fixed fin plus rudder
2. Aerofoil surfaces (rudder) in free-air propeller slipstream
3. Aerofoil surfaces (rudder) in ducted propeller slipstream
4. Aerofoil surfaces (rudder) in centrifugal or axial fan discharge
5. Rudder ducts
6. Puff ports
7. Skirt manipulation
    - 7.1 Skirt lift
    - 7.2 Skirt shift (cushion centre-of-pressure shift)
8. Ballast and centre of gravity shift
    - 8.1 Tank systems
    - 8.2 Body movement
9. Gimbal-mounted fans
10. Hydrodynamic surface-piercing surfaces

11. Hydrodynamic sideforce

12. Wheels

13. Elevators

14. Differential thrust

    14.1 Side-by-side propellers

    14.2 Low-speed air jets

6.1 Free-stream aerofoil surfaces

Free-stream aerofoil surfaces can only provide controlling forces if there is a relative air flow existing. If, for example, an ACV is on stationary hover and a natural wind is blowing, then forces will be generated. Or in still air conditions, forces will arise on the control surfaces as soon as the craft begins to move. Satisfactory control can be obtained from fin/rudder installations on small ACVs for which craft inertias are relatively low and hence low controlling forces can provide a reasonable response. The Dobson series of craft use a conventional fin and rudder but in combination with cushion control vents which can provide yawing control at zero relative airspeed.

6.1.1 Fixed fin

Fig. 24a shows the three definitive types (A1, A2 and A3) of free stream controls currently used. The plain fixed fin (A1) is really a directional stability device and is normally used to give a basically unstable hull form sufficient directional stability for the driver not to tire under normal straight path cruising conditions. British Hovercraft Corporation attempt to make all their craft directionally stable up to about 20° of yaw (Ref. 9). Excessive directional stability can cause difficulty in craft handling at low ground speeds (V_G) but high wind speeds (V_{WI}). In practice it has been found difficult to estimate the fin size requirement with any accuracy and changes have been made on a number of craft following trials experience. The Westland SRN2 required a rather larger fin than originally provided and the BHC SRN5/6 required a reduction in fin size. The Hovercraft Development Ltd. HD2 (2 swivelling pylons) had no fin but now two low-aspect-ratio fins are fitted, clear of the propeller slipstreams. Although the maximum lift coefficient of a low-aspect-ratio surface will be less than for high-aspect-ratios, stalling occurs at much higher angles of attack and sudden drops in C_L are not encountered as on high-aspect-ratio. For instance, C_{Lmax} values of around 1.0 are achievable at stall angles around 25° to 30°.

6.1.2 <u>All-movable control surface (rotatable fin)</u>

System A2 in Fig. 24a was used in a forward twin-fin arrangement on the Vickers VA-3 ACV. Provided other controls are available, not dependent upon relative free-stream air flow there could be a case for using this kind of control if weight, simplicity or cheapness considerations were of prime importance. However, the basic directional stability of the craft becomes a variable if no other fin is provided. This feature could of course be useful in low-ground-speed, high-tail-wind situations. Perhaps this type of control should be examined as an adjustable incidence fin, more suitable for craft in the 2500 lb to 5000 lb (1135 kg to 2270 kg) range than for very small ones.

6.1.3 Fixed fin, movable rudder

For small craft using cushion air propulsion of some form, this system (A3) appears to be satisfactory in being able to give reasonable control if used in conjunction with another system not dependent upon forward speed.

As directional controls, systems A2 and A3 would always be more powerful when working in a powered airstream such as a propeller slipstream or the flow from a centrifugal fan. The following paragraphs discuss these powered systems.

6.2 Aerofoil surfaces in free-air propeller slipstream

As a directional stability and control device the use of a rear-mounted fin and rudder surface, positioned in the slipstream of a propeller has been proved to be practical and effective for a number of ACVs. The precise arrangement has taken many forms on such craft as the B.H.C. range of SRN5 and SRN6, the SRN4, the Bell Voyageur, the Bell Carabao, the Bertin BC-8, the Hovermarine Transport Hovercat, the Mitsui MV-PP5 and MV-PP15, and numerous light sports ACVs.

By using a control surface in the slipstream, two advantages arise, one of which is particularly valuable when applied to the omni-directional nature of the aerodynamics of the ACV in the horizontal plane. Firstly, the slipstream will greatly enhance the effective lift coefficient properties of an aerofoil surface placed within a zone extending from 0.5 to about 3.0 diameters downstream of the propeller plane. Up to the normal stalling angle of the surface, the C_L versus α slope will increase with increasing propeller thrust coefficient. In addition, the stall will be delayed and at high thrust coefficients, angles of attack of around 40° to 60° will be reached before the C_L/α slope becomes negative. Even then, very large C_L values (3.0 to 8.0) are still being generated. Fig. 25 illustrates NACA test results (Ref. 12) for a semi-span wing/propeller model test which could perhaps be considered for an ACV fin application. The results shown are for zero rudder deflection. The second advantage is the wide range of flow angles (γ_A) which may be accepted by the fin/propeller combination without incurring sudden stall characteristics ($\gamma_A = \alpha$ in Fig. 25).

It can be seen, therefore, that the side force generated by the high C_L values possible can produce strong directional stability. The following example illustrates the difference in forces due to propeller slip stream for a typical installation at zero rudder deflection:

Assume T = 500 lb (225 kg)

Propeller diameter = 5.0 ft (1.52 m)

Relative free-stream air velocity = 35 knots (65 km/hr)

= 59.1 ft/sec (18 m/sec)

$q = 4.0\ \text{lb/ft}^2 = 17.0\ \text{kg/m}^2$

Aerodynamic yaw angle, $\psi_A = 15^\circ$

$$\text{Then, } T_c = \frac{T}{\frac{\pi}{4} D^2 \times q} = \frac{500}{\frac{\pi}{4} \times 5.0^2 \times 0.5 \times 0.002378 \times 59.1^2}$$

$$= \underline{6.15}$$

Interpolating on Fig. 25, at $\psi_A = 15^\circ$, $C_L = 2.6$

while without slipstream effects, $C_L = 0.975$

The corresponding forces generated are:

$q\ SC_L$ = 166 lb (75.5 kg) with slipstream and 62.3 lb (28 kg) without slipstream.

The effect of the slipstream on an aerofoil surface can be seen to be appreciable and at very large angles of attack (e.g. $\alpha = 40^\circ$ to 60°) as will be encountered in ACV applications, the effects are proportionately even greater. A free-stream aerofoil surface can of course produce no force in still air conditions, e.g. in stationary hover with no wind blowing, or when travelling at speed downwind with ground speed equal to natural wind speed. A side force can, however, be generated if a hinged fin ("all moving control surface") or a conventional rudder hinged on a fixed fin, is employed behind the propeller. With such an arrangement the thrust vector may be swung through an angle and a side force generated in still air conditions.

In Fig. 24a the three definitive systems, B1, B2 and B3, using aerofoil surfaces in a free-propeller slipstream are shown. With no control deflections and no propeller swivelling, these systems will have control force trends with angle of attack similar to those shown in Fig. 25 and as discussed above.

Additional forces can then be achieved by:

1. <u>System B1</u>

   Deflection of the whole control surface about a forward pivot point (not necessarily at or near the leading edge)

2. <u>System B2</u>

   Deflection of the movable rudder about its hinge axis

3. <u>System B3</u>

   Deflection of the movable rudder about its hinge axis in combination with swivelling of the upstream propeller axis.

All three systems are in well-established use but it seems unlikely that swivelling free-air propellers will be used on craft below 5000 lb (2270 kg) gross weight, though one application is believed to have been made on the Dutch NV Luchtkussenvoertuigfabriek B-2 craft (Ref. 10), a 23 ft (7.0 m) long by 12.33 ft (3.75 m) ACV.

Larger forces could be achieved from systems B2 and B3 by pivoting the main fin and hence obtaining a fin side force increment from slipstream angle of attack, but at the expense of some cost and weight increase.

The B1 system is mechanically the simplest, the lightest and the cheapest. Under zero relative free-stream conditions, the all-movable control surface may have the advantage by being able to be positioned at a large angle of attack to the propeller slipstream of generating a lift force (side force) greater than that obtainable by deflection of a rudder control surface with the fin at zero angle of attack to the mean slipstream flow. It is interesting to note that the General Dynamics SKIP-1 research craft was originally tested in an all-moving fin configuration (Ref. 11), which gave directional instability at low speed and insufficient control power above 20 m.p.h. (31 km/hr). A new twin-fin and rudder combination of larger size was installed and proved entirely satisfactory.

If reversible pitch propellers are used, the corresponding reverse propeller inflow is likely to cause separated flow over the control surfaces if deflected. This separated flow in turn will reduce the efficiency of the reverse thrust propeller. Fig. 26 illustrates this situation. Free-stream rudder controls could still remain effective but not, again, at low forward speeds.

In gusty wind conditions controls in the slipstream will tend to provide steadier aerodynamic forces than those exposed to free-stream flows.

6.3 Aerofoil surfaces in ducted-propeller slipstream

These systems, shown as C1 and C2 in Fig. 24b, are in wide-spread use on craft below 5000 lb (2270 kg) gross weight and also on larger craft. The control surfaces provide side force when deflected in the slipstream. There will be a slight asymmetry of side forces (port to starboard) due to slipstream rotation. When yawed, large side forces are available from the duct. Duct side force increases with increasing thrust coefficient. Fig. 27 illustrates the trends of this characteristic as established by NASA tests (Ref. 13) on a full-scale, 7 ft (2.12 m) propeller diameter model of a Bell Aerosystems X-22A ducted propeller unit. Poorly designed ducts, as have appeared on a number of small ACVs, would not give comparable results. At low thrust coefficients, stalling occurs in the duct outer surface but this is substantially delayed under high thrust conditions. Ref. 13 illustrates results on duct stalling and indicates that correctly designed ducts should be free of stalling up to angles of attack of about 35°.

The C_L values shown in Fig. 27 show that the ducted propeller provides a powerful side force capability when yawed, more so than for an equivalent-side-area, fin-in-slipstream system (Fig. 25). Hence craft fitted with stern-mounted ducted propellers may possess rather high directional stability unless the hull is strongly unstable directionally. Swivelling, small diameter ducted propeller units could possibly be considered for craft in the 4000 lb to 6000 lb (1750 kg to 2625 kg) range, where the engine is mounted as part of the thrust package.

To lessen the directional stability contribution of the duct, the external contour may be designed to stall at low yaw angles. This treatment, however, will lead to a higher external drag in normal zero-angle-of-attack conditions.

By positioning vane surfaces in the exit area of the duct, side forces can be generated sufficient to yaw the craft.

Side force test results obtained by Hoverproducts Ltd. (Ref. 14) on a 3 ft (0.915 m) diameter ducted propeller known as their QT-30 thrust package, are reproduced in Fig. 28. The form of this unit is shown in Fig. 29. The improvement in side force capability by increasing the number of rudders from two to four is most marked and perhaps greater increases might be possible with development. Weight, cost and complexity are of course increasing with additional rudders but if these factors are allowed for in the preliminary design of the craft then the increased turning effectiveness can be available. The optimisation of these systems would seem to offer a fruitful field.

In order to yaw an ACV fitted with such units, the side force from the rudder vanes must be greater than the side force produced by the duct when yawed. Initially at small yaw angles this situation is likely to prevail, but as the craft yaws in response to the vane deflection forces, angle of attack of the relative free-stream flow will build up and, depending upon the external profile of the duct, an opposing side force will be generated.

It should perhaps be pointed out here that the normal force of a free-air propeller inclined to the airflow is very small and does not present the apparent problem encountered when ducts are used.

If ducted propeller units are used at both ends of the craft, then the side force of each duct may be used as a contribution of the necessary side force for turning.

Instead of vanes, fin/rudder combinations may be used and these may be preferable for structural reasons although for a given size of total control surface (fin plus rudder) the force generated is likely to be less. A fin/rudder system in a slipstream is at zero angle of attack apart from swirl effects.

6.4 Aerofoil surfaces in centrifugal or axial fan discharge

With fan propulsion systems on the original SRN1 and more recently the Hoverjet HJ-100 and the Cushioncraft CC7, effective yaw control systems can be devised using vanes, one or more in number in part or all of the fan efflux. These systems are relatively insensitive to ambient airflow direction and speed and hence control forces available are determined by fan rotational speed (thrust) and vane deflection.

Systematic test results on the effect of number of vanes (between 2 and 5) are given in Ref. 15 for two duct airflow (thrust) conditions. These results are redrawn in Fig. 30, and show a worthwhile gain in "turning moment" by going to 5 vanes. When only 2 vanes are used they should be placed well within the core of the efflux for maximum effectiveness. Fig. 31 shows the final CC7 vane configuration.

The results of Ref. 15 indicate the variations possible and suggest that there is room for considerable optimisation in the design of these systems, in terms of vane spacing, size and aerofoil section. Greater effectiveness could also probably be achieved by using vanes with hinged trailing edges.

The turning moments in Fig. 30 are also expressed in a non-dimensional form by dividing by the product of cushion length and craft weight. This parameter is useful for comparative purposes but only in a very general way.

It should be mentioned here that when multi-vanes, as discussed above, are deflected some change in the fan operating point is likely to occur and could result in higher effective thrust.

An earlier vane rudder system was used on the Britten Norman CC5, Ref. 16, and shown in Fig. 32. Two low-speed air jets, fed by centrifugal fans exhausting rearwards for propulsion, were spaced 2 ft (0.61 m) from either side of the centre line. Hinged vanes on the sides of each duct deflected the flow by moving through $\pm$ 60° although the yawing moment was only equivalent to a 6° to 7° deflection of thrust line. This rather low effectiveness can probably be traced to the particular vane arrangement which effectively extends the sides of the ducts and, as shown in the "2 outer vane" configuration on CC7 (see Fig. 30), results in relatively poor side force generation. Test results are reported in Ref. 16 of the yawing moment to port and to starboard for various engine r.p.m. values.

(1)	(2)	(3)	(4)	(5)	(6)
Engine rpm	Total thrust airflow. ft^3/sec. (controls neutral)	Yaw moment to port lb.ft.	$\frac{\text{Yaw moment}}{W \times l_c} = \frac{(3)}{5600 \times 21.75}$	Yaw moment to starb'd lb.ft.	$\frac{\text{Yaw moment}}{W \times l_c}$
3900	1170			552	0.00453
3700	1133	- 271	- 0.00225	415	0.00340
3500	1090	- 224	- 0.00184	356	0.00290
3300	1030	- 176	- 0.00144	358	0.00294

Because of the simplified test conditions used, the accuracy of the above moments is only believed to be within ± 25 lb.ft (± 3.4 kgm). The differences between port and starboard moments are believed to be due mainly to lack of precise centering of the controls and to small pitch and roll attitudes causing yawing moment contributions.

The maximum value of yawing moment divided by the product of craft weight and cushion length achieved in these tests (0.00453) is very similar to that obtained for a similar vane configuration on CC7 which gave 0.0046 at 30° vane deflection, although the static thrust was only 60% of that of CC5.

6.5 Rudder ducts

Measurements of total thrust, without the propeller on, were made on an SRN5 (Ref. 2) and give an indication of the combined thrust from escape of air beneath the cushion and from the rudder ducts. Fig. 33 shows these results. The 300 lb (137 kg) of thrust at zero trim is a significant percentage of the total for the craft (2800 lb static) (1275 kg) but was really provided as an incidental result of having to improve rudder yawing forces on the SRN5 without involving large fin/rudder areas which would give too much directional stability. The power expended on this duct airflow would be better supplied to the propeller if thrust was the aim. Fig. 34 shows the rudder duct installation as used on SRN5 and SRN6.

6.6 Puff ports

Puff ports for yaw control (or side force control) have not appeared in the majority of light ACVs. Certainly craft may be satisfactorily controlled without them, but they have been shown to be highly advantageous to craft in the SRN5 and SRN6 series, and there would seem to be little reason for not incorporating them in very light ACVs. On the SRN5 and SRN6 craft puff ports were added after the design of the craft was complete. Fig. 35 is a photograph of the Bell SK-5 showing its puff ports open. The ports allow cushion air to be expelled from rectangular sideways-directed ports at a velocity of about 150 ft/sec (45.7 m/sec) from a plenum chamber feeding a cushion at about 28 lb/ft^2 (145 kg/m^2) in the case of an SK-5, Ref. 17.

If puff ports are fed from the main cushion supply, it is possible, if circulation of air within the cushion is not particularly free, that a heel may develop, producing a side force in opposition to the force desired from the puff ports.

If, say, four puff ports are used these may be opened to dump cushion air in order to achieve rapid cushion drag for braking.

Puff ports used in a downwind turn can reduce the air supply to the downwind side of the craft, thereby increasing the possibilities of a plough-in occurring.

Puff ports on N5 and N6 are opened or shut by simple hydraulically actuated doors. Since they allow the escape of cushion air, their operation will affect the stability characteristics of the cushion skirt system. The effects are likely to be greater when puff ports are fed from compartmented cushion systems and skirt bags than when taken from more "freely circulating" cushion systems.

Localised loss of air from a forward quarter of a craft could induce plough-in from two causes, a reduction in diagonal cushion stiffness and a reduction in effective cushion height in the same quarter. If, for instance, a forward puff port is operated to initiate a turn, then the corresponding quarter of the cushion will be affected and the craft's behaviour will be most sensitive to this advancing area. If, on the other hand, a rear puff port is operated, deprivation of the sensitive cushion area is avoided.

The effect of puff port operation on cushion height is given in Ref. 2 for the SRN5 at a weight of 14950 lb (6800 kg). At a rise height of 34.4 in (87.5 cm) corresponding to 2 in (5.08 cm) daylight clearance, opening of one puff port dropped rise height to 33.4 in (85.0 cm) and to 31.9 in (81.2 cm) skirts on ground with two ports open.

Ref. 18 is concerned with the H.D.L. HD2 research ACV. On this craft, puff ports, operated by a "roller-blind" device, were incorporated in the skirt loops and were found to be satisfactory from an installation point of view. As on a number of craft, puff port control forces were not high enough and being fed from the cushion more cushion air was thought to be necessary. Also they would have been more effective if they had been repositioned to give a maximum moment arm. If puff ports are built into the skirt structure, some flexible flap shielding of the lower areas of skirting are required, otherwise the air escaping through the puff ports may suck up parts of skirting in the immediate vicinity.

Loss of cushion air can cause an appreciable drag increase at speed, hence loss in speed, as well as introducing the risk of plough-in. It seems clear, therefore, that the use of air for puff port controls should be separated from the cushion supply, if at all possible, or regulated in such a way that no detrimental effects are felt or caused by the cushion.

For very light ACVs, flexible ducting structures might well be used for lightness and if air has to be taken from the cushion air or thrust air it would seem to be preferable to take it from the thrust system.

It seems to be generally agreed amongst craft pilots that more development is required with puff port arrangements to secure higher forces and moments. Quicker turning response is generally wanted and this really calls for higher forces and the ability to obtain maximum turning moments on the craft by their application. The existing puff port systems on craft such as SRN5 and SRN6 draw air from a system which was not designed to feed them. The usefulness of puff ports has, however, been recognised over the last few years and in any future craft they should certainly be incorporated in the basic design and suitable powering allocated for the purpose.

The forces available from puff ports on current craft are strikingly small when expressed as a percentage of craft gross weight. Measurements taken on an SRN5 (Ref. 2) give a good indication of what can be achieved by tapping cushion plenum chamber air. Single ports give a thrust equal to just over one-half per cent of craft weight ($T/_W = 0.005$) and with two operating on one side a maximum thrust of 1.14 per cent of craft weight ($T/_W = 0.014$) was reached.

TABLE 2 (REF.2)

STATIC FORCES AVAILABLE ON HOVER WITH SRN5 PUFF PORTS

Gross weight 14950 lb (6800 kg).

Control	Net force & direction		% wt.	M = Moment	$\frac{M}{W.l_c} = \frac{M}{14950 \times 29.4} = \frac{M}{439530}$
Skirt lift					
port fwd	210 lb (95.5 kg)	to port	1.40	-	-
port aft	220 lb (100 kg)	to port	1.47	-	-
port fwd & aft	280 lb (155 kg)	to port	1.87	-	-
stbd fwd	180 lb (82 kg)	to stbd	1.20	-	-
stbd aft	200 lb (91 kg)	to stbd	1.34	-	-
stbd fwd & aft	260 lb (118 kg)	to stbd	1.74	-	-
port & stbd fwd	70 lb (32 kg)	fwd	0.47	-	-
port & stbd aft	50 lb (23 kg)	aft	0.33	-	-
Puff ports					
port fwd	85 lb (38 kg)	to stbd	0.57	+ 600 lb.ft. + (82.5 kg.m)	+ 0.00136
port aft	100 lb (45 kg)	to stbd	0.67	- 1000 lb.ft. - (137.5 kg.m)	- 0.00223
port fwd & aft	160 lb (73 kg)	to stbd	1.07	-	-
stbd fwd	80 lb (36 kg)	to port	0.54	- 580 lb.ft. - (79.8 kg.m)	- 0.00132
stbd aft	100 lb (45 kg)	to port	0.67	+ 1050 lb.ft. + (144 kg.m)	+ 0.00239
stbd fwd & aft	170 lb (77 kg)	to port	1.14	-	-
port fwd & stbd aft	-	-	-	+ 1700 lb.ft. + (234 kg.m)	+ 0.00387
port aft & stbd fwd	-	-	-	- 1400 lb.ft. - (1920 kg.m)	- 0.00319
All skirt lift & puff ports used on one side	± 290 lb (132 kg)		1.94	-	-
Full stbd rudder	120 lb (54 kg)	to port	0.80	+ 1250 lb.ft. + (172 kg.m)	+ 0.00284
& port rudder no propeller	120 lb (54 kg)	to stbd	0.80	- 1050 lb.ft. - (144 kg.m)	- 0.00239

6.7 Skirt manipulation

The attitude of the craft in roll and pitch is determined to a very great extent by the air-cushion and skirt characteristics. A number of ACV designs have now successfully employed skirt movement mechanisms to assist in control. Examples are the Bell Carabao, the Bell SK-5, the H.D.L. HD2 and the B.H.C. SRN6. With segmented skirts the potential for greater roll control from skirt manipulation by varying the ratio of bag to cushion pressure has been referred to in Ref. 9. In this way, considerable skirt depth changes are produced, but the rolling effect of depth reduction could be offset to some extent by an increase in skirt span. Scooping by rear skirt segments can cause a deterioration in manoeuverability when the craft is yawed and rolled but this can be avoided by setting the tips of the fingers above those of the rest of the skirt.

Two main methods are at present in use on segmented skirts, skirt lifting and skirt shifting, and both would appear to be very suitable for use on light ACVs.

6.7.1 Skirt lifting

For segmented skirts this method involves a more or less vertical movement of the skirt hemline, achieved by pulling upwards in the vicinity of the segment inner attachment points, see Fig. 36. The lifting may be applied on forward and aft side-skirt positions on either side of the craft. The effect of local raising of the skirt is to cause the craft to roll down on that side and to incur some additional drag (Ref. 19) providing an initial yawing moment in the required direction. The idea was first tried on the B.H.C. SRN5 and has since proved most effective in a number of craft for inducing roll into turns, mainly at low speeds.

On the Bell Carabao, the skirt lifting mechanism was found to be of considerable value in control and manoeuvering. By using the resulting sideforce the vehicle could easily be held on course at an approximately 15° yaw angle into the wind during runs in a 90°, 15 knot (27 km/hr) cross wind.

Measured values of forces available from skirt lifting on an SRN5 are given in Table 2 extracted from Ref. 2, the highest sideforce achieved amounting to 1.87 per cent of craft weight.

The Hoverair Hoverhawk had a very definite tendency to roll out in a turn and many people who have driven this craft felt that it would have benefited from some form of skirt lifting.

6.7.2 Skirt shifting

This term is usually employed to describe a lateral movement of the perimeter of the skirt to achieve a shift in the cushion centre of pressure. Fig. 36 extracted from Ref. 9 shows two arrangements.

The H.D.L. HD2, Ref. 18, was fitted with lateral skirt-shifting, operated by movement of the inner attachment of the side segments, hence causing movement of the lower extremities of the segments.

The sideways movement of the cushion centre of pressure was found to roll the craft most effectively (up to 4.5°) and to produce a yawing moment due to skirt drag, the craft rolling into a turn. In beam wind conditions this system could be used to reduce downwind drift and/or yaw angle. At speeds in excess of 20 knots (36 km/hr) (Froude Number 1.2) this control had to be applied sparingly in order to prevent a severe tightening of the turn, followed by excessive yawing and subsequent uncontrolled pirouetting of the craft.

Model work performed on a BH7 model, Ref. 9, also provides further evidence on the effects of skirt shifting. Steady turns could be made using only skirt shift over water, while the radius could be reduced by a small amount of pylon movement.

In moderate winds, the skirt shifting was still effective for turning out of the wind but was relatively ineffective in other headings. Turning into wind from a cross wind heading, a lateral skirt shift barely offset the rolling moment induced by the wind and only a very gradual turn was achieved.

The skirt shifting system on the BH7 was discontinued because the loads required to operate it were considerably greater than those required for skirt lifting and the system could not be easily checked with the craft resting on its buoyancy tank.

The above methods do seem to be particularly attractive for small ACVs since the actuating parts are very simple, being mainly dependent upon cords or cables together with a few pulleys and a cockpit control. Care should be taken, however, to see that the risk of control lines snagging is minimised and that they are not liable to ice acretion.

6.8 Ballast and centre of gravity shift

6.8.1 Tank systems

Fuel or water ballast systems are in use on a number of ACVs, including the Hovermarine Hovercat, the B.H.C. SRN5 and SRN6 and the Bell Voyageur. These systems obviously involve a weight penalty and when fuel is used they are not available under maximum endurance or maximum range operations. Ballast systems are generally liked by ACV pilots for taking care of fore and aft trim. It is not easy, however, to avoid a slow response system and they cannot therefore be used satisfactorily as a dynamic control, for instance to avoid wave impacts. Obviously, the fastest reasonable transfer rate is desirable to facilitate change of trim following change of heading over waves, for example. One great advantage of using ballast for trimming the craft is that it is a purely internal system and is independent of the other control systems.

The weight penalty can be considerable. On SRN6, 100 gallons of ballast is carried in fore and aft tanks. The earlier versions had 25 gallons of ballast for trim but this was really not sufficient although it was accepted at the time. One hundred gallons weigh 800 lb (360 kg) which is 3½% of the craft gross weight. Military versions of SRN6 also permit cross-transfer of this same ballast and excellent trim longitudinally and laterally can be provided by this system. The Hovercat has provision for 300 lb (136 kg) of ballast, equal to 5.3% of gross weight.

On a craft such as the Hoverhawk, the athwartships trim was important and if a large passenger was being carried, one or both occupants would have to lean sideways to restore the horizontal trim in roll.

As a general design principle, the use of ballast should be avoided since unlike a ship power has to be expended in lifting it, even when the craft is not moving. It is suggested that considerable effort should be expended on devising skirt/cushion movement systems that can deal effectively with the requirements of longitudinal and lateral trim. Certainly for craft up to 5000 lb (2270 kg) in gross weight the weight saving should be appreciable (in cases where ballast appears to be required) without incurring appreciable cost or complexity.

6.8.2 Body movement

Partial control by body movement producing pitch and roll changes is a practical possibility for very small ACVs. With many light ACVs partial body movement control has often been employed. One craft which relied initially on such control was Colonel M.W. Beardsley's Little Skimmer II, a single-seat craft weighing 98 lb (44 kg) unloaded and powered by a single 5 h.p. engine driving a single fan for thrust and cushion at 4000 r.p.m. with a flow of

125 ft^3/sec (3.45 m^3/sec); cushion area is 35 ft^2 (3.25 m^2) and operating pressure 7 lb/ft^2 (35 kg/m^2). Colonel Beardsley's comments on his craft, received in a private communication, Ref. 20, are of interest:

> "The direct effect of leaning the body is to shift the c.g. and cause the vehicle to translate in the direction of leaning. Turning is caused by dragging a (usually) rear corner so that the resulting side force due to friction causes the change of heading. This requires a little coordination which comes naturally after a little practice, but the need for application of some skill keeps the operation interesting. For operation over land I affixed a 2 inch diameter rubber-rimmed furniture castor roller to each rear corner to provide better side friction for turning, especially over smooth paved surfaces. Control over water was superior to that over land due to the keel effect of the rear portion of the skirt being lower in the water. The turning radius was a function of speed, and I don't have any figures on it. From a standing start I could practically pivot about a rear corner of the craft. No numbers on stopping distance, but by leaning back and discharging cushion air out under the front of the skirt as the back of the skirt dragged the surface, stopping was fairly effective. As nearly

"as I could measure the slope climbing capability was what would be expected with the static thrust of about 18 lb (8.2 kg) and 250 lb (114 kg) gross weight, about 1/14 slope. For winds greater than an estimated 20 m.p.h. (30 km/hr) control was unsatisfactory - not so much because of the kinesthetic type of control as because of the directional stability of the vehicle with its rear location of the fan duct. The vehicle would weather-cock into a strong wind and could not be turned to a down-wind heading."

Whereas for large craft controls should be operable without the need to move the body, for very small craft (one- to two-seaters) controls should perhaps be designed to be coordinated with body movement. As an illustration of this, the Fishlock Mistral shown in Fig. 13 uses a stick for rudder control and when stick and body move to one side the craft is yawed and rolled in a coordinated manner.

6.9 Gimbal-mounted fans

Dr. William R. Bertelsen has developed several craft designs embodying gimbal-mounted fan systems with the specific purpose of improving controllability. Forces for lift, thrust and control are provided by a single source. Three craft types incorporating this principle have been built, the Bertelsen Aeromobile 13, 14 and 15. The following data is applicable to the Aeromobile 13:

Gross weight	3000 lb (1370 kg)
Empty weight	2000 lb (910 kg)
Power plant	two 125 h.p. Mercury outboard engines (about two-thirds thrust at maximum duct tilt, one-third lift.)
Cushion pressure at gross weight	20 lb/ft^2 (8.5 kg/m^2)
Overall length	21.5 ft (6.55 m)
Overall width	9.5 ft (2.9 m)
Cushion area	150 ft^2 (13.6 m^2)
Static thrust, forward	600 lb (270 kg)
Static thrust, reverse	600 lb (270 kg)
Side force	600 lb (270 kg)

Fig. 37 is a photograph showing the general layout of the craft. The engines drive 3 ft (0.915 m) diameter, 8-blade axial flow fans, in gimballed spherical ducts, one forward and one aft. Each unit may be rotated and tilted in any direction. Several specific modes of operation are possible:

1. Maximum thrust

   Fan rotating in vertical plane, 30% of air delivered to cushion.

2. Zero thrust

   Fan rotating in horizontal plane - total air discharged into cushion.

3. Normal operation

By tilting the fan plane of rotation forward (intake side on top) the duct design is such that the air from the fan is divided, some to flow aft over the deck of the craft and some to supply the cushion.

No trials results are available to the writer for these craft but the principle employed does offer the possibility of thrust vectoring without resorting to swivelling pylons. When weight, space and complexity are considered, however, it would seem that the system may have limited application since the craft layout is very much dictated by the installation. On the other hand, the system offers a unique control capability amongst ACVs in that side force can equal forward or reverse thrust.

6.10 <u>Hydrodynamic surface piercing control surfaces</u>

A vertical symmetrical hydrofoil surface is considered in Ref. 21 for the generation of side force. Placed beneath the X-axis centre line of the craft and with its centre of pressure beneath the transverse axis through the c.g., this surface would produce a rolling moment on the craft tending to roll the craft out of a turn. This rolling moment may, however, be countered by another device so it is worth examining the possibilities. The drag forces on the hydrofoil surface will produce a pitching moment on the craft but this is not so serious as the rolling moment. In addition, while the basic cushion rolling stiffness of an ACV does not normally vary significantly with speed, it is apparent that the hydrodynamic side force control by means of a foil can be used at low speed where the force it generates will be smaller but so will be the force required. At low speeds, therefore, a hydrodynamic surface piercing foil surface may be a useful control in certain circumstances (craft operating in deep-water canals for most of the time, for instance) provided the moment in roll generated could be accepted.

To oppose the unwanted rolling moment induced by such a control surface, the skirt shifting (centre-of-pressure-shifting) idea might be developed to achieve the required balance.

Fig. 38 presents lift and drag forces obtainable from a simple surface piercing foil (from Ref. 21) together with a calculation chart for rapid estimating.

6.11 Hydrodynamic side force

Carefully measured turning performance trials of the B.H.C. BH7 craft (Ref. 9) and subsequent analysis have shown the existence of a substantial hydrodynamic side force. Further model test work confirmed these findings and results from this work have been extracted from Ref. 9 and reproduced in this report as Fig. 39. One to two degrees of roll can treble the side force available at about 10° of yaw.

This force is believed to be due to skirt frictional forces and will obviously depend on the particular skirt configuration involved. No further information on hydrodynamic side force is available to the authors but Fig. 39 may be used as a guide to indicate the level of forces available for control.

6.12 Wheels

The use of wheels to obtain guidance from ground contact has been tried on several ACVs but development has not been carried very far. Consequently, there is little data on which to base an assessment of the idea. Two craft designed and built by Mr. G.G. Harding in the United Kingdom have demonstrated successfully the advantages of wheeled guidance and propulsion, Ref. 22. Fig. 40 is a photograph of Harding's "Wotsit I". For the size of craft, 22 ft (6.7 m) long and 11 ft 6 in (3.5 m) wide and weighing one ton, the various systems involve some complexity but the application of wheel drive has produced really practical results as far as control and braking is concerned. Also, by using wheel propulsion, the noise level is very low. The craft accelerates, steers, decelerates and reverses, very much like a car. The propulsion and steering unit is a standard final-drive and 850 c.c. engine unit from a Renault Dauphine. The lift system is powered by a 15 h.p. British Anzani 325 c.c. 2-stroke engine. Non-standard oversize wheels were fitted for which tyres could be obtained easily. For low-speed over-water work, eight 5 in x 5 in (12.7 cm x 12.7 cm) vanes were fitted to the inside of each wheel. Steering of the craft is achieved by differential braking on the two wheels. An additional propulsion means has been tried which has amphibious capability. Fig. 40 shows the craft fitted with vaned drums for propulsion, which float on the surface of the water and are capable of driving the craft also over land. The forerunner "Wotsit I" has climbed a one-in-three gradient with this system.

An earlier craft, the Folland Germ, was also equipped with wheels but only for guidance. They carried 5% to 10% of the craft weight, were positioned near the c.g. and could be braked for turning around.

The Vickers VA-2 was also fitted with wheels and these were found to be very useful when manoeuvering in confined spaces, and when proceeding along cambered roads. Over rough ground and at speed they had little value, however, and had to be raised to prevent damage.

Some interesting tests of manoeuverability over snow were carried out by the U.S. Army Cold Regions Research and Engineering Laboratory on a Bell Carabao ACV, a 3200 lb (1455 kg) vehicle with a single propeller and rudder in the slipstream, and equipped with harrow discs for ground contact guidance.

The following description of the tests is extracted from Ref. 4: "The undisturbed snow surface (0 to 2 in or 0 to 5 cm) in the

"Camp Century test area varied in density from 11.6 lb/ft^3 (0.186 g/cm^3) to 20.0 lb/ft^3 (0.320 g/cm^3), the average being 16.2 lb/ft^3 (0.26 g/cm^3). During prolonged hovering no significant erosion of the snow was produced after several minutes, although snow spray was present.

"Manoeuverability tests showed the relative effectiveness of the sideforce and the harrow discs as an aid in directional control. Fig. 19 shows the path of the vehicle and its yaw attitude while travelling around a rectangular course at a speed of 20 to 25 m.p.h. (31 to 39 km/hr) using various directional control methods. These manoeuverability tests were repeated several times with two different operators, and quite consistent results were obtained after a few trials.

"It can be seen from Fig. 19 that, when using only rudder and thrust control, from 150 to 250 ft (46 to 76 m) of turning room is required when entering the turn at a speed of 25 to 30 m.p.h. (39 to 48 km/hr). Without the sideforce effect it was not possible to maintain the desired speed and negotiate the corners without drifting away from the course. When the sideforce was used, only about 50 ft (15 m) of additional distance was needed, and the next heading was achieved in considerably less time.

"Besides providing improved directional control by deflection of the air-cushion, the use of the skirt-lift side force also resulted in additional skirt drag, which allowed for more effective use of the "thrust but of course reduced the vehicle speed.

"The wind effect was an important factor. The turns at the NW and SW corners could be performed more effectively than at the NE corner because of the yaw attitude of the vehicle with respect to the wind direction. When the vehicle was headed approximately into the wind, the thrust could be used effectively. By anticipating the use of rudders and thrust, as well as the sideforce, and starting the yaw before the turn was actually encountered, unnecessary swing-out due to wind and inertia could be averted. Unless the yaw was performed sufficiently early, thus positioning the vehicle in a direction for effective use of thrust, a considerable swing-out resulted.

"In the NE corner, after yaw to the left, the vehicle was heading with the wind, and the use of thrust was not as effective for maintaining the desired course. It was in this corner of the test course that the sideforce effectiveness was quite evident. The use of the thrust and rudder controls was most effective in the SE corner, since the vehicle was travelling into the wind.

"The use of the harrow discs was very effective for yaw control and for maintaining a heading in a cross wind. Manoeuverability, such as the ability to make sharp turns, was decreased. Almost as much turning space was required as when making a turn without using the skirt-lift. The discs, however, could be raised prior to a turn and lowered again when on the desired course.

"The effect of the harrow discs in yaw control was tested by heading the vehicle toward a specific point with the discs up and yawing the vehicle with rudders, then repeating the procedure with the discs penetrating the snow surface 4 to 5 inches (10 to 13 cm). The difference in yaw stiffness and in heading stabilization was apparent from the behaviour of the vehicle and the disc tracks in the snow. However, a considerable reduction in speed was noticed with the discs down, and acceleration was difficult.

"The maximum acceleration (or deceleration) of the vehicle during a test run around the rectangular test course in a counter-clockwise direction at 30 m.p.h. (48 km/hr) was (in terms of g):

Forward 0.43 g

Aft 0.81 g. "

The need for some form of ground contact is suggested also by Sir Vivian Fuchs in a paper on the subject of hovercraft in polar regions, Ref. 23. It is apparent that to ensure that reasonable reliance can be placed in a ground contacting control device, whether it be wheels, harrow discs or skids, the load carried by such a device should be maintained by a control link to the cushion air supply system. In this way, as the craft rose and fell in heave, the ground contact load would remain within acceptable limits.

6.13 Elevators

Opinions seem to differ considerably on the requirements for an elevator and there seems to be some preference for a good ballast system to take care of fore and aft trim. The SRN5 and SRN6 elevator control, however, has been found to be of good use in deep water situations with long swells where the craft can be "flown" with the elevator. Using the control in this manner avoids impacts, improves ride in general and in combination with the rudder the higher wind conditions encountered at the tops of the swell waves can be handled comfortably. The elevator as a trim device on SRN6 can only provide a small amount of pitch moment at cruise speed. On CC7 where the elevator control was, for all practical purposes, independent of craft forward speed but heavily dependent on thrust flow, the control could be used to assist in getting the craft over hump. The need for this control is further emphasized in the following CC7 trials' comments from Ref. 24:

> "When the craft is travelling into a brisk headwind, its bow is forced down by the wind. The trim flaps fitted to the rear of the craft are intended to apply a compensatory force to maintain trim but are, in fact, only capable of limited movement. Therefore, to raise the bow, the exhaust ports on the top of the vehicle must be opened, thrusting air in the same direction as the craft is moving and seriously hindering its forward progress. This handicap was most marked when travelling on water. The difficulty of maintaining longitudinal trim in a headwind appears to be a design fault that reduced the effectiveness of the machine in those conditions and terrain for which it might otherwise be well adapted."

On the Trans-African SRN6 expedition (Ref. 25) across West Africa, difficulty was experienced in getting over hump due to excess weight and high ambient air temperature. It was found though that by working the elevator a rocking motion could be set up "which helped the bow to step over the hump wave". If this failed, an alternative technique was to flick open the forward puff ports and then close them so that the lift effect at the bow coincided with the rocking effect of the elevator.

Following operational experience in the Hovermarine Canada Sandpiper, a horizontal control surface was slotted into the steering vanes on this craft to give trim control. As has been found on SRN5s and SRN6s this feature enabled the craft to get over hump more easily under critical conditions.

From the above practical results it is clear that an elevator control surface is particularly useful in difficult operating conditions. For maximum effectiveness it should be in the propulsion system airstream and not on the edge. As with fin/rudder vanes, two or more elevators in the airstream would markedly increase effectiveness.

6.14 Differential thrust

6.14.1 Side-by-side propellers

Side by side propeller arrangements using differential pitch offer a powerful means for yaw control but heavily influence the layout of the craft. In addition, costs are likely to be appreciably greater for the duplication of propeller and transmissions and such layouts tend to lead to the use of two or even three engines, again adding cost and, especially with the smaller ACVs, the risk of one or more engines not starting although this aspect can be argued from several points of view.

An example of a side-by-side propeller layout is shown in Fig. 41 which illustrates the Cushioncraft CC2-003. This version represents a major modification of the original CC2-001 craft which relied entirely on the cushion system for propulsion and control (Ref. 26), using deflection of vanes in the peripheral jet and having fixed fins but no rudders. The 003 version is fitted with rudders and two fixed-pitch propellers, directly driven by two Continental piston engines. Wind tunnel tests on the stability and control characteristics of this craft are given in Ref. 27. The CC2 type has had a history of changes to improve the handling characteristics and it might well prove to be a useful craft with which to establish, at relatively low cost, a series of control capabilities against the conditions proposed in the Section of this report dealing with control standards.

6.14.2 Low-speed air-jets

By suitable duct and valve design, craft employing low-speed air-jets for propulsion may obtain effective yawing moments. The Cushioncraft CC7 incorporates such a system and yaw control may be obtained either by deflection of the rudder vanes in the air-jets or by a combined deflection of the vanes and reverse thrust on one side of the craft. The system is such, however, that if reverse thrust is used on the outer fan efflux system the cushion flow tends to become asymmetric inducing a rolling out tendency. This results in a rather bad plough-in in overland operations, usually at about 90° of yaw producing a very uncomfortable sensation for those on board. Otherwise the controls on this craft are generally considered to be very good and well matched to its intended duties.

Fig. 42 shows typical results for CC7 using differential thrust.

7.0 TURNING BEHAVIOUR

The ability of a craft to turn in an acceptable manner is important because it is fundamental in securing good manoeuverability. The turning motion of an ACV is in some respects unlike that of any other vehicle although perhaps similar motions are sometimes encountered when turning a car on ice at high speed. The centrifugal force inherent in a turn must be balanced (in a constant radius turn) by an equal and opposite side force on the vehicle. The side force may be generated by the movement of the ACV through the air and in addition by forces arising from contact of the ACV with the surface over which it is travelling and by components of thrust directed towards the centre of the turn. Because an ACV above hump speed is principally dependent upon aerodynamic forces for control and guidance, it is correspondingly heavily dependent upon the wind conditions as far as its track over the surface is concerned. Also, surface waves or surface slope can have far reaching effects. The wind speeds are of the same order as the normal craft operating speeds. It is apparent, therefore, that the control of an ACV in relation to fixed points on its operating surface presents a very complex problem and this shows up particularly in turning motion.

Whereas for a ship very small yaw angles of only a few degrees will produce very large hydrodynamic side forces, this is not so for the ACV although some small but significant hydrodynamic side force can be obtained from the skirt-cushion system, as previously mentioned. The ACV is basically moving through the air but unlike an aircraft it cannot bank substantially in order to generate a major side force from a horizontal component of lift to oppose centrifugal force in a turn. Further, because the air velocities relative to small ACVs are low, (generally not greater than 50 knots (92 km/hr)), aerodynamic side forces, if they are to be large, must be provided by the biggest possible product of side force coefficient and corresponding hull reference area. Typically, maximum aerodynamic side force coefficients are generated between 30 and 60 degrees of yaw (ψ_A). At these large yaw angles the component of thrust normal to the track of the craft is also a major contribution to opposing centrifugal force. On large ACVs for which swivelling propeller pylons are a practical proposition a sideforce may be generated from the thrust system without involving craft yaw.

For analysing turning motion of an ACV it is convenient to draw upon normal naval architecture practice. Fig. 43 illustrates definitions of the turning manoeuvre for this purpose and the following account of a turning manoeuvre is taken from standard ship manoeuvring theory, assuming only a rudder is used to yaw the craft. It should be noted in Fig. 43 that two definitions are suggested for Advance, Transfer and Tactical Diameter, the first define these distances on change of craft heading, as is usual ship practice,and the second define them in terms of the track of the craft. For ACVs the differences can be quite large since the drift angles are excessive, with 40° or even more often being experienced.

The steady turn condition shown in Fig. 43 will only occur in still air conditions. In winds and gusts an approximately circular path can be flown by varying control settings and thrust settings. In practice, measurement of turning circles will often include these effects and in many instances the effect of sea state. The effect of winds on turns is shown pictorially in Fig. 51 of Section 10 and also in Fig. 44 which shows measured overall turning dimensions for a turn carried out by the Cushioncraft CC7 in a 20 knot (36 km/hr) wind. For this manoeuvre the pilot was requested "to do whatever he could to make a 360° turn in minimum width while maintaining speed."

Referring now to Fig. 43 the first stage of the turn starts as soon as deflection of the rudder commences. The consequent rudder force and moment cause accelerations on the craft which are initially opposed by the inertial reaction of the craft. The transverse acceleration, in a turn to starboard as illustrated, is directed to port consistent with the rudder force being directed to port to carry out a turn to starboard.

The accelerations arising from the rudder force and moment give rise to a drift or sideslip angle and a rotation in yaw. The second stage of the turn is now commencing. As a result of the drift angle, a side force SF directed to starboard is generated towards the centre of the turn and rapidly becomes larger than the port directed rudder force. The side force eventually comes into balance with the outwardly directed centrifugal force of the ACV. The rudder force will initially cause the centre of gravity of the craft to move to the port side of the original approach path but it will eventually move back as the craft side force predominates. There is likely to be some directional oscillation as these changes are taking place until eventually a steady turning condition is reached. Stage 3 then commences with the establishment of a new equilibrium of forces.

7.1 Measurement of turning performance

As an example of the detailed changes taking place during a turn, reference may be made to some SRN5 trials (Ref. 2) and the results (Fig. 45) may be assumed to be typical of a craft having a similar configuration and force and moment controls. The test technique used was to apply full skirt lift into the turn and use the rudder to trim the required steady rate of turn; the angle of sideslip obtained was recorded. Since the wind was light, airspeed and water speed were similar throughout the turn. Occasional small rudder deflections were necessary to correct small disturbances.

The maximum rate of turn of 5.5° per second was achieved at a sideslip angle of 45°. At the higher rates of turn the skirt in the inner side of the turn dipped into the water and the craft became directionally unstable and opposite rudder had to be applied.

The rudder deflections required to trim the craft at different rates of turn are also shown in Fig. 45. The craft was out of trim directionally during these tests and nearly 50% of full starboard rudder had to be applied to hold a straight course.

The thrust power requirement in the steady turns increased markedly when skirt contact with the water occurred and Fig. 45 shows the rapid rise of power needed as rate of turn increased from 2° to 6° per second.

7.2 Turning circle data

Measured turning circle data for a number of craft are given in Fig. 46. Such data can only be approximate since a pure circle is very unlikely to be achieved in practice. The "effective" side force of Fig. 46 is simply assumed to be equal and opposite to the centrifugal force in the turn. It is interesting to note that the highest values of $\frac{SF}{W}$ are achieved by the H.D.L. HD2 research craft and are around 0.20. This craft is equipped with two $\pm 30^\circ$ swivelling pylons, fore and aft skirt shift and puff ports. The effective side force achieved in a turn is, as discussed previously, the summation of all components, aerodynamic, hydrodynamic (surface contact) and propulsive. The aerodynamic components may be broken down into hull, control surface (partially opposing) cushion efflux and puff ports when used. On the small craft which are being considered in this report all these forces can be available although very few small craft have to date incorporated puff port or side thrusting devices.

To obtain good turning performance without the need for excessive yaw angles (potentially dangerous) a greater provision for side thrust seems to be worthwhile and skirt manipulation systems and the deliberate provision of powered side thrusting systems could be developed to provide this thrust.

7.3 Very low-speed turns

Very tight turning circles may be achieved by ACVs from near stationary conditions.

CC7, for instance, (Ref. 24) was shown to be capable of being turned in a radius of only 21 to 24 ft (6.4 to 7.3 m) at slow speed by using full rudder (low-speed air-jet vanes) and full differential thrust.

The 600 lb (270 kg) Pindair Skima can turn at 5 knots (9.2 km/hr) with a radius of 10 ft (3.0 m). Similarly the MHV Spectra II, a 1250 lb (568 kg) two-seater can turn at 5 knots (9.2 km/hr) with a radius of 20 ft (6.1 m).

Like many small craft, Sandpiper could be turned through 360° (Ref. 28) in a very small circle at slow speed; around a tree or buoy, for instance, the bow could be kept within a yard or less of the obstacle. Steering control from the vanes in the thrust ports was excellent and skirt drag and body movement could also be used to assist in a turn.

Normal turns at speed were affected by skirt configuration. In order to improve over-hump performance, the inner flaps of the rear skirt segments were extended and stiffened and while this improved over-hump time it gave slightly less cornering capability.

In many operational situations it is possible to slow down before turning and thus avoid attempting tight turns and the consequent difficulties which can be encountered.

7.4 Overturning

Turning at high speed with some ACVs can lead to the risk of overturning. The Hoverair Hoverhawk when being turned at speed called for ample manoeuvering space and anticipation and unless handled correctly could result in quite alarming sideways plough-ins and possible overturning (Ref. 30). In particular, attempting to turn in too short a radius, turning in cross-wind conditions, turning with uneven load conditions aboard, and turning too fast from the downwind condition, could all lead to a sideways plough-in of a fairly severe nature. The chances of overturning the craft under these conditions were considered to be very real. The craft had a basic weight of nearly 1300 lb (590 kg) and a static thrust of 120 to 125 lb (54.5 to 56.8 kg). (See also Ref. 29).

7.5 General comments

Some craft such as the Hovermarine Hovercat have been found to be more critical turning over land than over sea and the rolling out tendency is greatly increased in a downwind situation. The effect of applying constant rudder for a turn and turning downwind is for the rate of turn to increase steadily and for the ground speed to increase also. Continuing with fixed rudder could lead to a pirouette manoeuvre effectively discontinuing the intended steady turn of the craft. Over land this same manoeuvre can lead to the "outside" bow going down and grounding which in extreme cases could bring the craft to a halt. Both skirt drag and high rudder centre-of-pressure moments contribute to this type of behaviour. There is some evidence to suggest that the bottom segment angle of the inclination of the outer face of a skirt segment may have an important bearing on the level of drag forces set up in these turning conditions.

When skirt lift is provided, it is normal to operate it first to provide bank for the turn; then a small amount of rudder may be put on and a good coordinated turn can be obtained. If rudder is put on first, a skidding turn results in much the same way as with some aircraft. In practice, the movement of the craft away from the direction of the intended turn due to the sideforce of the rudder is of no real significance except when operating in close proximity to other craft or obstacles.

The most powerful way to reduce turning rate is simply to reduce speed. A turn attempted at too high a speed will on most craft result in a more or less straight line path with the craft travelling sideways or pirouetting. There is no need to slow down in turning into wind but in a downwind turn the control responses are much less. Where controls such as propeller pitch and skirt lift are provided, it is possible to perform more or less properly coordinated, approximately circular 360° turns in slight to moderate winds. If no control adjustment and coordination is carried out, then in down wind situations an elongated turn will result. On very small craft, which are most unlikely to have propeller pitch control as well as being limited in other control directions, it is very unlikely that properly coordinated turns can be obtained. Attempts to reduce cushion power to obtain a correct turn can prove to be dangerous under certain conditions.

8.0 STOPPING AND BRAKING OF CRAFT

8.1 Reverse thrust

If an ACV is to remain clear of the surface over which it is operating, then braking forces can only come from aerodynamic forces on the craft generated by the hull, control surfaces, propulsion system or cushion system. Of these forces the designer may look to the propulsion system for the largest component and the upper limit for this source would be set if a 100% conversion of forward thrust to reverse thrust were possible. Conventional air propellers, designed to be efficient (high lift/drag ratios) at the design cruise condition will employ blades having appreciably cambered aerofoil sections. These sections when operating at negative angle of attack in reverse thrust conditions not only then possess a poor lift/drag ratio but also encounter stall at a lower maximum lift coefficient. Lower-cambered sections could be used to avoid the worst effects in reverse thrust conditions but then forward thrust would be less unless blade area were to be increased. Increasing blade area has proved to be difficult on the larger craft propellers because of weight increases leading to the need for toughening up of blade root retention in the area of hub design. For small craft, though, (around 5000 lb) (2270 kg) it might well prove to be worthwhile to examine the use of relatively large blade areas combined with nearly symmetrical aerofoil section blades and a simple 2-position forward-to-reverse pitch changing mechanism.

With present day ACV propellers as fitted to craft such as SRN6, the reverse thrust capability is certainly no more than half the forward thrust and under many operating conditions it is down to one-third.

For fan-propelled craft such as CC7, flow is redirected in a forward direction to obtain reverse thrust. With CC7 (Ref. 15), the position of the reverse thrust outlet induces a large bow-up moment and therefore increases the reverse thrust by a component from the cushion. Despite this increment the reverse forces are not large, as the following table shows, for static thrust conditions:

Total s.h.p.	200	300	400	500
Reverse thrust / Forward thrust	0.218	0.207	0.194	0.181

8.2 Stopping distances

Trials have been carried out on a number of ACVs to record stopping distances. Various techniques have been used and in some instances not all the relevant facts are known concerning tests. Data on stopping distances for the Cushioncraft CC7, the B.H.C. SRN6 and the Bell Caíabao are presented here:

8.2.1 Cushioncraft CC7 over water

The following information is extracted from Ref. 24:

"The wind was rather strong for this type of test but time did not permit the schedule to be altered. The stops were made just off a jetty which ran parallel to the shore-line and, fortunately, nearly parallel to the prevailing "wind direction as well. The craft approached at normal cruising power and full reverse thrust was applied at the instant the end of the jetty was reached. No steering problems were encountered upon application of reverse thrust. The time required to stop was recorded and the position along the jetty was noted so that the distance could be measured later. When stopped, the craft was not on the buoyancy tanks but still on the air cushion with the engine at idle."

Wind:	18 to 20 knots (33 to 36 km/hr) from 250°
Average Current:	approx. 2 knots (3.6 km/hr) from 260°
Waves:	approx. 9 in (23 cm) with 1 ft (30 cm) swell
Gross weight on departure:	5200 lb (2360 kg) including fuel
Average trim:	2° by the stern

Direction	Time Reqd.	Stopping Distance	(Assume from)
Upwind	11 sec.	102 ft (31 m)	25 knots (45 km/hr)
Downwind	14 sec.	195 ft (59.5 m)	37 knots (68 km/hr)
Average	12.5 sec.	150 ft (45.5 m)	

8.2.2 B.H.C. SRN6 over smooth ice

Ref. 31 (p.93) gives results of stopping distance tests using propeller reverse thrust on the SRN6 craft. These tests were carried out to assess the effectiveness of the reverse pitch and pirouette stopping methods on a smooth surface and were run over smooth ice both into and with a 16 m.p.h. (24 km/hr) wind, in Button Bay just west of Churchill, Manitoba. In the words of the Department of Transport report: "reverse pitch was found to have some effect when travelling into wind but very little when travelling with it." A pirouette stop was completed in half the forward distance required for a reverse pitch stop against the wind. These results are shown in Fig. 47.

8.2.3 Bell Aerosystems Carabao over land

Ref. 4 presents measured braking distances for the Carabao using two different techniques.

Using full reverse thrust and skirt lift to give an aft force the shortest distances were obtained. Weight assumed = 3200 lb (1455 kg). The distances shown are for bring the craft to stationary hover.

Speed m.p.h.	(km/hr)	Direction	Braking distance ft	(m)
10	(16)	against wind	60	(18)
10	(16)	with wind	90	(27)
20	(32)	against wind	75	(23)
20	(32)	with wind	105	(32)
30	(48)	against wind	84	(26)
30	(48)	with wind	105	(32)

Considerable yawing of the craft occurred from the original heading. Better control of the vehicle during braking was obtained by moving the skirt lift control from the aft position to the side position. Thus the use of side force caused the vehicle to move sideways with a constant yaw attitude with respect to the original heading.

If throttle of lift and propulsion engines are simply cut and the craft allowed to "ground out" then rather longer distances for braking occur, but there is virtually no yaw, skirt drag contributing heavily to the braking:

Speed m.p.h.	(km/hr)	Direction	Braking distance ft	(m)
10	(16)	against wind	96	(29)
20	(32)	against wind	132	(40)
30	(48)	against wind	138	(42)

These distances are not the shortest possible since no reverse thrust was applied.

Stopping distances for small craft over water can be very short. From a speed of 40 knots (74 km/hr) the MHV Spectra II is capable of stopping in 40 ft (12.0 m), just 3.2 times craft length.

8.3 Emergency stopping (collision avoidance)

Collision avoidance tests carried out on an SRN5 by the Defence Research Board (Ref. 32) provide some useful data on distances to bring a craft to rest as quickly as possible using yaw ducts, skirt lift, rudders and propeller pitch. The tests were carried out over a natural snow surface and the results are shown in Fig. 48. Without the use of yaw ducts (puff ports) the space required increased by as much as 40%.

8.4 Stopping distance data

Fig. 49 presents collected data on stopping distances for various craft and shows the effective mean decelerations. The average "g" levels are low by automobile standards. Emergency stopping of cars on dry road surfaces typically reach 0.60 to 0.70 g, though at these values occupants must "hold on" or be strapped in, seated passengers probably receiving injuries at 0.5 g.

8.5 General comments

Until really effective braking systems are devised which can halt a craft in emergencies in just a few craft lengths, it seems that some form of survey ahead of the route will always be necessary, especially in snow and ice covered regions. In addition to providing effective braking, light ACVs should also be equipped with relatively large-area disc-shaped landing pads so that the craft can be set down at speed when travelling in any direction. If craft always have to be set down when travelling forwards, then in emergencies attempting to turn craft in a direction suitable for landing could lead to an accident.

The CC7 can provide braking in down slope operations and still maintain reasonable directional control. The craft can in fact be stopped on a slope, turn on a slope, and be held on a slope.

Very few light craft possess any form of braking but because of their low mass the distances in which to come to a halt are not great, especially over water. Over smooth ice the problem is entirely different.

Experience with SRN6 at Churchill, Manitoba, (Ref. 31) also led to a recommendation that a method of slowing the craft rapidly, other than reducing the hoverheight and dragging the skirt, should be investigated.

It is suggested that a close examination should be made of the braking methods of the Swedish hydrocopters. Braking is achieved by steel pins which are pressed into the surface of the ice by a foot-operated lever system. This possibility is taken up again in the Section dealing with new control ideas.

Smooth ski pads could be considered for braking on snow surfaces and the reader is referred to Refs. 33 and 34 for a full appraisal of skis operating on snow surfaces. This work, however, was not concerned with obtaining maximum coefficients of resistance but rather the opposite. Typical values of coefficient of resistance quoted for skis on snow range from 0.10 to 0.21 (depending upon ski surface type) over bearing pressures from 100 to 500 lb/ft^2 (495 to 2500 kg/m^2).

9.0 CONTROL STANDARDS

The six degrees of freedom possessed by the ACV in combination with the infinite number of environmental conditions which may be encountered present an apparently elusive situation as far as definition is concerned. Coupled with the variety of conditions which ACVs may operate in, there are also many forms that ACVs may take. Although the more extreme forms may disappear or find only very specialized application, there will doubtless remain a large number of different types reflecting the wide variety of operational uses and environments. At this very early stage in the development of entirely new types of vehicle it would be premature to lay down hard and fast rules as far as standards of control are concerned. The lack of systematic testing of craft in the area of directional stability and control and the commercially discreet nature of much related work which has been carried out has of course not helped to reach an understanding of the problem.

Despite these difficulties, certain trends have begun to emerge and also certain primary conditions in which an ACV should be both controllable and safe. The combinations of wind conditions and surface conditions in conjunction with craft headings and changes in heading may be represented in simplified form by a series of Standard Conditions for Control Assessment. The conditions are defined in words by Table III, and some by illustrations in Figs. 50, 51 and 52. Regardless of surface composition, overland surfaces are considered either as horizontal or sloping, and in the latter case craft movement, up, down and across the

Principal operating conditions \ Travel plane	Over land, snow, ice, bog, etc.: Horizontal land	Over land: Up slope	Over land: Across slope	Over land: Down slope	Over water, Calm: Shallow $d_w < l_c$	Over water, Calm: Deep	Waves – shallow water: Head sea	Waves – shallow water: Following sea	Waves – shallow water: Beam sea	Waves – shallow water: Quartering seas forward	Waves – shallow water: Quartering seas astern	Waves – deep water: Head sea	Waves – deep water: Following sea	Waves – deep water: Beam sea	Waves – deep water: Quartering seas forward	Waves – deep water: Quartering seas astern
1) STRAIGHT MOTION IN:																
Still Air	HL 1	US 1	AS 1	DS 1	CS 1	CD 1	WHS 1	WFS 1	WBS 1	WQFS 1	WQAS 1	WHD 1	WFD 1	WBD 1	WQFD 1	WQAD 1
Into Wind	HL 2	US 2	AS 2	DS 2	CS 2	CD 2	WHS 2	WFS 2	WBS 2	WQFS 2	WQAS 2	WHD 2	WFD 2	WBD 2	WQFD 2	WQAD 2
Down Wind	HL 3	US 3	AS 3	DS 3	CS 3	CD 3	WHS 3	WFS 3	WBS 3	WQFS 3	WQAS 3	WHD 3	WFD 3	WBD 3	WQFD 3	WQAD 3
Beam Wind	HL 4	US 4		DS 4	CS 4	CD 4	WHS 4	WFS 4	WBS 4	WQFS 4	WQAS 4	WHD 4	WFD 4	WBD 4	WQFD 4	WQAD 4
Beam Wind :~ up slope.			AS 4													
Beam Wind :~ down slope.			AS 5													

Initial travel plane \ 2) TURNING MOTION STARTING IN:	Horizontal land	Up slope	Across slope	Down slope	Calm: Shallow $d_w < l_c$	Calm: Deep	Waves – shallow water: Head sea	Waves – shallow water: Following sea	Waves – shallow water: Beam sea	Waves – shallow water: Quartering seas forward	Waves – shallow water: Quartering seas astern	Waves – deep water: Head sea	Waves – deep water: Following sea	Waves – deep water: Beam sea	Waves – deep water: Quartering seas forward	Waves – deep water: Quartering seas astern
Still Air	HL 5	US 5	AS 6	DS 5	CS 5	CD 5	WHS 5	WFS 5	WBS 5	WQFS 5	WQAS 5	WHD 5	WFD 5	WBD 5	WQFD 5	WQAD 5
Into Wind	HL 6	US 6	AS 7	DS 6	CS 6	CD 6	WHS 6	WFS 6	WBS 6	WQFS 6	WQAS 6	WHD 6	WFD 6	WBD 6	WQFD 6	WQAD 6
Down Wind	HL 7	US 7	AS 8	DS 7	CS 7	CD 7	WHS 7	WFS 7	WBS 7	WQFS 7	WQAS 7	WHD 7	WFD 7	WBD 7	WQFD 7	WQAD 7
Beam Wind	turn into: HL 8; turn out of: HL 9	turn into: US 8; turn out of: US 9	turn into / turn out of	turn into: DS 8; turn out of: DS 9	turn into: CS 8; turn out of: CS 9	turn into: CD 8; turn out of: CD 9	turn into: WHS 8; turn out of: WHS 9	turn into: WFS 8; turn out of: WFS 9	turn into: WBS 8; turn out of: WBS 9	turn into: WQFS 8; turn out of: WQFS 9	turn into: WQAS 8; turn out of: WQAS 9	turn into: WHD 8; turn out of: WHD 9	turn into: WFD 8; turn out of: WFD 9	turn into: WBD 8; turn out of: WBD 9	turn into: WQFD 8; turn out of: WQFD 9	turn into: WQAD 8; turn out of: WQAD 9
Beam Wind:~ up slope.			AS 9 / AS 10													
Beam Wind:~ down slope.			AS 11 / AS 12													

TABLE 3. STANDARD CONDITIONS FOR CONTROL ASSESSMENT.

slope is considered. The other primary surface considered is water, in four categories, calm, shallow and deep (depth greater than craft length) and waves, shallow and deep water. These surface conditions are then combined with craft heading relative to wind to arrive at "standard" conditions. First, straight motion in still air, into wind, down wind and in a beam wind are set as basic conditions. Second, turning motion in still air, and then starting a turn into wind, down wind and in a beam wind provide the second set of conditions. The various combinations which result are fully shown in Table III. A simple numbering system is proposed which allows the rather large number of conditions to be easily referred to.

The authors therefore would recommend that experience to date with ACVs (of all sizes) should be assembled and assessed against the suggested basic conditions shown in Table III. Unexpected results have already occurred in the control behaviour of craft in various conditions and some of these of course have led to accidents. An interesting example of a condition which has been experienced in the vicinity of Cowes Harbour in England has been an apparent complete reversal of directional stability of SRN5 and SRN6 type craft due to water depth effects when coming out of the harbour, and particularly noticeable in strong wind conditions. In practice, to maintain heading when this phenomena takes place, a change from full rudder one way to opposite full ruder the other way is required. This rather unusual effect only serves to illustrate the very wide range of conditions which may be encountered, the results of some not being fully understood. By exploring clearly defined operating conditions, however, it is suggested that patterns of craft behaviour and handling will begin to emerge which will be seen to be fundamental to the ACV concept.

Initially, it would even be valuable to set up control standards in the most general terms simply establishing that a craft is actually controllable under a given set of conditions, in other words, that the manoeuvre may be repeated over and over with negligible differences in the path travelled by the craft. Here again, consideration should be given to what is really meant by controllable and it would seem in this connection to be worthwhile establishing some rule of thumb definitions as a very preliminary step. Ideas along these lines are presented in the following notes to be read in conjunction with some of the standard conditions of Table III. These ideas are very tentative and are presented here to encourage discussion and further work in this area.

Condition HL1. (Straight motion in still air, horizontal land)

The craft should be able to accelerate from the stationary hover condition to its normal design cruising speed along a straight track. When in trim about all axes, the craft should be capable of being flown hands and feet off controls, though for very small craft a hand-held-on throttle control seems preferable. Although a change of attitude in pitch may occur with forward speed, this must not be excessive so that ground clearance is substantially diminished and should be capable of being trimmed out to within $\pm 1^\circ$ of the horizontal. Directional stability is considered to be essential but the level will be determined in conjunction with the down wind control standard, HL3.

HL2. (Straight motion, into wind, horizontal land)

Control requirements very similar to HL1. The ground speed will be less than the design cruising air speed and this will to some extent determine the maximum natural wind speed that the craft should operate in. A craft designed to give a 35 knot (64 km/hr) still air cruising speed over land would be almost at a standstill in a 35 knot (64 km/hr) wind but surface contact drag would be negligible so some forward speed would be left. It is suggested that a limiting wind speed should be set that enables the ACV to proceed at a ground speed not less than one-third of its still air cruising speed. Thus, disregarding surface contact drag a 35 knot (64 km/hr) design-cruise-speed craft should, for example, be able to proceed at 12 knots (21 km/hr) when operating in a headwind equal to that specified as limiting for the craft in question.

HL3. (Straight motion, downwind, horizontal land)

This condition is illustrated in Fig. 18. It should be possible to maintain any chosen ground speed, that is, there must be sufficient thrust and/or drag control to prevent the craft being

"Carried away by the wind". In addition, any tendency for the craft to weathercock into wind should be easily controllable through use of the normal yaw controls with heading divergence limited to $\pm 5^{\circ}$ in steady wind conditions. When the craft is travelling downwind at a ground speed equal to wind speed, full control over the craft's track and heading should still remain.

HL4. (Straight motion, beam wind, horizontal land)

In this condition most existing light craft have difficulty in holding station on hover without changing their heading into wind. Unless some form of ground contact is used it seems very unlikely that many ACVs in the very light weight range (350 to 2000 lb) (160 to 910 kg) would be able to have sufficient control power to hold station without changing heading.

When moving forward in beam winds up to the limiting wind, the craft should not exceed heading angles relative to the track, ψ_T of 30°.

US1. (Still air, up slope, straight motion)

The craft should be able to proceed up the maximum gradient, for which it is designed, in a straight path. Directional control should be sufficient to restore heading of craft, i.e. to counter the yawing moment of the c.g. over, say, $\pm 10^{\circ}$ of yaw, should a disturbance produce such a yaw. Trim in pitch should be provided in order to prevent the nose-up pitching moment caused by the rearward movement (in a horizontal plane) of the c.g. of the inclined craft, causing the rear skirt areas to drag.

Further suggestions could be made along these lines but a more useful approach would be to ascertain at least the capabilities of a number of existing craft against the conditions put forward in Table III for assessment. A current achievement level could then be established for the various conditions.

10.0 COCKPIT CONTROLS AND ERGONOMICS

Air-cushion vehicles ranging from 5000 lb (2270 kg) gross weight down to perhaps only 250 lb (114 kg) obviously call for very different cockpit arrangements and instruments. The higher weight craft such as the Hovermarine Hovercat and Cushioncraft CC7 are capable of carrying out a variety of industrial and commercial operations, some of which may involve long endurance journeys and must therefore be correspondingly equipped. At the lower end of the scale the single-seat sports craft will carry the absolute minimum of equipment and have the simplest form of controls. Many of the general principles of good practice apply, however, to the whole range of craft being considered.

A particularly useful paper, Ref. 35, discusses the control skills required of an ACV pilot. To some extent problems have arisen from cockpit layouts based on aircraft practice or boat practice and there has in fact been a general tendency to copy the controls of various existing vehicle types. This pattern is partly simply a reflection of the very early stages of a new form of vehicle. Even now it is not really possible to be dogmatic on the precise form controls should take but one can be dogmatic in saying that they should be designed specifically to deal with the unique ACV guidance problem. A basic theme suggested in Ref. 35 is that the designer should determine what craft motions are possible and which ones are required. Then the ACV driver-environment system can be looked at to find out the limitations within it in trying to produce the required motions. This approach would involve deciding what information the driver needs, what controls are best suited to the system and what skills are required of the driver. Ideally, cockpit controls should enable a complete marriage of the capability of the driver and the craft responses.

If instant and well placed control forces were to be available on a craft, for instance small rockets at all four corners of yaw, it does not follow that the driver could necessarily manoeuvre the craft any more successfully than with limited controls. There is a control load which each person can cope with and beyond that it may well be that the provision of higher forces or more controls simply produces a deteriorating situation. The ability to anticipate controlling actions and to respond to various stimuli is obviously called for in order to achieve safe and efficient craft control.

At the moment, hovercraft drivers have to ascertain what is going on through their senses. There is next to no instrument display provided in keeping with the motion characteristics of a hovercraft.

10.1 Control and cockpit requirements

When manoeuvering many amphibious ACVs, especially at low speed and in restricted spaces, it is frequently necessary to make rapid and coordinated use of rudder, throttle, propeller pitch, skirt lift and yaw ports. It is this control demand on the driver which has led to the need for both hand and foot controls on current craft.

Control of rudders by conventional aircraft-type rudder bar and pedal is recommended. Some quick release means of applying friction to hold the rudder bar in a selected position should be incorporated.

It is important that the movement of controls in the cockpit should be compatible with the desired movement of the craft.

It seems best in most instances to have full foot-operated controls in an attempt to allow hands to be available for duties other than control of the craft. There are always occasions when hands are needed to do something like map reading or taking refreshment, and in the worst conditions for bracing against the cockpit's sides.

On a small hovercraft, one- to two-seater, a fail/safe throttle control could perhaps be provided, i.e. should the occupant be flung out of the craft in an accident, the throttle should close automatically. Otherwise twist grip throttles appear to be attractive or, alternatively, a forward/aft movement quadrant arrangement.

Should skirt lift be employed on very light ACVs, the manual forces required will certainly be within any normal person's capability. In fact, there is little reason for manual control loads to be anything but light in craft up to weights of 5000 lb (2270 kg).

For craft which may be used for utility purposes as opposed to pleasure purposes, some operations may involve long endurance runs in beam wind or other conditions requiring continuous application of rudder. Some form of spring-loaded artificial centering system would be helpful, as used on the military SRN6, so as to relieve rudder pedal loads in such conditions. Another tiring condition which may arise with ACV rudder controls can exist in tail-wind conditions when, if the wind is strong, the rudders can be forced over to full deflection, calling for a continuous physical exertion to hold them in any intermediate position (Ref. 31).

Considerable attention should be paid to the layout of cockpit controls to see that at their full deflection they can all be reached by the hands and feet without involving body movement.

The ability to anticipate required controlling actions and to respond to various stimuli is obviously called for in order to achieve safe and efficient control over craft movements.

Throttle movements and linkages should be designed so that engine power is not sensitive to very small adjustments. On CC7 a twist grip throttle on a lever operated by the right hand tended to rotate when the lever was pulled backwards, thus closing the throttle. This rotation was the result of a hand movement automatically resulting from the arm movement.

Hand and foot controls should move in directions which are natural for the driver; in simple terms, one pushes the control in the direction that one wants to go. Further, controls should be placed in such positions that the driver knows where they are without having to look, that is when reaching for a control his hand will come naturally to it and operate it again without looking. Movements of controls should bear some relation to the craft and engine response resulting from their use. For instance, a fingertip throttle movement of ½" (1.27 cm) from idle to full throttle would be particularly unsatisfactory and a hand control swing of, say, 18" (45.72 cm) to provide the roll of the craft would be unsatisfactory.

The basic practices of good human engineering are well documented and may be applied to the new technology of air-cushion vehicles. The reader is referred to Ref. 37 for a full treatment of the subject.

10.2 Instrumentation

Ref. 36 is a brief report on the recommendations of a working party consisting of four experienced ACV pilots, set up to make suggestions for a standardised hovercraft instrument layout and cockpit layout for a hovercraft of SRN6 size. A number of the points raised are applicable to the larger craft in the range studied in this report up to 5000 lb (2270 kg) weight (e.g. the Hovermarine Hovercat) and have therefore been extracted and are included here.

In order to navigate with accuracy and handle his craft safely within its operation limitations, the report recommends that the driver should be provided with the following data:

a. craft heading

b. craft water speed

c. angle of drift

d. craft attitude in pitch and roll

e. relative windspeed and direction.

Craft heading:

Heading reference is a basic and essential requirement which can be most simply provided by a magnetic compass. (It should be remarked here that this is not so in the far North and a solution to this problem, certainly for the larger craft, is the Range Positioning System (RPS) developed by the Motorola Government Electronics Division. The system determines the X-Y coordinates of a vehicle (airborne or surface) in an arbitrary coordinate system from the RPS range-range data. Additionally, the deviation from a preselected course is determined and presented on a steering indicator so the craft can be kept on course.)

Craft water speed:

Water speed information is required for navigation and for correct control of the craft when approaching beaches or slipway ascents. The latter is particularly important at night. The speed information may be obtained from a doppler source.

Water speed should be displayed on a conventional round-faced moving pointer instrument, reading in knots.

Angle of drift:

Some direct indication of drift is important to supplement pilot judgement, both for accurate navigation and to ensure that craft operating limitations are not exceeded.

Drift angle should be displayed on a round-faced instrument showing a moving card under a fixed point indicating drift angle in degrees.

Craft attitude in pitch and roll:

To achieve best performance and maximum passenger comfort, the amphibious hovercraft must be correctly trimmed for the prevailing conditions. Roll attitude is easy for the pilot to detect but has a turning effect and causes heading errors. Pitch attitude is less apparent but large departures from the optimum are indicated by skirt contact and loss of performance. Excessive forward trim can contribute to "plough-in" and rapid deceleration. Until ACV development produces craft less sensitive to extremes of attitude, some indication of trim is necessary. Spirit level indicators would serve the purpose if heavily damped, but an indicator forming part of the main instrument display is preferable.

The instrument should be round-faced and combine pitch and roll angle in a dual presentation. The pitch scale should be sufficiently expanded to allow fine trimming adjustments to be made.

<u>Relative wind speed and direction</u>:

It is difficult to make an exclusive case for a relative wind indicator, but the information has enough of a "supporting role" in other areas to justify its inclusion in a basic instrument display. These areas are:

a. To provide the normal wind information required by the ACV driver;

b. as a back-up to the water speed indicator;

c. to support and provide a cross-check for the drift indicator.

Relative wind speed and direction should be displayed in a round-faced instrument having a dual representation. Relative wind direction should be indicated by a pointer, and speed by digital counters. The data source should be an anemometer and wind vane.

<u>Instrument arrangement</u>:

The instrument layout proposed by the working party is shown in Fig. 53. The "basic instruments" should be located in the upper part of the instrument panel to reduce the eye movement required from the pilot's normal line of lookout outside the craft.

10.3 Seating

Tiredness can affect the ability of an ACV pilot to control the craft. With small craft, craft random motions will be more severe in general and accelerations are likely to be relatively greater than for the larger craft. When such craft are used for special utility purposes such as communications, supplies, survey work, etc., journeys of many hours may be called for, for instance, along rivers and over extensive areas of ice, and therefore it seems wise to pay close attention to avoiding unnecessary causes of fatigue. C.B. Bolton of the Royal Aircraft Establishment (Ref. 38) in England has developed bead or "ventile incompressible cushions" which have been found to improve long-term sitting comfort, both in static and dynamic situations. Dr. Lovesey of the Department of Human Engineering at R.A.E. used one of these seats on the Trans-African Hovercraft Expedition and found that he could undertake particular tasks for much longer periods than those seated on more conventional seating. Ref. 39 remarks that reports from users of bead cushions indicate that the discomfort which normally results from sitting in one position for several hours on a conventional springy cushion is considerably reduced. Whereas the pressure points experienced with normal cushions remain practically unchanged, a slight wriggling produces a redistribution of the bead cushion filler and therefore a new support pattern. The bead cushion also has good self-ventilation properties which reduce discomfort.

Ref. 39 presents results from a vibration rig.

The R.A.E. had found that pilots very often were less efficient when fully strapped in than when not strapped in at all and so if some restraint was really necessary, a lap strap seems preferable. In hard-riding craft the comfort of a person sitting on a sponge cushion will be much worse when fully strapped in because the sponge cushion can resonate.

11.0 ENVIRONMENTAL FACTORS

The weather and operating surface with which an ACV must contend determine to a great extent the powering levels for the craft, for thrust, for control and for the cushion. The environment can be taken into account in setting up control standards but there are a number of interesting operational conditions which have now become apparent from the operational experience gained to date.

11.1 Winds

Meteorological wind recordings are normally made at a standard height of 10 meters (32.5 ft). Air-cushion vehicles up to 5000 lb (2270 kg) weight are low in height, as Fig. 3 shows, typically ranging from 4 ft to 10 ft (1.2 to 3.0 m). Because of the wind boundary layer gradient, the wind speed at these heights is only likely to be around 55% to 85% of the value measured at a height of 30 meters (97.5 ft), see Fig. 54.

The gradient curve for a large expanse of smooth water shown in Fig. 54 indicates higher wind speeds near the surface than over grass fields. Over normal rough water, however, this difference would be less. Similarly, rough ice and snow surfaces will generate rather thicker wind boundary layers. A fairly general observation has been that winds will be found to influence craft behaviour much more over land than over water. This result, however, is mainly due to the much greater surface contact when operating in winds over water and, in some instances, it is due to a higher level of gustiness experienced over land. With some form of surface contact device overland, wheels or skids for instance, controllability could be improved in winds.

11.2 Snow and ice surfaces

Visibility in over snow operations has been a problem on a number of occasions. In particular, when travelling downwind over snow, the craft may become surrounded by a cloud of snow generated by the cushion escape air. This condition can result in a complete loss of visibility and was experienced during SRN6 trials at Churchill in Northern Canada, Ref. 40. The extent to which snow is blown up around the craft by cushion air is likely to be very much less severe at cushion pressures relevant to small ACVs, see Fig. 7, since the amount of snow disturbed is a function of the discharge flow velocity beneath the skirt.

Operating over deep snow can cause problems. An ACV should move away quickly from a standing start as otherwise there is a risk of the cushion flow literally digging a hole beneath the craft. A discussion of this problem is given in Ref. 17 which presents results of tests with a Bell SK-5 with a peripheral-jet skirt.

When operating over hard flat snow or ice surfaces, very high speeds are possible since skirt contact drag will be negligible. At the same time, visibility may be difficult and hence the ability to change craft heading quickly or to brake and to come to a standstill in a short distance is essential. During operations on the Mackenzie during the break-up period, puff ports were found to be very useful for obtaining a quick response, despite the very small forces generated by them.

During SRN6 trials at Churchill, Ref. 31, pilots commented on the apparent loss of rudder control when travelling over land, snow or ice. The rear skirt bags of the SRN6 seemed to give little friction with the surface in relation to the "feel" experienced over water and the rudders seemed dead or slow to produce a turning action. Skirt lift and puff ports were therefore considered to be a necessity for this craft when operating over solid surfaces. Because of the reduced surface friction, the pilots found that finer and much more frequent and pre-planned manoeuvres were necessary.

11.3 Rapids

The ACV has been shown to be capable of safe operations over rapids on a number of occasions at Lachine in Canada, on the Amazon, and on the rivers in the Himalayas and Africa. By keeping maximum cushion height, minimum disturbance from the water surface is felt by the craft. The following extract is from a report on the Trans-African SRN6 expedition, Ref. 25:

> "Once again, the hovercraft demonstrated its exceptional performance over rapids. These were a real challenge to the craft and static waves over six feet high were crossed. It was found that the upstream passage was considerably easier than going downstream; the craft was more controllable into the current and the surface wind the rapids cause, and also the pilot was able to see hazards, such as rocks or violent turbulence, which would be masked on the downstream trip."

Probably the surface gradient in the downstream direction also reduces the controllability of the craft but it appears from reports on operations over rapids that control is not unduly affected.

11.4 Operation through surf

To some extent it is possible to draw upon experience with relatively large craft operations in order to indicate handling practices which could be applied to smaller craft, though it should be borne in mind that there are many opinions on handling.

Ref. 41 suggests that in operations through surf (SRN5 and SRN6 trials) in really small waves of the order of cushion depth it is safe to head straight out to sea, accepting the occasional impact on the bow of the craft which had little effect on the overall speed of advance. For appreciably larger waves, it is best to head the craft at about 45° to the wave front, enabling the craft to climb and roll safely over spilling surf up to heights of about $2\frac{1}{2}$ times cushion depth. By avoiding impacts it is possible to keep above hump speed.

Coming into shore it is possible for the craft to station itself in the trough between two rollers and maintain speed in this smooth water area right into shore where it can accelerate through the broken water and run up the beach.

An entry angle of about 45° to the surf line is recommended in Ref. 42 (leaving the beach above hump speed) and then, if a break can be seen in the next approaching wave front the craft should be taken through. This procedure can be repeated through further waves until the craft is able to ride safely over them.

Coming ashore in surf conditions is best done by taking up a position in one of the wave troughs just behind a proceeding wave line. Ref. 42 quotes an average wave front speed proceeding inshore as about 12 knots (22.2 km/hr). Good directional control is required in this situation and a technique which may prove necessary is to reduce cushion air so as to drag the skirt in the water and then to use more thrust in order to give the directional control surfaces more effectiveness without increasing craft speed. The craft should be accelerated up the beach, well clear of the breaking waves, otherwise there is a real risk of the craft skirt being caught in the undertow from the breaking waves, pulling the craft back down the beach and exposing it to the full force of the next breaker.

Another opinion as to the best technique for coming ashore through surf is given in Ref. 43 which disagrees with the above suggestions. In Ref. 43 it is strongly advocated that when coming ashore in surf conditions the approach should always be above hump speed and that whilst the craft will tend to decelerate and plane on the top of each curler, intelligent use of power and trim will assist the craft over the wave towards the beach. This technique is felt to offer far less risk of "broaching" and above the hump the craft may also safely surmount the under-tow of sand and shingle-laden water.

The above two opinions illustrate once again the differences which exist when handling techniques are discussed by experienced pilots of ACVs. Also these opinions indicate how fluid the present state of the art is as far as control and handling are concerned. The importance of defining the environmental conditions, however difficult and tentative this may be, is again emphasized.

With small ACVs below 5000 lb (2270 kg) in weight, craft inertias are low and violent motions could result if care is not taken in surf conditions. In fact, except for the largest craft in the range it would be wise to avoid operations in all but the slightest of surf conditions.

11.5 Ice accretion on ACVs

When craft are operated over water in conditions just below freezing, a steady build up of ice can occur from the spray generated by the cushion. Protuberances in particular are likely to suffer from a rapid build up and two main control effects result. Firstly, a film of ice may build up over the whole structure if wind and spray patterns combine adversely. Secondly, control surfaces may be affected, both by becoming coated and possibly being jammed if icing becomes severe and the control is not in constant use. The first effect may increase the weight of the craft by 20% or more and unless de-icing and/or anti-icing techniques are used, sufficient installed power should be allocated in the design to cover the eventuality if the craft is intended for operation for much of the time in areas where icing will be prevalent. The second effect will require special attention during design, both from the point of view of avoiding obvious features leading to freezing up and also to minimise the extent of accretion.

Some indication of the extent of the problem is given by figures recorded during the Churchill trials of the SRN6, Ref. 31:

Date 1968	17 Jan	18 Jan	30 Jan	1 Feb	2 Mar	6 Mar
Air temp. °F	9	- 10	- 21	- 34	15	5
Water temp. °F	30	30	30	30	32	32
Wind speed mph	15	14	10	10	20	12
Sea smoke	Patch yes	Yes	Dense	Yes	Yes	None
Propeller	Spinner only	Nil	Nil	Nil	Spinner only	Nil
Rudder and elevator lower leading edges	3/8"	¾"	½"	3/16"	Nil	1"
	0.95 cm	1.9 cm	1.27 cm	0.48 cm	-	2.54 cm
Rudder and elevator upper leading edges	Nil	Nil	Nil	1/16"	Nil	1/8"
	-	-	-	0.16 cm	-	0.32 cm

Ice accretion was never considered alarming on these trials but a recommendation was made that pilots should employ techniques which raise as little spray as possible. De-icing methods should be provided to deal with rapid ice build-up conditions, particularly on controls.

Another aspect of icing and freezing which should be watched carefully in the design stage is the likelihood of control cables, slides, pulleys and associated systems, either becoming restricted in movement or jamming solid.

12.0 SAFETY ASPECTS

Without acceptable control and guidance properties ACVs can in no sense be considered as safe. At this stage in the development of ACVs no effective control standards have yet been set and, fortunately, few accidents have occurred. Those that have occurred have been more concerned with cushion behaviour over varying surfaces, such as smooth-water plough-in and ice-to-water transition, than with collision avoidance, although there have been a number of less serious accidents in this category. It should, however, be recognised that very few ACVs are yet operating in relation to other forms of transport and recreational vehicles, and judged in this light there can be no complacency over the safety record to date. Positive directional control and effective braking is essential for safe operation and research and development effort in this area is necessary now in order to ensure that when craft begin to appear in large numbers they will be safe and well-proven designs.

With small recreational ACVs particular attention should be paid to protection of the occupants in the event of the craft being in collision. Avoidance of sharp edges and projections in the cockpit area is necessary and grids should be fitted over propeller and fan intakes. Care should be taken also to see that control surfaces, puff port doors, control cables and linkages, that are exposed to people handling the craft do not endanger fingers. Starting handles should be so positioned that scarves cannot possibly become entangled with rotating machinery. While control loads may be tiring for operators of some craft, starting loads of some engines can be excessive and this point should be watched in relation to heart attack risks. Similar risks can arise if controls are insufficient to keep craft clear of becoming stuck in difficult areas, when extreme physical exertion may be used in an attempt to free the vehicle.

Because ACVs can travel in areas inaccessible to other types of vehicle, rescue aspects have a special significance. Very light-weight mobile VHF-FM transmitter-receivers are now available (weight less than 8 lb) (3.6 kg) which would seem to fit in very well with the needs of small ACVs operating far from base.

12.1 Snowmobile Accident Experience

Although there are many dissimilarities between ACVs and Snowmobiles, the accident record has not been good for Snowmobiles and some of the situations which have resulted in accidents to them could well be duplicated for light recreational ACVs. The following review is extracted from Ref. 44:

"The National Safety Council, Inc. (NSC) has published an informal report of available information on snowmobile accidents for the 1970-71 winter season. Data were obtained from newspaper surveillance, individual reports to NSC, verifications (in some cases) by vital statistics, bureau reports, and with the co-operation and assistance of State officials and agencies. This rather involved procedure was necessary in the absence of official reporting of snowmobile accidents to any central agency.

"The NSC report shows at least 102 snowmobile deaths in the 1970-71 season, compared to 84 for the 1969-70 season and 54 the year before that. Included in the reports were 428 persons injured in the 1970-71 winter compared to 306 the year before. NSC did not report exposure data.

"According to the International Snowmobile Industry Association of Minneapolis, Minnesota, there were in 1971 approximately 1,022,000 snowmobiles registered (or estimated) in a total of 31 States. In the combined States of Michigan, Minnesota, New York, Wisconsin and Illinois, for which States NSC reported a total of 82 snowmobile deaths in 1970-71, there were 677,000 snowmobiles. This would average out to one fatality for each 8,250 machines. Based on this average, the national total would have been about 124 fatalities. That the NSC figures were probably on the low side is supported by the fact that NSC reported no deaths for 13 States which had a combined snowmobile population of over 117,000 machines.

"A study conducted in the State of Maine during three winter periods (1968-69, 1969-70 and 1970-71) and which is continuing under the joint operation of the Maine Department of Inland Fisheries and Game and interested private persons, has indicated the rate of growth in the sport of snowmobiling which may be indicative of its national growth. In the winter of 1969-70, some 29,000 machines were registered under

"Maine law (no registration required if the machines are used entirely on private property). By the winter of 1971-72, this number had grown to 50,000 machines excluding many thousands used on private property only.

"Maine found that 215 persons were injured in the winter of 1970-71, and four persons killed. Thus, based on Maine's experience, the injury to fatality ratio is of the order of 50 to one. If this is applicable everywhere, there would have been approximately 6,000 snowmobile accident injuries in the nation as contrasted with the 428 reported by NSC for 1970-71.

"Maine reported that the causal factors most commonly identified were, in descending order: travel too fast for conditions, operating in unfamiliar area without reasonable caution, mechanical failure, operating on a public way, inattention, striking unseen object, or being thrown from machine. No details of causes were reported. Parts of the body injured were lower extremities (37 percent), head and neck (34 percent), upper extremities (19 percent), chest and trunk (6 percent), and back (4 percent). These conform closely to the NSC analysis of injuries. NSC reported that 32 percent of "serious injuries" involved the head and neck but that 80 percent of the fatalities involved the head and neck.

"NSC reported that at least 14 deaths (1970-71) were from drowning, which points up a specific hazard of operation on rivers and lakes. Two deaths from exposure illustrate the wisdom of the "buddy" system (operation in pairs) in travel off the beaten path. The high ratio of deaths from head and neck injuries attests to the need for helmet use. NSC reports of snowmobile injuries and fatalities by age groups cannot be interpreted because of the lack of pertinent exposure data. Absence of any licensing requirement (other than a minimum age level) or formal accident investigation (or reporting) procedures obscures the significance of the raw data on accidents, injuries or fatalities; accident causation or interactions of the driver/vehicle/environment factors cannot be determined on the basis of available data.

"Exemplifying the diversity of factors involved in snowmobile crashes (and fatalities) are four Maine accidents which are summarized:

"1. On December 10, 1971, two young girls, high school students, were riding together on a snowmobile which became stuck in a snowdrift. While they were trying to free the vehicle, by pushing it with the motor running, one girl's scarf became entangled in the drive mechanism and drew her into the machine. She was strangled.

"The machine had the usual engine cowling but the addition of a simple screen-type guard would have prevented "this tragedy. The accident illustrates the hazard of wearing clothing or accessories of a type that might become entangled in the equipment or which can snag on environmental posts, wires, or branches.

"2. On Christmas Day, 1971, a 61-year old experienced snowmobile operator was travelling on a local lake, with which he was known to be familiar as he had warned other snowmobilers of hazardous ice patches. Despite his experience and familiarity, he ran onto a dangerous patch and drowned when his machine went through the ice.

"The especial hazard of snowmobile operations on ice is demonstrated in this accident. Changing currents, especially during mild spells, can drastically alter the thickness of ice almost over night. Disregard of the "buddy" system and the absence of any flotation item delayed rescue efforts.

"3. On December 27, 1971, a young man experienced in snowmobile operation, familiar with the area, was engaged in racing at 50 to 60 miles per hour on a local lake front. His machine struck an obstruction which deflected it into a tree on the lake shore. He was wearing an approved-type safety helmet with full face shield; it is speculated that shield fogging may have partially obstructed his view. In the impact, the helmet shattered and fatal head injuries were received.

"The minimal occupant protection offered by snowmobiles, the ease with which control is lost, and the limited protection of safety gear in certain types of crash are all illustrated in this case.

"4. On January 23, 1972, two adult males were riding a snowmobile on a private roadway which had been posted against snowmobile operations. At a turn in the roadway, the snowmobile cut to the left and ran headlong into a pickup truck at the crest of a small hill with such force that $800 damage was done to the truck. One snowmobile rider was injured critically, and the other was dead on arrival at the area hospital.

"That snowmobiles are no match for automobiles or trucks in collisions is graphically illustrated in this crash. Having disregarded the signs prohibiting snowmobile use, the operator compounded his error by travelling on the wrong side of the road in an area with limited view ahead, so that neither driver had a chance to take evasive action."

The above experience is sobering and it should be remembered that the snowmobile has a high degree of control in relation to the ACV, although lack of control is not the sole source of accidents of course. The experience emphasizes the wide range of drivers which must be designed for in recreational craft and the operational conditions which should be avoided. Many such considerations are common to a wide variety of vehicles if they are to be handled safely and the ACV is no exception.

13.0 A DISCUSSION OF A PRACTICAL CANADIAN DEVELOPMENT OF A CONTROL SYSTEM

13.1 Introduction

The objective of a control system is to enable a vehicle to be operated safely by a competent driver. For the class of ACV being considered in this Section, the degree of training must be minimal to meet the economic considerations of the small or pleasure craft market.

When Canive Industries Ltd. entered the air-cushion field in 1968 it was apparent that either the basic French or British patents could be used to design a suitable skirt. However, there was not a control system available that could provide the manoeuverability necessary for a small ACV.

A programme of research and development was initiated to obtain basic data and several experimental vehicles were constructed to evaluate the various design concepts.

This Section summarizes the results of the programme together with subsequent tests carried out by Jones, Kirwan and Associates.

13.2 Integrated lift/thrust system

Unlike Europe, year-round use of ACVs in Canada will entail operation over hard surfaces rather than water.

The results of initial testing indicated that surface porosity such as granular snow, muskeg, etc., could become a major problem to the extent that the cushion could dissipate through the surface under the vehicle without reaching the pressure required to lift the craft.

Although the degree of porosity has not been determined for various surfaces, experience has shown that if a large percentage of the total installed power could be used initially to inflate the cushion, then this problem would be overcome for all the surfaces presently encountered. The technique is to dump much of the propulsion air into the cushion, with the craft being accelerated by the remaining thrust. As the vehicle moves forward, the cushion has less time to dissipate through the surface and more air can be transfered to the propulsion system until the correct relationship between lift and thrust has been achieved. This integrated lift/propulsion system is featured on all vehicles described in this Section and is considered to be part of the control system.

13.3 Skirt configuration

The Bertin concept has been chosen for the test ACVs because the multicell configuration offers better protection against cushion decay over deep ditches, ruts, etc.

13.4 Control requirements

In the absence of any specific regulations governing the performance of small ACVs, the interpretation of "safe operation" was considered to apply to craft whose control system would enable them to avoid obstructions larger than the obstacle-clearing capability of the flexible skirt, taking into account driver identification and reaction time.

It was assumed that in an emergency the engine would be shut off and the craft be permitted to skid along the ground. The cushion decay time would then become a critical parameter in determining skid length.

Perhaps the most important requirement is that the controls are presented to the driver so that they can be moved without any undue physical effort. They should reflect the intended direction of the craft, for instance, if the control is pushed forward, the vehicle should move forward. Every effort should be made to make the system simple and coordination between hands and feet should be avoided where possible. To achieve these requirements, the vehicle must be provided with:

a. thrust

b. reverse thrust

c. side force

d. ability to turn

e. ability to dump propulsion air into cushion.

13.5 BV 101

A test vehicle was built using the suggested design criteria and designated BV 101. It was intended that this wooden rig would provide data for the design of a suitable control system for a projected two-seat vehicle aimed at the pleasure market.

The general layout of the vehicle is presented in Fig.55 and shows a centrifugal fan pressurizing a plenum chamber from which there is one thrust and one reverse duct. Exits in the chamber floor supply air to the cushion.

A control wheel is linked to the two doors through a control box as presented diagrammatically in Fig.56 . The operation of the control wheel is as follows:

a. Wheel in the central position. Thrust and reverse doors and half open giving zero net thrust.

b. Wheel pushed forward. Rear thrust duct door is progressively opened while front door is shut.

c. Wheel pulled back. Front thrust door is progressively opened giving reverse thrust while rear door is shut.

d. Wheel move sideways. Rudders situated in the reverse and thrust ports are moved in the same direction to provide a side force.

e. Wheel moved down. All control doors are progressively shut until all the air is being directed into the cushion.

f. Wheel rotated. Rudders move in opposite directions to give a turning rotation to the craft.

The operation of the mechanism is as follows (see Fig.56): When the wheel is moved forward or rearward it rotates arm "A" pivoting about axle "B" which is rigidly attached to the vehicle. The other end of arm "A" is attached to a cable "W" which connects the front and rear doors such as one opens and the other shuts. Therefore, as the wheel is moved forward the rear door opens beyond the neutral half open position to provide thrust.

A cable shortening device "M" is situated on the cable "W" and consists of three pulleys, the centre pulley being movable so that the distance between it and the other two can be changed, thereby lengthening or shortening "W" as required. If the three pulleys are moved closer together, the cable will effectively lengthen and cause both the front and rear control doors to shut progressively until all the fan discharge is ducted into the cushion. The device "M" is activated by movement of the control wheel in a vertical direction; this changes the distance between the two securing points of the inner and outer sections of a conventional "Bowden" cable shown in Fig. 56 as "X" and "L".

If the wheel is rotated, it rotates axle "E" in housing "D" and causes arm "G" to rotate in a similar direction to the wheel. The upper point of arm "G" is attached to rod "O", bell crank "Q" and via another rod to rudder "R". Similarly, the bottom point of arm "G" is linked to rudder "S". Therefore, if the wheel is rotated the rudders are moved in opposite directions to provide a turning movement to the vehicle.

If the wheel is moved sideways, arm "G" also moves sideways causing the rudders to be rotated in the same direction, resulting in a side force being applied to the craft.

13.5.1 BV 101 test results

The BV 101 was tested over snow and ice during the spring of 1968 and clearly demonstrated the need for an integrated lift/propulsion system for this size of vehicle.

The control system provided adequate guidance, especially in close proximity to buildings, but the driver was required to concentrate to maintain a vehicle heading. It would seem that a driver subconsciously favours the use of one hand over the other and as the wheel was pushed forward, for instance, a right-handed driver will also tend to push to the left, giving the vehicle an unrequired side force. It was further found that if the wheel moved forward the hands tended to rest on the wheel which caused it to move downwards and close off the thrust doors, a condition contrary to that desired.

During these tests the period when each control was used was carefully noted and two significant points became apparent. Firstly, it was usual to yaw the vehicle to correct for drift at speed because the application of side force reduced the thrust and hence vehicle speed. Secondly, the effect of soil porosity became negligible over 10 m.p.h. (16 km/hr) and ducting propulsion air into the cushion above that speed was unnecessary. A summary of the tests suggested that the control system should be modified to make it simple to operate during the majority of the vehicle running time, which would be in the open at speeds above 10 m.p.h. (16 km/hr). An additional control for low speed was therefore included to actuate the side force doors and the lift integration device.

Because of the deteriorated condition of the BV 101 and the advanced state of the design of a prototype two-seater, it was decided to abandon further experiments on the BV 101 and introduce the two-stage control system on the BV 102.

13.6 Two-seat BV 102

The specification sheet for the BV 102 is presented in Fig. 57 and shows an ACV 13.0 ft (3.95 m) long and 7.0 ft (2.1 m) wide. A driver and passenger are seated side by side in a cabin in the front of the craft. Behind this is located the central centrifugal fan driven by a single engine situated at the rear. The fan pressurizes a plenum chamber which feeds air to the two reverse and two forward thrust ports. Internal ducts supply air to the cushion.

The BV 101 control system was modified to include the four door configuration. During the redesign a method was found which would automatically close all the doors when the control column was in the "neutral" or the "no thrust" position, thus eliminating the need for a separate lever for integrated lift. However, a separate control was still required for side force. Furthermore, it was believed that the vehicle would have added sales potential if it could be controlled from either of the front seats. The control stick was therefore mounted between the two front seats, which dictated that the wheel must be removed and replaced by a stick that could be controlled by one hand. Side force was achieved by a separate lever also located on the central console.

The main control sequence was as follows:

Stick central.	All doors shut, complete fan discharge being ducted into cushion. No thrust.
Stick forward.	Rear doors open; forward thrust.
Stick back.	Front doors open; reverse thrust.
Stick sideways.	Opposite forward and reverse thrust doors open to provide a turning movement.

The mechanical details of the control box are presented in Fig.58

The control stick "A" is located in a housing "B" which is attached to an axle "C" located in the structure of the vehicle. A cross arm "D" is attached to lever "A". Rods "E" and "F" link two tee pieces "S" and "H" to the ends of arm "D". The ends of the two tee pieces are attached to the four push-pull cables "I", "J", "K" and "L" which actuate the doors. The tee pieces are located vertically by radius rods "Y" and "Z" which pivot about axle "C". When the control is in neutral, all the four cables are in the closed position and the tee pieces are kept up against the control cable steps by springs "M" and "N". As the stick is moved forward, therefore, tube "B" rotates about the axle "C" and causes arm "D" to move downward, which in turn rotates the tee pieces about the pivot in arms "Z" and "Y", since the ends of the tee pieces "I" and "L" must move forward, pulling the c le and opening the rear thrust doors. The sequence is similar when the control stick is moved backwards, in which case the control cables attached to points "J" and "K" are pulled, thereby opening the reverse doors.

If the stick "A" is moved sideways, one end of arm "D" rises and the other lowers, thereby opening the reverse port on one side and the thrust door on the other thereby providing a turning motion to the craft.

13.6.1 BV 102 test results

Tests showed that the new system was much superior to the BV 101 and required much less driver concentration. However, it was found that small movements of the stick sideways resulted in relatively high rates of turn, coupled with the fact that in order to turn, one of the thrust doors required to be partially closed, which reduced vehicle speed. This "course" relationship between stick and craft movement required the average driver to be continuously moving the stick from side to side to maintain a desired heading and it was difficult to achieve maximum speed. The problem was overcome by placing a rudder in each of the thrust ducts and connecting them to a twist grip on top of the stick.

The technique for cruise was to push the stick fully forward so that the control cables were up against stops and the stick could not be moved sideways; maintaining a heading was then achieved by a simple wrist movement to turn the twist grip and hence the rudder.

This modified system permitted the craft to be controlled safely.

13.6.2 Cam box

Unfortunately, some mechanical problems had developed in the system; in particular it was found that grit and dirt could collect on the sliding position of the push-pull cable and increase friction.

This resulted in a condition where the stick could be returned to the neutral position but the spring may not have enough force to pull both cables against the stops. Hence a door could be left fully or partially open and there would be a change in the response of the craft to the movement of the control stick.

A solution was sought whereby the springs could be replaced by a positive mechanical action. The result was a cam box, shown diagrammatically in Fig.59 . The tee pieces were retained but rollers were added to the ends where they attach to the cables. These rollers ran in grooves, the shape of which was defined by a radius of a distance equal to the length between the outer races of both rollers and a centre which was at the outermost part of the race when the tee piece was against both cable stops in the neutral position. Because the vertical distance between the two grooves decreased towards the point where they joined, and because the distance between the two rollers was mechanically fixed, the tee piece must swing about one of the rollers when it is up against a stop. The tee piece cannot move forward and will always come up against a stop providing a positive mechanical link between the stick and control doors.

The BV 102 programme was shelved before the control system could be modified, but it was incorporated in the side force door system with great success.

13.7 BV 106

During the development of the BV 102 a larger vehicle, designated BV 106, was being constructed. The specification is presented in Fig. 60.

The integrated lift/propulsion system featured a single engine driving two vertically mounted centrifugal fans located either side of the machine. The fans discharged into scrolls which ducted air to the cushion, the thrust ports located at the rear of the vehicle and reverse and side exits located in the top of the scroll.

Two cam devices, similar to those described in paragraph 13.6.2 were positioned between the forward and reverse thrust doors located on either side of the vehicle. The cam boxes were actuated by levers which only moved fore and aft, selecting forward or reverse thrust on that particular side of the vehicle; turning was accomplished by differential movement of the levers. The side force doors were opened by foot pedals, the right pedal moving the craft to the right and the left pedal to the left.

Each fan fed the stability jupes situated on that particular side of the craft and there was no cross-ducting. Therefore, as side force air was bled from the left hand side, the air flow to that side was diminished and the vehicle rolled. The roll was accentuated by the moment resulting from discharge of the side force air from the top of the scroll. The net result was the roll to the left was sufficient to decrease the hover gap on the left and increase it on the right side, giving a side force from the cushion itself. The concept is shown in Fig. 61.

This method provided a strong side force which proved effective both at high and low forward speeds.

13.7.1 Test results

Initial tests showed that the craft was difficult to control directionally, the problem being traced to the rudder effect of the shut-off doors located in the thrust ducts. From aerodynamic and design reasons the doors were hinged at the quarter chord position and the hinges attached to the frame at the duct exit. Therefore, when the duct was fully open, the trailing sections of the doors were outside the duct and acted very much like rudders. Consider a turn to the left; the thrust from the left duct must be reduced to provide the turning moment due to the unequal thrust between the left and right hand sides. The doors closed off the duct by rotating inwards which produced a rudder effect opposing the turn (Fig. 62).

In the particular case of the BV106, the longitudinal distance between the thrust exit and the centre of gravity was greater than that between the duct and the vehicle centre line, resulting in the turning moment due to the rudder effect of the doors being greater than that from differential thrust for small angular deflections of the doors. This caused the vehicle initially to turn in the opposite direction to that desired for small movements of the controls; for the mid range the moments were substantially balanced and no turning occurred. With the doors nearly shut the correct turn was negotiated.

This condition was clearly unacceptable. Several door configurations were tried and one in which the two doors in each duct moved opposite ways (Fig.63) was acceptable from a performance consideration. However, in the event of a control linkage failure the doors would open resulting in an unsafe condition. The two doors were replaced by buckets (Fig.64) which transferred the aerodynamic load back to the hinge point for all door open positions resulting in little effort being needed to move them. A light spring ensured they would shut if the linkage failed, thus meeting the safety requirements.

Tests proved that the mechanical and control aspects of this system were good but that the driver should be required to operate only one lever. A control box similar to the BV 102 was considered but was not installed.

For similar reasons to the BV 102, two rudders were located in the thrust duct exits and controlled by a twist grip on the right hand lever.

13.8 BV 104

The results of a market survey, supported by the lack of sales of other small ACVs, indicated that pleasure craft were not yet at a stage where they had gained public acceptance. However, the analysis did show a possible potential for a small commercial vehicle with four or five seats or a half-ton payload capability.

A cost effectiveness study suggested that the cost, weight and maintenance could be substantially reduced by replacing the two centrifugal fans and scrolls of the BV 106 with a single axial fan and shroud.

The integrated lift/propulsion system was still considered desirable and a fan was selected with characteristics that would avoid stall when the flow was reduced by shutting off the reverse and forward propulsion ports.

The vehicle specification is presented in Fig.65, and the details of the control doors in Fig. 66.

By reference to Fig. 66 it can be seen that the circular duct in the plane of rotation of the fan changes shape until at the rear of the machine it is nearly square. A scoop is situated in the centre to duct air into the cushion.

The control doors consist of two concentric buckets pivoted on a common axis and located in the thrust duct, the thrust was reduced by swinging the inner bucket across the thrust duct. Reverse thrust is obtained by also swinging the outer bucket across the thrust duct, thereby exposing a series of deflectors to turn the flow and discharge it forward at 45°. The control box in the cabin was similar to the BV 102 with a control stick actuating four push-pull cables.

There was a slight change to the operating technique because as the two thrust ducts were so close together there was little turning moment due to differential forward thrust. The real turning force came when reverse thrust vector was used to provide the turning moment. The magnitude of this force was approximately 25% of the total thrust.

Tests showed that rudders were required at the high forward speed and these were actuated by the conventional twist grip on the control stick.

Analysis of the installed fan and duct characteristics indicated that the fan was close to stall when all the doors were shut, and there was little increase in hover gap between all doors shut and the reverse doors open. It was therefore decided to simplify the control system further by eliminating the reverse doors, neutral position now being when the reverse thrust equalled the forward thrust.

The two-cable control box is presented diagrammatically in Fig. 67.

13.8.1 <u>Side Force</u>

The duct layout precluded the side force air being supplied from anywhere except the cushion. The magnitude of the force was below 2% of the vehicle weight and its effect on the guidance was negligible. Because of the folding sides of the BV 104 the mechanism of a side force control located in the sponsons became somewhat complex and it was decided to exclude this feature from any production craft.

13.8.2 <u>Wheels</u>

The test results had shown that some method must be included in the control system to stop sideways movement in a cross-wind, etc., when in confined areas. An alternative to side force was through ground contact by wheels. An undercarriage was therefore fitted to the BV 104 that could be raised and lowered by hand from the cabin, and the ground pressure could be adjusted to take up to 10% of the gross weight. It was found that below 5% the tyres would not make sufficient contact with the ground and a considerable amount of skidding occured resulting in excessive tyre wear. At 5% and above, excellent tracking was maintained in side-winds up to 40 m.p.h. (64 km/hr) on a runway surface, and sharp 90° turns were executed at speeds below 20 m.p.h. (32 km/hr).

A cost effectiveness study showed that the cost difference between including side force or an undercarriage on a vehicle was negligible, and the wheel assembly resulted in approximately 50 lb (23 kg) increase in weight. During the test it became apparent that considerable advantage would be gained by strengthening the undercarriage and using it when trailing or moving the vehicle without the cushion. This modification was introduced at the cost of a further 40 lb (18 kg).

The only operational problem encountered was with the lowering and raising mechanism. It was found difficult for the driver to try to maintain station in windy conditions and at the same time adjust the undercarriage.

13.9 C 105

The C 105 was designed by Jones, Kirwan and Associates as a production vehicle capable of carrying a driver and four passengers or a half-ton payload. It was fundamentally a stretched BV 104 and incorporated all the experience gained in previous vehicles. The control box was a productionized version of the two-cable system and was located centrally between the two front seats. A two-bucket door configuration was used for thrust and directional control. Rudders were also fitted but experience on the other vehicles had shown some wrist fatigue if a twist grip was used on the control stick; rudder bars were therefore introduced.

The undercarriage was redesigned to be lifted by an electric winch in the cockpit. The assembly weighed 5% of the vehicle weight and dropped under its own weight. Two locking devices were swung into position when the vehicle was on the cushion to lock the wheels down for ground handling with the engine off.

Some problems were encountered in reverse thrust where the fan swallowed the discharge. This was overcome by repositioning the vanes.

13.10 <u>Summary</u>

Experience gained by some 300 hours of testing had suggested the following criteria for the design of control systems for small Canadian ACVs:

a. An integrated or partially integrated lift/propulsion system should be installed to overcome soil porosity.

b. Two control systems are necessary, one when the vehicle is at speed and an additional control for manoeuvering in confined spaces.

c. The main control system should be actuated by a single stick managed by one hand.

d. Rudders are necessary for small directional adjustments at high speed. The control could be a twist grip located on the main control stick or rudder pedals.

e. The additional low speed control could be either side force or ground contact wheels.

f. Cost effectiveness studies suggested that an undercarriage system was competitive to side force, especially if it could be locked down to permit vehicle handling with the engine off.

14.0 POSSIBLE NEW CONTROL DEVICES

From the work carried out for this study, the following ideas have arisen which are considered to be worth further investigation:

14.1 Optimum positioning and angling of puff ports

For maximum effectiveness in yaw, puff ports should be at the extreme corners of the craft and angled to give a maximum moment arm about the centre of gravity. If four puff ports are used as suggested in Fig. 68, then all four, if angled as shown, could be used to execute a yaw manoeuvre. The weight of the puff port installation would be approximately the same but twice the air power requirement would be called for, giving an increase in yawing moment of about 2.3 times present practice for an SRN5 type configuration. This type of arrangement could almost certainly be applied to craft of 4000 to 5000 lb (1750 to 2270 kg) weight and in simplified form to smaller craft.

14.2 Swivelling fin/rudders in ducted propeller slipstream

Multiple all-moving vanes or rudders have been shown to be capable of producing effective side forces for yaw control when positioned in a slipstream as on the MHV Spectra II or in the efflux of a ducted fan as on the Cushioncraft CC7. The vanes are symmetrical plain aerofoils and the lift coefficients they can generate are limited to those corresponding to plain aerofoil characteristics. If these vanes were to be fitted with trailing edge "flaps" then increased lift coefficients could be generated, giving enhanced control forces. The weight might be too great for very light craft, 250 to 500 lb (114 to 227 kg) but acceptable for the larger craft.

14.3 Variable weathercock stability devices

In order to extend operations of light ACVs into higher limiting windspeed conditions, some form of variable weathercock stability device seems to be required to enable craft to be operated with minimum control movements in tail winds in excess of the craft ground speed. A retractable forward fin could probably achieve this, perhaps of inflatable form. Alternatively, boundary layer control might be used on rear-mounted cylindrical fins for the larger craft, being capable of enhancing or destroying fin forces as required.

A variety of vertical fins were tried on Sandpiper (Ref. 28) to examine their effects on weathercock stability and turning. This work led to the belief that an adjustable fin was required to deal effectively with the varying wind conditions.

14.4 Boundary layer control rudders

Greatly increased low-speed effectiveness can be obtained for ACV control surfaces by application of boundary layer control. The question of powering needs some investigation in order to come up with cheap, low cost, low weight solutions, but the basic technology already exists from light planes upwards.

14.5 Reversible-pitch axial-flow fans mounted to rotate in the vertical plane on the sides of a craft

This arrangement shown in Fig. 69 enables a side force to be obtained from the thrust system without of course affecting the cushion system. The efficiency of the "reverse thrust" side force will depend on the blade camber and the shaping of the normal forward thrust duct outlets, as well as the internal duct losses. If the fans are near the centre of gravity of the craft, the combined remaining thrust on the inner fan in a turn and the side thrust of the outer fan should enable a turn to be carried out with rather less sideslip than when craft total thrust has to be vectored to provide a major component of centripetal force. In addition, the rolling moment is likely to roll the craft into the turn.

14.6 Automatic control of wheel loadings

If wheels or similar surface contacting devices are to be used for guidance it is important that the forces which can be obtained from them remain steady and do not fluctuate with craft heave, roll or pitch variations as may occur in gusty conditions. A solution worth exploring is to use an automatic control link between cushion air feed and wheel loading so that wheel guidance forces may tend to remain more or less uniform and dependable.

14.7 Braking for over-ice operations

At the present time most craft depend on using either reverse thrust, or a pirouette manoeuvre or skirt drag for braking. The first method is not particularly effective since propeller reverse thrust is always less than half forward thrust; the second method is potentially dangerous, and the third method leads to high skirt wear costs as well as being not particularly effective over ice.

The idea is suggested here of using some form of braking pad which can be pressed down into the ground surface. The use of steel pins on Swedish hydrocopters to achieve braking over ice may well provide an immediate solution for various craft sizes in the range of up to 5000 lb (2270 kg) weight. While many craft carry considerable weight in ballast for trim and roll control (3½% on an SRN6), there has been a reluctance to carry weight for braking purposes.

A two-stage system could perhaps be devised, as shown in Fig. 70, where for use over earth, gravel, grass type surfaces, a plain hard-wearing curved ski-shaped pad is pressed down for braking, while for emergency use over those surfaces or for ice and snow surfaces a second stage of operation is brought into action. This second stage consists of a pad, the lower side of which is fitted with a number of steel spikes which normally rest in holes in the main brake pad. Upon application of a second stage, the spiked pad moves downwards and the spikes descend and protrude beneath the underside of the main braking pad.

The braking forces available from spikes cutting into ice are not available at the time of writing but some information is on various skid materials used for the landing gear of the North American X-15 research aircraft, Ref. 45. The coefficients of friction over the speed range of 60 knots to 10 knots (111.0 to 18.5 km/hr) tended to vary from about 0.15 to 0.4 at 60 knots (111.0 km/hr) to about 0.15 to 0.7 at 10 knots (18.5 km/hr), for a range of both skid and lake-bed surface types.

An alternative arrangement, especially attractive for craft fitted with longitudinal inflatable roll-stability keels is to provide a steel-studded underside to the keel in conjunction with an internal press-down linkage mechanism. A very heavy duty polyurethane keel undersurface should be provided and internally attached to the linkage in such a way that when braking is not required, the linkage is at a height (within the keel) at least equal to cushion depth. Means must be provided to locate rigidly the flexible braking surface to the internal press-down pad as soon as contact is made.

With both these ideas, strong nose-down pitching moments would arise pointing to the need to position such braking devices well forward of the centre of gravity.

14.8 <u>Side force generation by boundary layer control</u>

This application of boundary layer control has already been examined in Canada, see Ref. 46. Further examination is recommended and in conjunction with the application of boundary layer control to control surfaces, as previously mentioned.

15.0 CONCLUSIONS AND RECOMMENDATIONS

The work conducted during the course of this study has shown that very little attention has been paid to the control of light ACVs (below 5000 lb, (2270 kg)) in comparison with such aspects as performance, static stability, weight, thrust methods and manufacturing techniques.

In addition, few measurements of control capability have been made for light ACVs. Consequently, most of the background data considered during the course of this study has come from tests on larger craft such as SRN5 and SRN6. No substantial scale effect is believed to exist, however, and the principles of control and general findings are applicable to the smaller craft.

It is apparent, especially with small ACVs, that very seldom has any allowance been made for the power requirements of control systems so that performance penalties on many craft are quite severe when controls are applied or difficult environmental conditions are encountered. Ground contacting control possibilities have also been much neglected though they appear to offer a very powerful means for control.

The following specific recommendations are made:

1. Control trials should be undertaken against the Standard Conditions for Control Assessment proposed in this report, or some similar framework. Consideration might be given to using two dissimilar craft, such as one of the Canive ACVs and perhaps the Cushioncraft CC2-003, which could be made available. These trials would be aimed at discovering satisfactory and unsatisfactory

areas of control with the object of working towards the setting up of desirable control standards.

2. Ground contacting wheel systems should be investigated for providing positive steering control wherever surface conditions permit their use. Some system of automatically maintaining wheel loading by controlling the cushion air supply should be investigated also.

3. Design studies should be carried out on over-ice braking systems, following up proposals contained in this report for ice abrading pads.

4. Design studies should be carried out for very simple, two-or-three-position reversible pitch axial fans and propellers, suitable for light ACVs.

5. Boundary layer control possibilities should be examined and practical examples worked out for the generation of enhanced hull side forces and the improvement of control surface forces available at low craft relative airspeeds.

6. The general feasibility of a ground contacting amphibious form of propulsion which can also provide directional and braking control should be studied.

7. The effects of ice build up on the control problem should be examined carefully and particularly in relation to skirt movement systems which offer a good potential for improved control for light ACVs.

8. Skirt shifting and skirt lifting techniques should be fully examined for application to light ACVs and special attention should be paid to icing problems with any arrangements proposed. These same techniques should also be investigated as a complete alternative to weight penalizing ballast systems which are now in common use.

9. It is suggested that a section for a basic light ACV design manual could now be built up covering control and guidance aspects.

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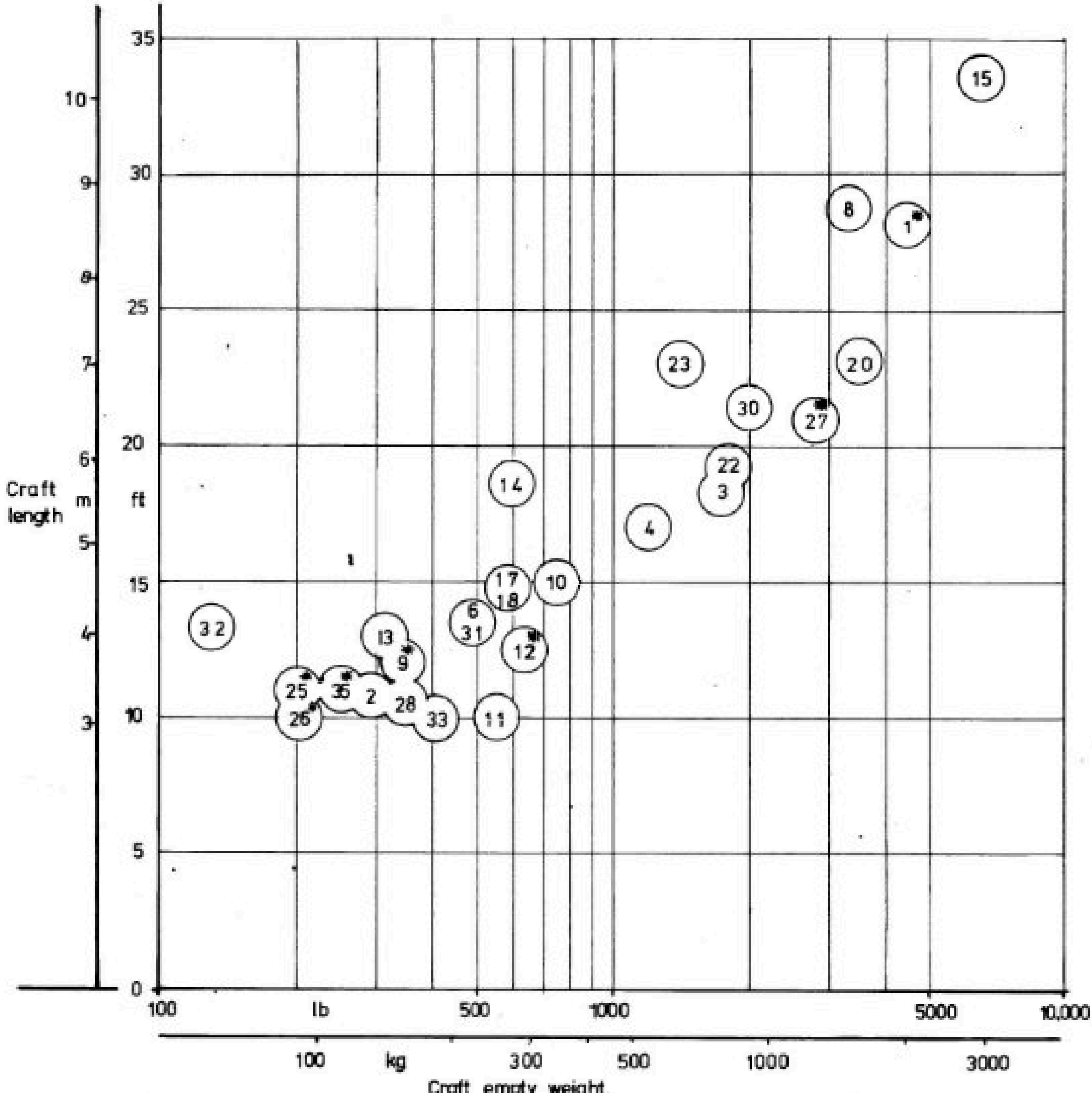
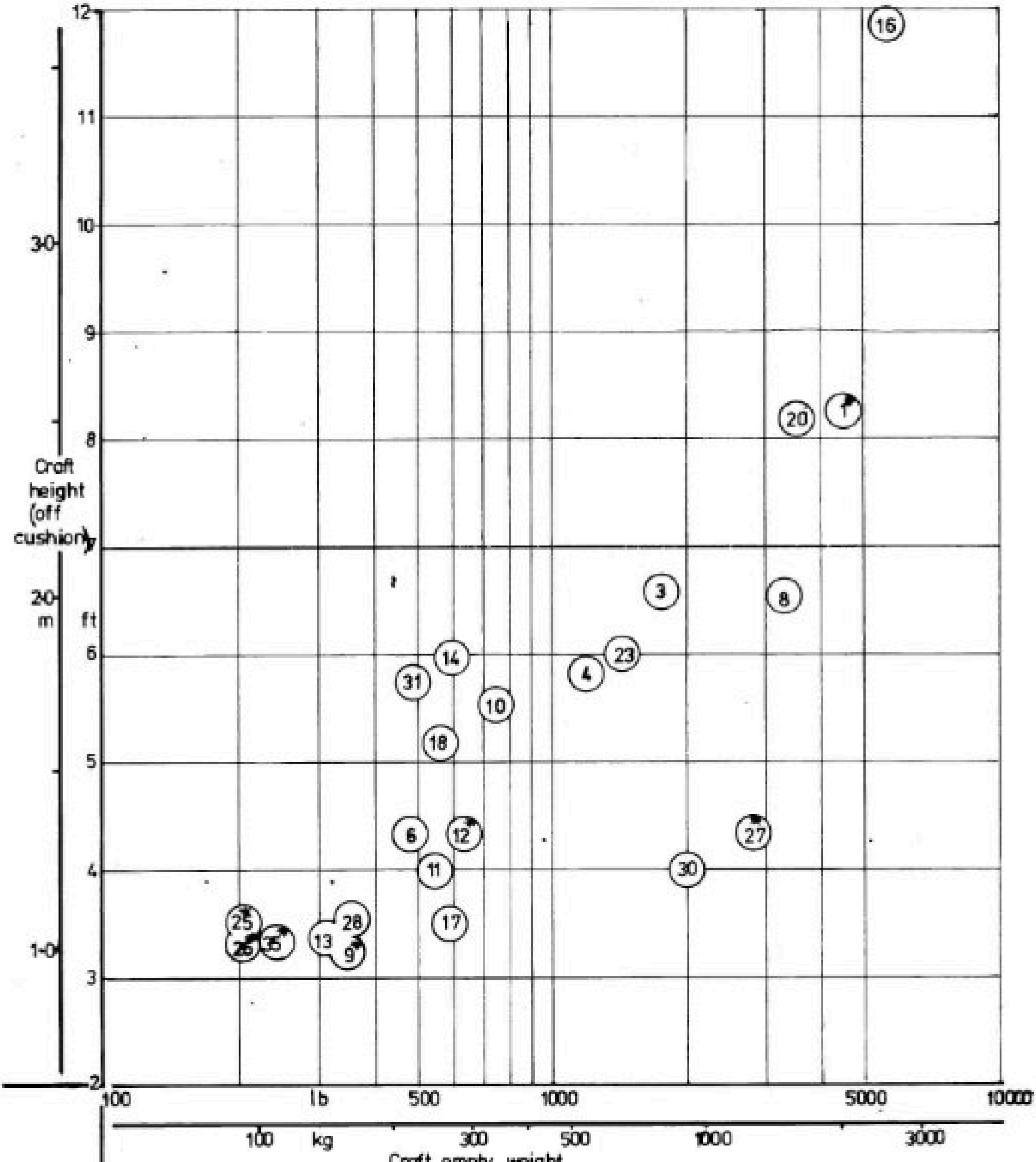


Data points marked thus are taken from manufacturers figures. All other figures extracted from Ref. 3

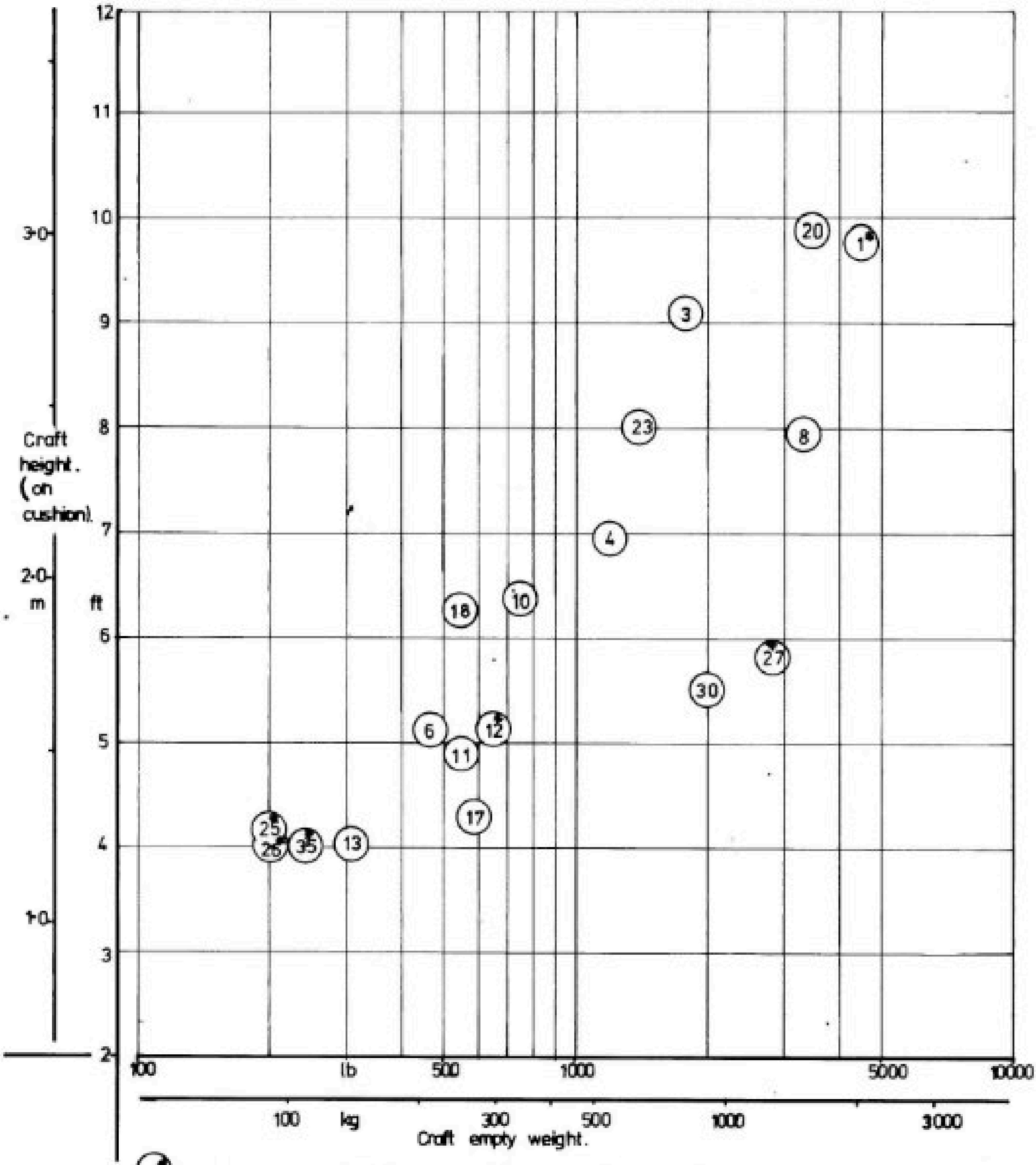
FIG. 1. CRAFT LENGTH vs. EMPTY WEIGHT FOR A RANGE OF LIGHT A.C.V.'s.

(See Table 1)



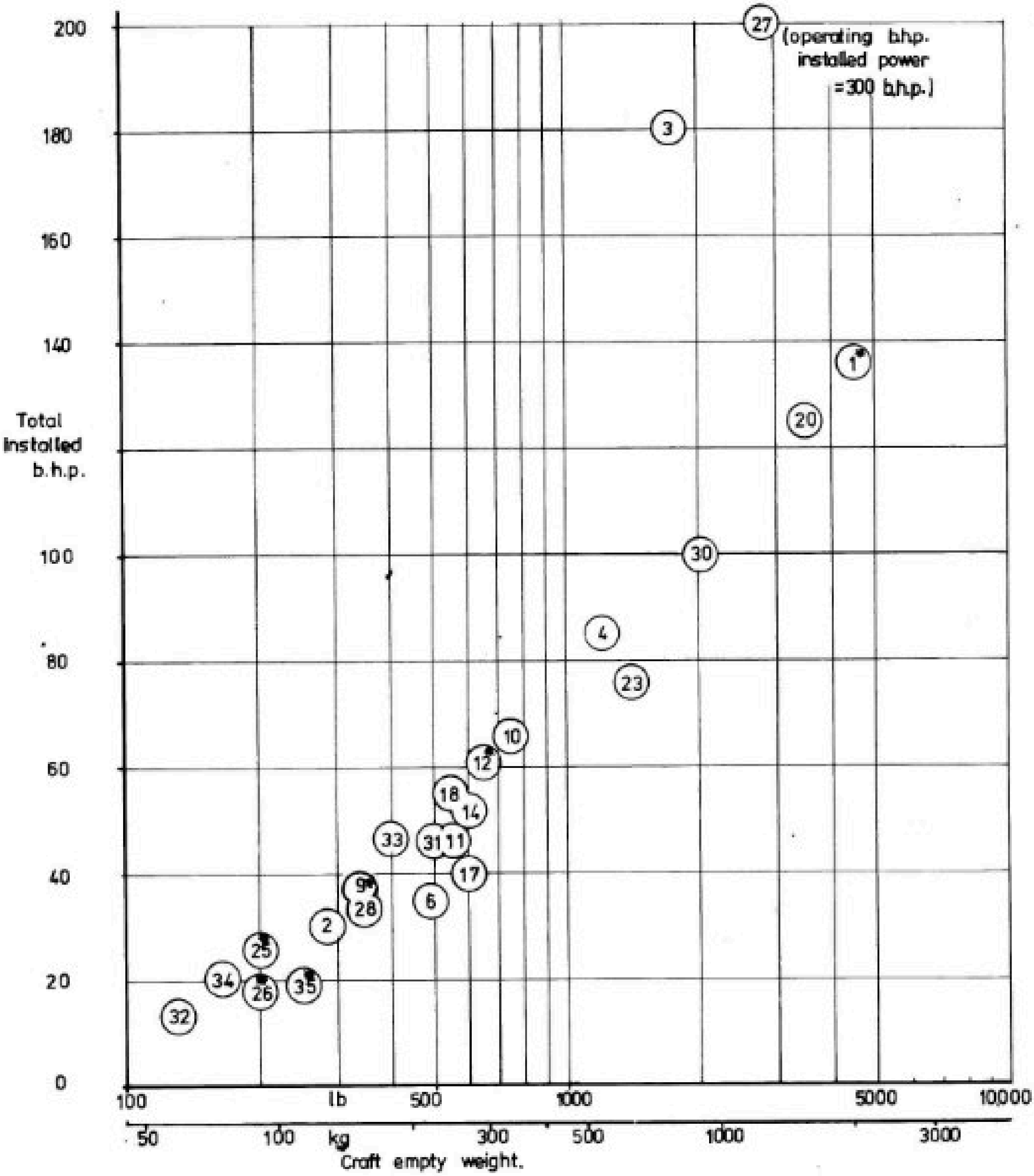
(77) Data points marked thus are taken from manufacturers figures.
All other figures extracted from Ref 3.

FIG. 2. HEIGHT, OFF CUSHION, vs EMPTY WEIGHT FOR A RANGE OF LIGHT A.C.V.'s.



77 Data points marked thus are taken from manufacturers figures.
All other figures extracted from Ref 3.

FIG. 3 HEIGHT, ON CUSHION, vs EMPTY WEIGHT FOR A RANGE OF LIGHT A.C.V.'s.



77 Data points marked thus are taken from manufacturers figures.
All other figures extracted from Ref 3.

FIG. 4. TOTAL INSTALLED POWER vs. EMPTY WEIGHT FOR A RANGE OF LIGHT A.C.V.'s

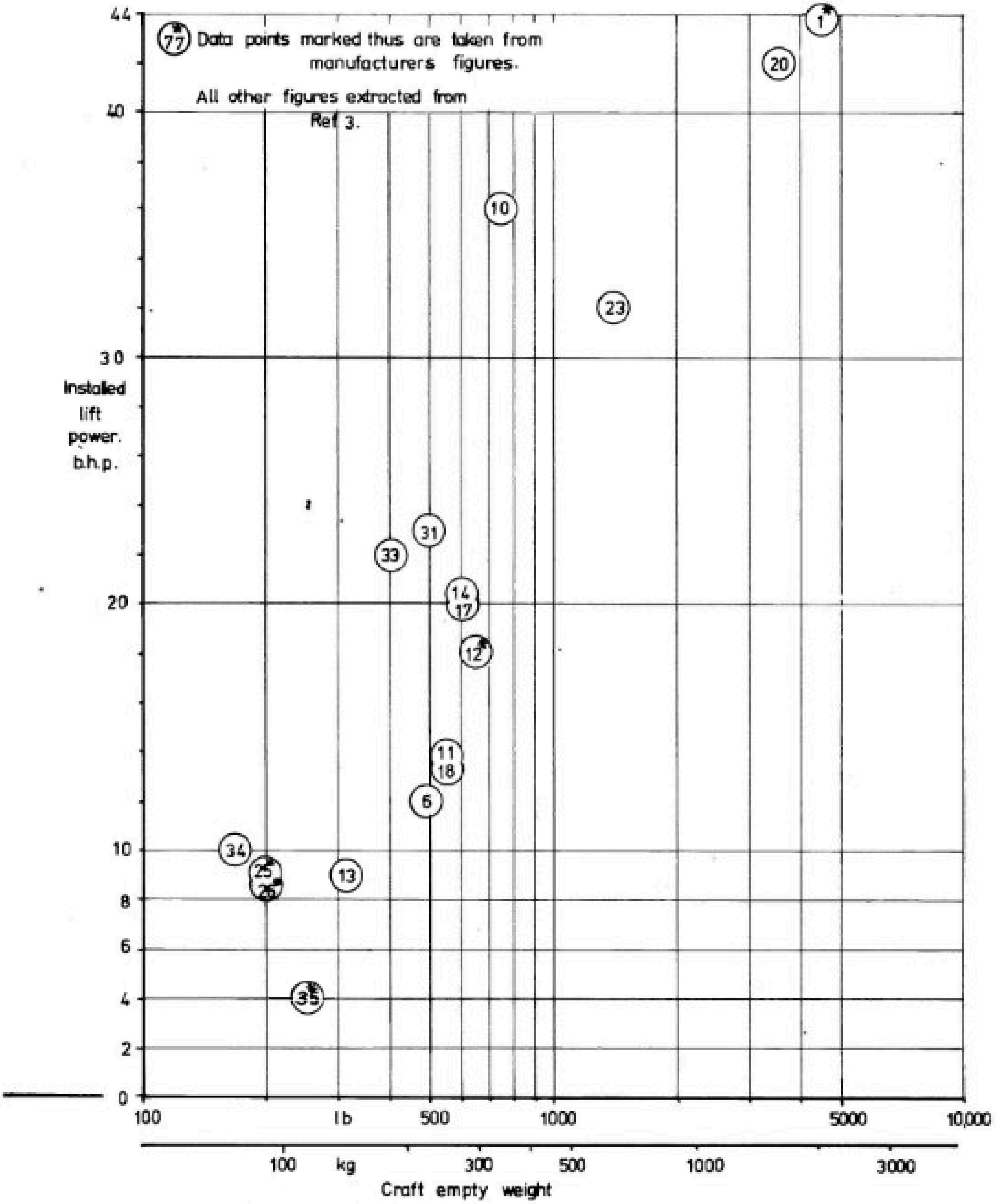
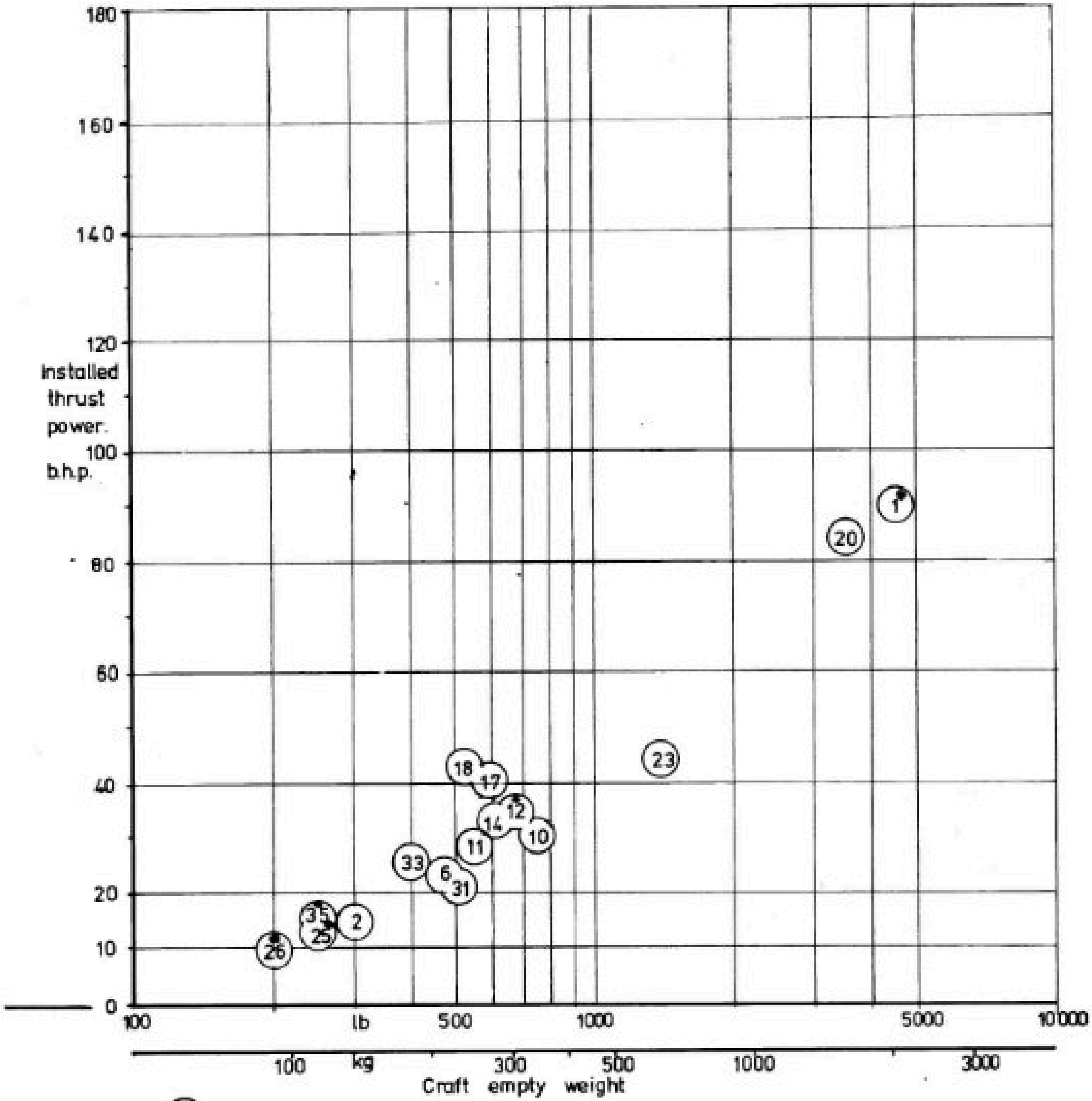


FIG. 5 INSTALLED LIFT POWER vs. EMPTY WEIGHT FOR A RANGE OF LIGHT A.C.V.'s



(?) Data points marked thus are taken from manufacturers figures.
All other figures extracted from Ref. 3.

FIG. 6 INSTALLED THRUST POWER vs. EMPTY WEIGHT FOR A RANGE OF LIGHT A.C.V.'s

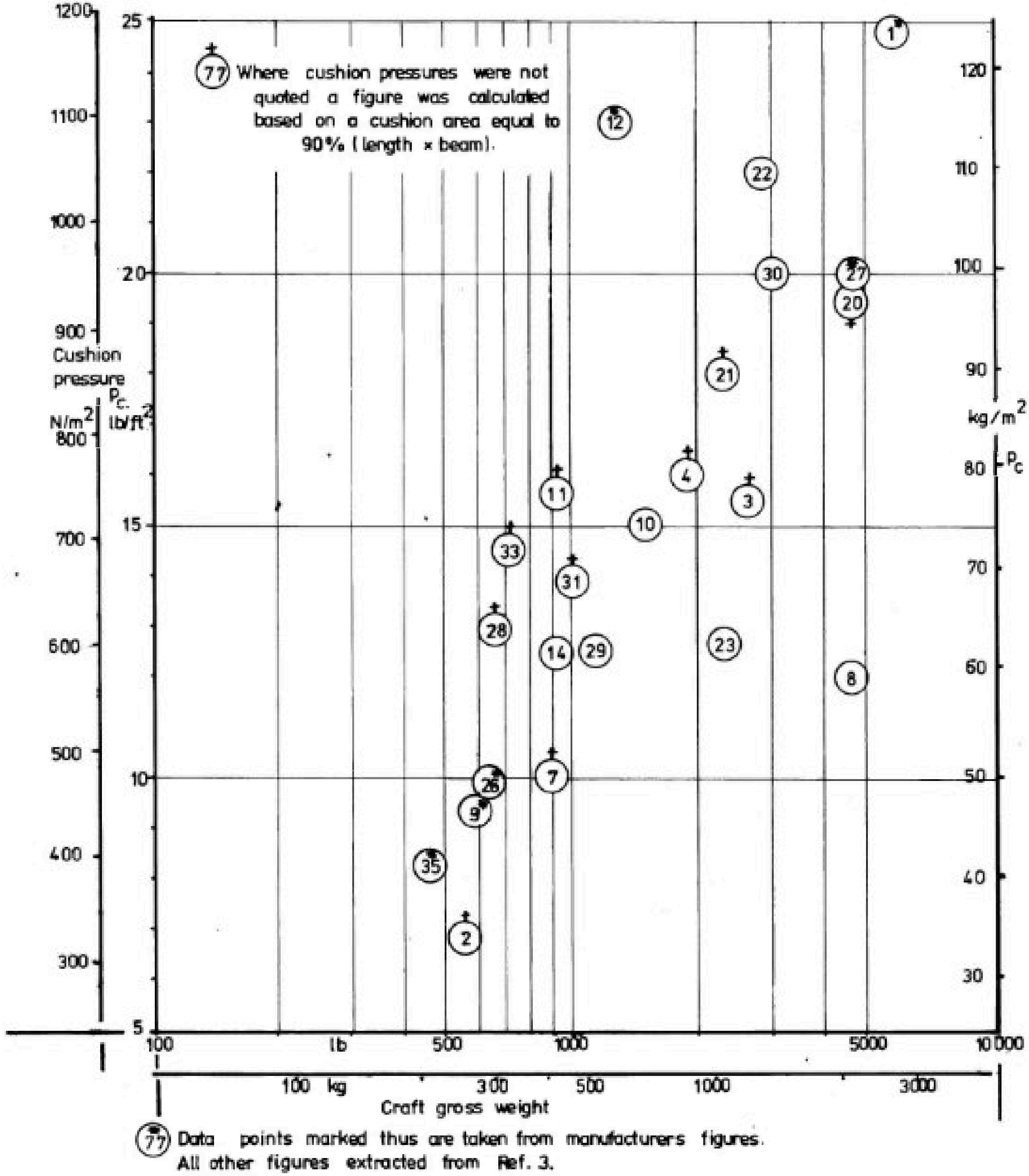
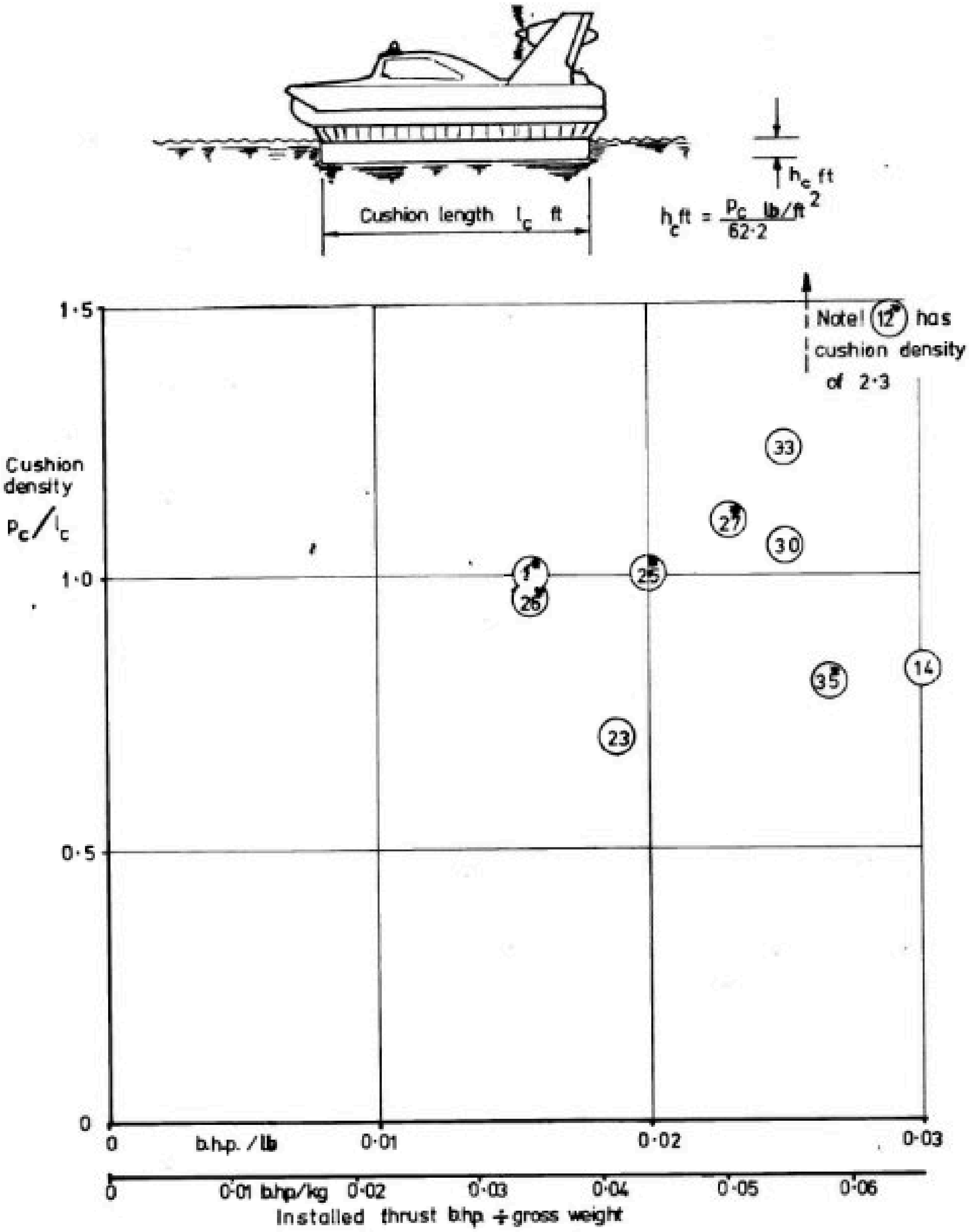
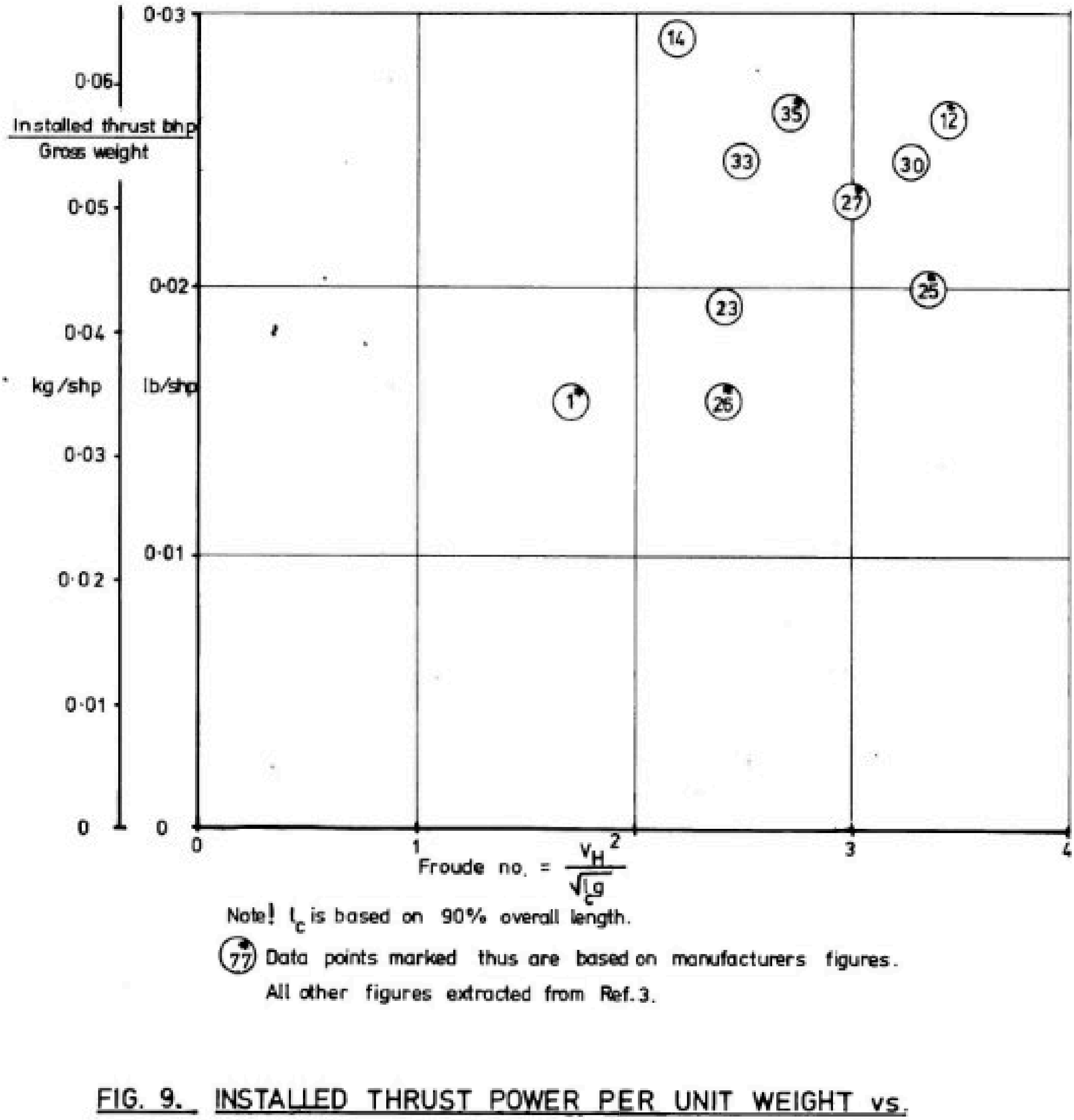


FIG. 7. CUSHION PRESSURE vs. GROSS WEIGHT FOR A RANGE OF LIGHT A.C.V.'s



(77) Data points marked thus are taken from manufacturers figures.
All other figures extracted from Ref.3.

FIG. 8 CUSHION DENSITY vs. INSTALLED POWER PER UNIT WEIGHT FOR A RANGE OF LIGHT A.C.V.'s.



Note! l_c is based on 90% overall length.

(77) Data points marked thus are based on manufacturers figures. All other figures extracted from Ref. 3.

FIG. 9. INSTALLED THRUST POWER PER UNIT WEIGHT vs. FROUDE No. FOR A RANGE OF LIGHT A.C.V.'s.

FIG. 10 HOVERAIR HOVERHAWK Mk.III W.

FIG. 11 HOVERMARINE CANADA SANDPIPER.

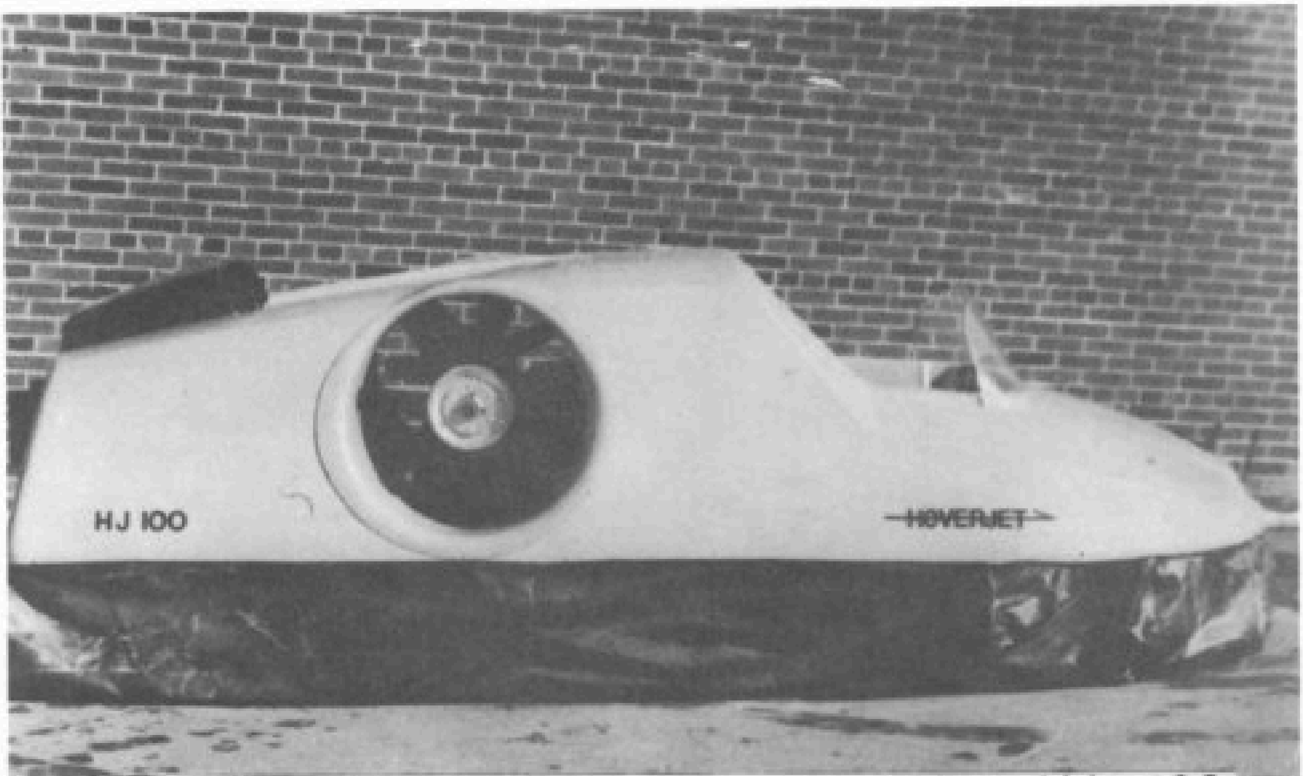


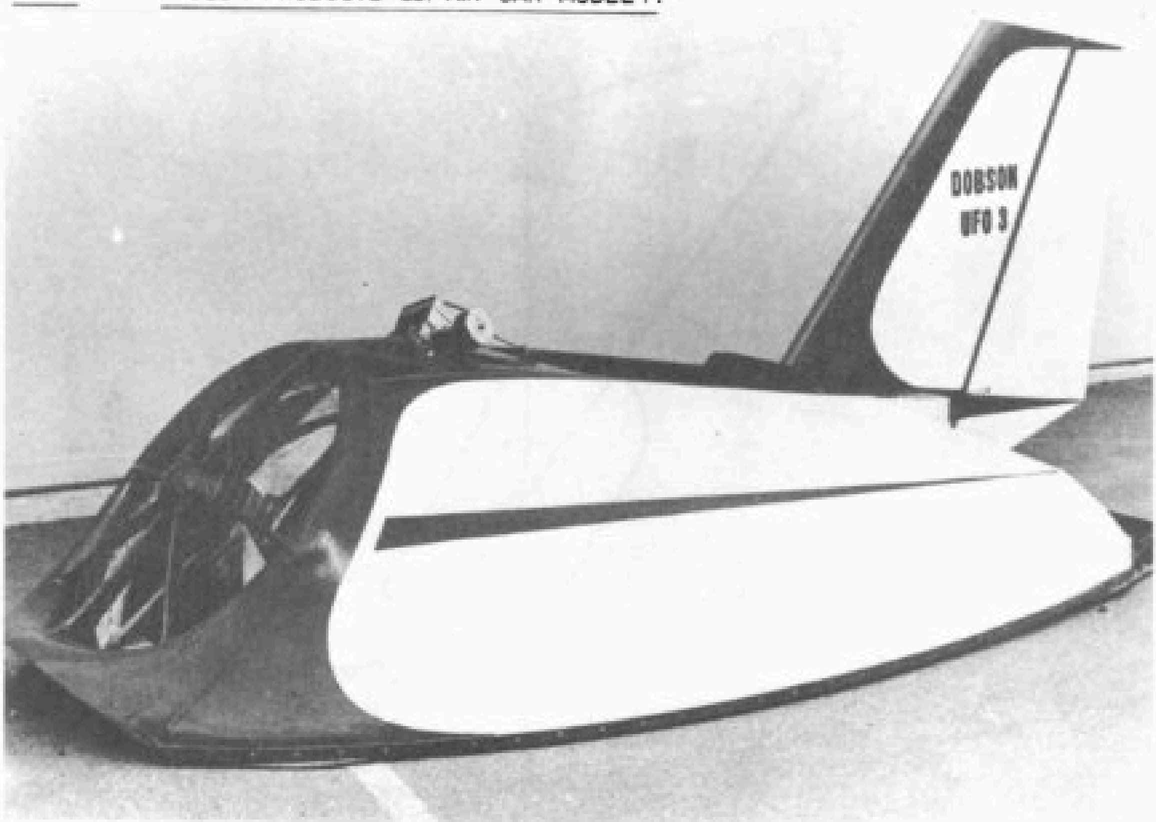
FIG. 12 HOVERJET INC. HJ-100

FIG. 13 FISHLOCK / HOWE MISTRAL

FIG. 14

MODERN HOVER VEHICLES LTD. SPECTRA II.

FIG.15 DOBSON PRODUCTS CO. AIR CAR MODEL F.



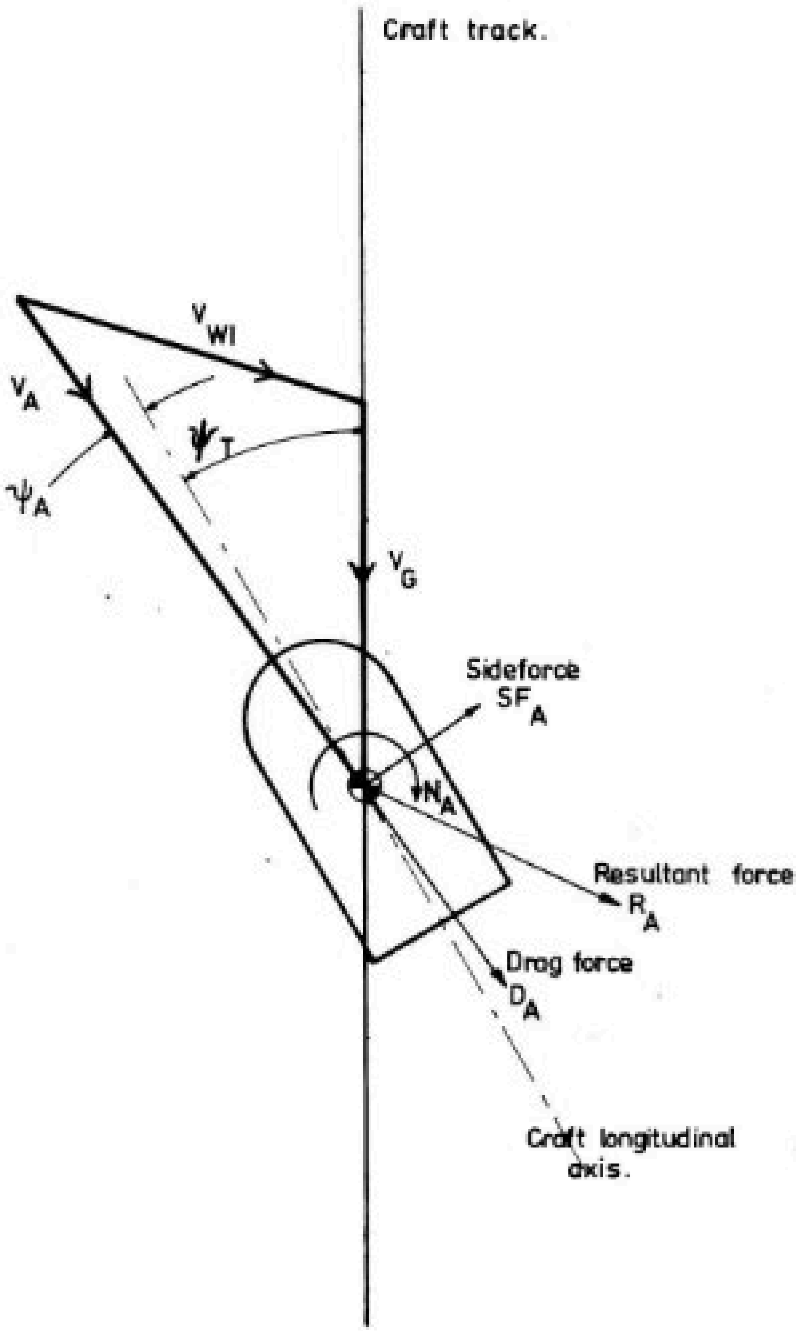


FIG. 16 AERODYNAMIC VELOCITIES, FORCES AND MOMENTS, AND THEIR RESULTANTS ACTING ON AN A.C.V. (RELATIVE AIR FLOW AXES)

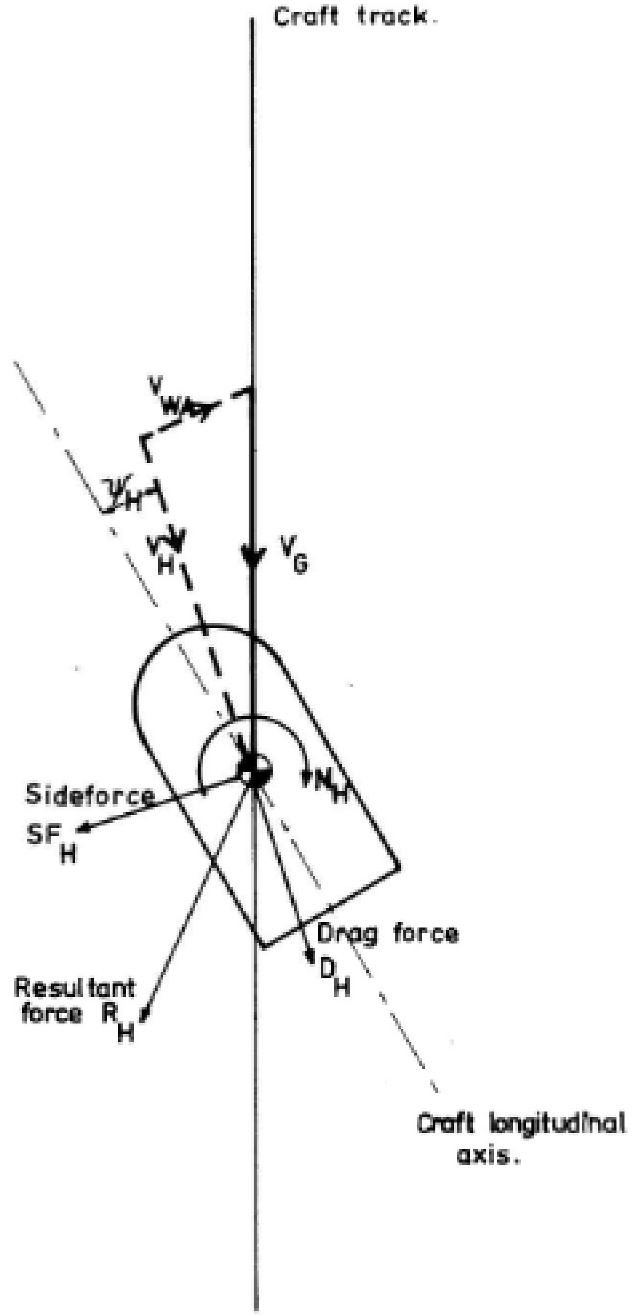


FIG. 17 HYDRODYNAMIC VELOCITIES, FORCES AND MOMENTS, AND THEIR RESULTANTS ACTING ON AN A.C.V. (RELATIVE WATER FLOW AXES)

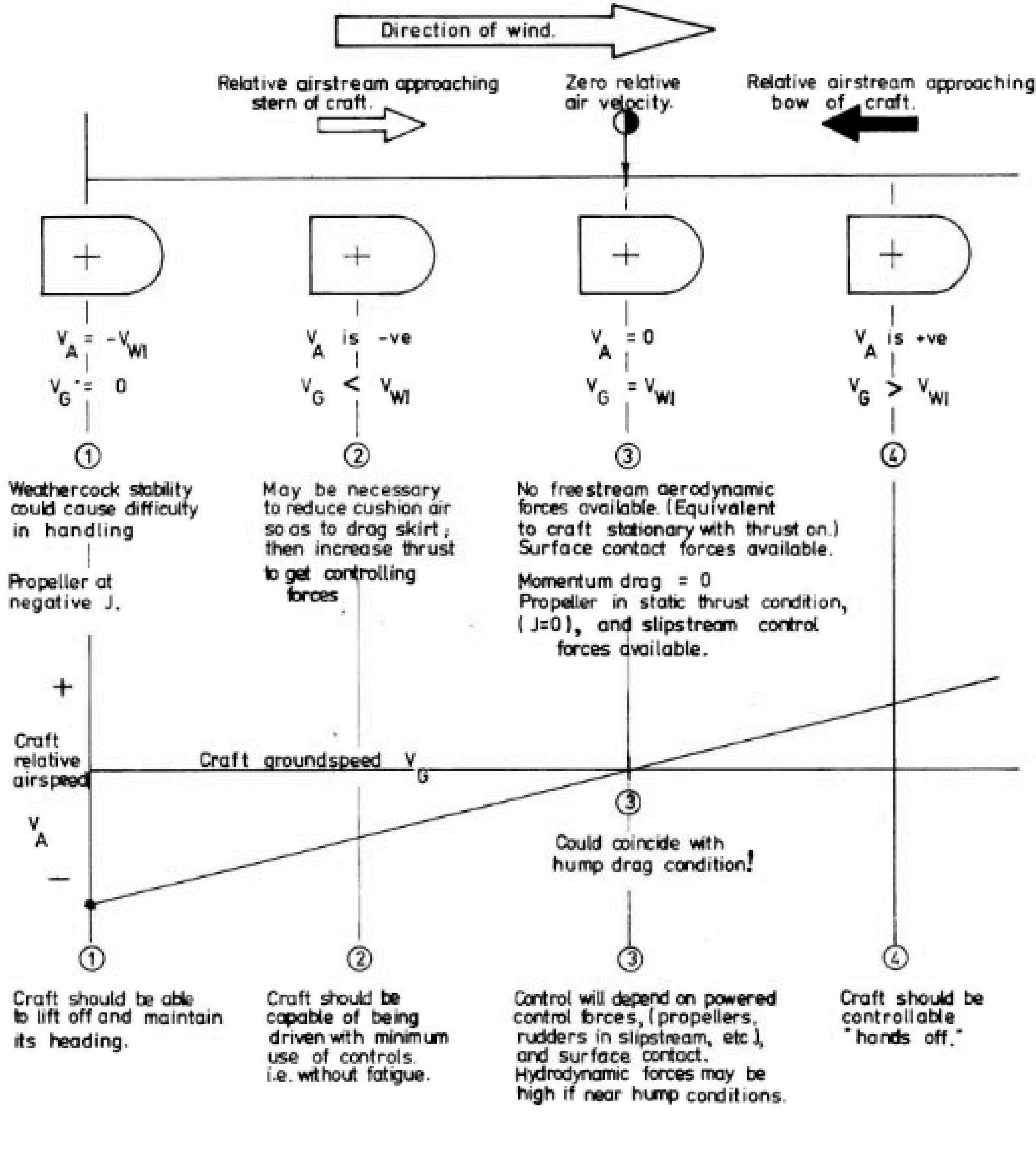
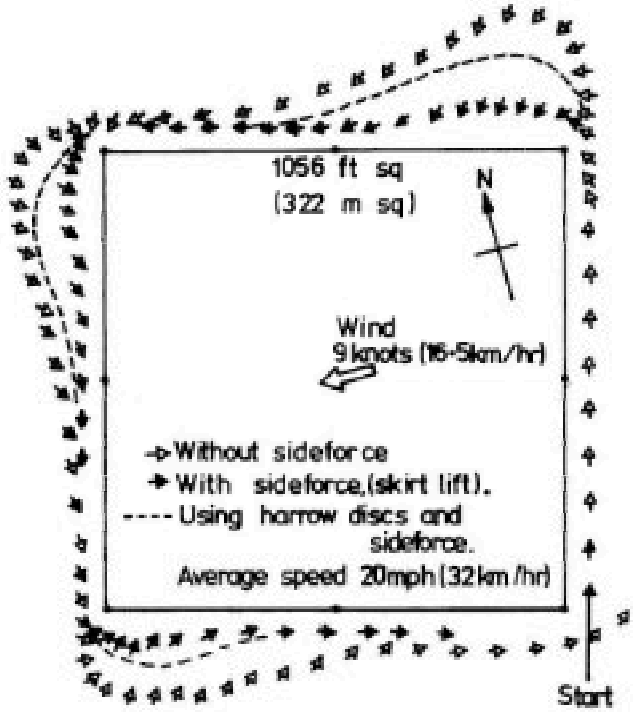


FIG. 18. ILLUSTRATION OF THE FOUR RELATIVE VELOCITY CONDITIONS ARISING WHEN AN A.C.V. ACCELERATES FROM REST IN A DOWNWIND DIRECTION.



Vehicle path & yaw attitude using various control methods.

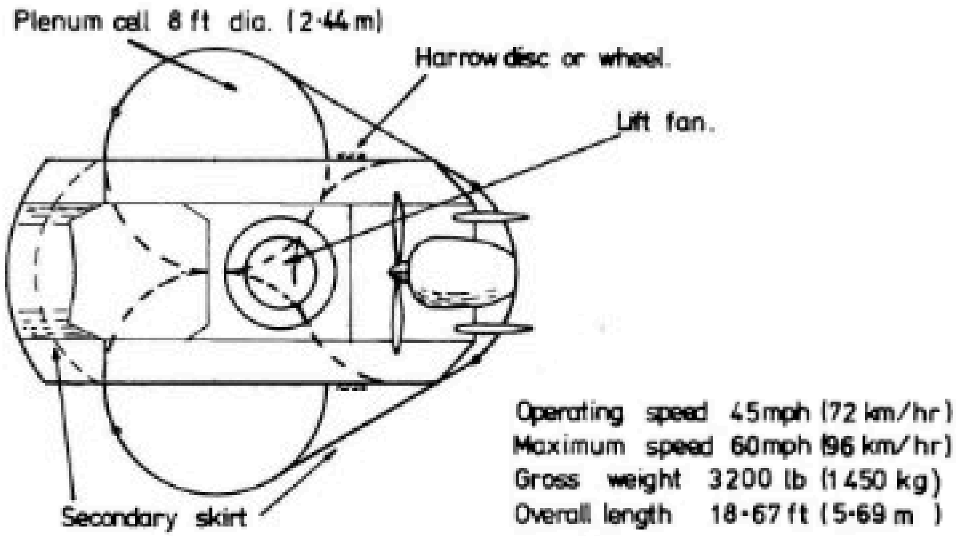


FIG. 19. MANOEUVRING CAPABILITIES OF BELL CARABAO A.C.V.

(Extracted from Ref. 4.)

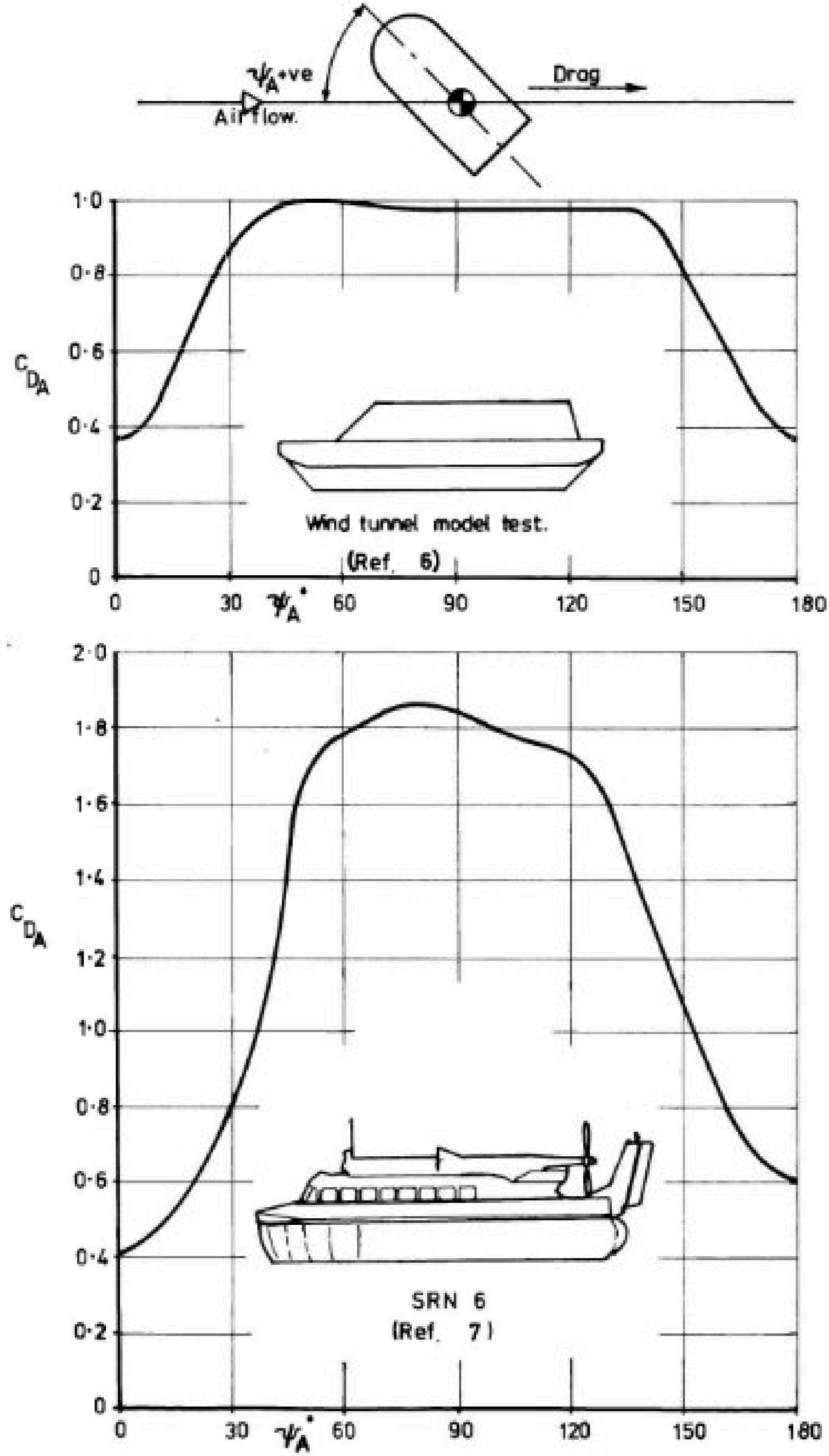


FIG. 20 EXAMPLES OF AERODYNAMIC DRAG COEFFICIENT VARIATION WITH YAW ANGLE.

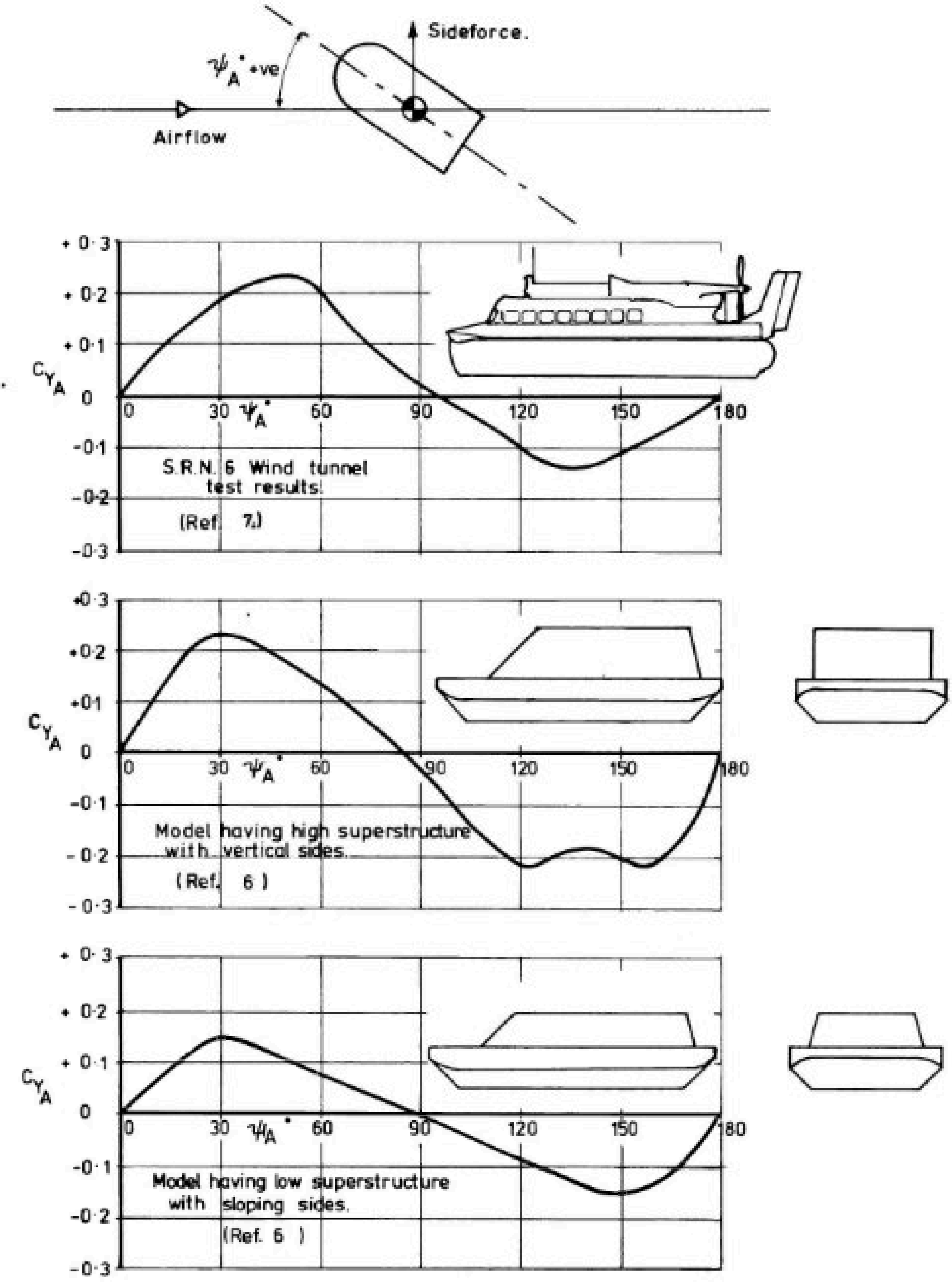


FIG. 21 EXAMPLES OF AERODYNAMIC SIDEFORCE COEFFICIENT VARIATION WITH YAW ANGLE.

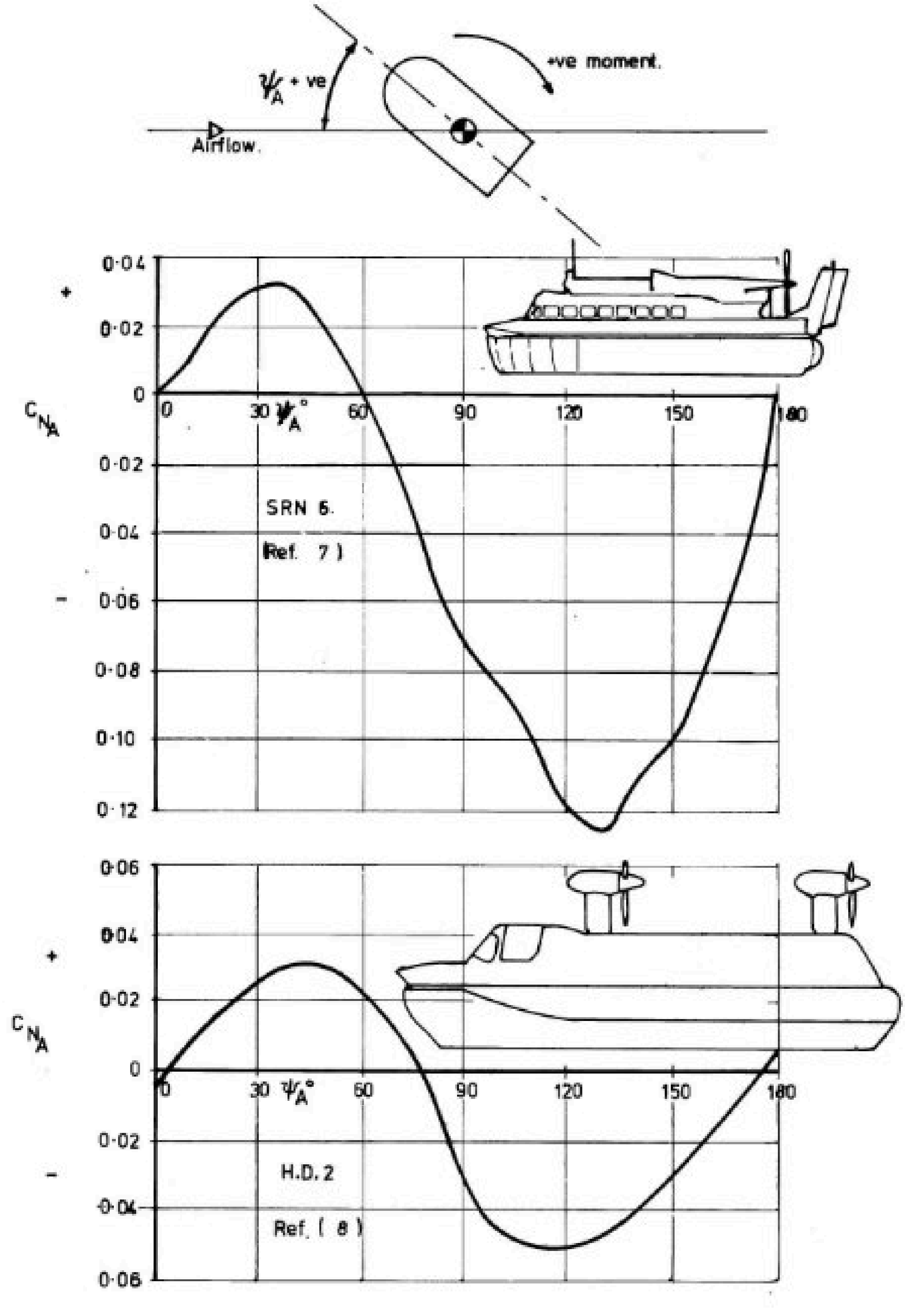


FIG. 22 EXAMPLES OF AERODYNAMIC YAWING MOMENT COEFFICIENT VARIATION WITH YAW ANGLE.

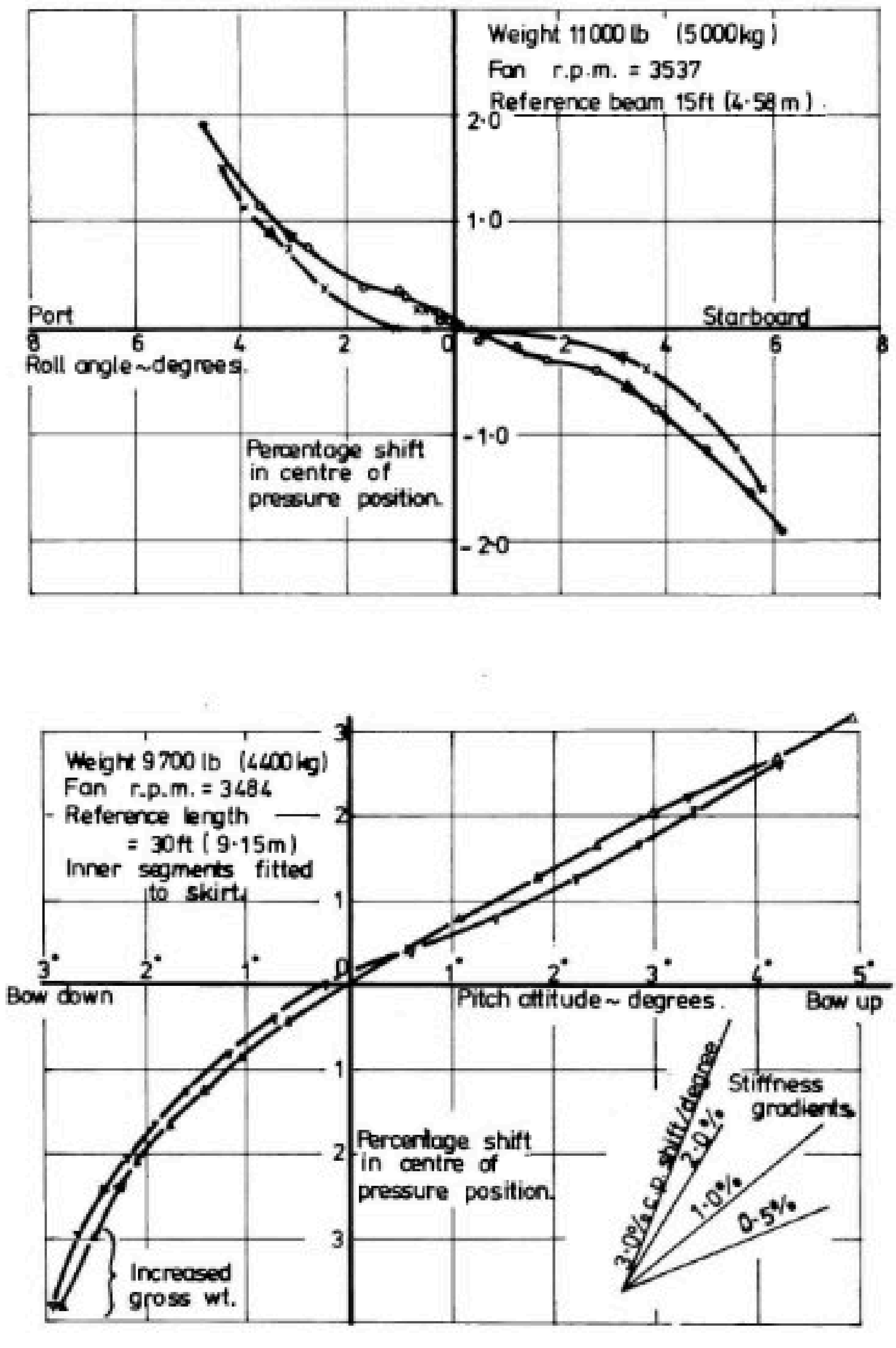
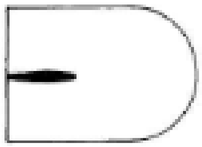
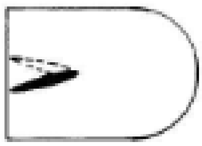
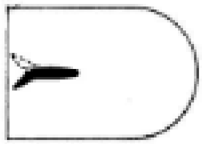


FIG. 23 OVERLAND STATIC STABILITY CHARACTERISTICS OF H.D. 2, IN ROLL AND PITCH MODES.

(Extracted from Ref. 8).

FREE STREAM AEROFOIL SURFACES.

(DEPENDENT UPON RELATIVE FREE-STREAM AIRFLOW)

	DEVICE	SCHEMATIC PRINCIPLE.
A1	Fixed fin in free-stream.	
A2	Rotatable fin in free-stream.	
A3	Fixed fin & moveable rudder in free-stream.	

AEROFOIL SURFACES IN FREE-AIR PROPELLER SLIPSTREAM.

(DEPENDENT UPON FORWARD THRUST)

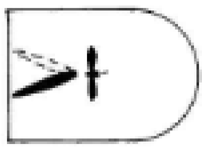
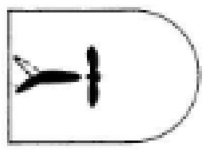
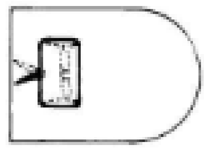
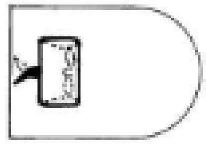
B1	Rotatable fin in free propeller slipstream.	
B2	Fixed fin & moveable rudder in free propeller slipstream.	
B3	Fixed fin & moveable rudder in slipstream of swivelling free air propeller.	

FIG. 24a EXISTING BASIC CONTROL SYSTEMS FOR AIR CUSHION VEHICLES.

AEROFOIL SURFACES IN DUCTED PROPELLER SLIPSTREAM.
(DEPENDENT UPON FORWARD THRUST)

	DEVICE	SCHEMATIC PRINCIPLE
C1	Ducted propeller with rudder vanes.	
C2	Ducted propeller with fin & rudder.	
C3	Ducted swivelling propeller.	

AEROFOIL SURFACES IN CENTRIFUGAL OR AXIAL FAN DISCHARGE.
(DEPENDENT UPON FORWARD THRUST)

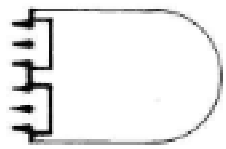
D1	Low speed air jet with rudder vanes.	

FIG. 24 b EXISTING BASIC CONTROL SYSTEMS FOR AIR CUSHION VEHICLES.

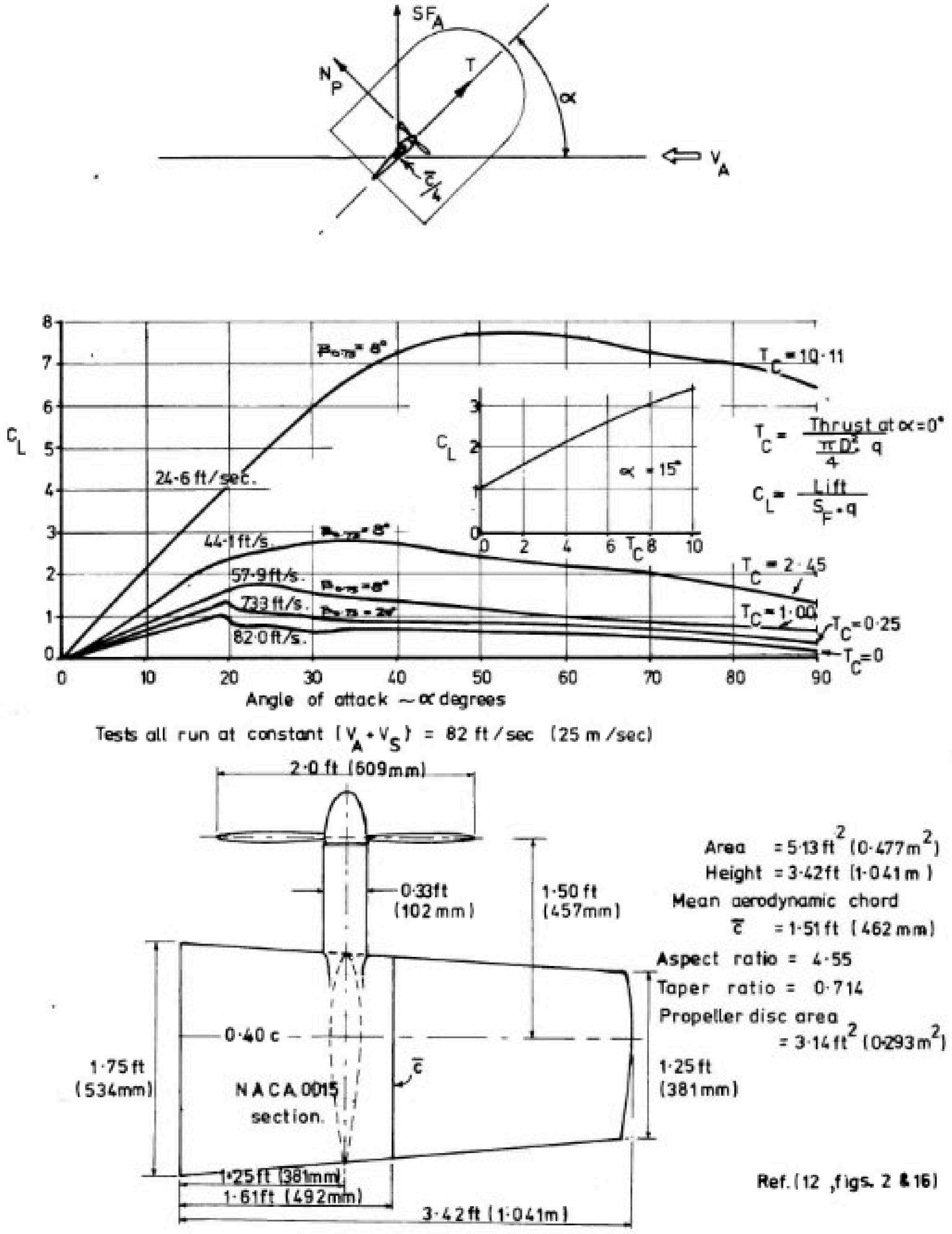
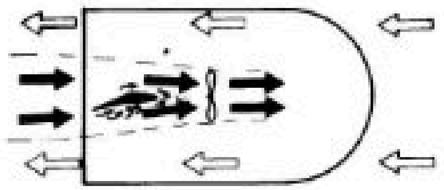
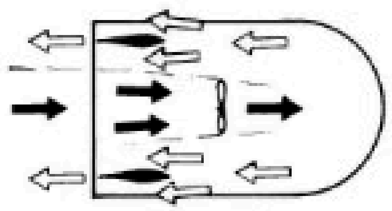


FIG. 25. THE EFFECT OF PROPELLER SLIPSTREAM ON EFFECTIVE FIN LIFT COEFFICIENT (INCLUDING PROPELLER NORMAL FORCE).

Slipstream flow. Freestream flow.

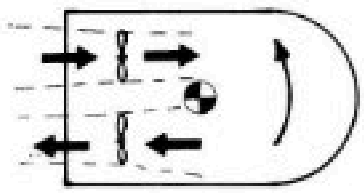


In reverse thrust condition rudder control is lost, and propeller reverse thrust is spoiled by probable separated flow from rudder, if deflected.

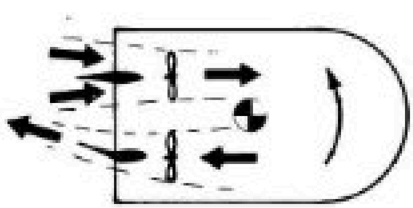


In reverse thrust condition freestream rudder control remains effective at forward relative airspeeds.

REVERSE THRUST CONDITIONS.



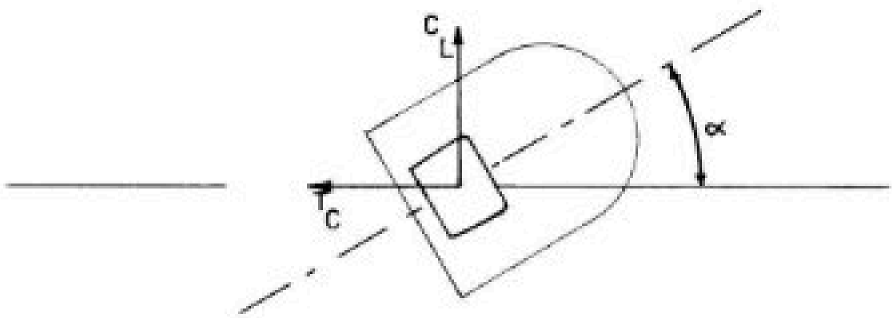
With no rudders yawing control may be effectively achieved by applying differential thrust.

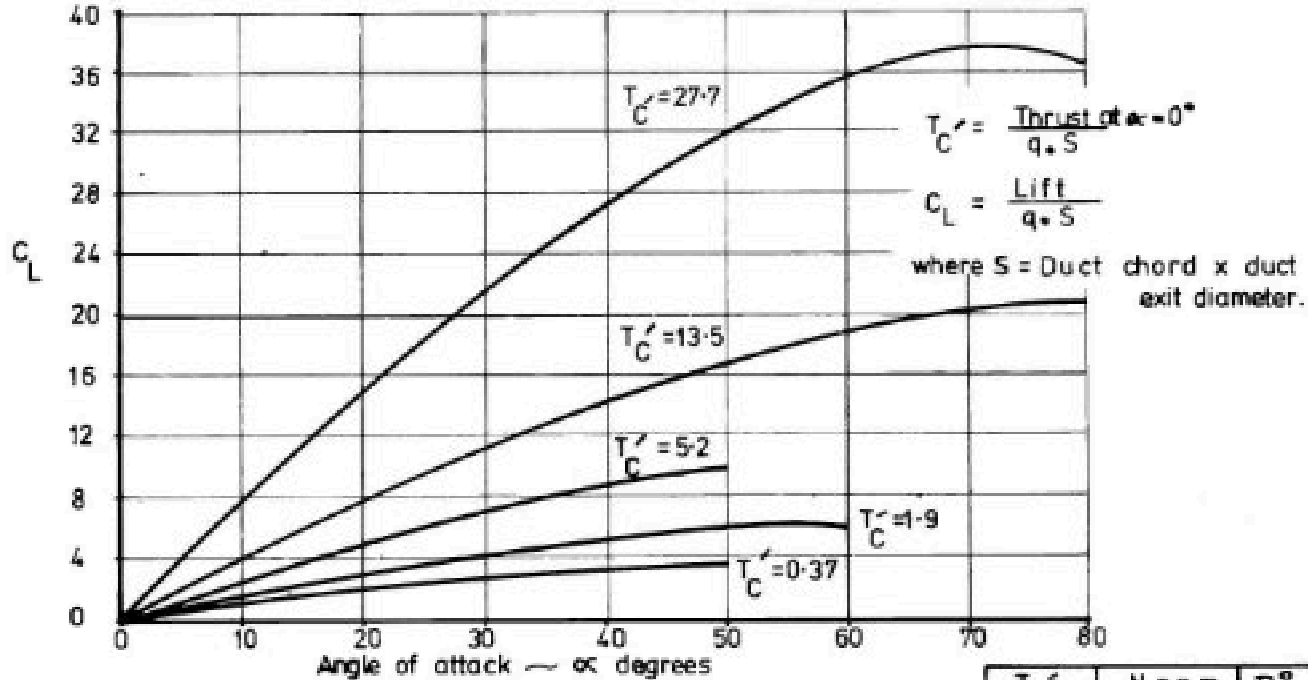


With rudders, only the rudder in the forward thrust stream is effective in inducing yaw. Rudder in reverse flow should remain undeflected to enable propeller to give maximum reverse thrust.

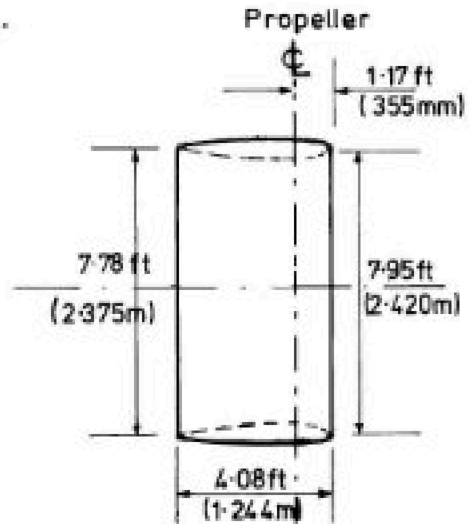
YAWING CONTROL

FIG. 26 PROBLEMS OF REVERSE THRUST PROPELLER FLOW INTERACTION WITH FIN/RUDDER COMBINATIONS.





T_C'	N r.p.m.	$\beta°$
27·7	2330	29
13·5	2330	19
5·2	2330	29
1·9	2330	29
0·37	2330	19



Propeller diameter = 7·0ft (2·137m)

Maximum external duct diameter = 8·46 ft (2·580m)

Duct chord = 4·08ft (1·244 m)

Exit diameter = 7·78ft (2·375m)

Net exit area = 44·08 ft^2 (3·800 m^2)

Net area at propeller = 37·84 ft^2 (3·475 m^2)

Propeller station, % chord 28·6

Tip clearance = 0·4 in (10·2 mm)

No. of blades = 3

Total activity factor 504

Integrated design C_L 0·43

Ref. 13, fig 8)

FIG. 27 CHARACTERISTIC VARIATION OF TOTAL LIFT COEFFICIENT WITH ∝ AND T_C FOR A DUCTED PROPELLER.

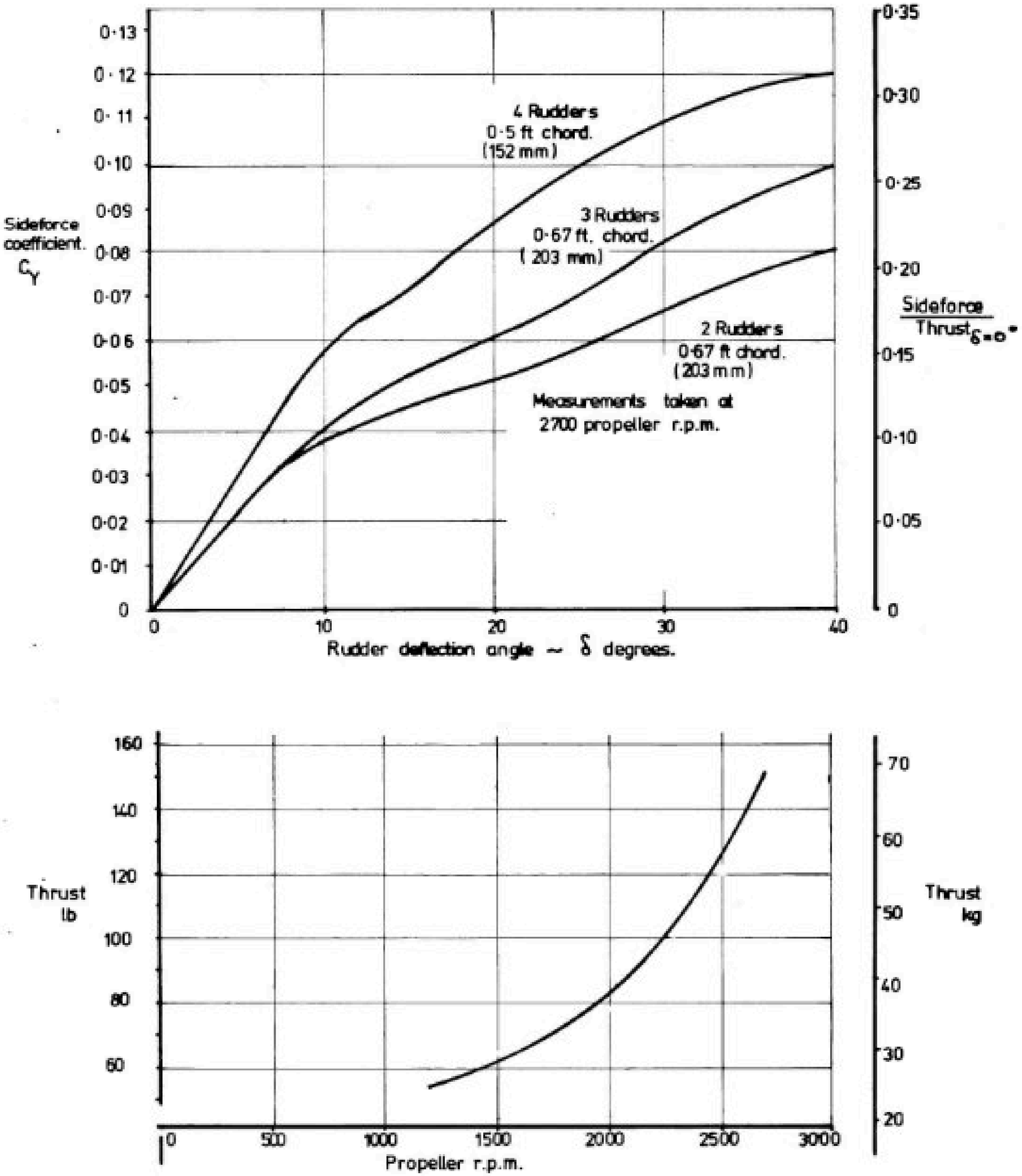


FIG. 28 SIDEFORCE AND THRUST CHARACTERISTICS OF HOVERPRODUCTS LTD. Q.T-30 THRUST PACKAGE

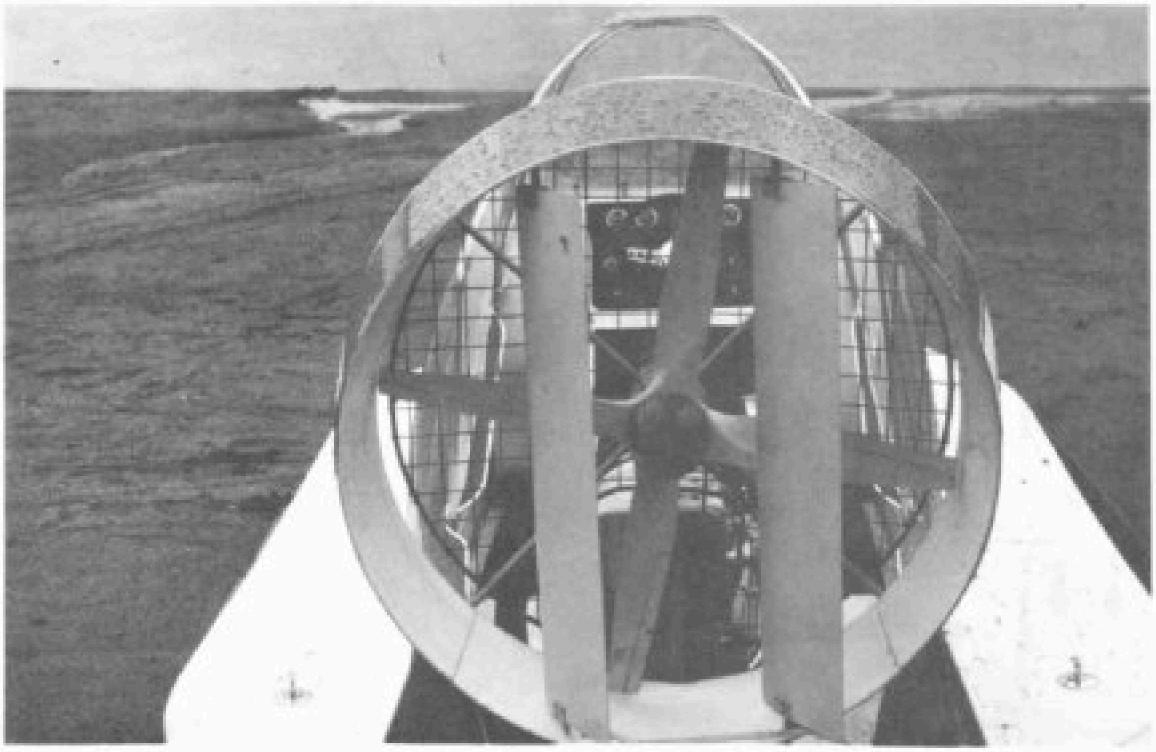
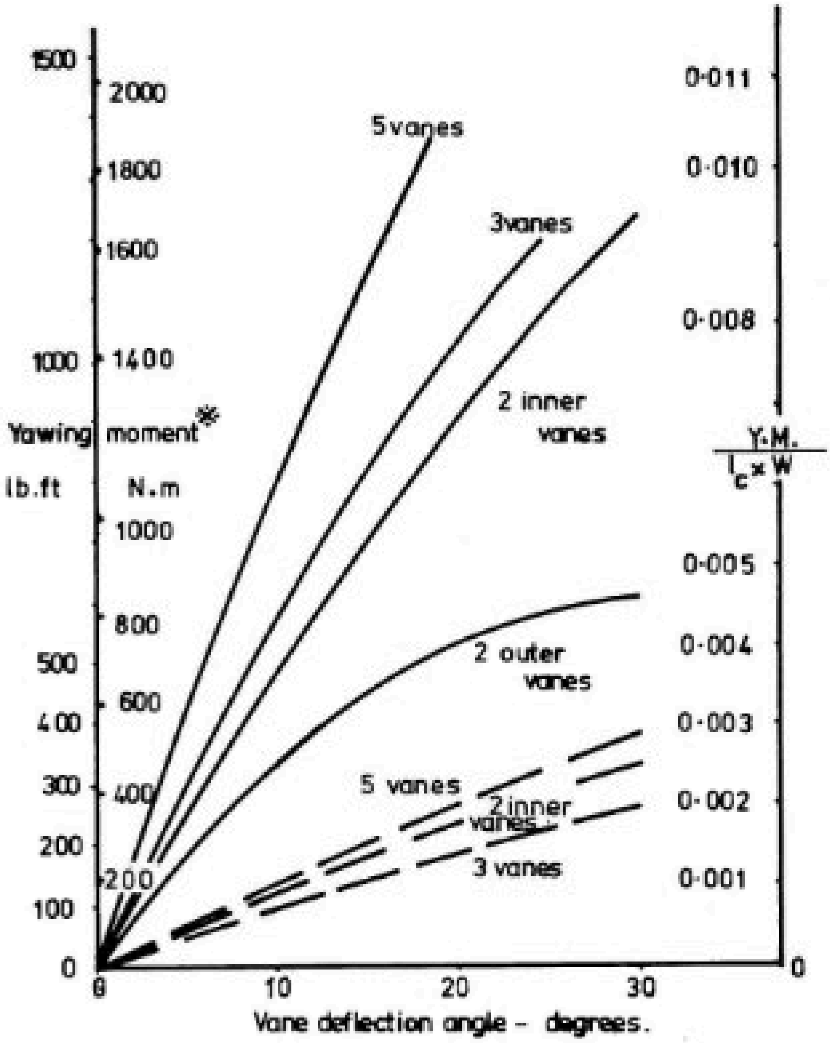


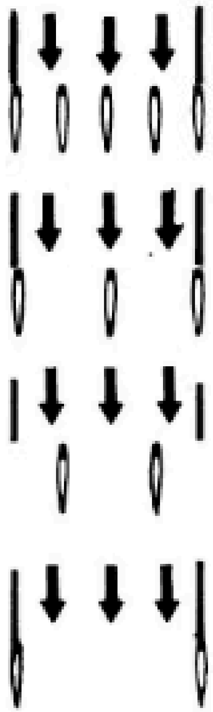
FIG. 29 HOVERPRODUCTS LTD. QT-30 THRUST PACKAGE, AS FITTED TO THE MHV SPECTRA II.

——— Yawing moments plotted at 700 lb (3·09 kN) static thrust. (zero control deflection)

— — — Yawing moments plotted at 300 lb (1·335 kN) static thrust. (zero control deflection)



<u>Rudder vane configurations.</u>



5 vanes set in flow.

3 vanes set in flow.

2 inner vanes set in flow.

2 outer vanes set in flow.

➡ Indicates fan output flow

Vane height = 15 in (380 mm)

Vane chord = 7 in (178 mm)

Cushion length, l_c = 23 ft (7·0 m)

Weight, W = 5700 lb (2590 kg)

Volume flow at 700 lb (3·09 kN) thrust with zero vane deflection = 1350 ft^3/sec (38·5 m^3/sec)

Volume flow at 300 lb (1·335 kN) thrust with zero vane deflection = 920 ft^3/sec (26·0 m^3/sec)

Duct exit area/side = 3·14 ft^2 (0·293 m^2)

Single vane area = 0·73 ft^2 (0·068 m^2)

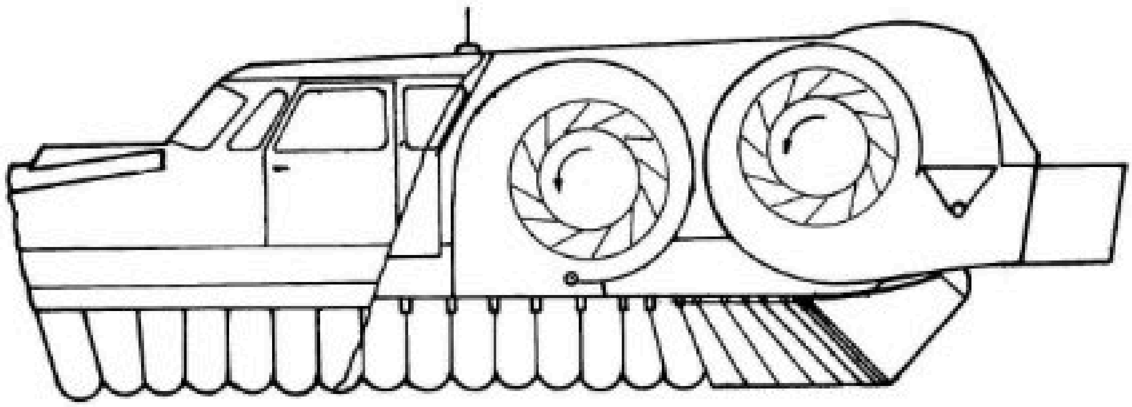
※ Total moment, either port or starboard.

FIG. 30 YAWING MOMENTS ACHIEVED ON CUSHIONCRAFT LTD. CC7 001 A.C.V. USING RUDDER VANES AT EXIT OF TWO LOW-SPEED AIR-JET NOZZLES. (Ref. 15)

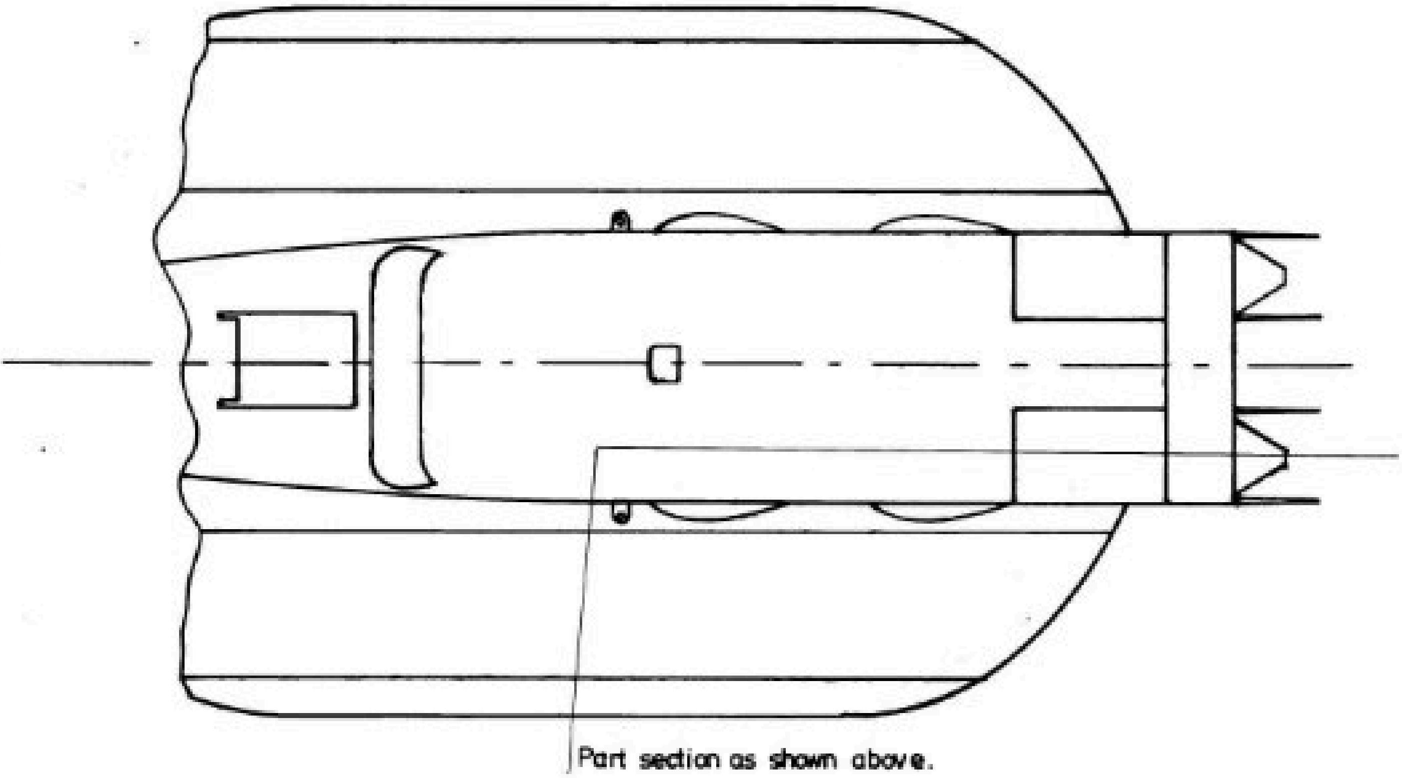
FIG. 31

CUSHIONCRAFT CC-7, SHOWING RUDDER VANE AND ELEVATOR CONFIGURATION.

(By courtesy of B.H.C.).



PART-SECTION THROUGH CRAFT SHOWING VOLUTE DETAILS.



PART PLAN VIEW OF CRAFT.

FIG. 32 EARLY VANE RUDDER SYSTEM AS USED ON BRITTEN NORMAN CC-5.

(Extracted from Ref. 16)

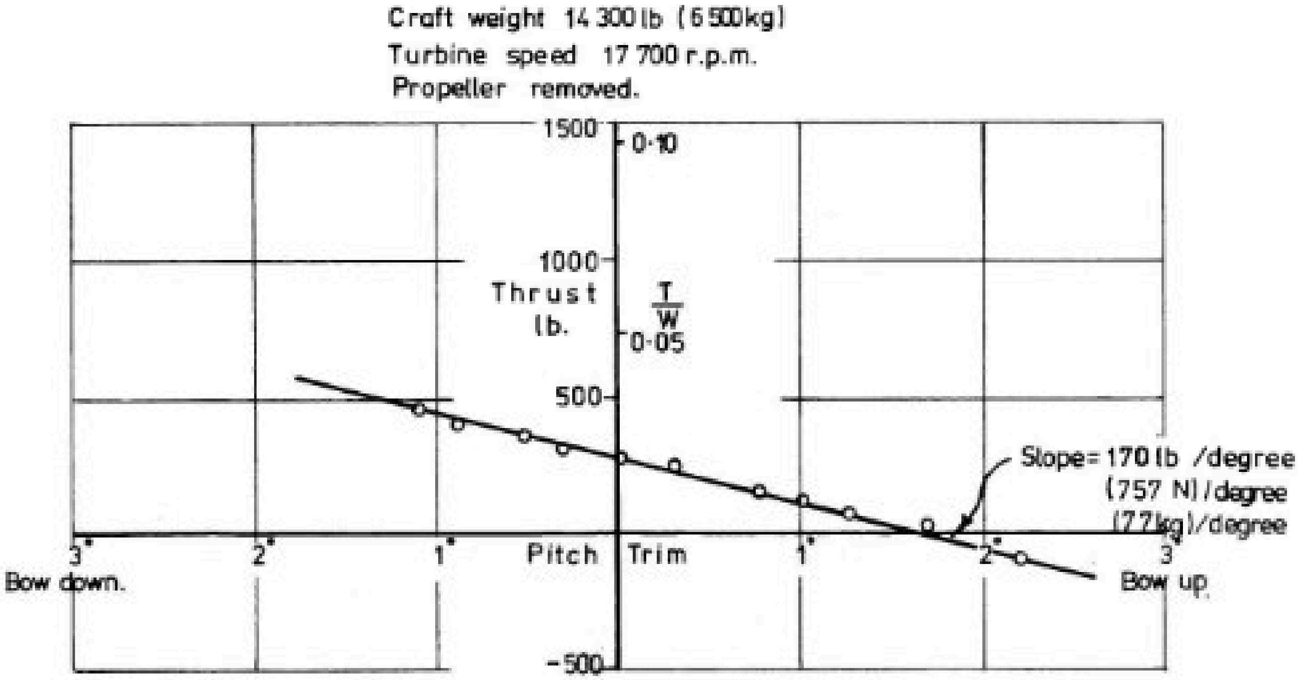


FIG. 33 THRUST FROM RUDDER DUCTS AND CUSHION ON SRN 5.

Ref. 2

FIG. 34

RUDDER DUCTS AS FITTED TO SRN 5 AND SRN 6 CRAFT.

(By courtesy of B.H.C.)

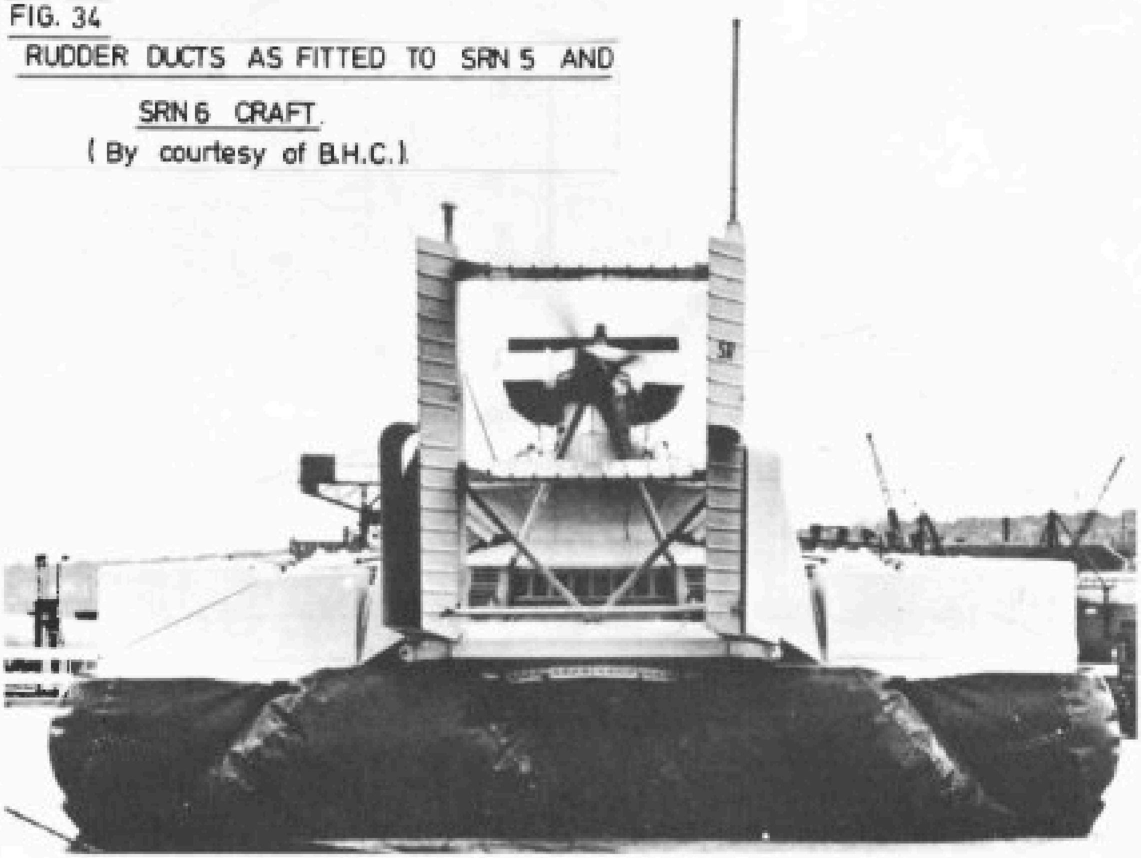
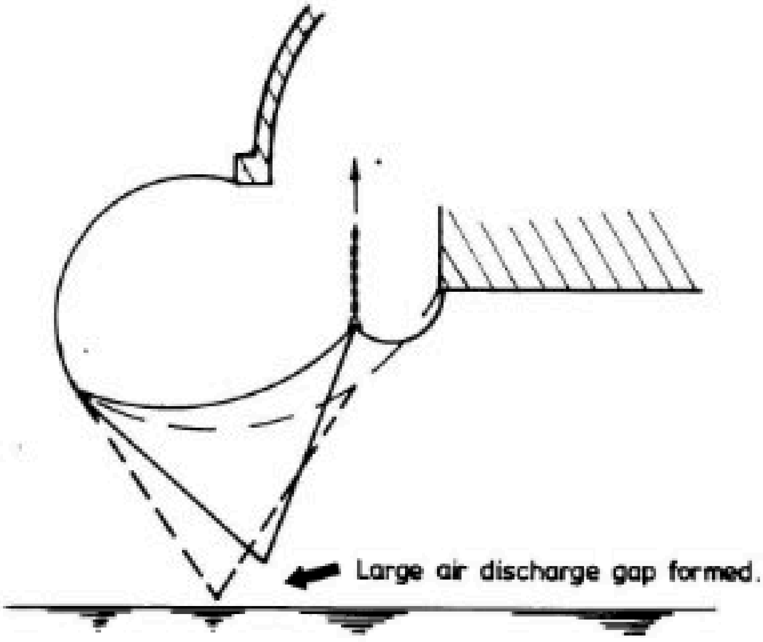
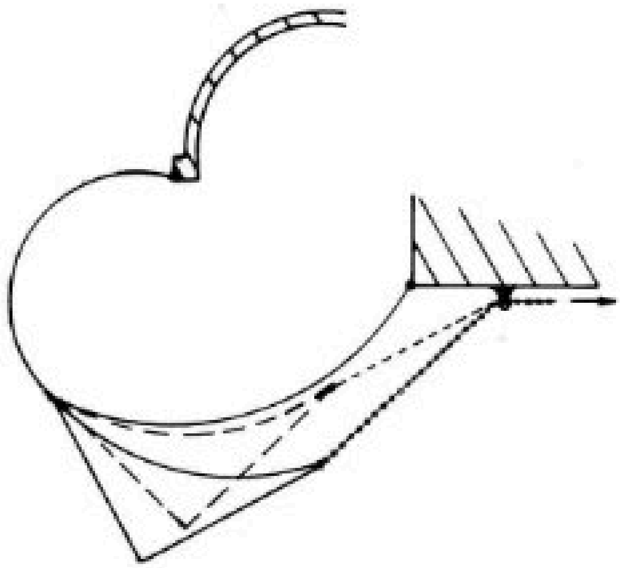


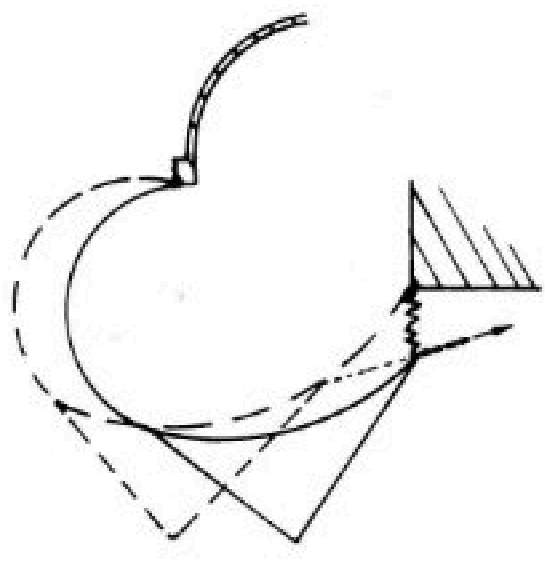
FIG. 35 BELL SK5 SHOWING PUFF PORTS OPEN ON PORT SIDE.



SKIRT LIFT.



Segment angle change.



Pulling in peripheral bag.

SKIRT OR CUSHION SHIFTING.

(Extracted from Ref. 9)

FIG. 36 SKIRT AND CUSHION MANIPULATION.

FIG. 37 THE BERTELSEN INC AEROMOBILE 13, WHICH USES GIMBAL MOUNTED FANS FOR PROPULSION & CONTROL.

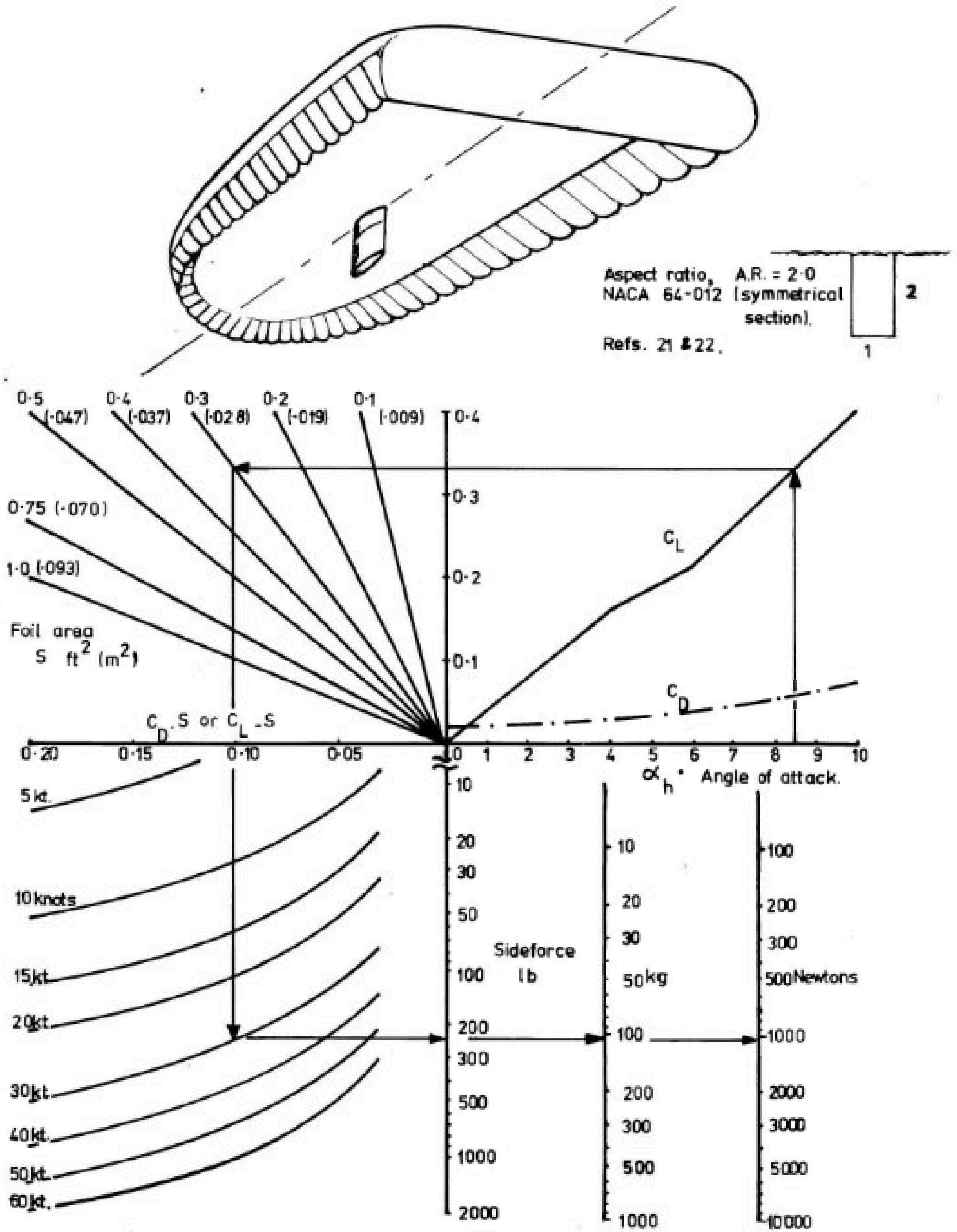
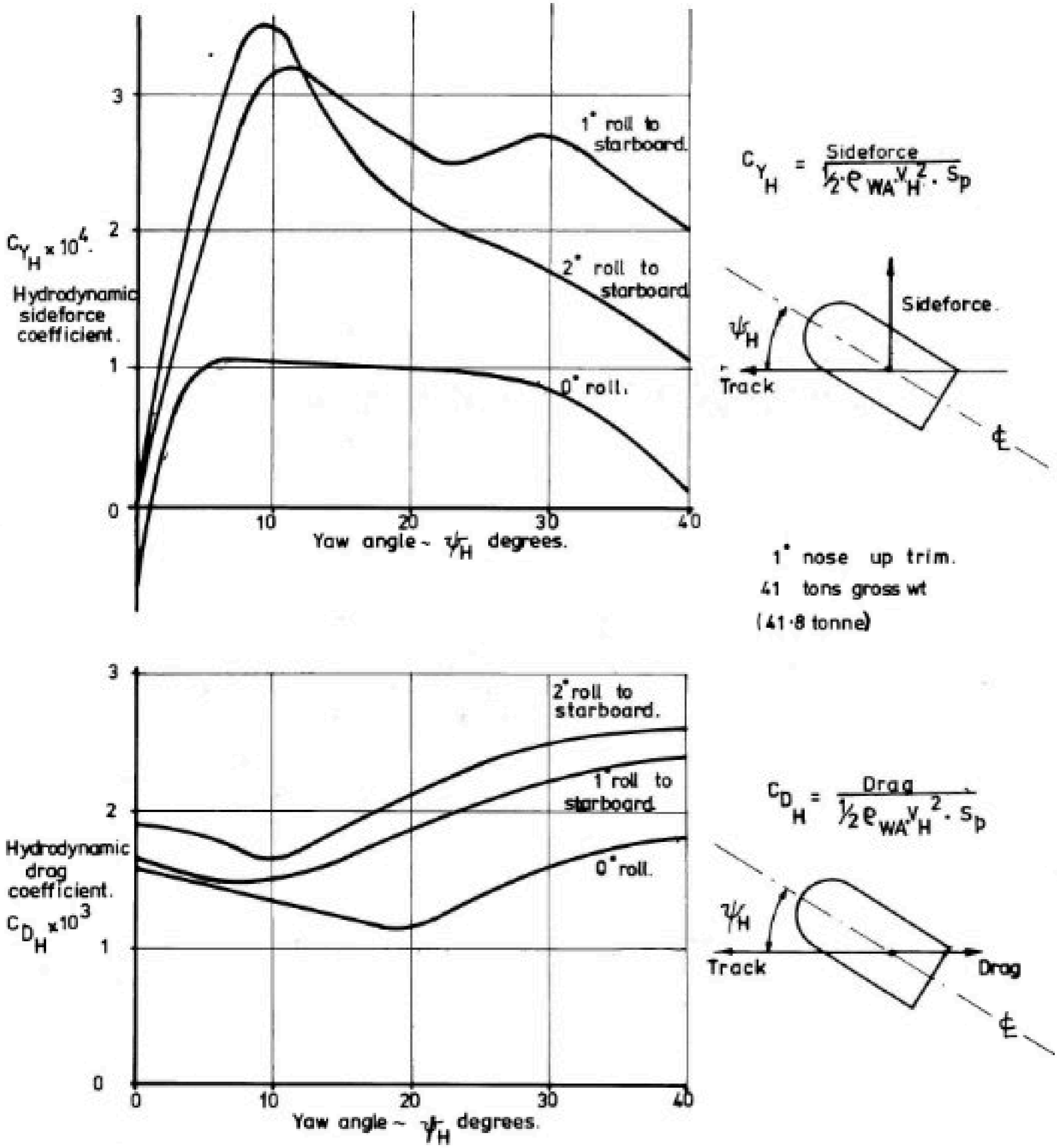


FIG. 38 SURFACE PIERCING FOIL CHARACTERISTICS.



Note!! Froude No. not available, but probably equivalent to 35 knots for a craft length of about 71 ft (21·6 m), giving a Froude No. of approximately 1·25.

FIG. 39. EXAMPLES OF HYDRODYNAMIC SIDEFORCE COEFFICIENT AND ASSOCIATED DRAG COEFFICIENT. (BHC BH7 MODEL).

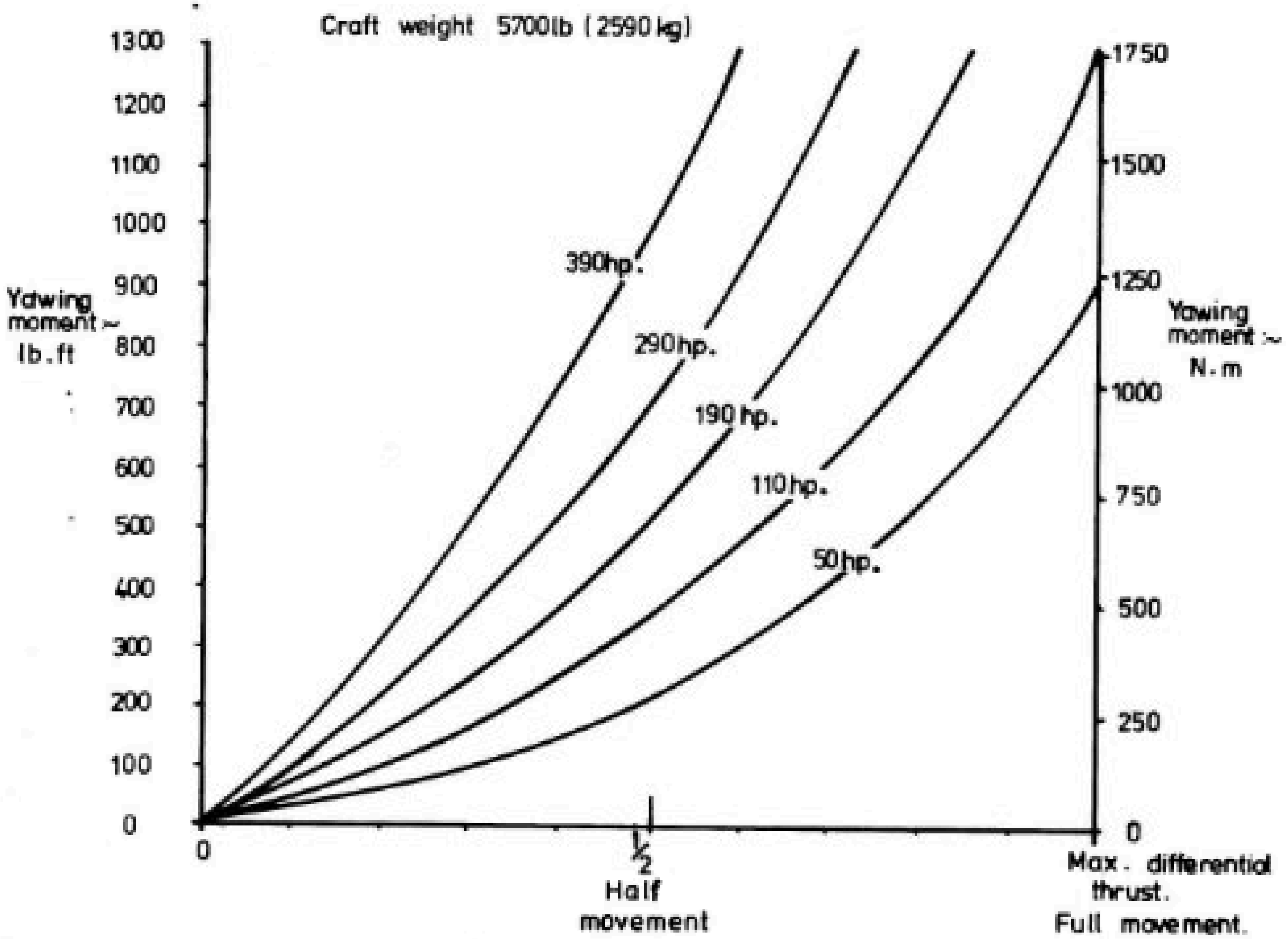
Ref. 9

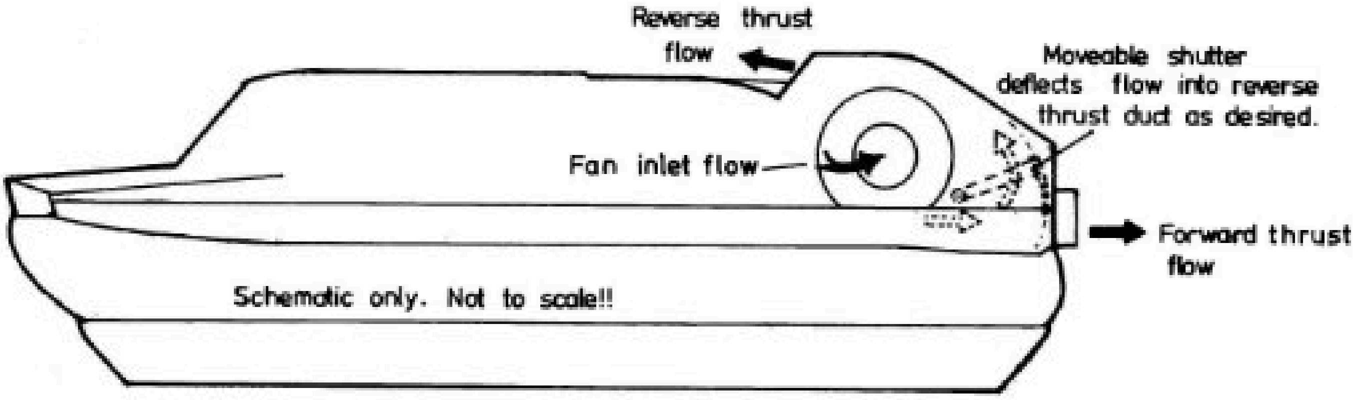
FIG. 40

G.G.HARDING'S WOTSIT I, FITTED WITH AMPHIBIOUS PROPULSION AND CONTROL SYSTEM.

FIG. 41 BRITTEN NORMAN CUSHIONCRAFT CC2-003.

(By courtesy of H.D.L.).





Differential thrust, & yawing moment, is obtained by independent operation of the moveable hinged shutters in the two fan outlets. Maximum differential thrust is obtained with all flow from one fan deflected by fully closing the corresponding shutter, and leaving the flow from the second fan undeflected.

FIG. 42 CC7 YAWING MOMENTS ABOUT C.G. AVAILABLE FROM USE OF DIFFERENTIAL THRUST. Ref. 15

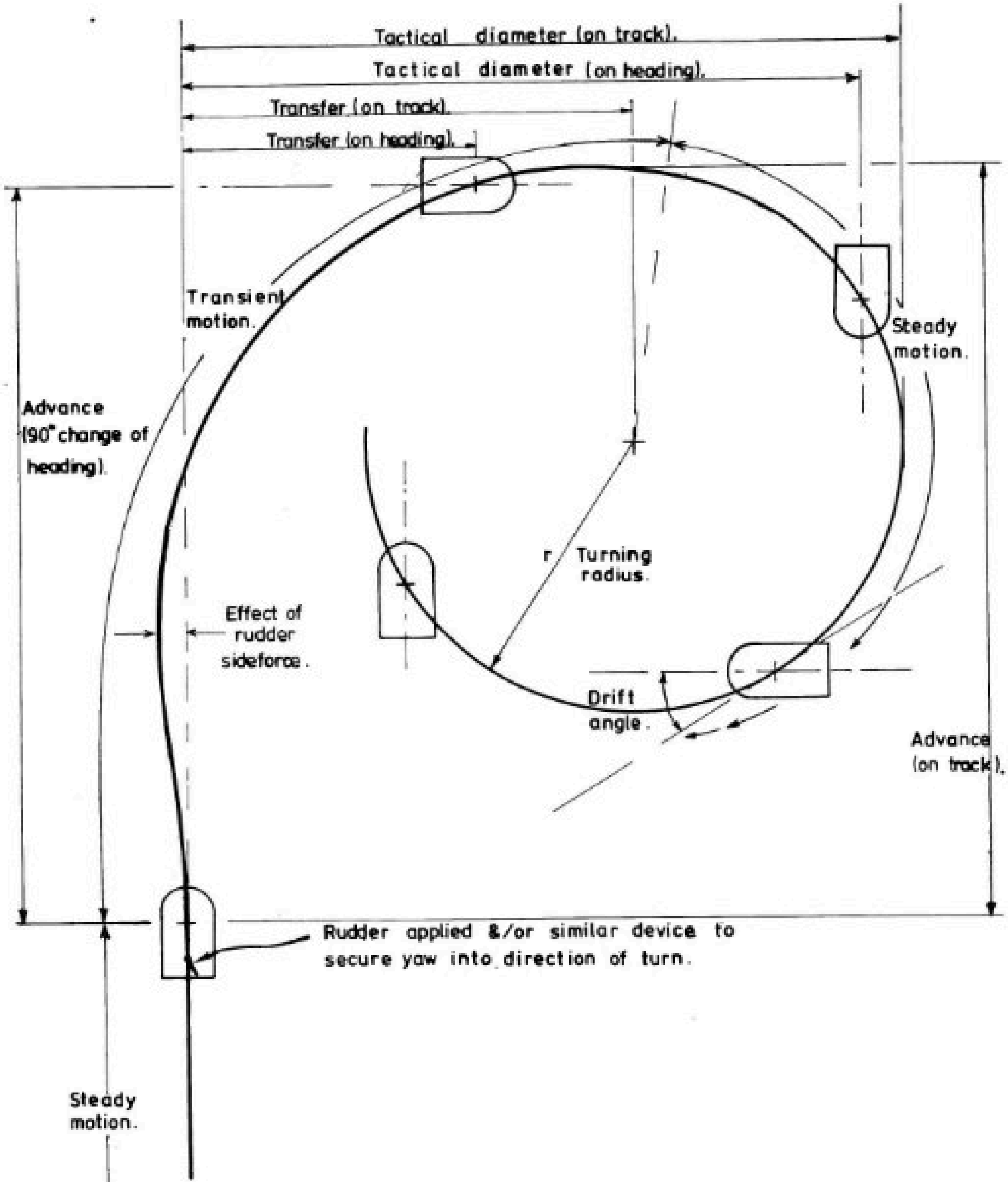


FIG. 43 DEFINITIONS OF TURNING MANOEUVRE,

(calm water, zero wind, constant control setting, constant power setting).

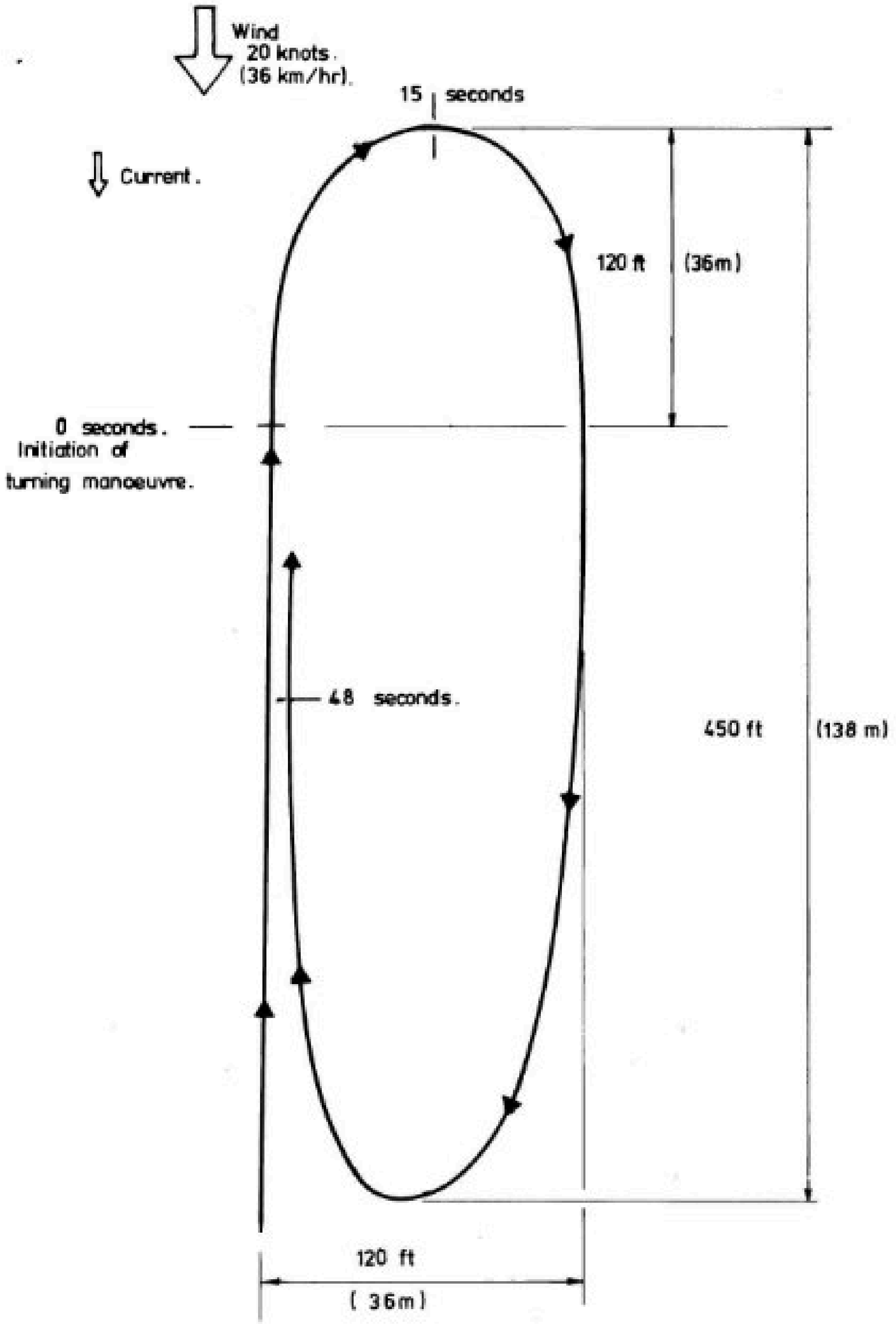
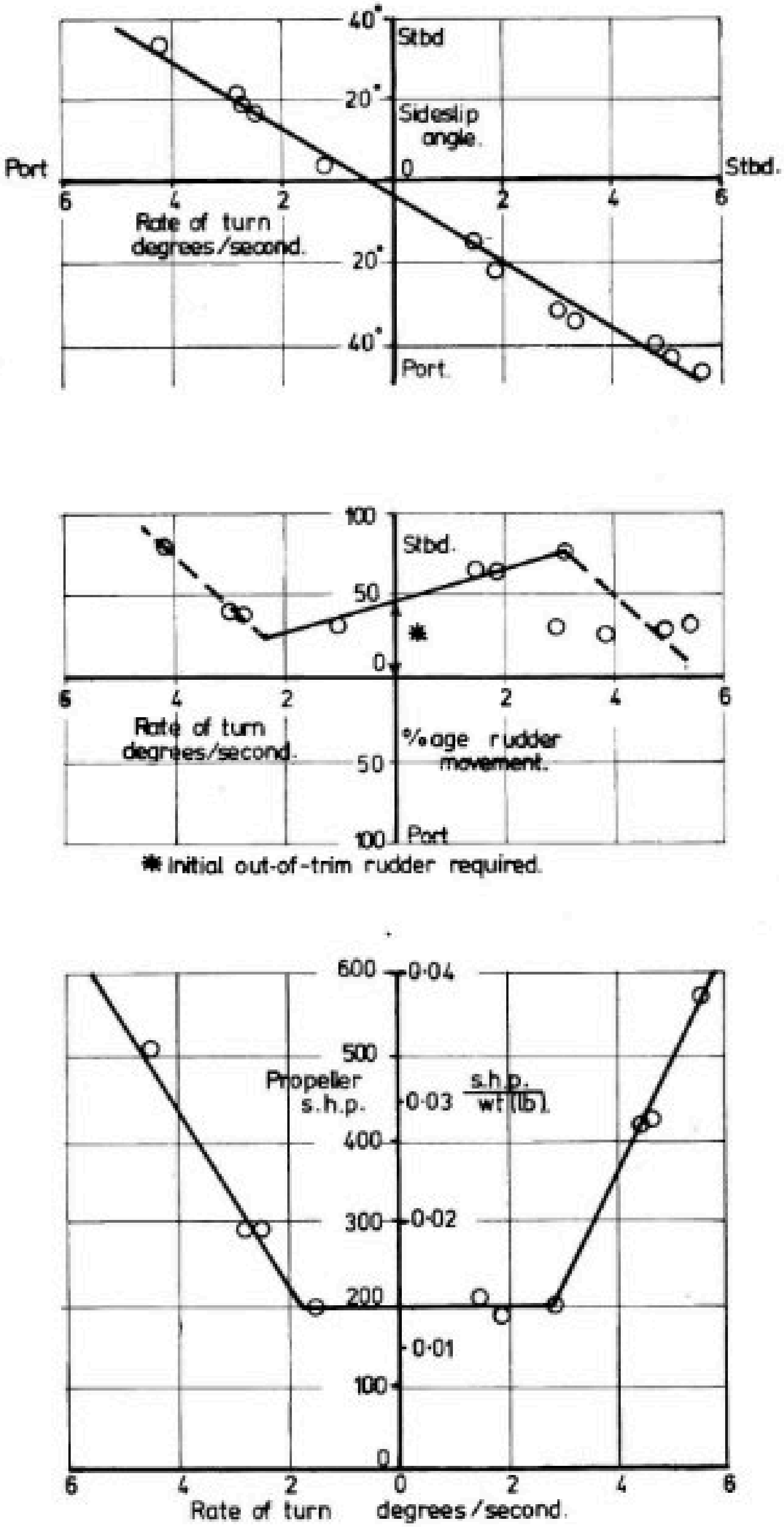


FIG. 44. EXAMPLE OF 360° TURN IN MINIMUM WIDTH BY CC7 WHILE MAINTAINING SPEED. Ref. 24.

(Only overall dimensions to scale).



Craft type,
SRN5, No.XT 657.
Craft weight,
14 950 lb
(6 800 kg)

FIG. 45 SIDESLIP ANGLE, RUDDER REQUIRED & PROPELLER POWER REQUIRED TO MAINTAIN 30 KNOTS AT VARIOUS RATES OF TURN.

(Ref. 2)

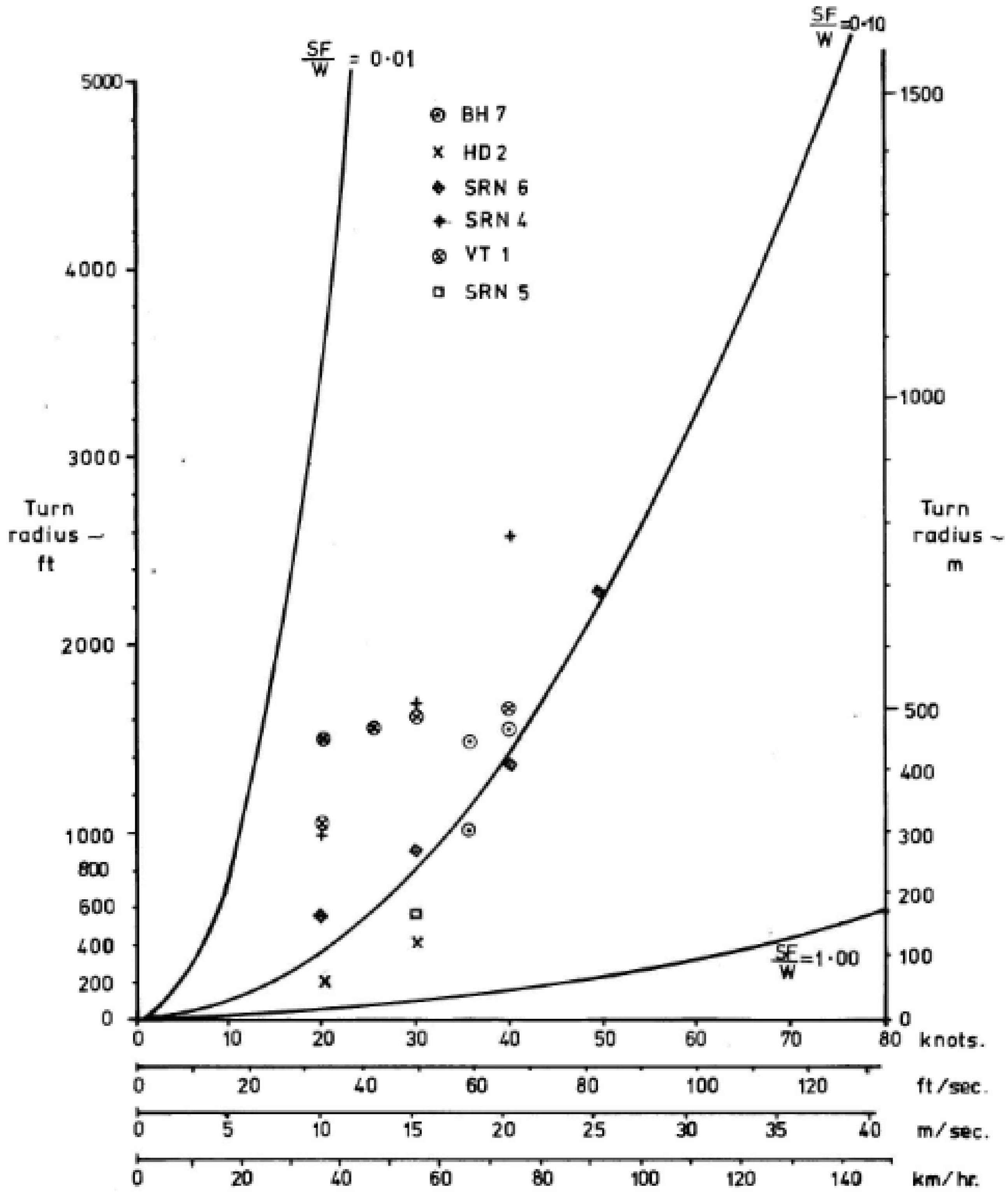


FIG. 46. TURNING PERFORMANCE OF CURRENT A.C.V.'s IN TERMS OF EFFECTIVE SIDEFORCE AND WEIGHT.

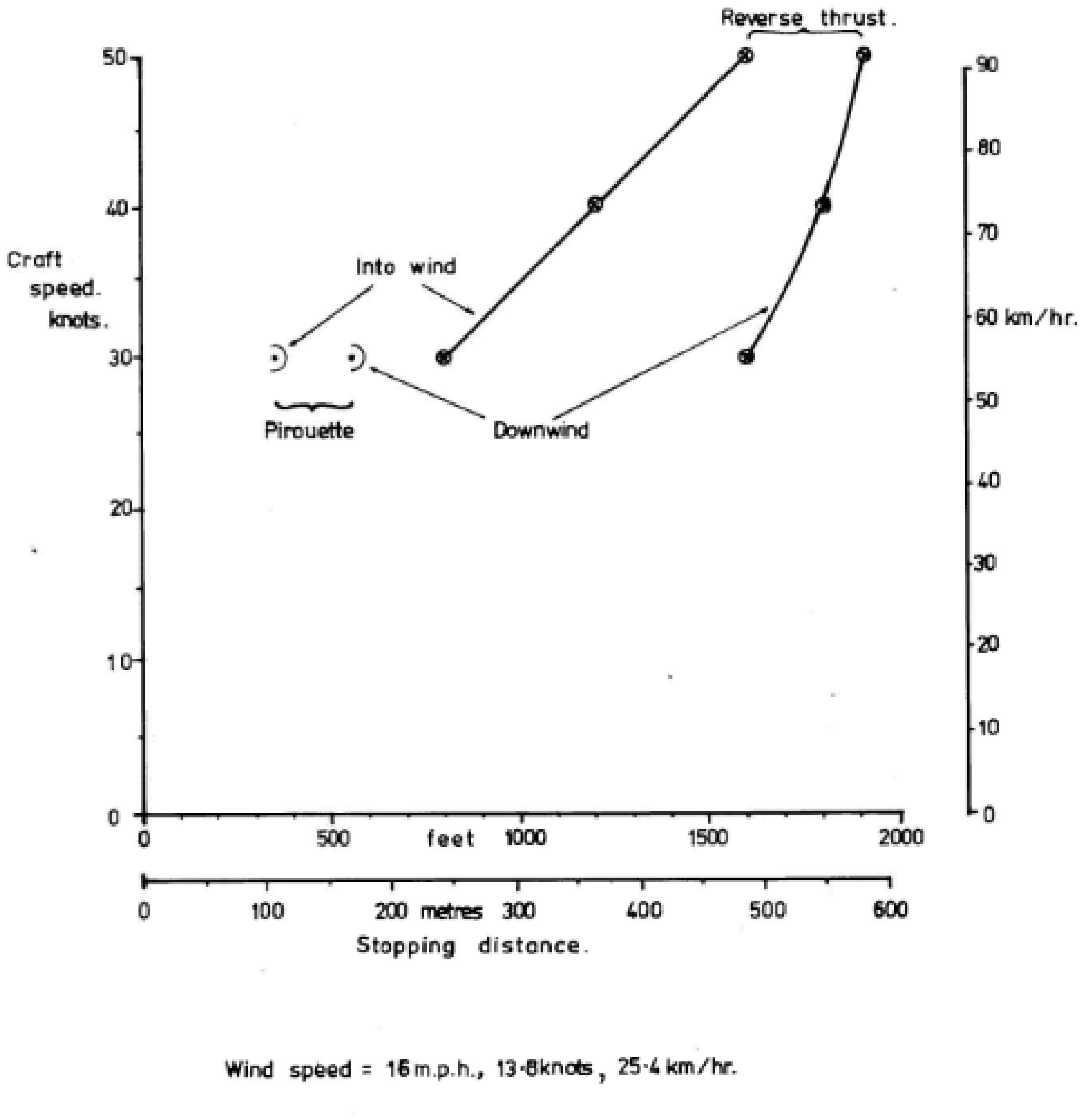
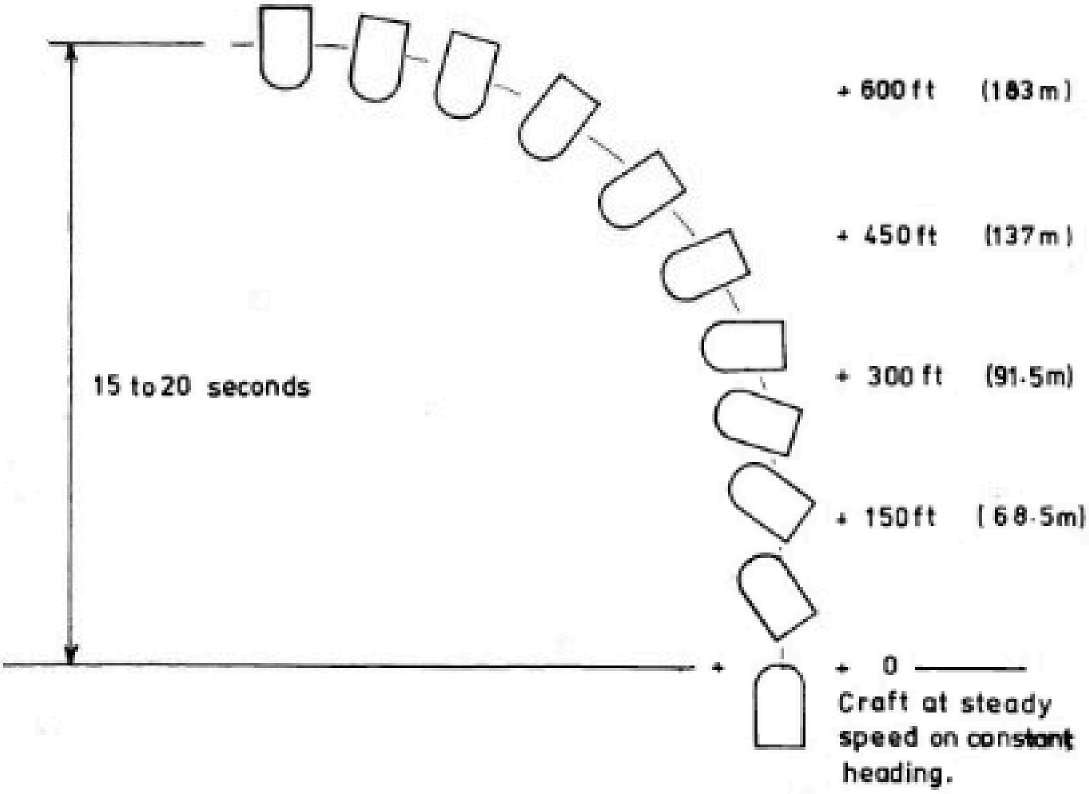
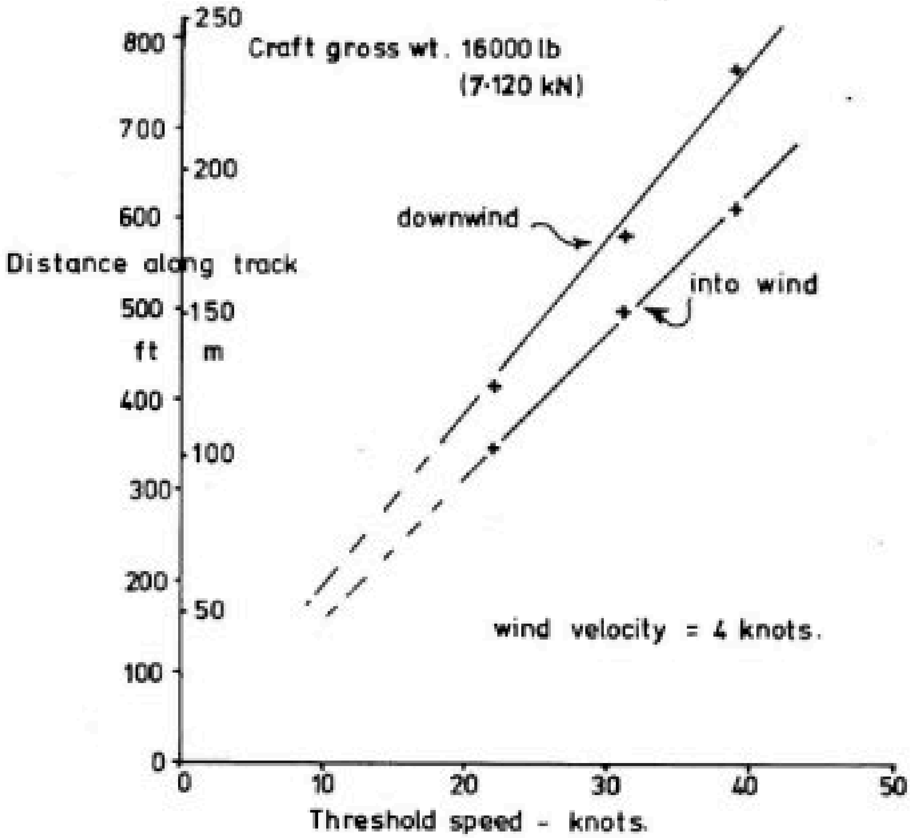


FIG. 47 SRN 6 STOPPING DISTANCES OVER SMOOTH ICE.

(Ref. 31)



TYPICAL COLLISION AVOIDANCE MANOEUVRE*



COLLISION AVOIDANCE DISTANCES*

* Extracted from Ref. 32

FIG 48. SRN 5 EMERGENCY STOPPING DISTANCES, OVER SNOW.

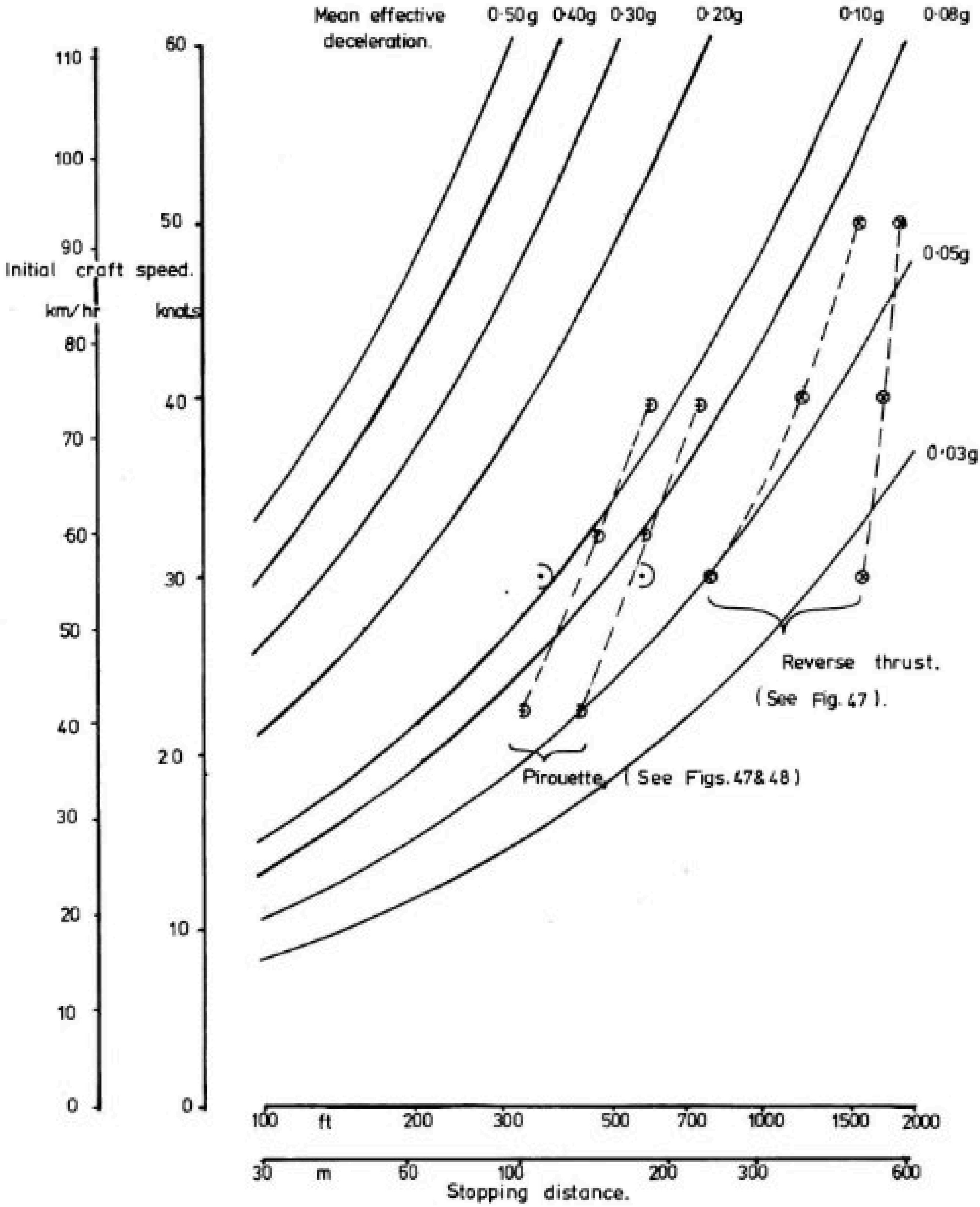


FIG. 49. CRAFT SPEED vs. STOPPING DISTANCES FOR SEVERAL A.C.V.'s.

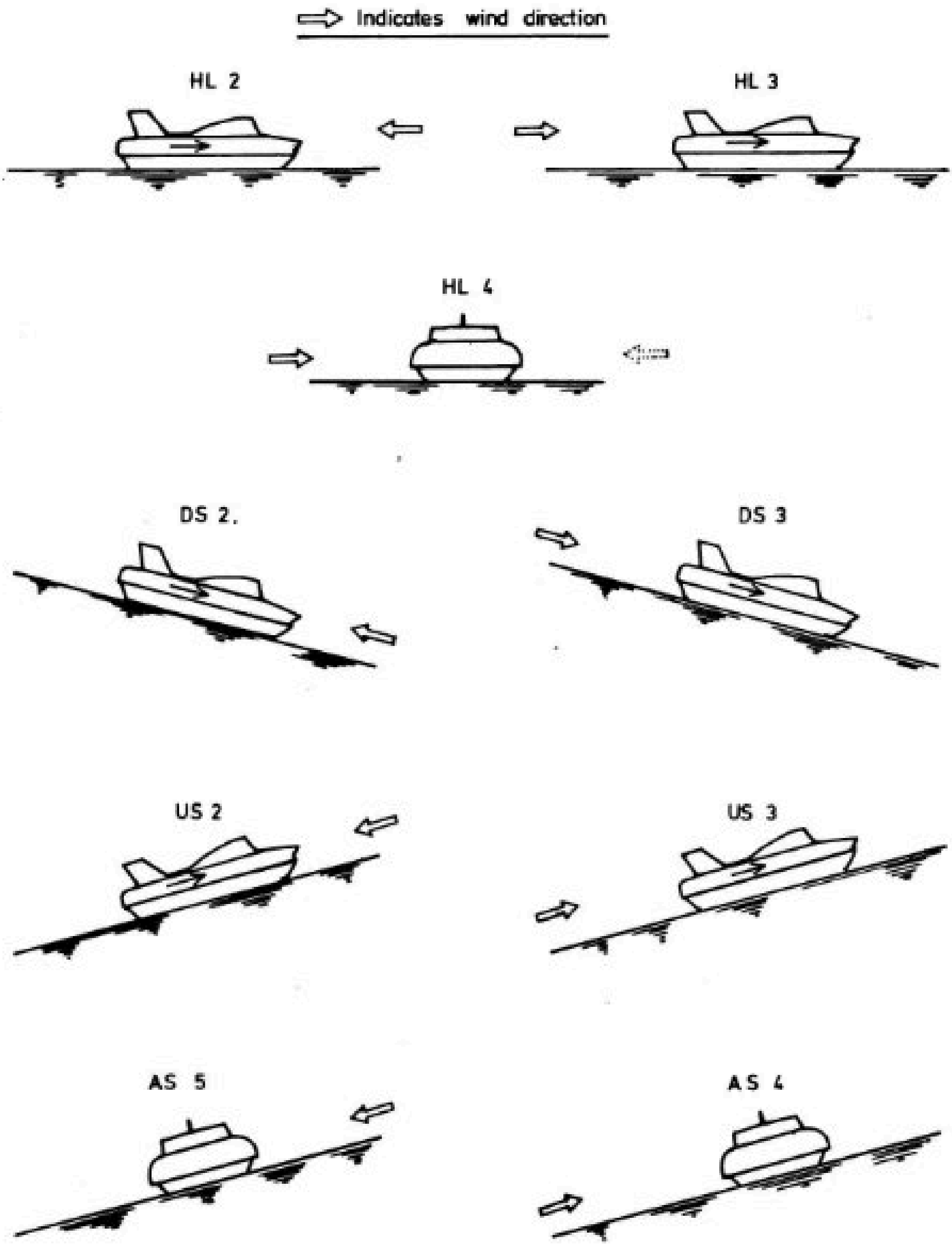


FIG. 50. ILLUSTRATION OF STANDARD CONTROL CONDITIONS FOR A.C.V.'s IN STRAIGHT TRACK MOTION IN WINDS.

(See Table 3)

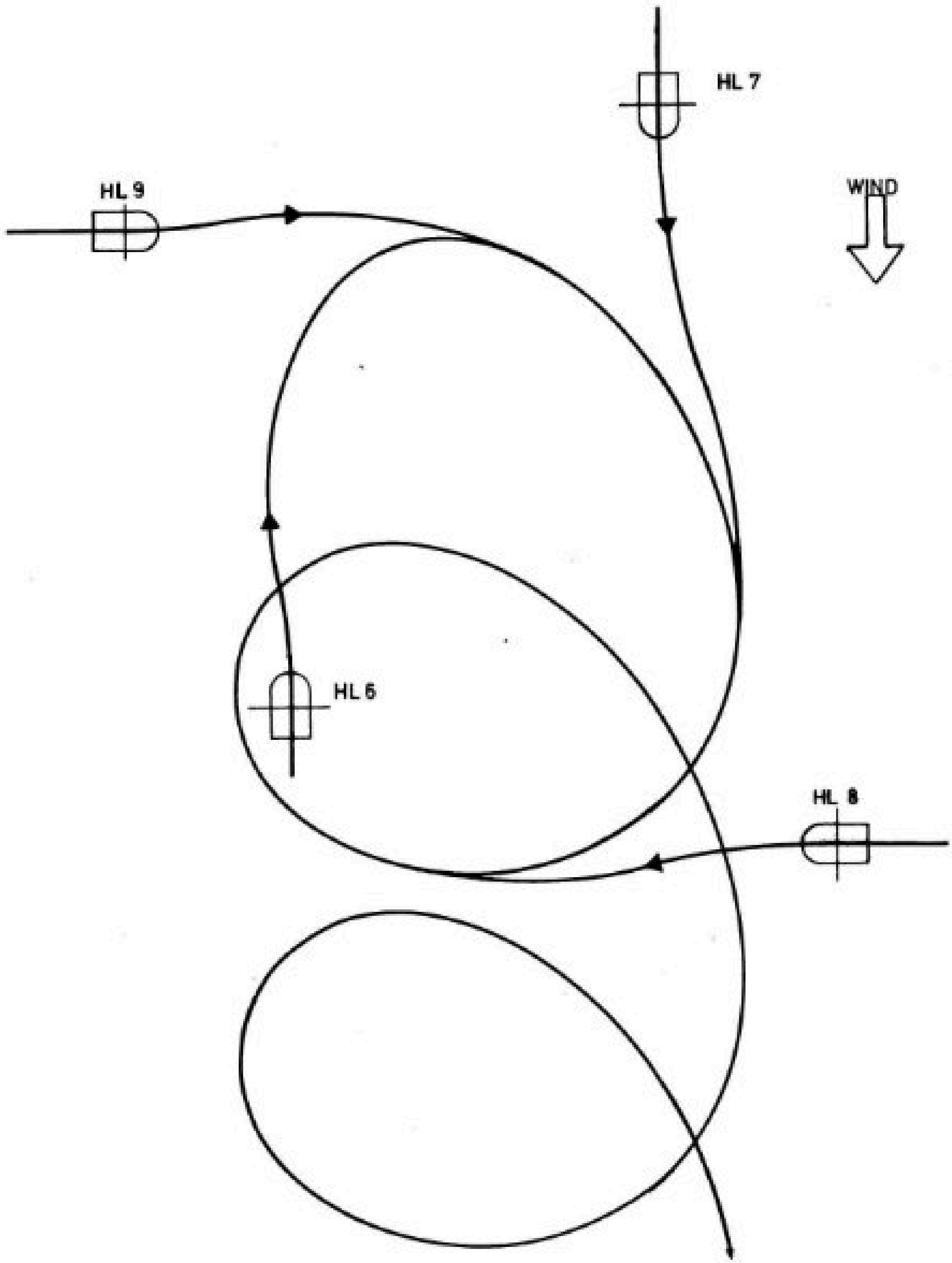


FIG. 51. ILLUSTRATION OF STANDARD CONTROL CONDITIONS FOR A.C.V.'s IN TURNING MOTION ON HORIZONTAL SURFACES IN WIND.

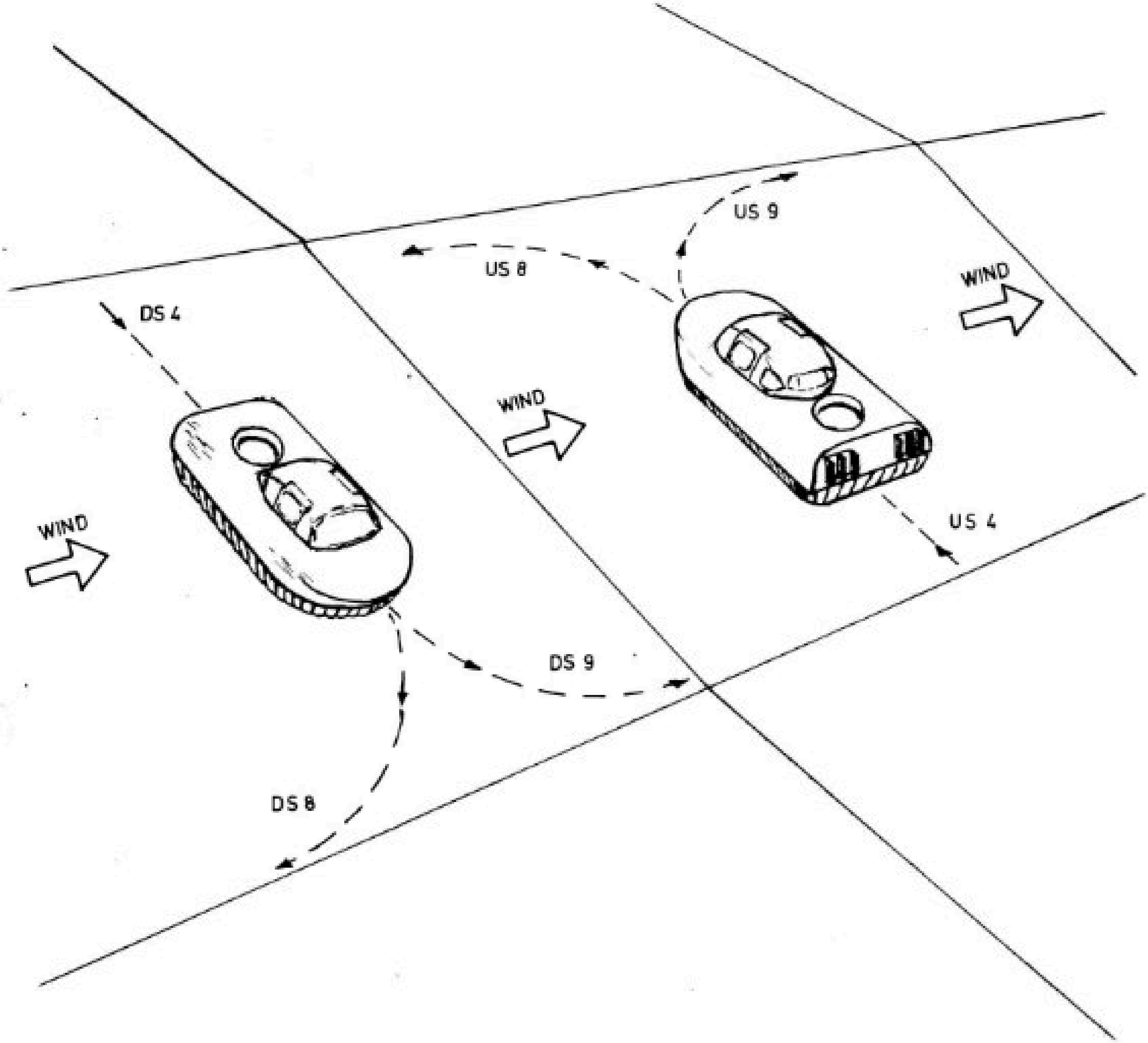


FIG. 52. ILLUSTRATION OF STANDARD CONTROL CONDITIONS FOR A.C.V.'s IN TURNING MOTION ON A SLOPE WITH A WIND BLOWING ACROSS THE SLOPE

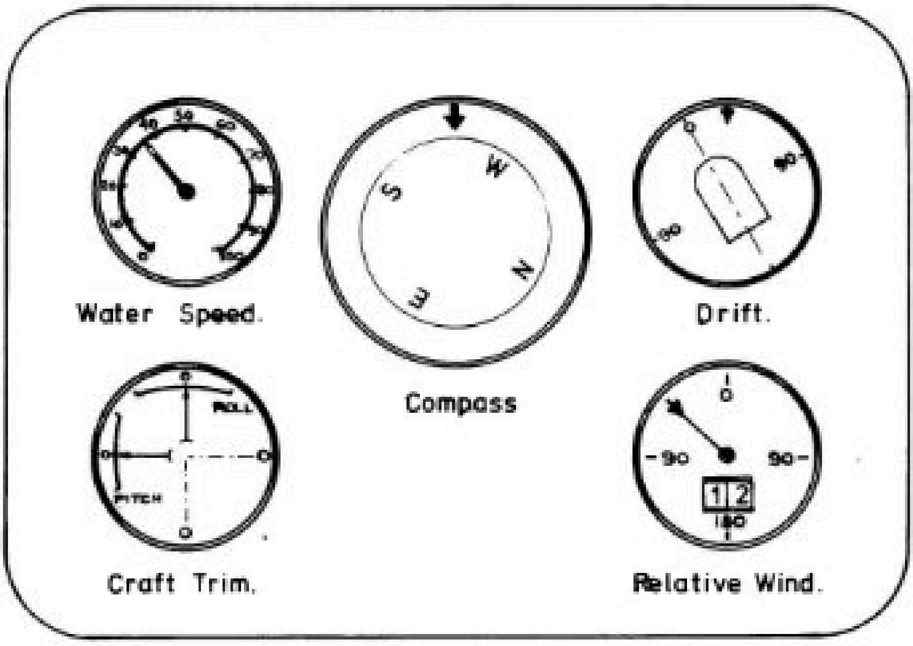


FIG. 53. STANDARDISED NAVIGATIONAL INSTRUMENT LAYOUT AS PROPOSED BY I.H.U. WORKING PARTY ON COCKPIT LAYOUT AND INSTRUMENTATION. (Ref. 36).

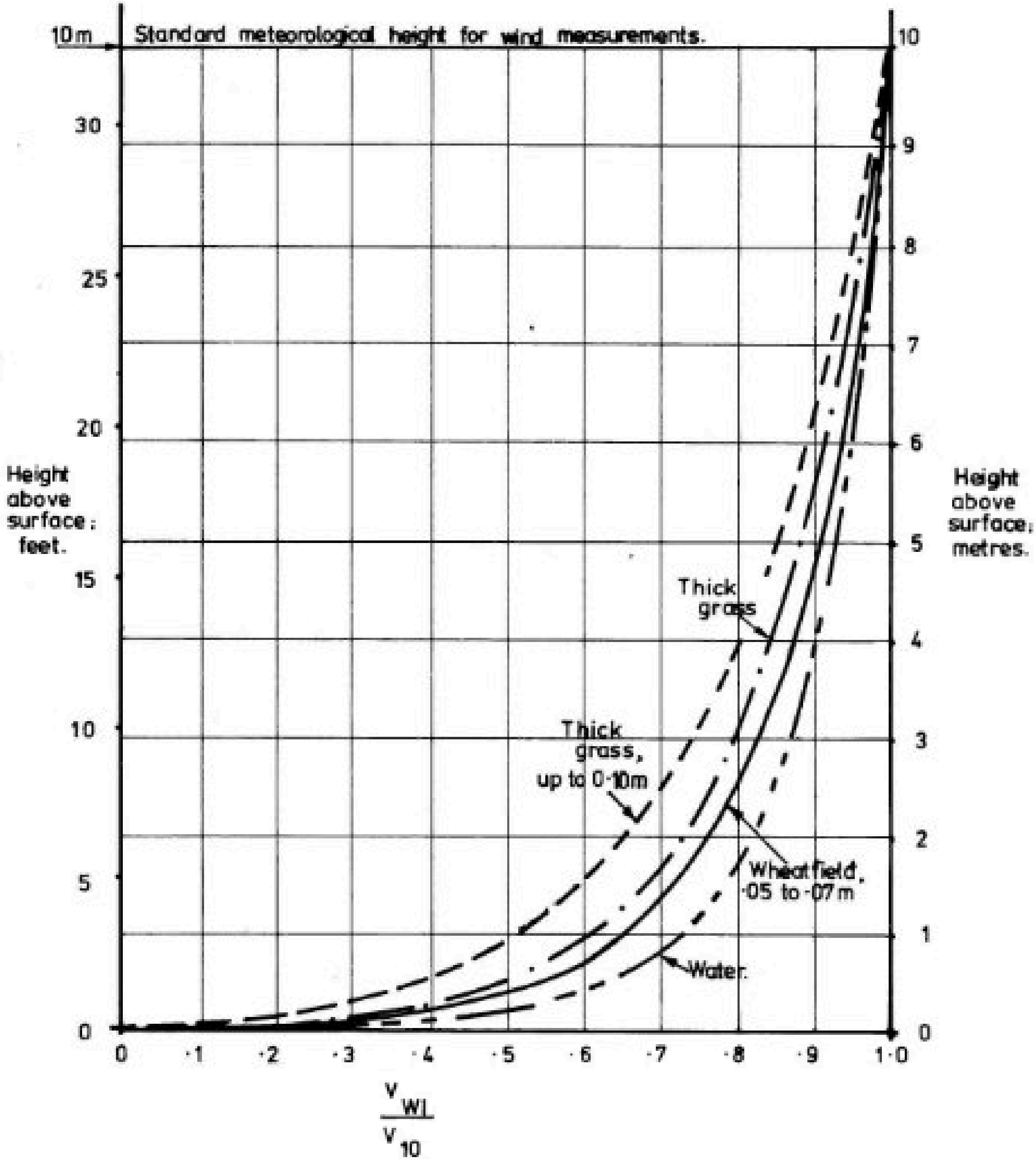


FIG 54 WIND BOUNDARY LAYER GRADIENTS GIVING RELATIONSHIP OF NEAR-SURFACE WIND SPEED TO STANDARD METEOROLOGICAL WIND SPEED AT 10 METRES HEIGHT.

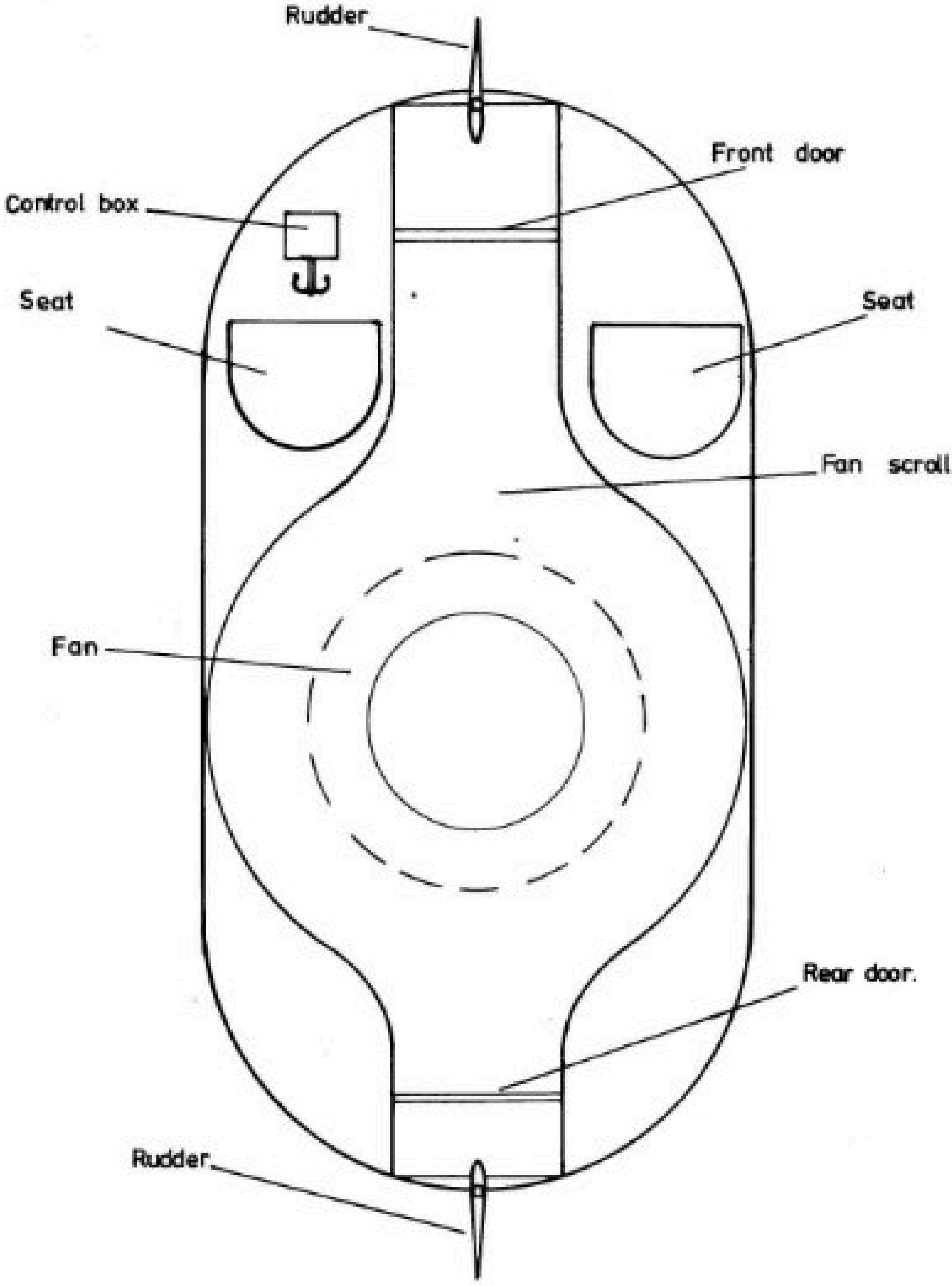


FIG. 55 GENERAL LAYOUT OF BV 101.

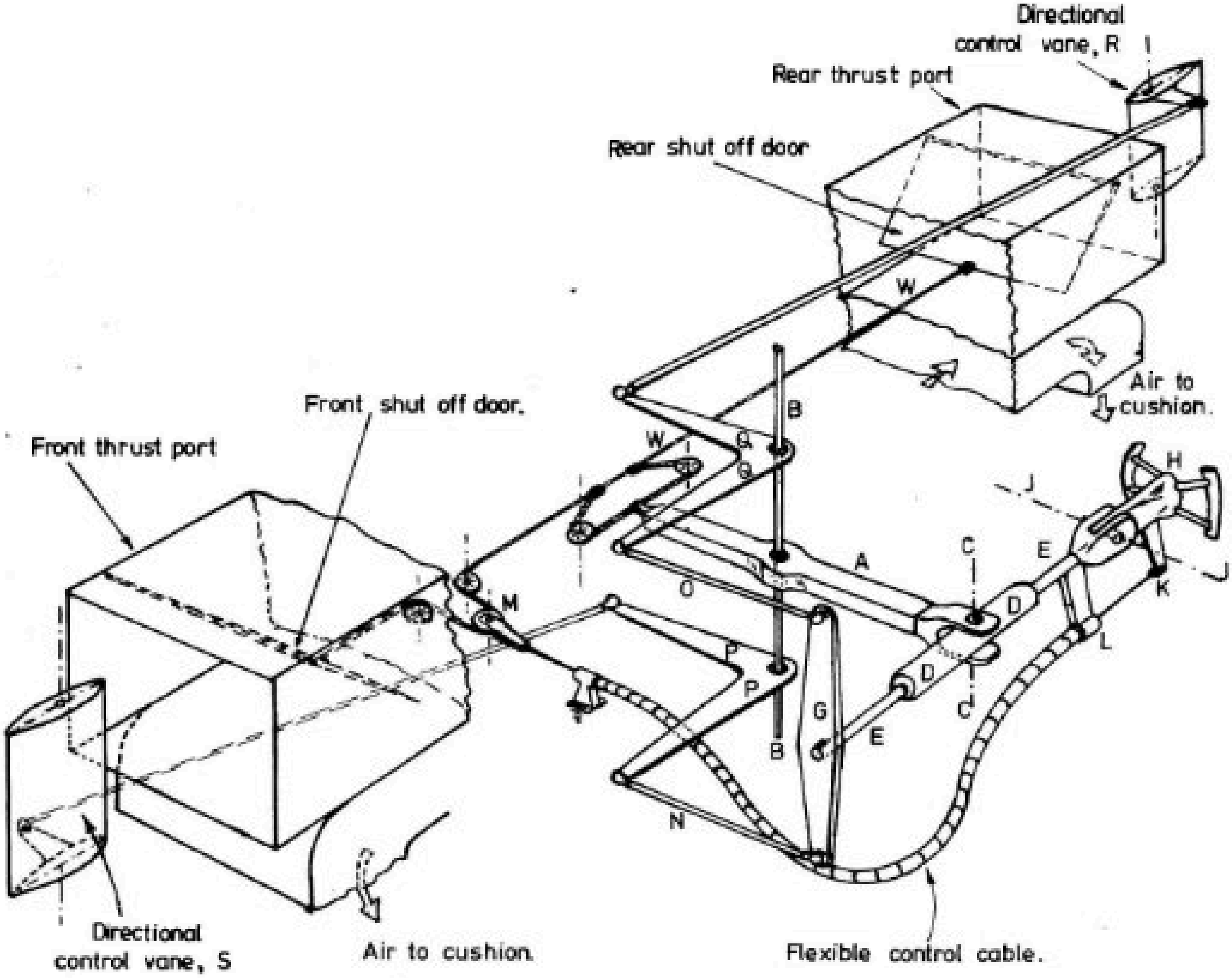
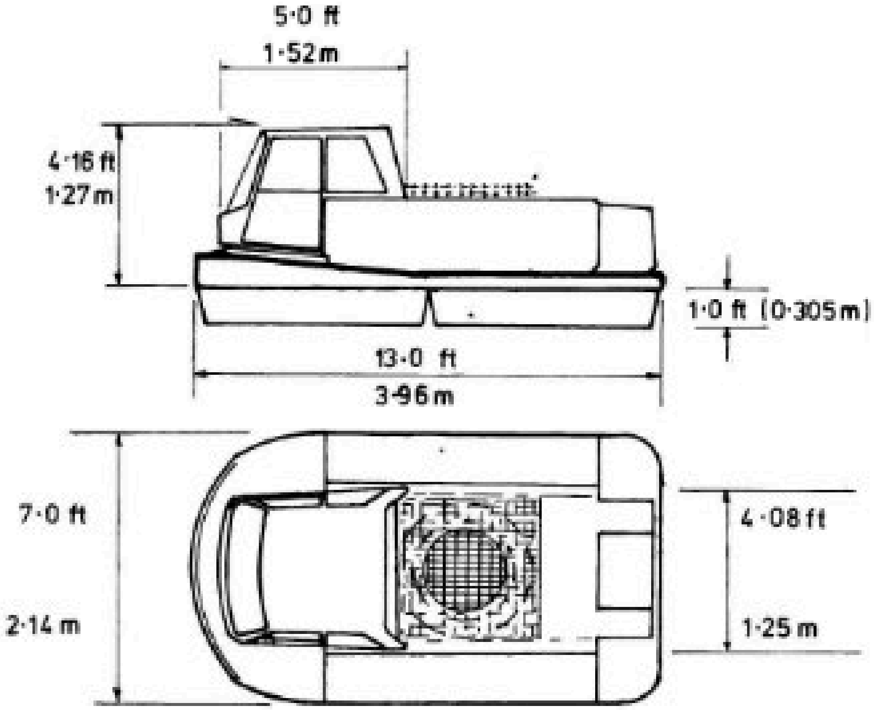


FIG. 56. CONTROL SYSTEM FOR BV 101.



Specification

Length.	13·0 ft (3·96 m)
Width.	7·0 ft (2·14 m)
Height, on cushion.	5·16 ft (1·58 m)
Hard structure clearance.	1·0 ft (0·305 m)
Passenger capacity	2 persons

FIG. 57. CANIVE BV 102S VEHICLE G.A. & SPECIFICATION.

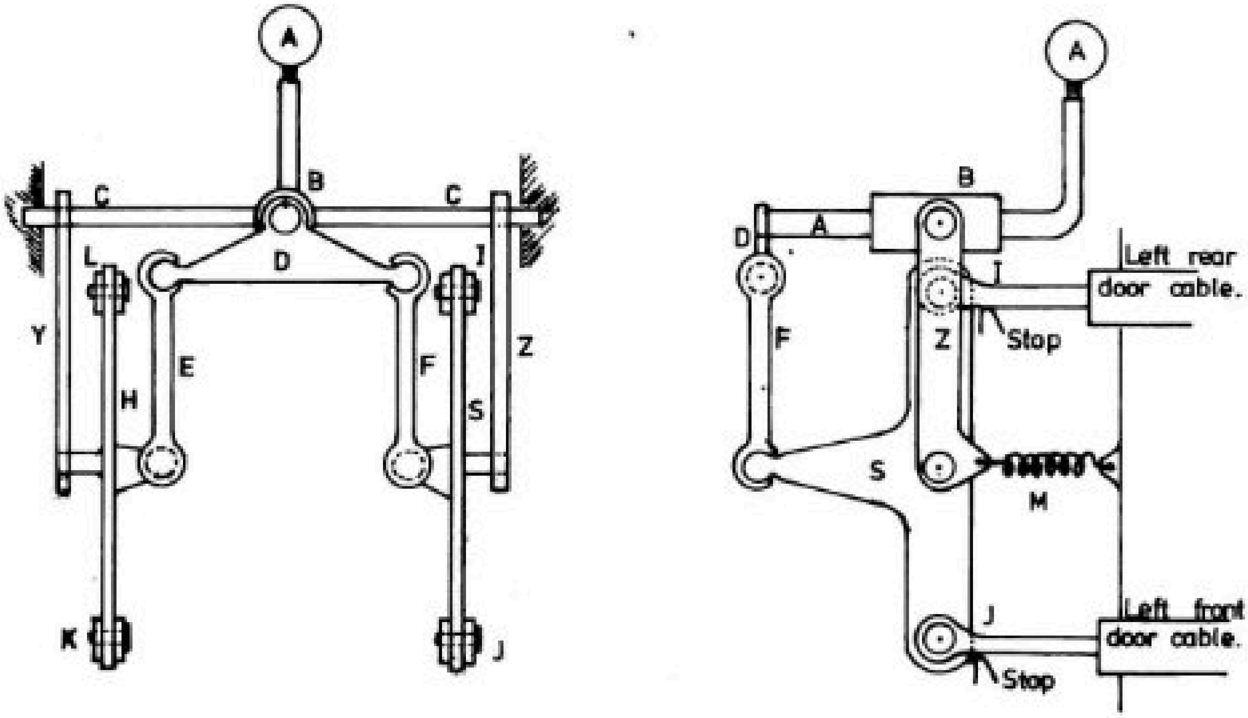


FIG. 58 SINGLE STICK, 4 CABLE CONTROL SYSTEM BV 102.

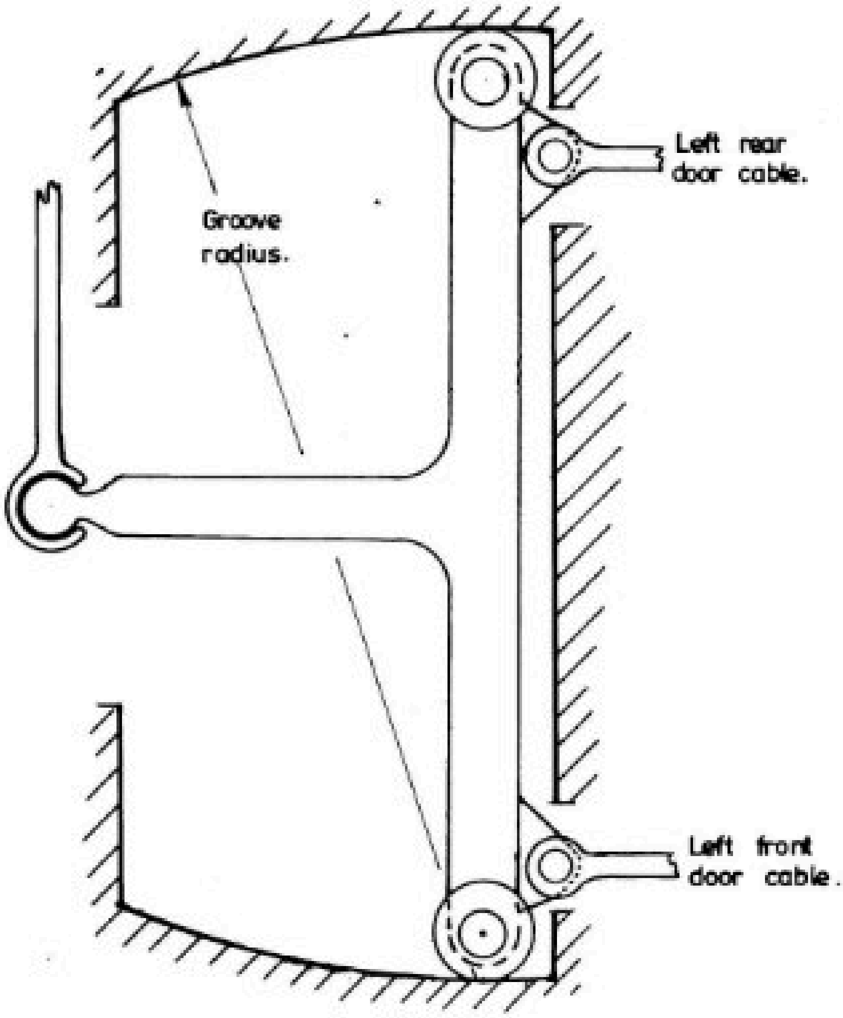
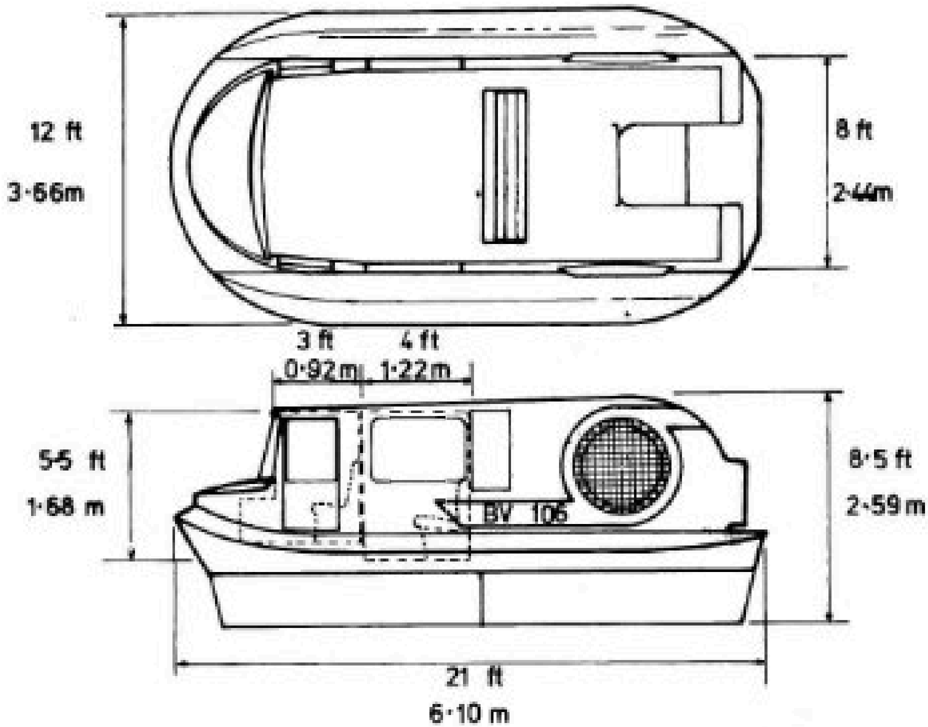


FIG. 59 CAM BOX.



Specification.

Length.	21	ft (6·10 m)
Width (operating).	12	ft (3·66m)
Width (without sponsons)	8	ft (2·44m)
Height.	8·5	ft (2·59 m)
Disposable load.	1200	lb (545 kg)
Gross weight.	3000	lb (1365 kg)
Electrical system.	12	volt.
Passenger capacity.	6	persons.

FIG. 60 CANIVE BV 106 VEHICLE G.A. & SPECIFICATION.

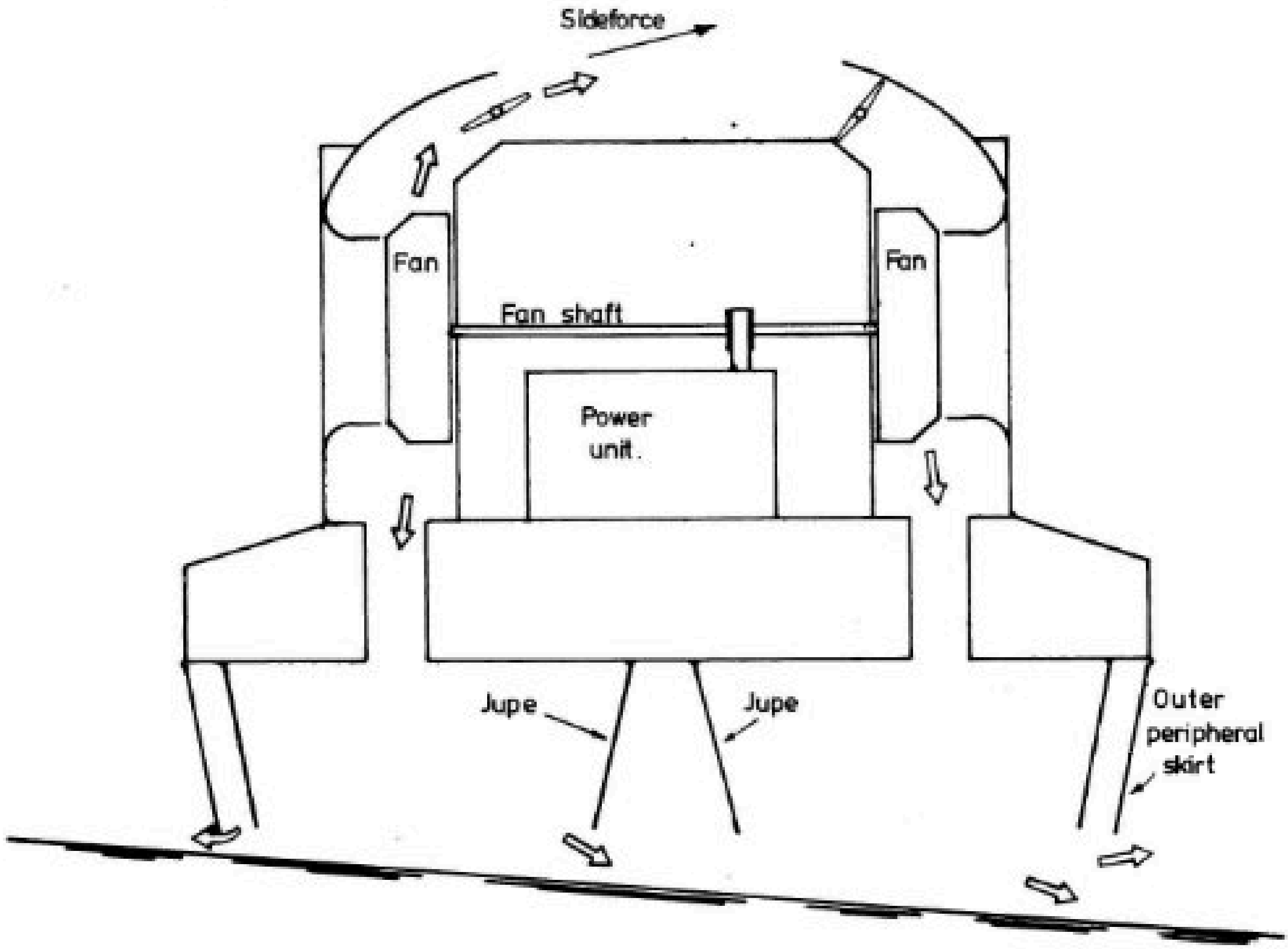


FIG. 61 SIDEFORCE WITH ROLL, BV 106.

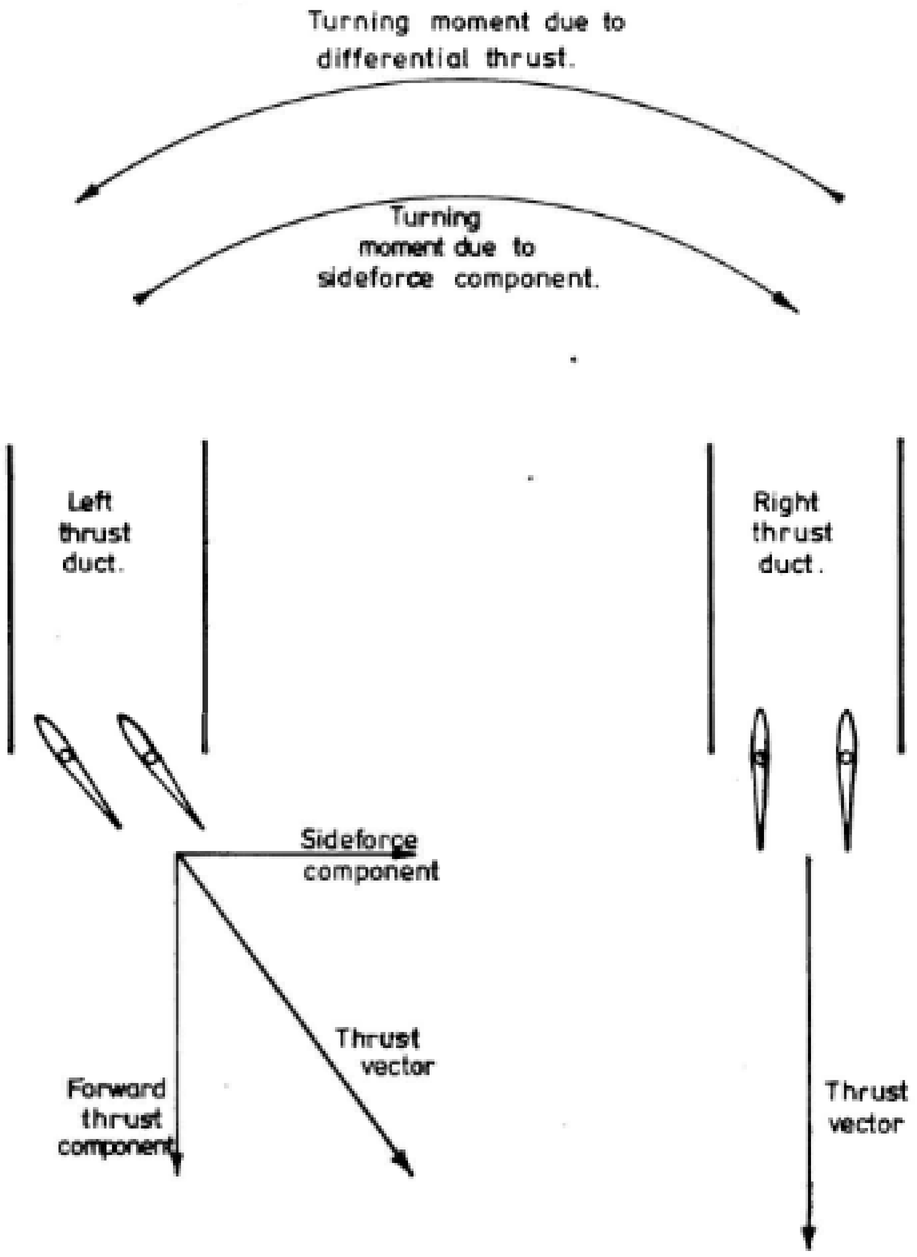


FIG. 62 CONTROL DOORS FOR BV 106 THRUST DUCTS, ORIGINAL DESIGN.

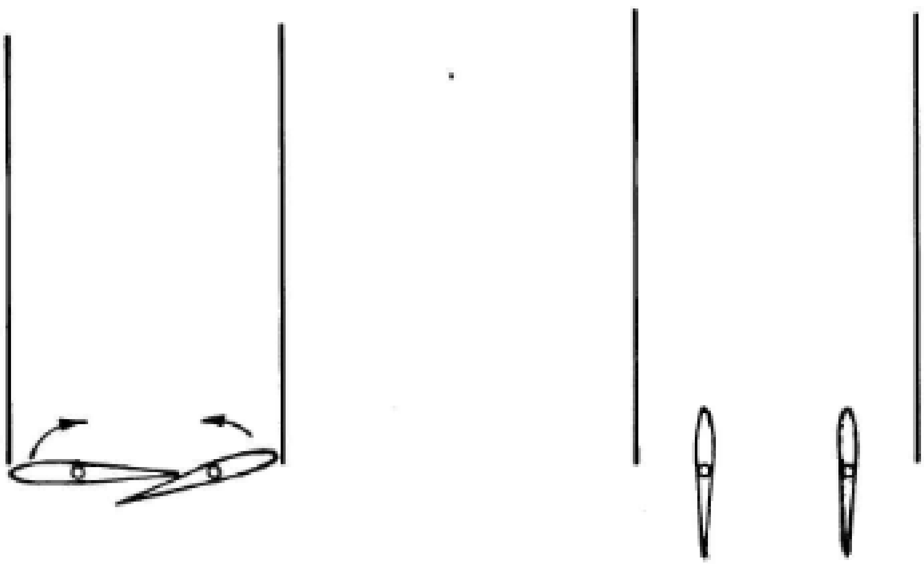


FIG. 63 CONTROL DOORS FOR BV 106 THRUST DUCTS, SECOND DESIGN.

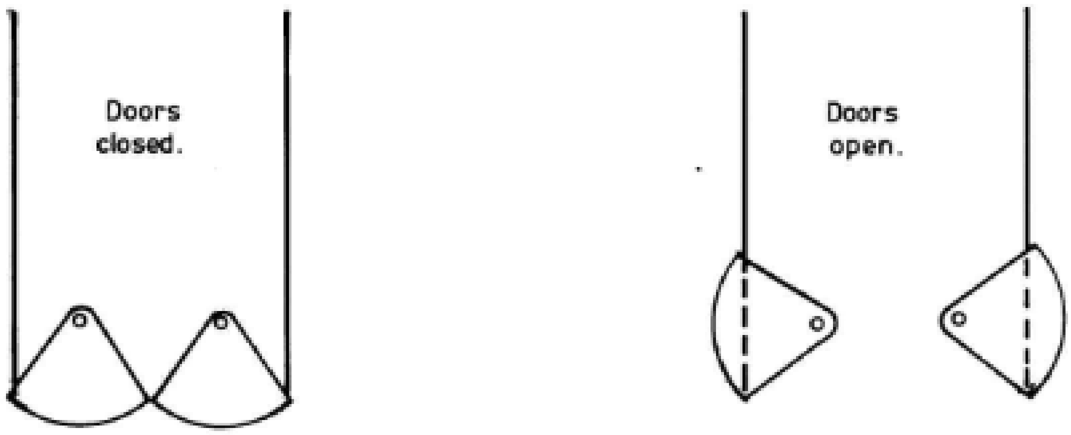
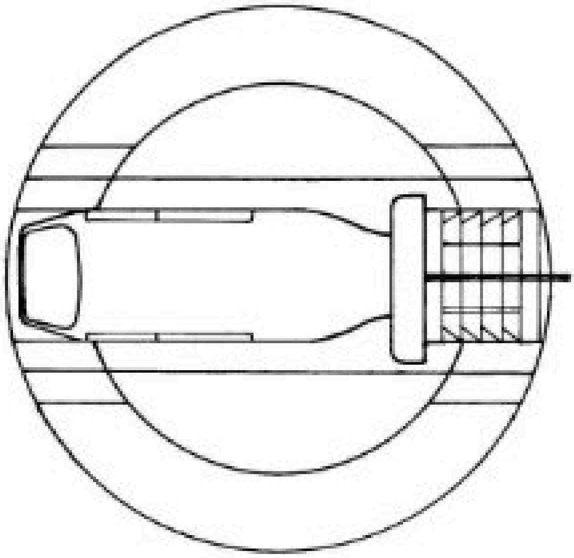


FIG. 64 CONTROL DOORS FOR BV 106 THRUST DUCT, BUCKET DESIGN.

Specification.

Diameter.	18 ft (5·49 m).
Width, (towing).	6·5 ft (2·0 m).
Height.	7·5 ft (2·29 m).
Gross weight.	2000 lb (910 kg).
Engine.	Ford V 8.
Hard structure clearance	1 ft (0·30 m)
Passenger capacity	4 persons



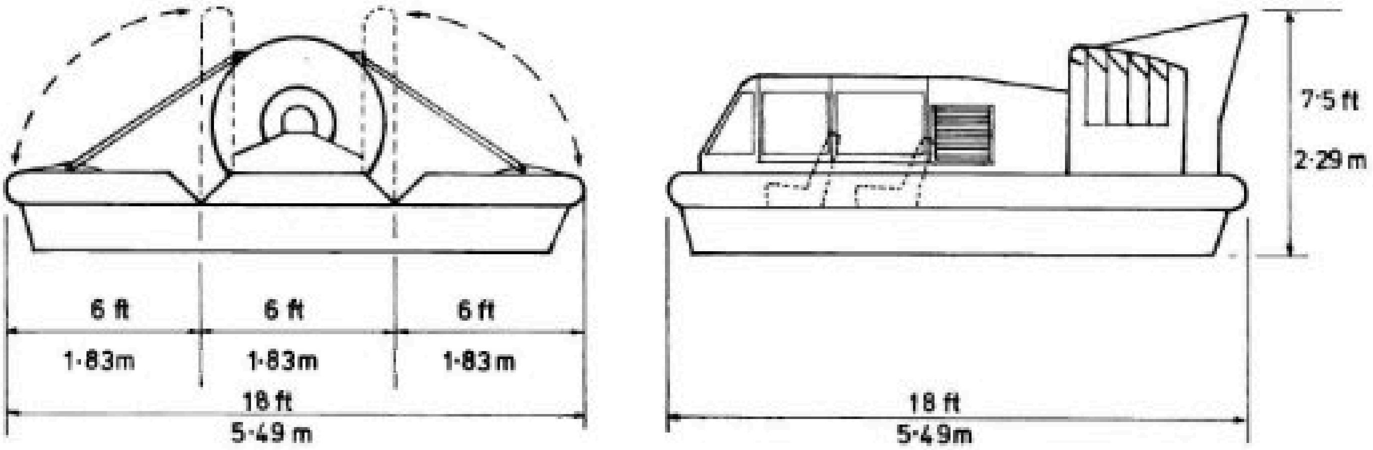


FIG. 65 CANIVE BV 104 VEHICLE G.A. & SPECIFICATION.

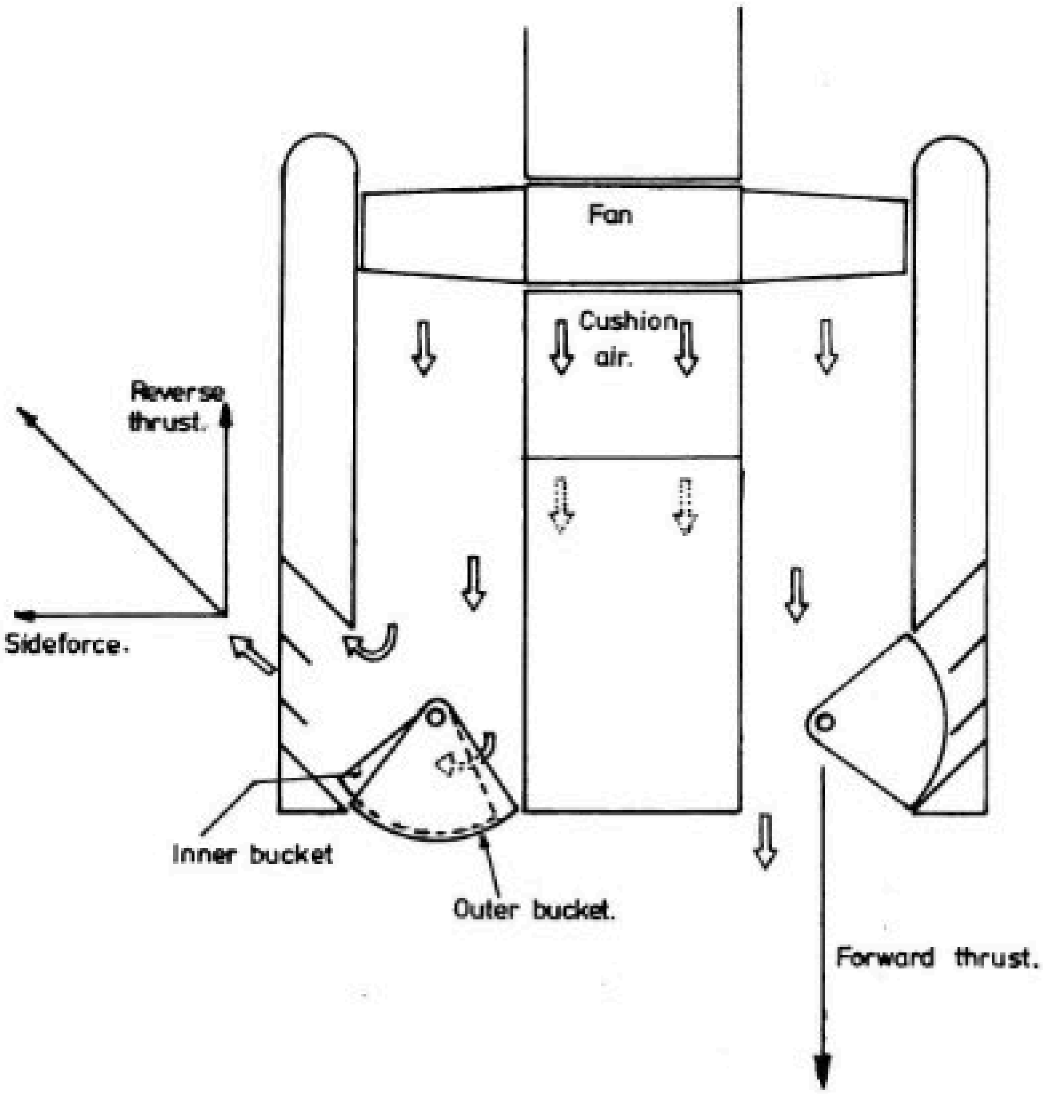


FIG. 66. BV 104 CONTROL DOOR ASSEMBLY.

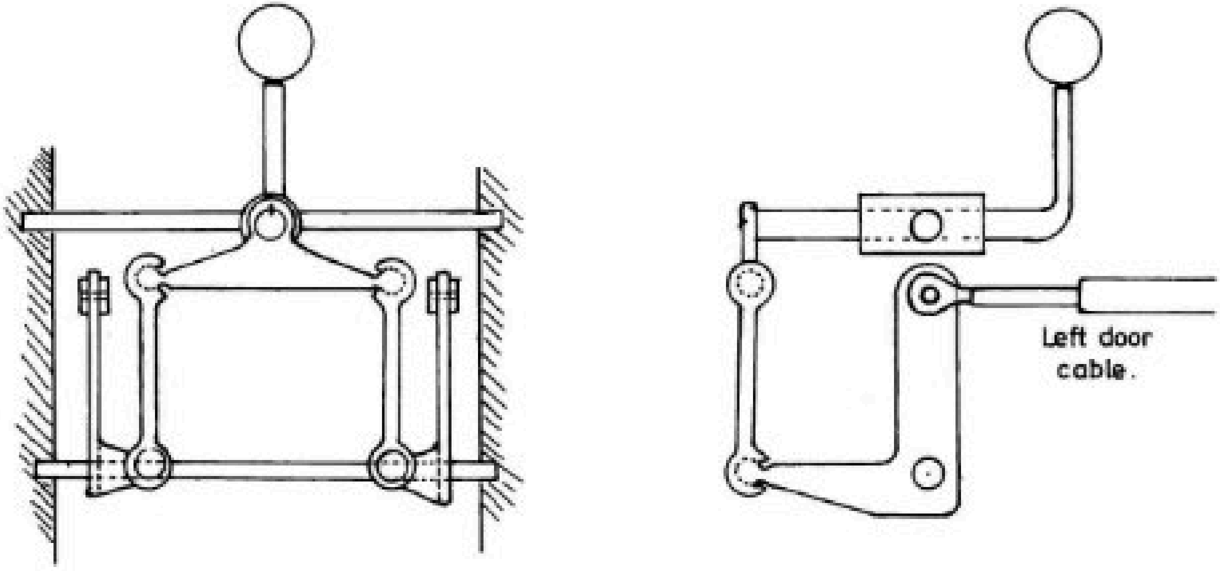
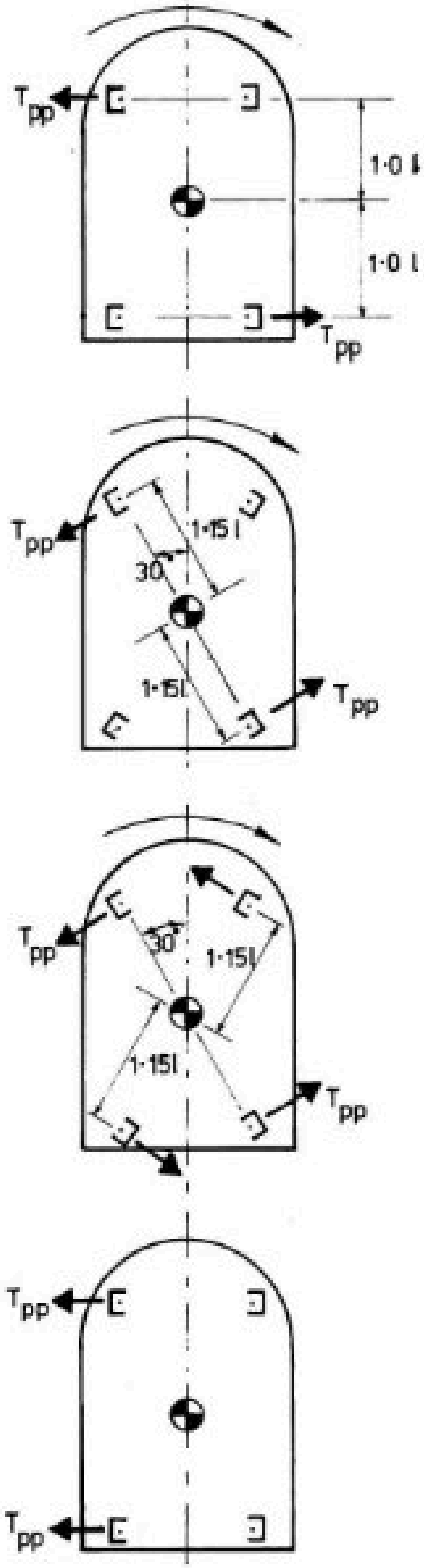


FIG. 67. C 105 TWO CABLE CONTROL BOX.



Present practice

Turning moment available on craft is

$$2 \times T_{pp} \times 1{\cdot}0\, l.$$

where T_{pp} is thrust force available from one puff port and l is distance of line of action of thrust force from craft c.g.

$$\text{Total moment} = 2{\cdot}0 \,.\, T_{pp} \,.\, l$$

Suggested improvements.

1) Using ports angled as indicated, and activating two ports only, it is possible to produce a turning moment of $2 \times T_{pp} \times 1{\cdot}15\,l$, using the same power as in present practice, thus giving

$$\text{Total moment} = 2{\cdot}30 \,.\, T_{pp} \,.\, l$$

2) Considering arrangement shown it is possible to use all four ports to yaw craft, with moveable vanes for changing airflow direction. If four powered ports are used the total power requirement is doubled. Then,

$$\text{Total moment} = 4{\cdot}60 \,.\, T_{pp} \,.\, l$$

3) If two ports on one side are opened, then a direct side force control is available = $2{\cdot}0 \,.\, T_{pp}$.

FIG. 68. YAW CONTROL AND SIDEFORCE CONTROL OF CRAFT BY USE OF THRUST VECTORING PUFF PORTS.

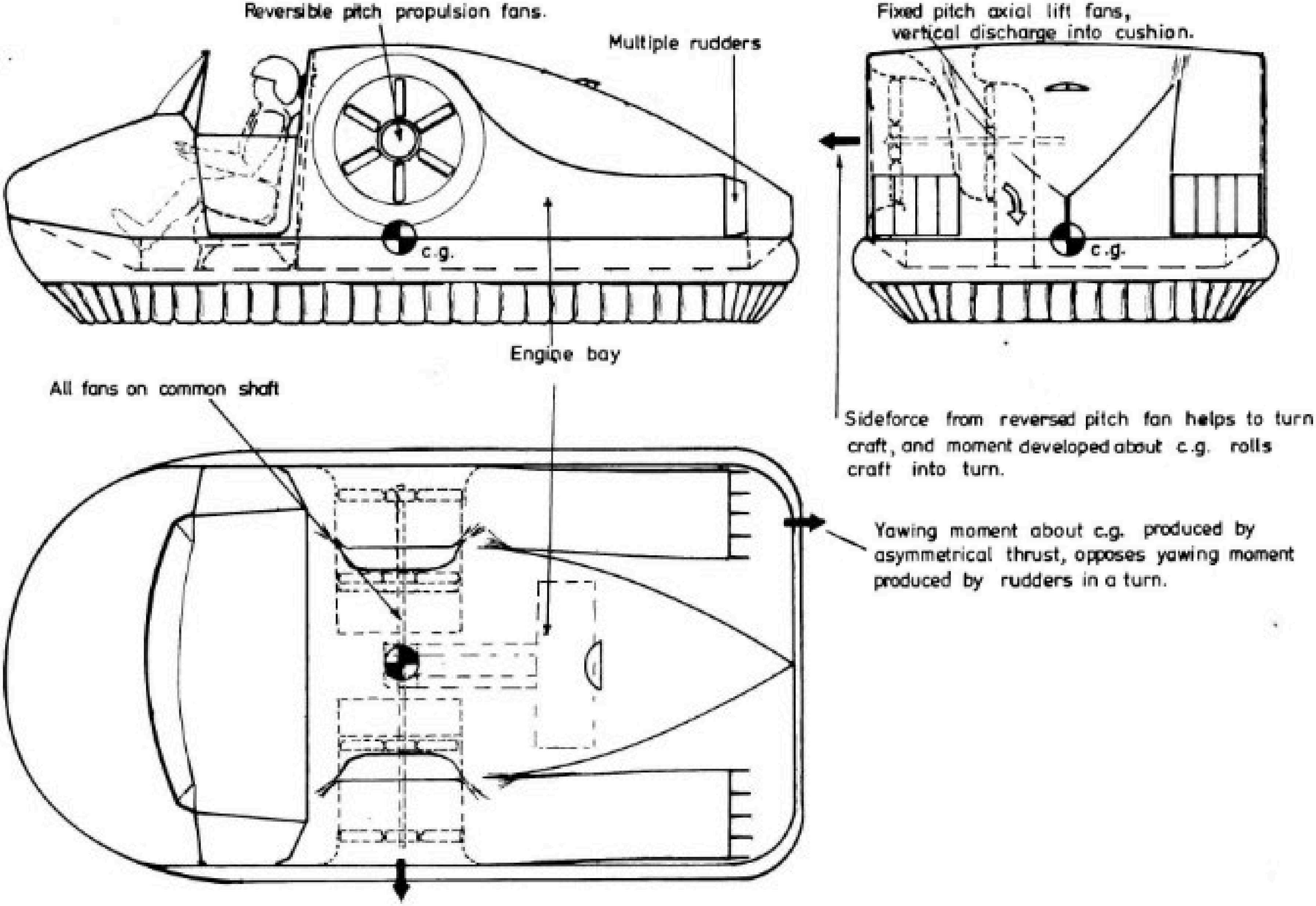


FIG. 69. SUGGESTED METHOD OF PROVIDING SIDEFORCE TO ASSIST TURNING.

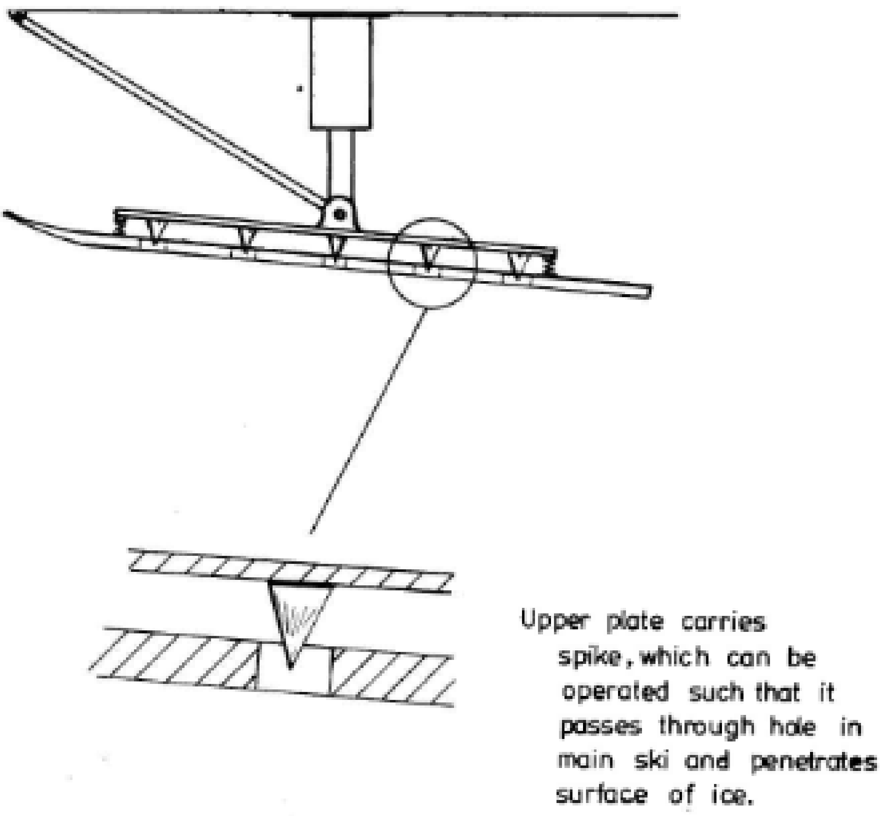
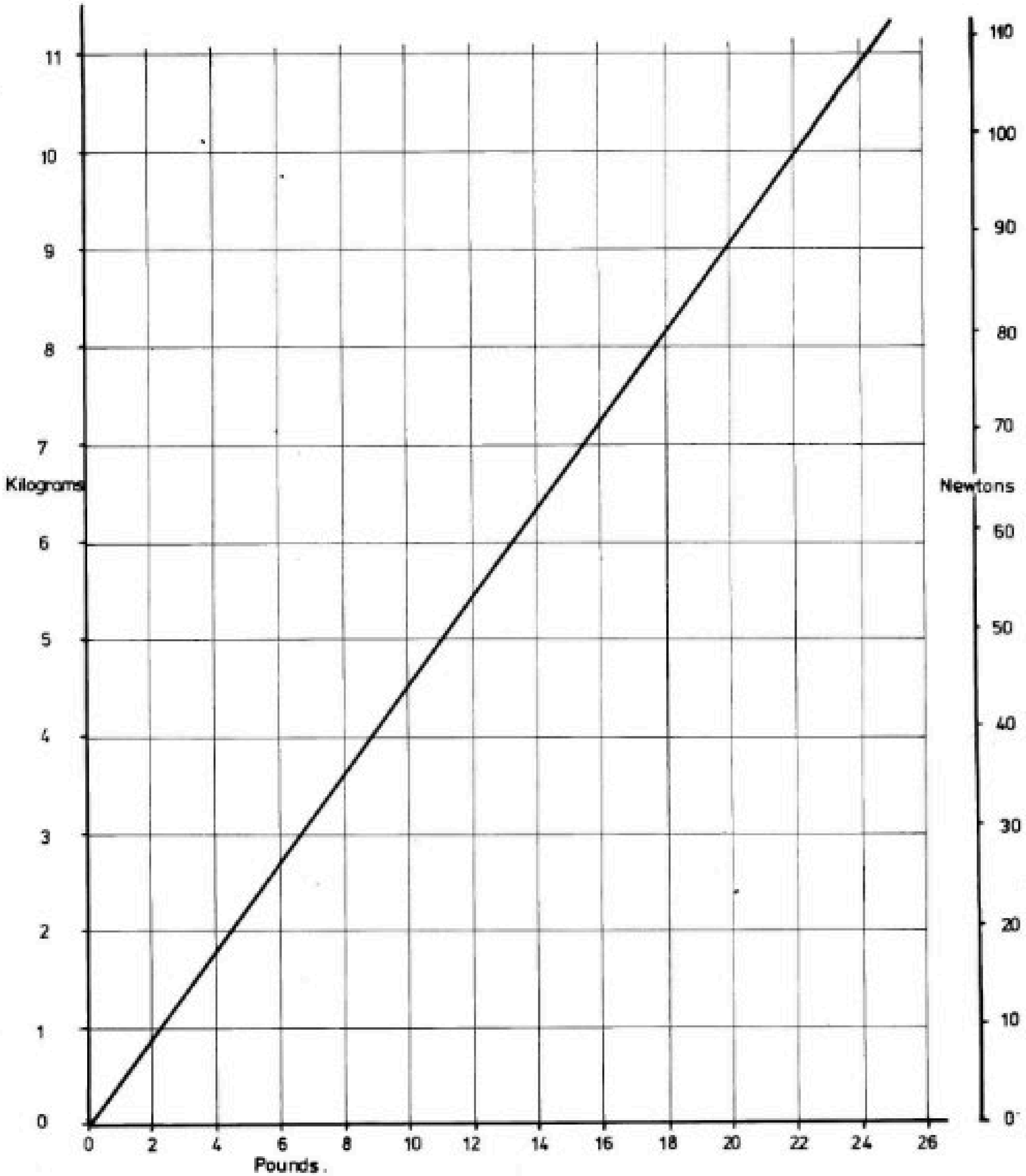


FIG. 70. SUGGESTED BRAKING PAD SCHEME FOR USE ON SMOOTH ICE.



CONVERSION CHART, POUNDS ~ KILOGRAMS ~ NEWTONS.