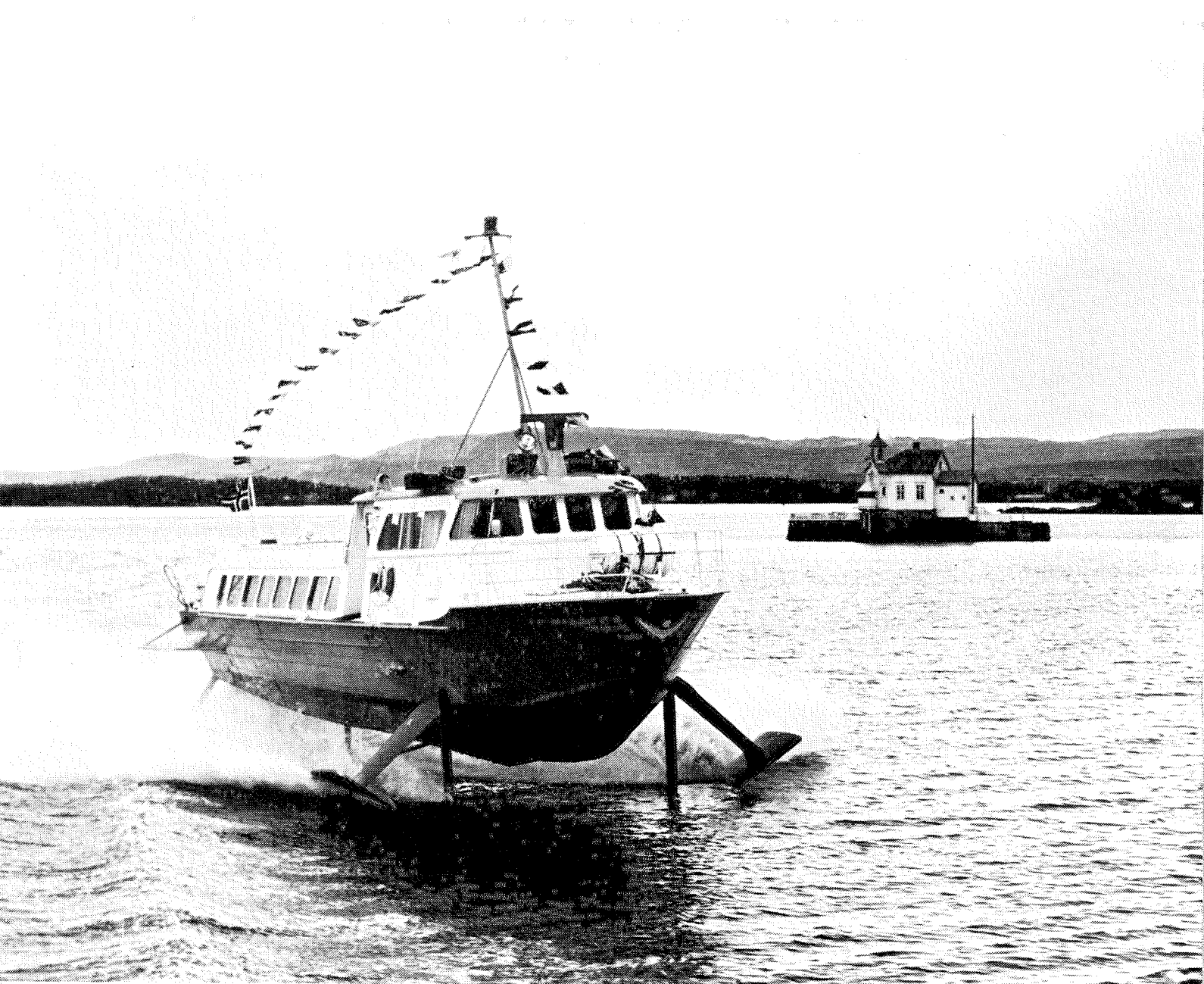


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# **HOVERING CRAFT & HYDROFOIL**

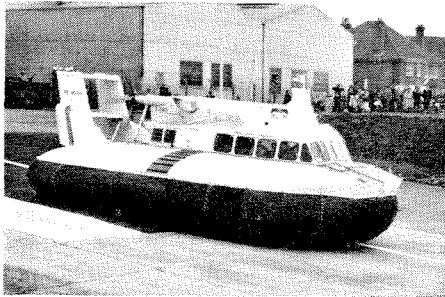
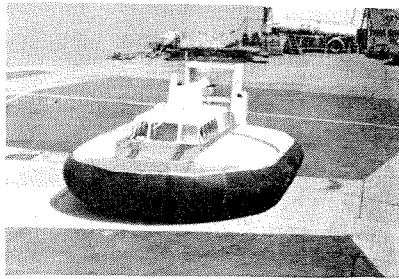
THE INTERNATIONAL REVIEW OF AIR CUSHION VEHICLES AND HYDROFOILS



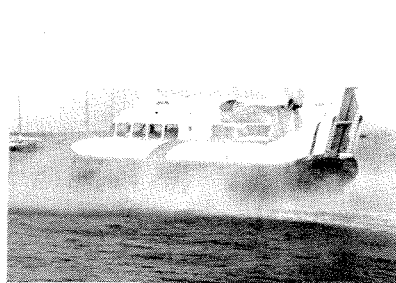
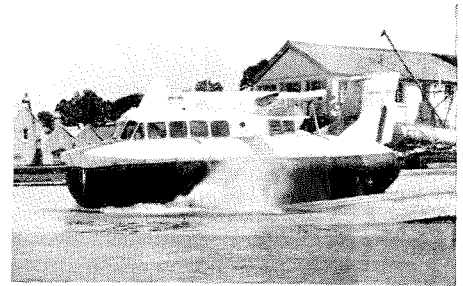
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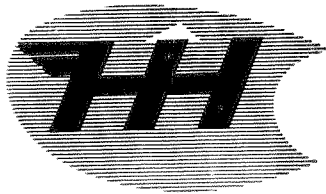
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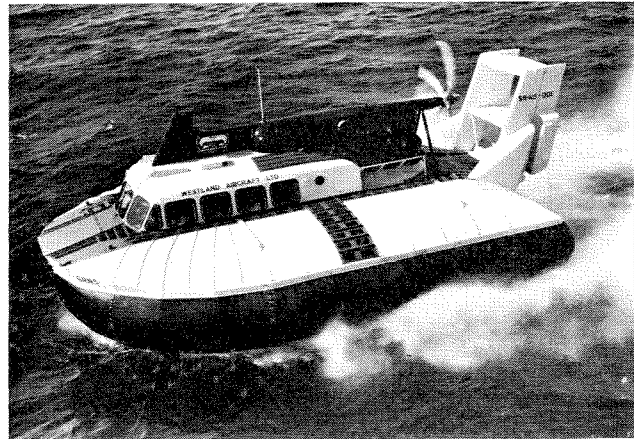
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## HOVERING CRAFT & HYDROFOIL

FOUNDED OCTOBER 1961

First Hovering Craft & Hydrofoil Monthly in the World



The latest development of Westland's SR.N5 showing the air ducting attached to the rudder structure, air being bled from the main pressure chamber and passed through the extension surfaces on the rudder to provide control stability

# WHERE ARE BRITAIN'S HYDROFOILS?

THERE is a demand in Britain at the moment for large passenger carrying hydrofoil craft. In fact, a market exists for sea-going hydrofoils capable of carrying 100-150 passengers at cruising speeds of 25-30 knots over distances of 10-200 miles. A well known city broker is currently searching for a British Company which can supply, within two to three months, two such craft. He is, of course, advised to deal with an overseas organisation. In view of the increasing demand for these craft, one can only register feelings of bewilderment and frustration at the apparent apathy of British designers, manufacturers, and investors.

Why does this pathetic state of affairs prevail? Is it because we are limited by small "back garden" concerns? Do designers have the courage and technical and financial resources to undertake the design of large craft? Are designers too pre-occupied with proving that their own ideas are the best ones? Is the limited commercial hydrofoil activity in this country the result of an apparent total lack of Government support and interest?

There would seem to be four known organisations in Britain currently concerned with commercial hydrofoil development.

One is of Dutch origin and is producing craft of Dutch design on a limited scale. Another is producing small craft of German design under license to a Swiss firm. The other two are struggling valiantly on limited resources to produce small craft of their own design.

The world's leading builder of commercial hydrofoil craft has more than adequately shown that the large hydrofoil passenger vessels which operate throughout the world are deserving of the demand and respect that has been accorded to them. Is it really logical to devote so many years to the task of designing small "runabout" craft which have yet to prove the superiority which their designers claim, while totally ignoring the very real demand which exists for less sophisticated, auto-stable passenger vessels?

This predicament in which we find ourselves is a challenge to British hydrofoil concerns and to those responsible for providing financial support to a sphere of engineering in which the British were among the pioneers. If someone has the ultimate in commercial hydrofoil design please do not just talk about it, build it. In the meantime buyers will continue to spend their money abroad.

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**COVER PICTURE:** One of the two PT20 hydrofoil craft operated by Hydrofoiltrutene A/S in the Oslo Fjord. The craft link the towns from Oslo as far as Tønsberg and Hankø, and are built by Westermoen Hydrofoil A/S, one of the Supramar Ltd licensees

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JUANITA KALERGHI

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# Future Air Cushion Craft Studies

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University of Wales



J. A. Sandover

**T**HIS conference has proved to be of great value, providing an opportunity for the exchange and presentation of information. The method of presentation has proved to be most successful and the contributions to the discussion have been informative, well-considered and at times, downright provocative. The presence of private consultants, industrial designers and research workers, has added materially to the value of the exercise and, in particular, it was most heartening to welcome a number of air cushion craft enthusiasts from overseas.

It is evident from the written and spoken contributions that there are yet a very large number of specific problems in air cushion craft design that need attention at both the basic research and the development level. The work already carried out can only be regarded as a preliminary clearing of the ground before systematic and detailed investigations are undertaken. Some of the problems that need attention, not necessarily in any order of importance, are as follows :

## 1. Separation in the Nozzle

This occurs at a variety of jet angles and will certainly be aggravated as the vehicle heaves. An appreciation of this effect is important as it implicates modifications to existing theories and in particular when flexible extensions (skirts) are used. The research worker needs to investigate this problem closely, but the designer is more concerned with the need to know the magnitude of the change in jet angle under extreme conditions and the effect on the lift of the craft. Two and three dimensional studies are required. The papers of Hughes and Mc-Daid are concerned with this problem.

## 2. Cushion break-down

At a critical forward speed the frontal portion of the jet curtain will be swept backward under the craft. What changes in attitude will occur at this critical velocity? The results of Alexander and West and others are at the best inconclusive and the spoken contribution of Mr N. K. Walker was most valuable in this context.

## 3. The relationship between two and three dimensional studies

Hughes has shown that work on relatively small, two-dimensional models can be scaled-up to correspond with the results from much larger two-dimensional models. The next stage is to compare the larger 2-D models with the 3-D ones and then to compare these with the prototype. It is then possible to work backwards and determine the effectiveness of 2-D models in predicting 3-D prototype performance. Alexander has shown some of the pitfalls that can occur in this respect.

## 4. The necessity for moving ground boards in model tests

Thunholm's paper underlines two points. It is necessary to have an appreciation of the effects of working without a moving ground-board, on model measurements but, it is also true that many measurements are much the same, with or without moving ground. Thunholm's work must now be extended to the differences in measurement that occur with different configurations.

## 5. Flexible Extensions to the bases of Air Cushion Craft

A variety of these have been developed and work well but a great deal of effort is required in order that a full understanding of their effect is obtained. A large scale series of model and prototype tests is required.

## 6. Internal Aerodynamics

These can be divided into six parts.

(a) The position and shape of the air intake has largely been determined by practical considerations. A determination of the effect of change in position and of the shape of different types of intake is needed.

(b) Although some work has been undertaken by Keiller at Bedford a much greater effort is needed to determine the characteristics of the "ideal" fan for a particular job.

(c) The duct geometry should be considered most carefully to ensure minimum head losses and to provide the best entry to —

(d) the nozzles. There is still considerable conflict of opinion regarding the best nozzle shape — if in fact there is such a thing as *a* best. The optimum shape may well depend upon other characteristics of the craft.

(e) The jet region has been the subject of many studies but there are still a number of fundamental and development problems to be solved. Again there is a great need to compare and contrast 2 and 3-D results. One particular item of interest is the bifurcated jet.

(f) It is usual to regard the cushion pressure as constant under the base of the craft. It is realised, particularly at high hoverheights, that this hypothesis does not hold and an understanding of the change in cushion pressure with location is important to both the research worker and the designer, since the stability of the craft will depend to a large extent on the pressure distribution. The possible variation needs to be determined for non symmetrical steady attitudes and (much more difficult) when the motion is unsteady in pitch, roll or heave.

7. How far inboard should flexibility of the nozzles and ducts be considered and what would the effect be on performance?

8. Should the air cushion craft of the future be designed to obtain lift from the upper surfaces even at moderate forward speeds?

9. If such lift is obtained the effect of attitude on performance must be considered.

10. Some preliminary investigations of dynamic stability have been carried out but much more work is required at all levels of thought and development.

11. Lift and thrust devices are of necessity somewhat primitive. Attention should be paid to the possibilities of the Bertelsen method of using one unit for both lift and propulsion. Further, attempts should be made to develop monobloc systems of fan and prime mover to improve their overall characteristics.

12. Comparisons should be made between the efficiencies of propulsive units, including air-propellers, fans, marine screws and water jet pumps or combinations of these.

13. Recirculators, ejectors and other devices must be investigated even though it would appear from a study of the history of technology that the simple device, although marginally less efficient, is usually cheaper to produce, install and maintain.

14. The work of Everest at the National Physical Laboratory opens up an interesting and intriguing study of the effects of jets on water surfaces.

15. Barnes' work on flight simulation whilst of practical interest from a tuition point of view also suggests the extremely interesting possibilities of predicting handling behaviour even prior to the construction of a projected craft.

16. Is the peripheral jet concept likely to be the most economical in all circumstances? It has been suggested that the inefficiencies of the simple plenum chamber type craft may imply a smaller efficiency penalty than that incurred in cramming air at high speed through relatively narrow nozzles.

17. Cranfield appears to be the only place in this country where the "ram-wing" concept is being studied and yet in my opinion, this is likely to be the high speed, trans-oceanic air cushion craft of the future. It appears to be most uneconomical not to use the lift generated on an appropriate surface shape at high speed. This is a most fruitful field of study particularly following the interesting work of Ando. The scope of this subject is much too large for detailed suggestions to be put forward at the moment.

18. Another concept that Hovercraft Development Ltd and Bertin et cie are investigating and appears to have most interesting possibilities is the "Hover-train" or "Aerotrain". This is a vehicle which effectively has a rail passing through it and an air cushion is provided between the rail and the vehicle. There are many problems that need tackling in this context and in particular the question of the use of the "linear-motor" for propulsion.

19. The Bertin method of providing the air cushion should be investigated.

20. What is the potential of combined systems, i.e. of hovercraft and hydrofoil?

21. Investigations should be put in hand to determine the possibilities of reducing the cost of existing types of air cushion craft which are prohibitively expensive to produce at the moment.

A number of conclusions can also be reached as a result of this conference. First, that there has been, in the past, a certain duplication of effort. Admittedly this is not always to be deplored, but with the limited resources available it is imperative that overlap should be reduced to a minimum. The second conclusion follows from the first, that to avoid duplication it is essential to have at least one person who can act as a co-ordinator of research. To a certain extent this office is performed by the exchange of information system set up by the Ministry of Aviation. However this office needs to be operated more precisely and it is essential that one person be appointed to coordinate all the air cushion craft in this country. A preliminary duty would be to ensure the preparation of a complete bibliography of the subject (carefully cross referenced) and following this with a literature survey. The reference list and survey should be added to as each piece of information is received. In addition there should be close collaboration between this administrator and each research group with regular discussions and visits. It should then be possible for a detailed revue of the state of knowledge and of the research programmes to be made at any instant. Finally, it might be possible for this person to assist in the standardisation of symbols and terminology.

A third conclusion is that there is far too great a gap between research work and its verification by measurements on prototype craft.

There are also a number of general remarks that might not be out of place.

It is essential that everyone interested in air cushion craft maintain an open mind. It is highly unlikely that the ideal craft has yet been devised and although Westlands have developed some magnificent craft, everyone, including the designers, must be continually asking themselves, "Can we improve these designs or is there some even better alternative".

One of the most frustrating facets of a research worker's life in this subject is the great difficulty in obtaining information from commercial concerns and Hovercraft Development Ltd. I think it is true to say that the majority of developments in this country have been supported by the tax-payers' money and although commercial secrecy has to be observed there is a great deal of information that could be released without prejudicing the companies' potential. Further in this day and age it is likely that each industrial organisation had a fair idea of the work of its rivals but cannot profit unduly from this knowledge without infringing the patent laws. Therefore, little would be lost if all but the most up-to-date information were divulged to bona-fide research workers.

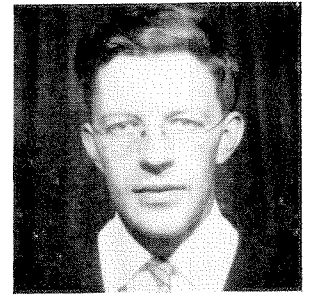
Mr Christopher Cockerell states that we are likely to lose our lead to the Americans in the near future, a forecast echoed by Mr N. Walker, a consultant from the USA who claims that they will catch up with us within two or three years. It is likely that this breast-hugging of information, this determination of certain organisations to do it all alone may lead to their own industrial suicide if it is not halted. We can only hope for the sake of this country that a more liberal attitude may prevail in the future. I must qualify these remarks to a certain extent as Messrs Vickers have been kindness itself in supplying us with information.

With or without assistance it is essential that much more money should be provided to finance air cushion craft work through all stages from fundamental research to operating services. It may well be thought that I should not grumble as the Department of Scientific Research have awarded me more than £18,000 for this research, spread over five years and British Petroleum have very kindly helped with equipment valued at approximately £2,000. Even this however is "small beer" since it provides little more than the salaries of one senior research worker and two technicians for part of this period. An ideal University research team would consist of possibly six research workers and six technicians with adequate provision for materials, equipment and various sundry items. There is no doubt that a team of this size would produce through cross fertilisation of ideas, a large volume of work. Further, from the number of potential research projects already listed it is evident that several teams of research workers could be kept busy for a number of years.

At the other end of the scale there is the need for adequate support for the projected cross-channel air cushion craft ferry-services. The capital required to start a reasonable service in two years' time (the quoted three years is too far into the future with the Americans on our heels) would be probably £20,000,000 and this could be raised in several ways. Either a stock issue, which would probably be over subscribed by the small investors who welcome a speculative enterprise, or by Government loan, or, and most suitably, the investment of public funds by the Government, so that everyone in the country would have a stake in this venture.

Finally, some acknowledgements. As Chairman, I have had an easy passage due to the extremely hard work of the organising secretary Mr David Hughes; and his committee members Mr Michael Hughes, Mr Tony West and Mr Victor Treasure. I am most grateful to them and to all the delegates; busy people who have taken time off to attend this conference, and to the Council of Swansea University College for permission to hold the Conference here.

# AIR CUSHION CRAFT RESEARCH AT THE UNIVERSITY OF SWANSEA\*



D. L. Hughes

D. L. Hughes  
University of Wales

## 1. INTRODUCTION

THE ultimate object of the programme of research in progress at Swansea is a study of dynamic stability of an air cushion craft at significant forward speeds. This is regarded as a long term project and we are at present engaged in laying the foundations by carrying out a variety of small experimental and theoretical pilot studies, and by building up our facilities.

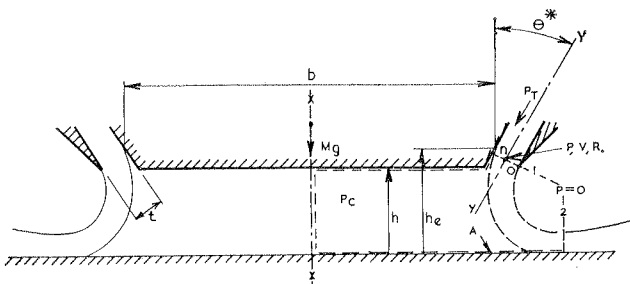
Stability is a property of an equilibrium state, so one of the first requirements is a careful definition of the conditions under which equilibrium exists. Then it is normally possible to obtain useful information about dynamic stability by examining the effects of small disturbances, from the steady state, assuming all changes to occur linearly.

Michael Eames<sup>1</sup> has in fact described an extensive analysis on these lines using a modified version of Chaplin's<sup>2</sup> thin jet theory, but it seems probable that his work has been extended much further than the limits which his assumptions justify. At the outset of this present study, however, it was thought that a theoretical analysis could be based most conveniently on his

work, using the basic assumptions of one of the other simplified theories, which provided better agreement with experimental data. A certain amount of work was carried out using the exponential theory, but it soon became evident that neither this nor the vortex theory<sup>3</sup> would be completely satisfactory as a basis for un-steady analysis. Both of these theories do, of course, provide empirical expressions which agree with experimental data, but they do not necessarily satisfy Newton's equations of motion under all conditions.

For this reason it was decided to concentrate initially on an attempt to produce another, possibly more realistic, simplified analysis of the curtain jet in the steady state. In fact, it has become known recently that Barratt<sup>4</sup> did produce an analysis on roughly similar lines as long ago as 1961, but this information was not made known to us and the work to be described here was carried out quite independently.

Using this steady state analysis to define the equilibrium condition, a theoretical model of the heave mode, occurring in isolation, has been produced but no experimental verification has been attempted as yet.



\* NOTE -  $\theta$  IS NEGATIVE AS DRAWN

Figure 1a. Definition of theoretical model

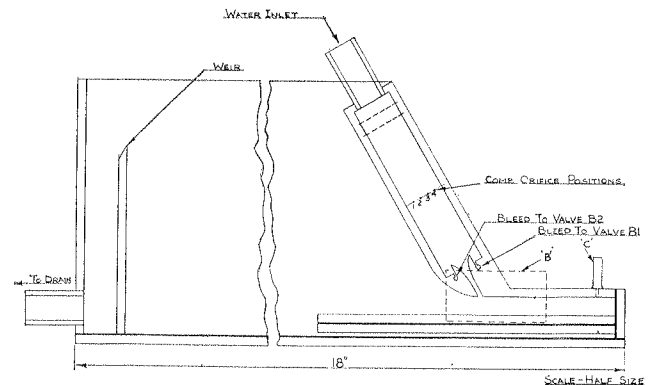


Figure 1b. Flow visualisation model

\* This paper was presented to the Research Symposium on Air Cushion Craft held in the Department of Engineering, University College of Swansea, from July 21st to July 23rd, 1964

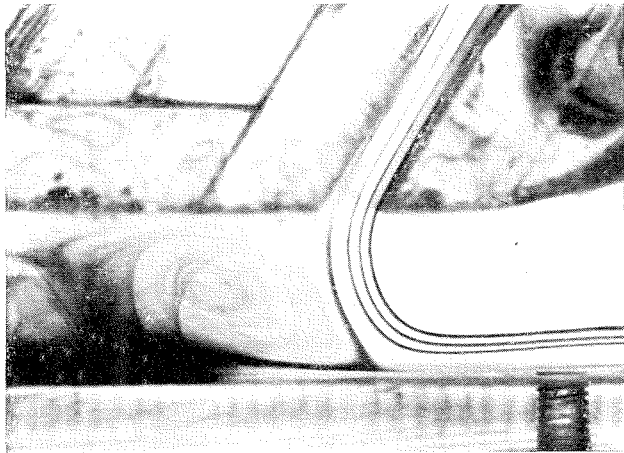


Figure 2a

**2. ANALYSIS OF THE CURTAIN JET OPERATING UNDER STEADY CONDITIONS**

There appears to be little possibility of obtaining a rigorous solution, of the flow within a real curtain jet, in a conveniently simple form. Referring to Fig. 1, and using the accepted simplifications of fluid mechanics, however, it is possible to write down the energy and continuity equations for section 1 (at the nozzle exit) and 2 (where the jet is fully expanded), the overall horizontal momentum balance equation for the boundary A, and the radial force balance equation at the point n. The latter pair of equations are not entirely independent and the inclusion of both implies that the solution to one must satisfy the other under all conditions.

These equations do not define the flow completely and the main obstacles to their solution are the inclusion of the streamline radius of curvature R, which is an unknown function of the co-ordinate n across the exit section, and the indeterminate energy losses between sections 1 and 2. Barratt apparently avoids the latter problem by assuming that the jet is fully expanded when it leaves the nozzle. This is obviously not strictly true but it may well be a reasonable assumption.

Some initial visualisation experiments showed that section 2 where the flow becomes locally straight and parallel to the ground can be very close to the jet stagnation point. The loss of energy due to turbulent mixing between sections 1 and 2 should be quite small and, even though there might be a substantial loss due to impulsive deceleration of the flow, it was thought reasonable to assume that the losses were negligible.

In an attempt to establish how the radius of curvature varied, with the co-ordinate n, a rather more sophisticated programme

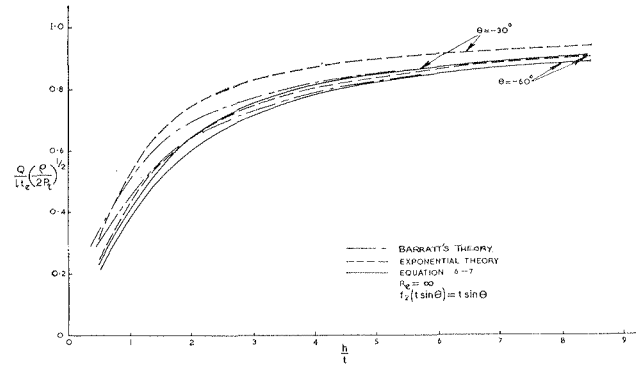


Figure 3 THEORETICAL VALUES OF  $\frac{Q}{t\sqrt{2R}}$  AGAINST  $\frac{h}{t}$  FOR A TWO DIMENSIONAL MODEL.

of flow visualisation was carried out, on an idealised two dimensional model, Fig. 1b. This had a jet  $\frac{1}{2}$  in wide inclined at  $30^\circ$  to the vertical, with an aspect ratio of 10:1, and used water as the operating fluid. By maintaining laminar flow conditions, and injecting dye into the fluid through a small bore comb situated well upstream of the nozzle, very clear flow patterns were obtained, Fig. 2a.

Assuming that these dye streak patterns were equivalent to streamlines, it was found that they could be represented very closely by concentric ellipses, having radii of curvature at the exit section directly proportional to n (Fig. 2b).

Little direct evidence was obtained to show that this conclusion also applied to a jet in which the flow was turbulent, but a selection of Ben Chie Yen's<sup>5</sup> streamlines were also analysed. These showed that the streamline patterns at high Reynolds numbers with different jet angles were also quite closely represented by concentric ellipses.

One further very interesting point was gleaned from these flow patterns. The nozzle was originally designed with a parallel section at exit, having a length four times the jet width, in the hope of establishing the actual angle of the jet flow. With a non-uniform flow, particularly in the presence of wall boundary layers, this was not achieved. The streamline curvature commenced, and the jet broke away from the inner wall, well within the nozzle and the angle of the jet at the exit section differed appreciably from the angle of the nozzle. It appeared that a reasonable allowance could be made for this effect by assuming that the jet operated at some effective height  $h_e$

(Fig. 1), which was larger than the actual hoverheight h. Purely for convenience this effective height was defined in terms of the jet width as

$$h_e = h - f_2(t \sin \theta)$$

where  $f_2$  is an empirical function.

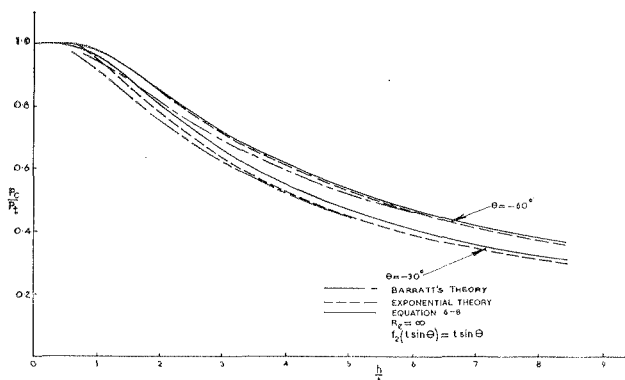


Figure 4 THEORETICAL VALUES OF  $\frac{Q}{t\sqrt{2R}}$  AGAINST  $\frac{h}{t}$  FOR A TWO DIMENSIONAL MODEL.

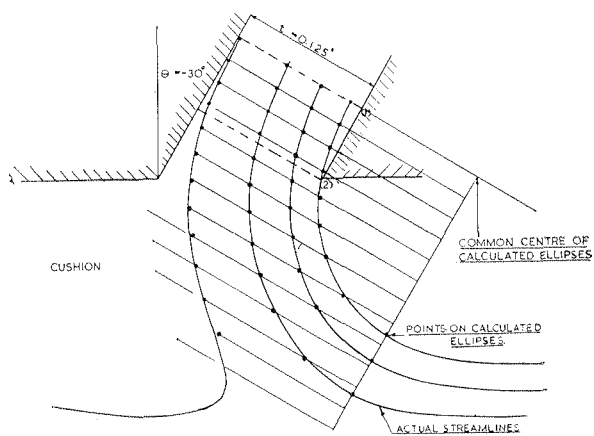


Figure 2b. Streamline patterns for a two-dimensional jet

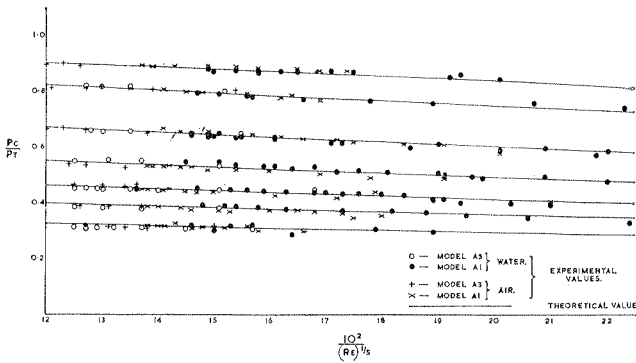


Figure 5 THEORETICAL AND EXPERIMENTAL VALUES OF  $\frac{P_c}{P_T}$  AGAINST  $\frac{1}{Re}^{1/2}$  FOR MODELS A1 AND A3 OPERATING ON AIR AND WATER.

Using these assumptions it is not possible to obtain an explicit expression  $P_c$ ; but the equations may be solved explicitly for  $h/t$  and  $Q$ , when  $P_c$  is regarded as an independent variable, i.e.

$$\frac{h_e}{t} = \frac{P'}{P'-1} \left( \frac{2P'}{P'^2-1} \log_e P' - \sin \theta \right) \quad (1)$$

$$\frac{Q}{lt_e} = \left( \frac{2P_T}{c} \right)^{1/2} \frac{\log P'}{P'-1} \quad (2)$$

$$\text{where } P' = \frac{1}{\left(1 - \frac{P_c}{P_T}\right)^{1/2}}$$

Presentation of the data in this form is not as inconvenient as it might appear at first sight, and the result of solving these equations is compared, on conventional non-dimensional plots (Figs 3 and 4), to Barratt's theory and the exponential theory.

Barratt's theory underestimates the momentum flux in the jet, while the present theory overestimates the energy available. Hence Barratt's equations should give low values for cushion pressure with high values for quantity flowing; while the present theory should predict higher pressure with lower flow rates. It is particularly encouraging to note the small discrepancies between the two theories over the range of parameters shown in Figs 3 and 4, which leads one to believe that the answer obtained is not too sensitive to the exact nature of the

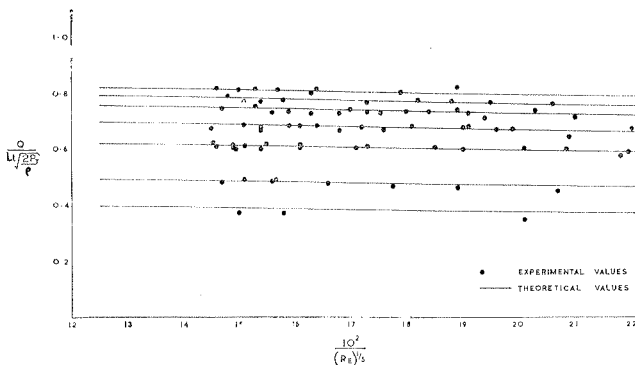


Figure 6 THEORETICAL AND EXPERIMENTAL VALUES OF  $\frac{L}{\sqrt{2R}}$  AGAINST  $\frac{1}{Re}^{1/2}$  FOR MODEL A1 OPERATING ON WATER.

basic assumptions. As might be expected, the two theories tend to converge as the jet angle becomes less negative and as the height becomes greater.

Because the programme of experiments involves very small models the effects of viscosity within the nozzle cannot be ignored, and an attempt must be made to correct the equations for these effects. If one ignores the pressure gradient across the main body of flow, it is possible to use the normal flat plate boundary layer theory to calculate an effective jet width, i.e. assuming a turbulent boundary layer.

$$t_e = t \left( 1 - k \left( \frac{x}{t} \right)^{4/5} \frac{(P'^{1/5} + 1)}{Re^{1/5}} \right) \quad (3)$$

$$\text{where } Re \text{ is defined as } \frac{t}{\nu} \frac{2P_T}{c}$$

It is then suggested that the pressure gradients may be taken into account, by including an empirical function  $f(p')$ , in the second term of equation (3). This amounts to treating the entire flow through the nozzle as roughly analogous to boundary layer flow, but this is only a loose analogy and should not be pressed too far.

When momentum flux is considered the value of  $t_e$  will differ from the value obtained when quantity of flow is considered, but the accuracy of the basic assumptions does not justify the complication of applying the two separate values to equation (1). A mean value is used instead.

The results of fairly extensive tests, at low Reynolds numbers using air and water as the operating fluid in two models, are compared to equations (1) and (2) corrected in this way in Figs 5 and 6. The models used are the  $\frac{1}{4}$  in jet A1 shown in Fig. 1b and a second model A3 scaled up by a factor of three.

The values for the empirical factors  $f(p')$  and  $f_2(\sin \theta)$  were estimated for the results in Fig. 6, and some justification for their use is obtained from the fact that the same values could be used to correct Equation (1) for Fig. 5. The values of  $k$  differed for the two equations, as one might expect.

The agreement seems to be very good, and the equations predict the general variation of the results with height and Reynolds number quite accurately. It should be pointed out, however, that during initial tests the larger model appeared to operate with a laminar boundary layer under all conditions, while flow in the smaller model was turbulent over most of the range of  $Re$ . This was thought to be due to a slight discontinuity at the nozzle throat in A1 caused by correcting accidental damage. Artificial roughness had to be introduced in the throat of A3 to produce the agreement shown, and, in fact, the degree of roughness on the nozzle walls has a marked effect on the cushion pressure in these small models.

The work carried out on these models has revealed more problems than it has solved and Mr West is now extending this particular line of study.

## HEAVING MOTION

The air cushion craft has six degrees of freedom, all of which may be equally important from an analytical point of view, but to limit the complexity of the problem only the heave case has been analysed initially. This analysis may not have much meaning when applied in isolation to a full scale craft, but it does describe a case which may be simulated realistically in the laboratory. It should be possible to extend this analysis to cover the coupled motions, which almost inevitably occur in free operation, in due course.

To provide some experimental justification for the additional assumptions required, further flow visualisation was carried out on the model shown in Fig. 1b. An approximately sinusoidal pressure variation was applied in the cushion and photographs were obtained of the flapping jet. These showed that the distribution of curvature of the dye streaks remained reasonably

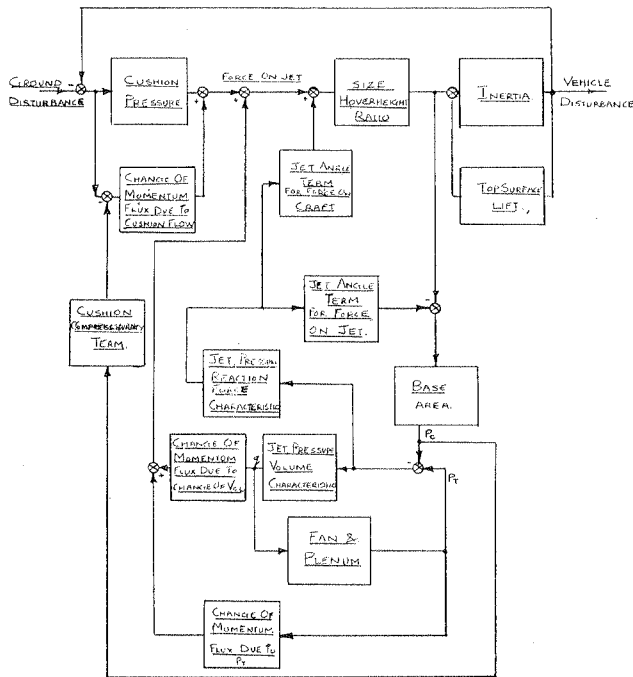


Figure 7. Air cushion craft heaving motion

constant during small oscillations, and it was thought that the instantaneous radius of curvature could be represented by  $R + r$ ; where  $r$  is time dependent, but is independent of  $n$ .

The original equations for the jet system may then be solved to produce expressions for all the small linear changes which occur as the vehicle heaves. Depending on how many of the changes are included, this process will produce a dozen or so simultaneous equations, which are most easily combined on

a block diagram, Fig. 7. This particular block diagram includes the effects of the fan characteristic and plenum chamber delay but ignores inlet momentum forces and gyroscopic forces which may not always be present in a laboratory model.

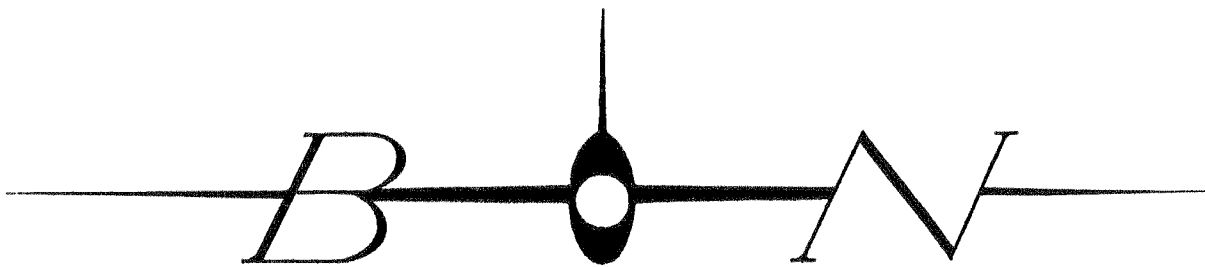
The block diagram itself gives a fairly lucid physical picture of a heaving air cushion craft and lends itself readily to analogue simulation, but it is not too easy to derive an analytical equation of motion from this source.

The experimental programme which is intended to verify this heaving mode analysis has not advanced very far as yet. It is proposed to make use of a model running under water in the initial experimental work. The first model is about 1 ft diameter based on a prototype 10 ft diameter weighing 800 lbs. It is not possible to achieve complete dynamic similarity under these conditions, but this is not serious if the model is considered as an analogue rather than a simulator of the prototype. Dynamic similarity may be obtained if the prototype is very much lighter or very much larger, and we may well build an intermediate lightweight model for this purpose.

This has, of necessity, been a very brief outline of the work in progress at Swansea, but it is hoped that a reasonable overall picture of the programme has been provided.

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# Is The Hydro Being Foiled?

by

**Richard L. Barkley**

## THE AUTHOR

is President Aquanautics, Inc. He was awarded a BS, US Naval Academy, 1937, and MS, Stanford, 1950. After completing graduate work in Engineering at Stanford, Mr Barkley took a position with National Motor Bearing Co, Redwood City, Calif. He became Manager of Central Production Planning and then Chief Manufacturing Engineer of the Company. In 1955 he was promoted to Works Manager of the Redwood City plant. A former Navy Commander, Mr Barkley was a qualified naval aviator in both heavier and lighter-than-air and radio controlled aircraft. He commanded one of the largest maintenance and overhaul squadrons in the Navy and received two letters of personal commendation for his technical and administrative accomplishments. His development achievements include improvement in recovery of cruiser and battleship aircraft, portable land and ocean mooring of airships, present day remote flight control system for airships, and the first gyro stabilized flight control system for non-mancarrying drone aircraft.

\* \* \*

RECENT articles in various magazines have conveyed the thought that the hydrofoil, as a sea going vehicle, is an accomplished fact, that the engineering and design matters are settled, and that it is now time for the operators to take over. Where there is much to be said for the operators taking a more active part in the evolution of the hydrofoil craft in order to gain that vital element of experience for feed-back to the designers, it is not right to assume with finality that the engineering and design matters are settled. This is especially so when it is considered that only one road has been explored and that tremendous economic and social consequences are in the balance.

Only a select few naval officers are aware that the world is on the verge of a revolution in marine transportation. Of all the commercial vehicles of transportation now in use, the ship alone has not increased its speed at least tenfold since its initial introduction. The first commercial steamship of note, the *Great Western*, did 14.5 knots in the mid 1800s and the fastest today is less than 40 knots.

An appreciation of what such a revolution might bring about can be gained by examining one which has taken place during our lifetime. Most of us have been privileged to witness, consciously or not, probably the greatest revolution of economic consequence the world has experienced—that of the change from the animal-powered transportation system to the engine-powered system, the automobile. The introduction and commercial development of the automobile which took place during the first half of the century is often viewed with placid unconcern. Few realize that the automobile is largely responsible for our present high standard of living.

The automobile gained its support from the simple human desire to move, at will, from place to place on the earth, singly or in small groups. The railroads and river boats offered restricted movement to large groups on fixed schedules of relatively infrequent and unreliable occurrence. There was therefore a great need for a system which could provide nearly unrestricted transportation for individuals. The automobile was the base of this system.

For the economy of the western world the automobile did much more than simply fulfill this want. Its evolution brought

about a continuously expanding mass market for the development of other new materials and equipments which did not exist before. These in turn found their way into other areas of the economy where in some cases they are used more extensively than in automobiles.

The automotive system, developed without the assistance of a formal systems management as is now common in the military, has greatly affected nearly every facet of our lives, and was the basic ingredient in the building of our major industries. A few examples will serve to demonstrate the far flung complexity of this system:

**STEEL**—to build the cars and trucks, filling stations and pumps, garages and tools, oil refineries and drums, drilling rigs and well casings, pipe lines and tankers, road building equipments and farm implements, roads and bridges, street lights and signs, more steel mills and associated plants.

**CEMENT and ASPHALT**—for roads, parking lots and centres, fabricating plants, and dams for electric power for plants.

**RUBBER**—for tyres, air and fuel hoses, synthetic rubber and adhesives, gaskets and rocket fuel.

**MISCELLANEOUS**—glass, batteries, hydraulic equipment, synthetic paints and fabrics, state police forces with extensive radio and telephone networks, traffic signals and parking meters.

Now compare this with the major items the automobile systems replaced:

**STEEL**—for horseshoes and nails, wagon parts and buckles, one furrow ploughs.

**WOOD**—for wagons, blacksmith shops, feed barns, stables, and corrals.

**LEATHER**—saddles, harnesses and buggywhips.

**HORSEBREEDING**—

Clearly a change from one system to another can bring about great economic and attendant social changes.

It can be said generally that in Western Civilization a system resulting in a reduction in time to accomplish a task will be sought and accepted. The closer this system is to man's natural environment and inclinations the wider its acceptance.

The airplane is an example of limited acceptance as compared with the automobile. The case of marine transportation lies somewhere in between these two systems, possibly closer to the automobile. A substantial increase in speed of marine transportation should result in significant economical and sociological changes of considerable importance. Because the oceans are the primary transport lanes between nations and continents the impact of these changes should be more world-wide than national.

We are now in the early stages in the movement toward higher marine speeds. Military interest has been kindled by the fact that submerged submarines can now outrun surface vessels. As a consequence most of the hydrofoil development in the US to date has been sponsored or carried out by agencies of the federal government. Until this recent federal interest all work in the hydrofoil field was done by scattered individuals on a limited scale, because the larger economic interests have not yet seen fit to replace the present system. (The Studebaker Corp is often held up as being one of the few firms to survive the transition from the buggy to the automobile.)

Examination of the way in which some other transportation equipments evolved will provide us lessons against locking the door on the engineering and design of hydrofoil craft. Technical door-locking, or a head-in-the-sand attitude on the part of those occupying positions of singular authority, can affect the lives of many individuals and be very costly to the nation.

The example of the development of the submarine offers a case in point. Captain W. D. Roseborough, Jr, USN, recently had this to say: "Not only did *Holland* incorporate practically all the principles found in present day conventionally powered submarines, but it also possessed many features optimizing submerged performance. Among these features were a hull form of near optimum length-to-beam ratio, a minimum of reserve buoyancy, and a very small and well streamlined superstructure. A large diameter, a slow-turning propeller, mounted on the longitudinal axis of the hull, further enhanced her propulsive efficiency. *These features were re-discovered during the research and development leading to the design of the now famous 'Albacore,' a half century later.*" (Italics and underline mine, AUTH.)\* Naval historians record that John Holland spent twenty-five years trying to sell his submarine. He was successful in 1900 and the USS *Holland*, SS-1, was built.

The first attempts to design automobiles resulted in the straight application of an engine to a carriage or wagon and was aptly called the "horseless carriage." Fortunately this approach was discarded by many of the 250 odd individuals and companies attempting to enter the field. Today the only resemblance between the carriage and the automobile is the number of wheels. In this instance no one authority dictated the design.

The development of the helicopter provides an example of how one design can, for an extended time, lock out another of greater potential. The helicopter has been predominantly developed and used by the military. The recent sad experiences in Laos perhaps will force a serious reconsideration of its military utility. By virtue of its seemingly inherent inefficiencies it has not yet achieved commercial usage to any significant degree. The helicopter, however, was successful in diverting attention and funds from vertical take-off aircraft in the early 1950s. We are now finally getting around to the serious development of the VTOL which possesses much greater potential. The ability to "hover," though valuable, was oversold.

The hydrofoil has been approached in somewhat the same manner as the submarine and the helicopter. Current design has simply involved the *attachment* of some kind of a foil system to a conventional hull. The problem of cost has been compounded by the adaptation of aircraft fabricating techniques to such hulls. One is almost tempted to believe that these craft are supposed to be ships first and hydrofoils second. Perhaps that is what current designers have in mind. However, this approach is subjugating the prime attribute to the secondary.

\* Sperryscope, Vol 15, No 12, First Quarter, 1962.

It has been said that rough water is the big obstacle to the Navy's use of hydrofoils. Apparently size is another, for Rear Admiral R. K. James, USN, Chief of the Bureau of Ships, said in a House sub-committee hearing in May 1960 "The hydrofoil craft has certain applications that are limited as we see the state of the art today to something in the order of 300, possibly 400 tons maximum." Later in this hearing the size limitation was attributed to the cube-square law.

Captain D. E. Cummings, USN (Ret.) had an interesting comment on this now oft quoted law in his "Aviation Joins the US Fleet" in the January 1963 issue of *Shipmate*, the US Naval Academy alumni publication. He said, "At that time (Apparently early 1920s. AUTH.) Pensacola textbooks reportedly proved mathematically that planes had already reached their maximum size, since the lifting surface varied in area as the square of the linear dimensions while the volume increased as the cube. Of course earlier, not long before the Wright brothers flew, some expert proved it couldn't be done — just as it can be proved that the bumblebee can't fly. This cured me of any skepticism regarding scientific limitations."

The hydrofoil craft has so much potential in the scheme of things that it merits its own design. It deserves a better fate than that of being merely a warmed over ship or boat with such mediocre or marginal performance as to bring only limited acceptance. In the approach to its design the basic attribute, the foil system, should be kept foremost in mind, and all design criteria should revolve around it. When a suit of foils is fitted to a conventional displacement hull the foil system is severely restricted by the many compromises in the hull design. First the hull must be long and narrow (length-to-beam ratio 8 to 10) or it will end up using most of its power in making waves not headway. Second the hull must have compound curves on the underwater body or the drag gets too high. Third, stability problems, particularly those related to roll, must be carefully considered. Then all the packaging compromises come into play — where and how to put the boiler, main engines, spring bearings, etc. When the beam of the craft is finally set the dimensions of the foil system are fixed, and to a great degree the height of waves the craft can handle is established. Because of these limitations on the foil system the tonnage is greatly influenced. All this effort because of the attempt to use a conventional hull.

By its very nature a hydrofoil craft should be hull-borne only a minimum of its operating time. Operationally the hull is secondary and should be so considered in establishing design criteria. The hull should only be a means of tying an effective foil system together and providing for limited speed displacement operation at sea and in harbours.

Fortunately in the annals of the art of shipbuilding there can be found descriptions of a hull type with many attributes which lend themselves admirably to the design of hydrofoil systems. This is the twin hull or catamaran design. The twin hull has long been considered an oddity or freak by naval architects. Only in recent years have individuals revived the design primarily for sailing. The resulting twin hull sail boats are gaining in use steadily because they have proven themselves to be superior to conventional sailing hulls in speed and sea keeping ability.

The history of the twin hull is nearly as old as man himself. It achieved its greatest acceptance in large sizes in the latter half of the last century. The English built a number of twin hull channel steamers up to 2,000 tons. The largest *Popoffka*† reported, built in 1880, was the Russian Imperial Yacht, the *Livadia*, 4,720 ton, 250 ft long with a 153 ft beam, 7 ft draft. Its top speed was 16 knots with 12,000 ihp. In a severe storm in the Bay of Biscay she never rolled more than 4° to a side in 25 ft waves. While there is no general explanation as to why these designs did not find wide acceptance it can be assumed that the limitations of metal strength and fastening methods were barriers to its development. The wide beam no doubt posed some problems in rivers and harbours which at that time were pretty much as nature made them. Tradition, strong in the shipbuilding industry, probably had some influence also.

† *Popoffka*: A circular or near circular hull, named after Vice-Adm Popoff, Royal Russian Navy.

The twin hull displacement system in itself has many advantages but most of all, in the hydrofoil application, it allows nearly complete freedom of foil system design. It is the means of giving to the prime attribute the emphasis it deserves. Fig. 1 shows a simple comparison between a conventional displacement hull system and a twin hull system both using fully submerged hydrofoils. Fig. 2 illustrates the use of surface piercing foil systems. It is obvious that the foils on the twin hull arrangement can be attached at a variety of positions, longitudinally as well as laterally, and can be easily retracted for docking and servicing. With stability factors being equal, it also demonstrates that the twin hull system is more adaptable to operating in high seas without danger of hull slam, because the supporting struts can be considerably longer. An analogy can be drawn here between the relative stability of an airplane with centres of lift far from the centre of gravity and the single rotor helicopter with the centre of lift and the centre of gravity in line.

In the displacement condition the twin hull configuration has many desirable features. Because it is not concerned with efficient hull operation in a wide variety of sea states, it can be designed with good planing or take-off characteristics. Preliminary model tests indicated that the hull can be built without planing steps because the forward foils can be used to bring the hull up onto the plane. Without complex compound curves planing hulls are cheaper to construct. The accompanying reduction in draft, usually at least 30% less than that of conventional hulls, is advantageous both from the propulsion and operational standpoint.

In the improbable event of complete engine failure the twin hull provides better sea keeping and stability in heavy seas than does a conventional hull. The wide deck and above-water storage spaces with the absence of deep holds offers many advantages for naval and commercial use. Propulsion units can be distributed and oriented more efficiently and not restricted to fore and aft installation. Roll-on and roll-off features similar to those of the USNS *Comet*, recently designed by the Bureau of Ships for fast loading and unloading, could be greatly improved, as could dock and cargo handling facilities. Gigantic cranes could be eliminated. Turn about time, an important item to commercial interests in peace time and the military in war time, could be significantly reduced. But most of all the twin hull design opens the door to the construction of large tonnage hydrofoil vehicles capable of operating at high speeds in extreme sea conditions.

To date nothing has been done on twin hull design except in a limited way by a small company in California. Not intended to be a twin hull hydrofoil craft is the recently publicized catamaran powered by a jet engine, built by the Boeing Company for the Bureau of Ships, purely for testing various foil shapes and it functions in lieu of a high speed tow tank or swinging arm rig, the hydrodynamic equivalent of a wind tunnel. Its power system and general construction does not appear to be easily adaptable to a good test bed for the purposes of establishing empirical parameters of twin hull configuration. So far nearly all efforts have gone into the shotgun marriage of a foil system to a conventional displacement hull with all its incompatibilities intact.

The two principle authoritative federal groups supporting this design approach are the Maritime Administration, funding the HS *Denison*, 80 tons, and the Bureau of Ships the PCH, 110 tons and the AG(EH), 300 tons. No programme has been instituted to develop the twin hull system. Perhaps it will have to wait for the commercial interests, now slowly stirring from their long and comfortable hibernation, or for the reluctant bride to strike back against her tormentors. In respect to the needs of the times and the efficient utilization of national wealth neither seems to be an acceptable way of stepping up the pace of the pending revolution in marine transportation which holds promise of so many benefits to civilization.

Perhaps a new name for the vehicle would help!

LEOPOLDO RODRIQUEZ  
SHIPYARD  
MESSINA - ITALY



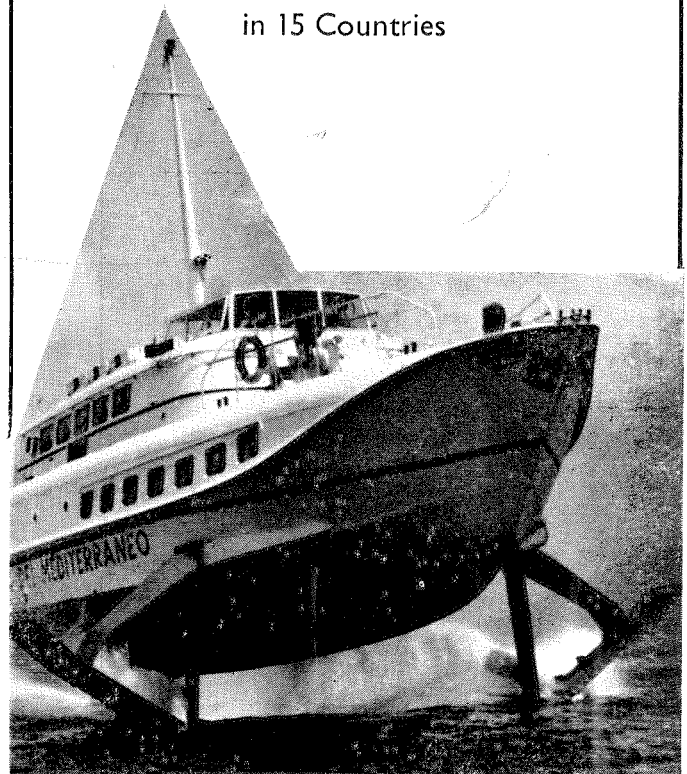
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# Factors Affecting Hovercraft Performance at Low Speed Over Water\*

by J. T. Everest  
National Physical Laboratory

## 1. Introduction

Hovercraft wave making is being investigated as part of a programme of research on the hydrodynamics of hovercraft under contract to the Ministry of Aviation. Earlier work in this programme has explored the forces acting on a fixed circular model, with the attention largely concentrated upon hump speed. (This work is described in Ref. 1). Briefly it was found that the energy measured in the wave pattern agreed well with theoretical estimates of wave drag, and with measured drags when the craft was set at the appropriate trim. The effect of other trim angles was also investigated.

Subsequent work has confirmed the suggestion that hovercraft operating over water are strongly influenced by the interaction of the hydrodynamics of the water surface and the aerodynamics of the craft cushion and ducting system. This note attempts to explain some of these interaction effects, so that a clearer picture of the forces acting on a hovercraft over water may be obtained. Suggestions for further work are mentioned.

## 2. Discussion of the Problem

In the previous Report (Ref. 1) a description was made of the manner in which the horizontal force required to generate waves was transmitted to the water by virtue of the balance of forces within the air cushion. With the craft trimmed parallel to the disturbed water surface under the model, the leakage of air around the craft periphery was considered to be uniform. Change of trim from this value caused an out of balance within the cushion, resulting in cross flow, and increased leakage at the higher end of the craft. The cushion equilibrium was retained by the momentum change of the escaping air. Since the overall peripheral jet sealing efficiency would be reduced in this condition, to maintain a given cushion pressure and centreline hoverheight would require an increased lift power. In this manner it was argued that wave making can be paid for by a penalty in lift power.

The condition of cross flow described above would result in changes in the operation of the peripheral jet, since underfeeding and overfeeding would occur at the low and high ends of the craft respectively. The overall lift efficiency of the complete craft would be reduced, and some changes of jet velocity and therefore air momentum would be expected around the periphery of the craft. In the limiting case with zero clearance at the bow, no jet momentum would be required to support the cushion at this station. The rate of onset of this effect with increase of trim is uncertain, but it is likely to depend upon:

- a. Jet and cushion geometry and flow condition.
- b. The characteristics of the medium over which the hovercraft is travelling.

### (a) Jet and Cushion Effects

The effects of jet and cushion effects upon craft stability and upon the forces acting on a craft have received a great deal of attention by other workers in this field. However the larger part of this work has been restricted to over ground conditions, often using static two dimensional models. Results of earlier static tests with the circular model over ground (Ref. 2) suggest that the variation of jet velocity around the peripheral jet was quite small for realistic angles of trim (10% for 65% of the maximum trim possible before ground contact). This leads to the suggestion that the horizontal force as measured on the craft would at least approximate to the product of lift and the sine of the angle of trim. Unfortunately further detailed study of jet and cushion effects is outside the scope of the existing apparatus, and a great deal of modification would be required to enter the field.

### (b) Characteristics of the Medium

The "over smooth ground" case can be regarded as datum condition. Neglecting modifications due to dynamic pressures directly associated with forward speed, it is reasonable to expect changes from zero forward speed conditions to be fairly small, although the influence of the moving ground under the model will obviously increase to some extent with increase of surface roughness.

The over water case is rather different. At high speed over water the length of a wave produced by a transverse jet is very long relative to the effective width of the jet. The result is that the change of water level from front to rear of the jet is very small, and the surface can be regarded satisfactorily as not responding to the passing of the jet. In this condition the generation of spray would be low, and it is probable that the jet would react very similarly to corresponding conditions over ground. (The problem would probably be more complicated for a longitudinal jet, resulting in some variation of characteristics around the craft). The length of the hovercraft cushion at these speeds is considerably longer than the region of pressure associated with the air jets, and the influence of the cushion pressure causes waves to be produced which are felt by the craft. The hovercraft will tend to trim parallel to the average waterline, the backward component of lift producing a drag force. Craft trimmed at some other condition at high speed over water will suffer cross flow and will lose lift, but the variation of jet momentum around the periphery is likely to be similar to over ground conditions. In general the drag should approximate to the backward component of lift force, although large angles of trim between model and water will produce some variation from this.

At all speeds over water there will be some variation of clearance around the jet periphery, even for a craft free to

\* This paper was presented to the Research Symposium on Air Cushion Craft held in the Department of Engineering, University College of Swansea, from July 21st to July 23rd, 1964

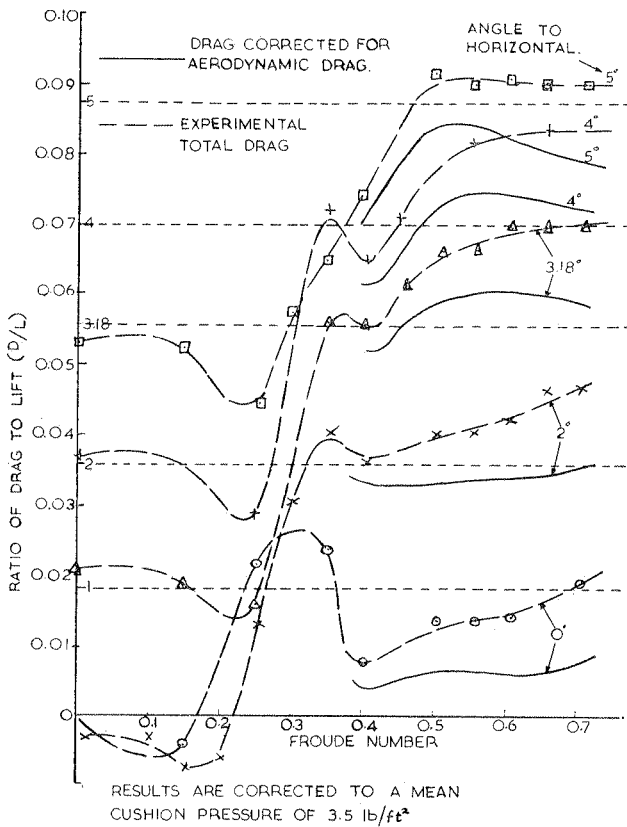


FIG. 1 VARIATION OF DRAG WITH SPEED FOR RANGE OF TRIM ANGLES

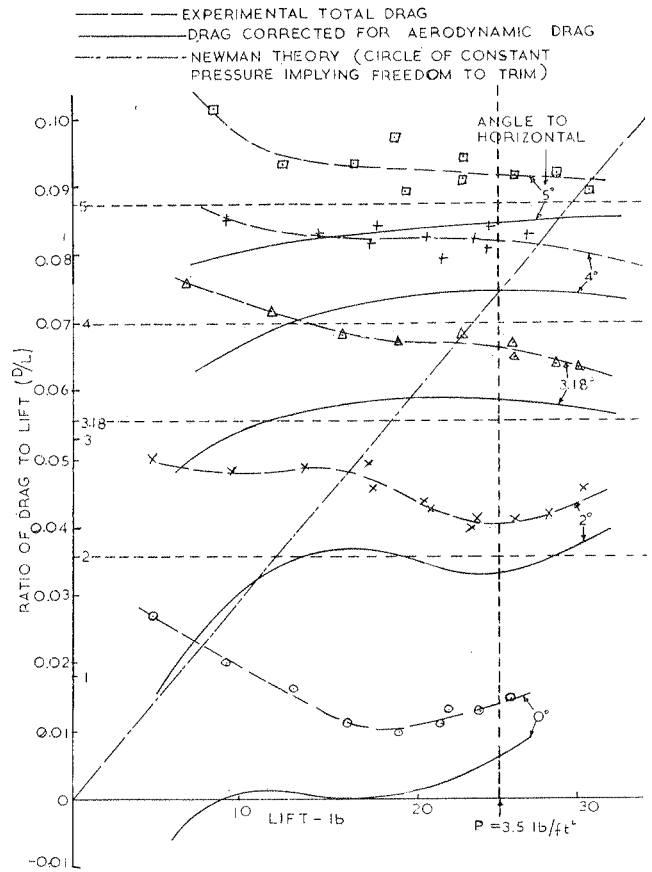


FIG. 2 VARIATION OF DRAG WITH LIFT AT HUMP SPEED

trim, but for speeds above hump the effect is generally small, and the similarity with overground operation is probably reasonable. Measurements of jet velocity made at hump speed with the craft trimmed approximately  $4^\circ$  from the average water surface showed little difference in velocity between bow and stern, supporting these conclusions. At speeds less than hump speed the variation of clearance is increased (with the reduced transverse wavelength), and it is likely that the conditions would depart from any similarity with the over ground case.

At lower speeds over water the surface is increasingly influenced by the jets. A depression is created in the region of the jet, resulting in:

- (i) Spray generation,
- (ii) A modification of the forces acting on the air curtain.

The flow pattern is considerably more complex than for the case of over ground operation, the angle of outflow for the cushion probably being affected markedly by jet pressure, nozzle height and angle, and strength of cross flow. Further the local water gradient and local stability of the wave created by the craft itself will probably affect the situation. In view of these remarks it would be quite unlikely that the air supply to the jet would bear any similarity to conditions over ground.

Considering firstly spray generation. The momentum required to produce spray is derived from the hovercraft lift system as a loss of sealing efficiency, and hence no horizontal force is necessarily involved during its generation. The subsequent impingement of the spray upon the craft will produce forces having horizontal components, the motion of the spray droplets defining its direction (which could be forward).

If a craft was trimmed so as not to be parallel to the disturbed waterline, the resulting cross flow would modify the jet characteristics. Over ground these modifications were found to be small for modest angles of trim, but as mentioned above this conclusion does not follow at low speeds over water.

### 3. Experimental Schedule

#### a. Forward Speed Testing

The tests were made in Number 3 tank Feltham using the 3 ft diameter circular hovercraft model described more fully in Ref. 1 Tests were carried out for trim angles of  $0^\circ$ ,  $2^\circ$ ,  $3.18^\circ$ ,  $4^\circ$  and  $5^\circ$  over a range of Froude numbers from 0 to 0.7, with the emphasis on the range 0.4 to 0.7. A centre-line clearance from the undisturbed water level of  $1\frac{1}{2}$  in was used. For consistency with previous work, the majority of the measurements were made at  $3.5 \text{ lb/ft}^2$  mean cushion pressure (corresponding to a lift of 25 lb approximately). However at the hump speed ( $Fn = 0.55$ ) the variation of resistance with lift was carried out for the range of lift from 5 to 30 lb approximately. Measurements of resistance and lift were made in all cases.

#### b. Static Testing

In the light of results from the above work it was decided to undertake further static testing. Both over ground and over water conditions were used, and the lift force was varied over as wide a range as possible. Trims of  $1^\circ$ ,  $2^\circ$ ,  $3^\circ$  and  $4^\circ$  were investigated. Unfortunately lack of time precluded any systematic measurement of jet pressures, but some measurements were possible at bow and stern for the  $2^\circ$  case. It was felt that this model was not ideal for this purpose, and hence repeat testing was not envisaged. Possible alternative testing will be mentioned later.

The model was also tested over water with a thin gauge polythene sheet floating on the surface. This surface sheet was found to distort satisfactorily to the applied pressures while eliminating any generation of spray.

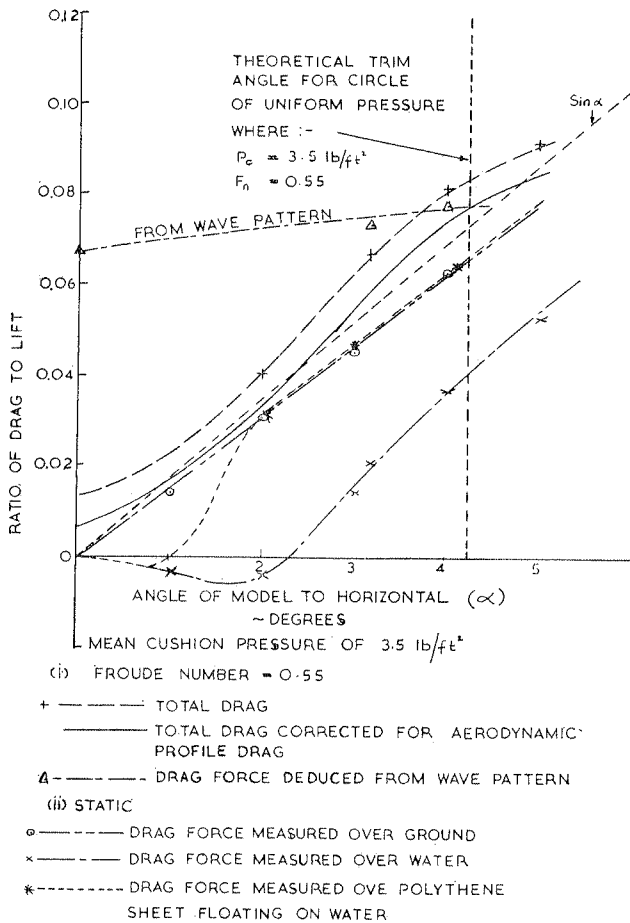


FIG. 3. VARIATION OF DRAG WITH ANGLE OF TRIM FOR VARIED CONDITIONS

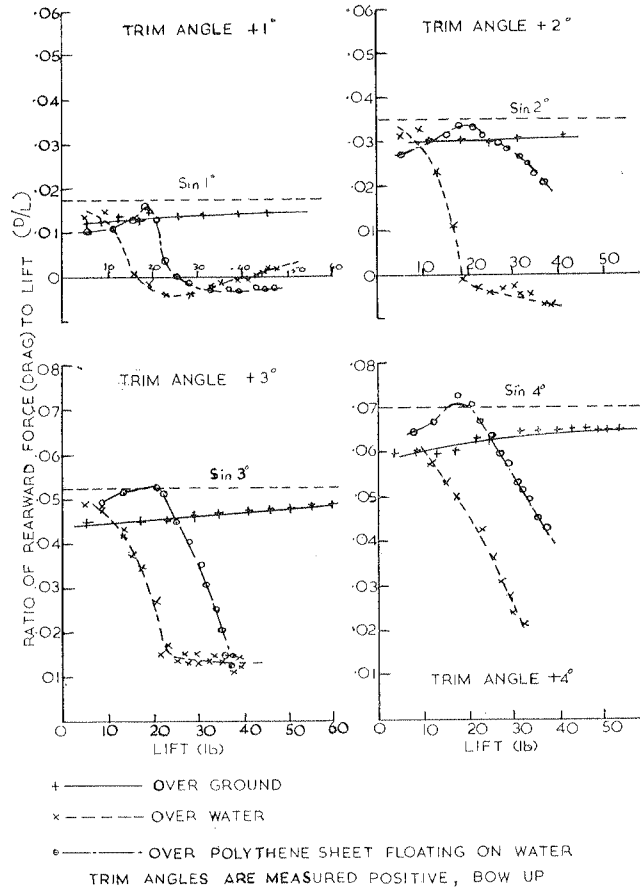


FIG. 4. FORCE MEASUREMENTS AT ZERO FORWARD SPEED

## 4. Results

### a. Forward Speed Testing

The ratio of drag to lift for the range of trim angle and Froude numbers is shown in Fig. 1. (A correction for aerodynamic profile drag is included down to  $F_n = 0.4$ ; below this speed it has been omitted for clarity, but its value is small).

At speeds greater than  $F_n = 0.5$  the drag/lift ratio approximates to the sine of the trim angle. Fig. 2 illustrates that this effect is maintained through a large range of pressure. However a slight tendency for the drag at low trim angles to exceed  $L \sin \alpha$ , and for high trim angles to be less than  $L \sin \alpha$  does exist where  $\alpha = \text{trim angle}$ . The implication is that the drag force is mainly influenced by the trim angle to the horizontal. (In practice changes of lift performance involving increases in air intake momentum drag would have some further effect). This result supports the contention that the breakage of the water surface by the jet is not severe at these speeds, for the pressures employed.

At speeds up to  $F_n = 0.5$  the ratio of drag to lift is seen to vary markedly from the high speed results. There is some evidence of humps and hollows in the curves, and apart from the low trim angles there is a general reduction in drag/lift ratio when compared with the high speed results. These results agree with suggestions made regarding the break-up of the water surface under the jets. The humps and hollows at the higher end of this speed range can be explained by the variation of wave pattern under the craft with change of speed, resulting in changes in cross flow direction and also in changes in jet clearance to the local waterlevel and slope. Both these factors will influence drag, by way of changes in the jet-water interaction and spray impingement.

Some zero forward speed measurements were made during these experiments. In these the large discrepancy from the high speed results was maintained at the cushion pressure used for the tests. (See Fig. 3). Further static testing was thought to be desirable over a larger cushion pressure range to increase knowledge of this effect.

### b. Static Testing

Fig. 4 shows the results of the subsequent static testing. It is very apparent that over ground the ratio of drag to lift is influenced very little by changes of cushion pressure (or lift). A value, slightly less than the sine of the trim angle was retained throughout. Over water, however this was not the case; the ratio dropping rapidly with increase of pressure. For the cases of  $1^\circ$  and  $2^\circ$  trim a small force in the forward direction was recorded. However for each trim (excluding the  $4^\circ$  case where the range of pressure studied was probably not sufficient) a point was reached where further increase of pressure caused only small changes of drag/lift ratio. It is thought probable that the rapid drop in this ratio resulted from spray-making, which was observed to influence progressively a greater part of the craft periphery with the increase of pressure. For low cushion pressures, only the lower end of the craft was affected, the spray and air emerging almost vertically and impinging on the overhang of the craft. At high cushion pressures spray was generated over the complete circumference of the craft. The outlet angles varied from near vertical at the lowest point to near horizontal at the highest. The majority of spray impingement was confined to the rear (i.e. lower) half of the craft. Using a periscope it was ascertained that for the higher pressures spray effects reached from the lower jet to the centre of the cushion. It is certain that horizontal forces were generated by these spray effects, although a direct assessment of their magnitude would not be easy. Fig. 5 illustrates the effects diagrammatically.

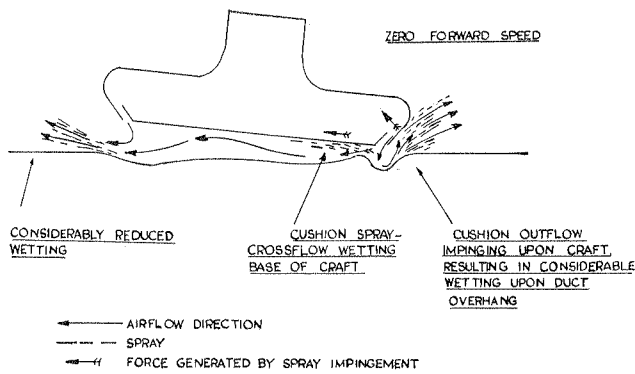


FIG.5 SPRAY AND AIRFLOW EFFECTS ACTING UPON THE CRAFT

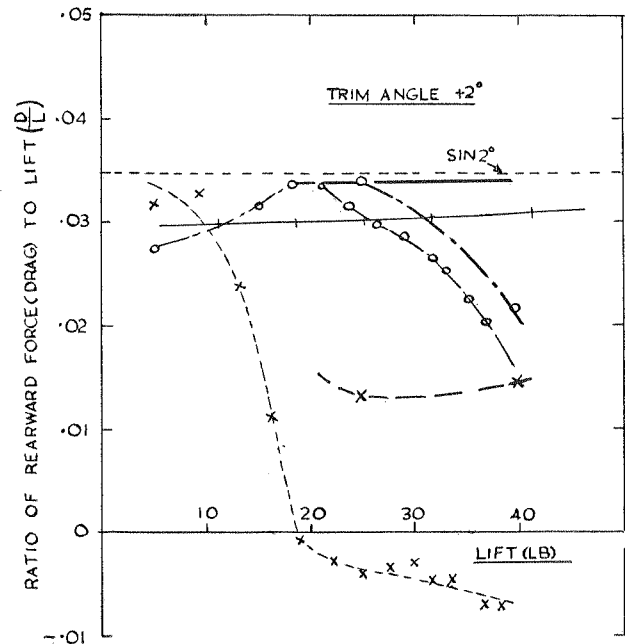
The results of experiments made over a thin polythene sheet floating on the water surface are also shown in Fig. 4. The object of these experiments was to eliminate spray making while operating over a deformable surface. If spray impingement had been the only extra influence acting on the craft the results would obviously follow the over ground measurements. It is seen that some similarity did occur, up to a given value of cushion pressure, after which further increase of pressure caused a drop in the drag/lift ratio. It follows in these cases that the deformation of the surface did have some influence on the forces acting on the craft. Since the deformation is most pronounced in the region of the jets, it is reasonable to expect some modification of the air outflow angles, and hence probably some effect on jet pressures. To obtain some knowledge of any such effect, pressure measurements were made in the jets at 2° trim. All three surface conditions were considered at a common cushion pressure. The measurements were made at the highest and lowest points of the periphery (bow and stern respectively), the pressures being recorded at the centre of the jets. Shortage of time did not allow complete traverses to be made; nor was it possible to measure flow angles. For these reasons, these data can only be used as a guide to the understanding of the drag mechanism. The results are shown in Table 1.

It is at once apparent that over water the pattern of flow to the peripheral jets was not uniform. This effect was reflected in the increase of static pressure at the stern over that at the bow. Horizontal forces would result. Over ground and over the polythene sheet, the effect was less marked.

TABLE 1

Jet Pressures measured at 2° Trim, (bow high)  
Hoverheight at centreline, 1½ in

	Over Ground		Over Water		Over Polythene Sheet floating on water	
	Bow	Stern	Bow	Stern	Bow	Stern
<i>Cushion Pressure, 3.5 lb/ft<sup>2</sup></i>						
Total head, inches water gauge	1.14	0.98	1.97	1.92	1.40	1.32
Static head, inches water gauge	0.15	0.10	0.23	0.70	0.10	0.10
Jet velocity, ft/sec	66	62	87	73	75	73
<i>Cushion Pressure, 5.6 lb/ft<sup>2</sup></i>						
Total head, inches water gauge	—	—	3.79	3.60	3.86	3.73
Static head, inches water gauge	—	—	0.30	1.15	0.10	0.30
Jet velocity, ft/sec	—	—	124	104	128	123



LIGHT LINES — REFER TO EXPERIMENTAL RESULTS  
HEAVY LINES — REFER TO VERY APPROXIMATE CORRECTION TO EXPERIMENTAL RESULTS TO ALLOW FOR JET THRUST EFFECTS

————— OVER GROUND  
- - - - - OVER WATER  
- · - · - OVER POLYTHENE SHEET FLOATING ON WATER

FIG.6 EFFECT OF JET THRUST UPON FORCE MEASUREMENTS AT ZERO FORWARD SPEED

In an attempt to obtain a very rough estimate of the order of the forces involved, it was assumed that the variation of jet velocity around the periphery was sinusoidal. It would be very difficult to justify the choice of this variation on the meagre information available and some other power law would probably be just as suitable. However since a complete estimate of the jet forces around the circumference would require the measurement of velocity and flow angle in two planes, this approximate approach was thought to be justified. The results are shown in Fig. 6. At 3.5 lb/ft<sup>2</sup> cushion pressure, the drag adjustment due to this effect caused the drag/lift ratio to rise, both the over ground and over polythene results approaching the sine of the trim angle. Over water approximately 50% of the deficiency in drag was involved. It is assumed that the remainder was caused by spray impingement. At 5.6 lb/ft<sup>2</sup> over water, similar results were obtained. Unfortunately over ground, no results were obtained at this pressure. Over polythene the adjustment was not sufficient to re-attain the over ground result. It is probable that at these high pressures the air, which was escaping nearly vertically from the cushion at the lower end, would be modifying the pressure distribution around the outside of the craft. Over water, under similar conditions the same effect occurred, but in this case the jet was charged with spray droplets, and its overall momentum was probably considerably greater.

As a result of these static tests it is clear that very different air flow phenomena exist between over water and over ground conditions, and it is clear that the difference in result cannot simply be ascribed to spray impingement. Nevertheless, this latter effect is thought to contribute some considerable force on the model. The attempt to simulate the water profile under the model using a polythene sheet appeared initially to be successful, but jet pressure measurements showed some modification.

## 5. Further Work

Interest should now be focussed upon the action of a jet upon the water surface, since the manner in which spray is produced not only influences lift efficiencies and stability, but also drag forces on the craft. A two dimensional rig would be more suitable for the purpose, since the volume of work required could be drastically reduced. Further, air flow irregularities within the ducting would be eliminated. The supply of air to the jets could be entirely independent, and hence one jet could only influence the other through changes in pressure within the cushion. To make a rig of this form suitable for high speed testing over water would be a large effort. The sidewalls required would need to extend well in front and to the rear of the craft, and their depth would also need to be great. For this reason, it is proposed that initial tests will be made with a single two dimensional jet over water. The jet would not support a cushion pressure. The effects of varying forward speed, jet pressure, angle to the vertical, height from the water, and jet thickness would be determined.

## 6. Conclusions

It is considered that the following major effects contribute to the hydrodynamic drag of a hovercraft moving over water:

1. The generation of waves directly influencing the trim of the craft, so producing a drag force equal to the product of lift force and the sine of the angle of trim to the horizontal. Craft caused to trim at some other condition will suffer cross flow and will lose lift until an equilibrium state is re-established. The energy transferred to the waves can be considered as imposing a penalty on the lifting system of the craft.
2. A variation of jet momentum around the craft periphery caused by large variations in the clearance between the craft and the local water surface. These effects would be expected to have maximum influence at speeds somewhat below the hump speed. (Froude Number of 0.55 for the circular model tested).
3. A break-up of the water surface under the jets, up to a forward velocity dependent on a number of factors, of which jet pressure and geometrical considerations are undoubtedly very important. This velocity will obviously not depend directly on the craft Froude Number. At speeds at which the water break-up is liable to occur, it is considered that small variations of clearance between the craft and the local water surface can cause large variations in jet momentum around the periphery. It is suggested that at low speeds over water, the air outlet angle from the cushion is more critically affected than for similar conditions over ground, causing these large air momentum differences. Large drag differences have been measured between water and ground operation for the static case.
4. Spray impingement upon the craft bottom and sides. This effect, linked closely with the break-up of the water surface, has been observed in the tests, and is undoubtedly an important factor. Unfortunately no measure of the forces involved has been possible.

Further work should be directed towards some understanding of the water surface break-up, and subsequent spray generation.

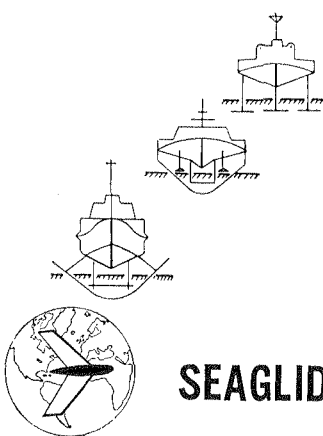
### Acknowledgement

This work was carried out as part of a contract to the Ministry of Aviation.

The author wishes to thank all members of the NPL staff who have contributed to this study.

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# CONTROL AND PERFORMANCE OF BRITTEN — NORMAN CC2-001 CUSHIONCRAFT

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*This memorandum represents the personal views of the author. It does not carry the authority of the Royal Aircraft Establishment*

## 1. Introduction

Research on hovercraft at the Royal Aircraft Establishment, Bedford, has been based on the Britten-Norman CC2-001 Cushioncraft. One of the problems that has received particular attention has been that of control when operating over land.

Over land operation of hovercraft is substantially different from over water operation. It has the advantage that there are no problems with waves, hump speed, and spray and thus the measurement of the forces acting on the craft can be more straightforward. It has the disadvantage that the vehicle is very sensitive to ground slope and that water drag cannot be used to assist control, in addition the presence of numerous solid obstacles emphasizes the need for adequate control.

In this Paper some of our handling experience with CC2 is described and representative results of the control effectiveness tests are given.

## 2. Description of CC2-001 Controls

The general arrangement of the CC2-001 is shown in Fig. 1. The method of control was by means of vanes and restriction flaps in the jets. These controls were operated by a whipstave for each hand and two foot pedals.

The whole of the 8 ft straight portion of both transverse jets could be closed; the starboard foot pedal (the accelerator) controlled the flap in the forward jet and the port foot pedal (the brake) controlled the flap in the aft jet. The flaps in the longitudinal jets were each 5 ft long and were controlled by outward movement of the whipstaves; the starboard whipstave moving the starboard flap and the port whipstave the port flap.

There were moveable vanes in both the stability jets which could be moved from  $-40^\circ$  (deflecting the jet forward) to  $+50^\circ$ . The starboard vanes were operated by fore and aft movement of the starboard whipstave and the port vanes by the port whipstave. Fixed vanes, with a deflection of  $+30^\circ$  at their bottom edge, were fitted for the whole length of the longitudinal peripheral jet.

## 3. Handling Experience

The control of CC2-001 was basically simple in concept but, because of the weakness of the forces available—particularly in yaw—and of substantial secondary effects, it was much more complex in practice.

Fore and aft forces on the craft were produced by the fixed aft inclined vanes, movement of the stability jet vanes, by means of closing the fore and aft jets, and trimming with ballast.

Yaw control was intended to be by use of differential whipstave but this was usually inadequate. It was found that a yawing moment could also be obtained by use of the roll vanes (due to some loss of thrust from the fixed vanes on one side) and that the restrictor flaps in the transverse jets also had a short term yaw effect—depression of the starboard pedal caused yaw to port and of the port pedal yaw to starboard. The yawing moments produced by these three methods were approximately equal and all had to be used to the full if the craft was to be made to point in the direction intended by the driver.

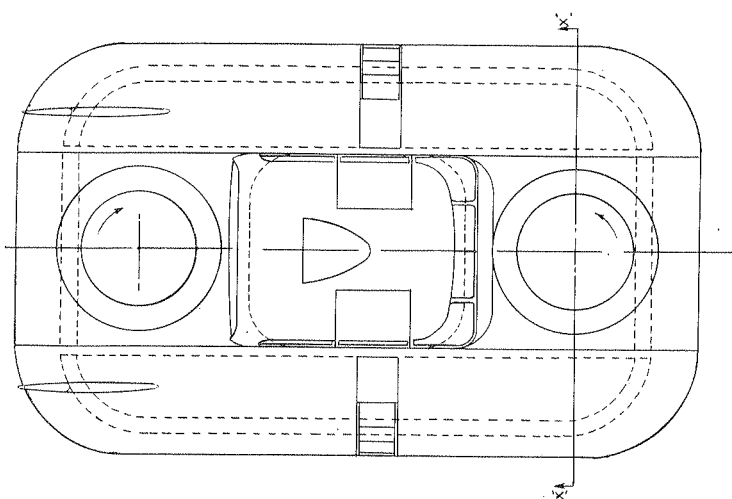
Lateral control of the craft was by means of the roll vanes. As this control was also weak correct lateral trim was very important.

There are two major considerations to be borne in mind when driving a hovercraft over land. The first is that one is operating in the air, although near the ground, so that the craft is carried along bodily by the airstream and all the controls produce motion relative to the air mass and not relative to the ground a short way beneath. The second is that a hovercraft does not operate at a set altitude but at a fixed distance above the ground; gradients therefore have a very marked effect, so that superimposed on the tendency to be carried along by the movement of the air mass is this second tendency to flow to the bottom of all dips and valleys on the surface of the ground.

As the largest thrust force available was in a forward direction the only way of dealing with a significant slope or wind was by heading up into them. With the control forces avail-

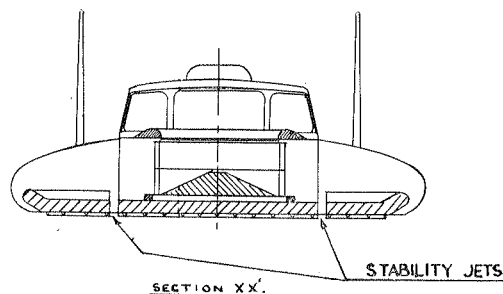
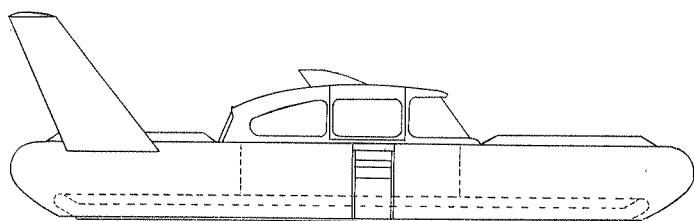
\* This paper was presented to the Research Symposium on Air Cushion Craft held in the Department of Engineering, University College of Swansea, from July 21st to July 23rd, 1964

FIG. 1.



DIMENSIONS AND DATA.

1. OVERALL LENGTH:- 27 FEET.
2. OVERALL WIDTH:- 17 FEET-1 INCH.
3. OVERALL HEIGHT TO TOP OF FIN:- 8 FEET-6 INCHES.
4. WIDTH OF CENTRE BODY:- 8 FEET.
5. MAX. DEPTH OF PLENUM CHAMBER:- 2 FEET-6 INCHES.
6. DIA. ACROSS FAN BLADES:- 5 FEET-4 1/2 INCHES.
7. CUSHION AREA (INCLUDING JETS):- 330 SQ. FEET.
8. WIDTH OF JETS:- 4 INCHES.
9. ANGLE OF PERIPHERAL JETS TO HORIZONTAL:- 30°.
10. FORWARD FAN ROTATES ANTI-CLOCKWISE.
11. AFT FAN ROTATES CLOCKWISE.



BRITTEN-NORMAN CC2-001 CUSHIONCRAFT.

SCALE IN FEET:- 1 2 3 4 5 6 7 8 9 10

able a slope of 1 in 30 or a wind of 15 knots were found to be about limiting conditions. A further consequence of the largest thrust force being in the forward direction was that the most effective method of stopping the craft was to make an 180° turn and apply full forward thrust—as rearward vision for the driver was not good this manoeuvre had its limitations.

Due to the fixed aft inclined vanes in the side jets the craft normally had a tendency to travel forward. If it was desired to hover without moving forward, such a large proportion of the available control forces were required to counteract this tendency that control became impossible. For low speed manoeuvring it was thus essential to trim the craft stern down to counteract the forward thrust but this naturally had an adverse effect on the forward speed.

Only low rates of turn were possible but this did not cause undue difficulty either when manoeuvring in the hangar or on the airfield provided that excessive sideslip was not allowed to develop. Over reasonably level ground figure of eight turns were quite practical.

Because of the limited control power the craft response was very slow. With the control system fitted to CC2-001 control was completely dependent on hover height and it was found that a fairly small decrease in hover height caused a very marked deterioration in control.

In spite of the serious shortcomings in control, CC2-001 was a most interesting vehicle to drive and the driver found that he had a surprising ability to arrive at his destination. It says much for the craft that there was no handling accident either in the confines of the hangar or on the airfield at airspeeds up to 25 knots and groundspeeds up to 35 knots or so.

#### 4. Some test results

The test results given in this Paper were obtained with CC2-001 tethered in a hangar. The size of the hangar was large enough to ensure that circulation effects were negligible. The craft was tethered by four steel cables in which the tensions were measured by strain links; all the results have been corrected for the couples applied to the craft by these cables. In all these tests it has been assumed that the CG of CC2 was at its centre; this was obviously not strictly accurate but the only effect is on the axis of the graphs. Tests were made at a mean weight of 4,560 lb and at a hover height of 8.1 in for the pitch tests and 9.4 in for the roll tests. The craft rotation was found to be essentially about the centre of its base and thus change of angle had little effect on the mean hover height; at the hover heights used for these tests the maximum possible angles of pitch and roll were  $\pm 2.8^\circ$  and  $\pm 5.5^\circ$  respectively.

Hover height is defined as the distance from the ground to the bottom of the jets and the clearance height was  $1\frac{1}{4}$  in less than this due to the rubbing strakes on the bottom. Hover height was measured simultaneously by two cameras at right angles.

The effects of weight and fan speed on hover height are given in Fig. 2. Experimental points are not given in this Figure as it has been cross plotted from the actual results but the consistency of the results obtained with the cameras was very good. Earlier attempts to measure the hover height with four hand held measuring sticks were not satisfactory as continual movement of the craft made accurate measurements impossible.

It will be seen from Fig. 3 that the stiffness of the craft in

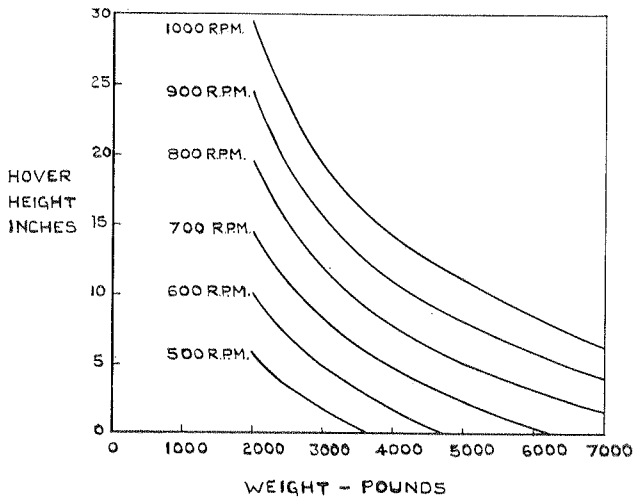


Figure 2. Change of hover height with weight and fan speed

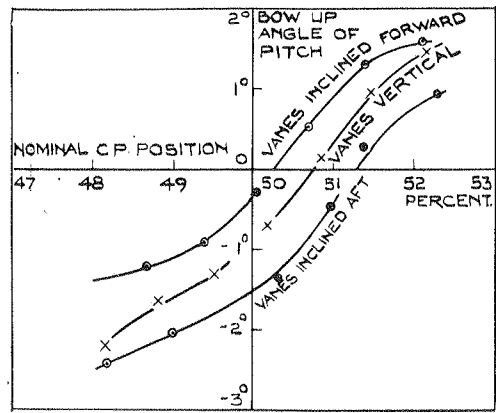


Figure 5. Pitch of craft with CP movement and stability vane control

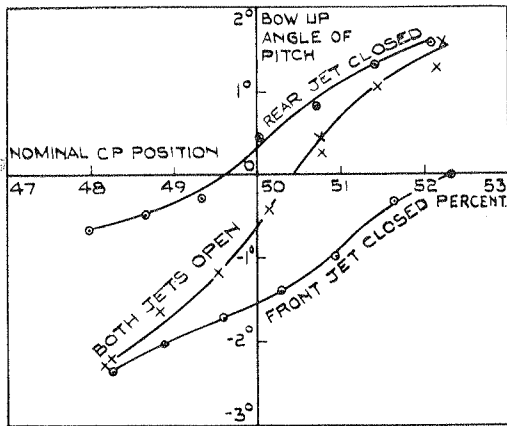


Figure 3. Pitch of craft with CP movement and pitch control

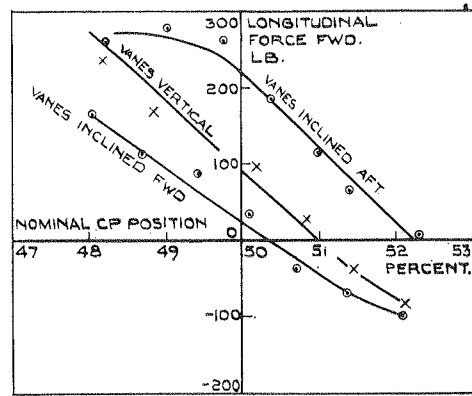


Figure 6. Change of longitudinal force with CP movement and stability vane control



Figure 4. Change of longitudinal force with CP movement and pitch control

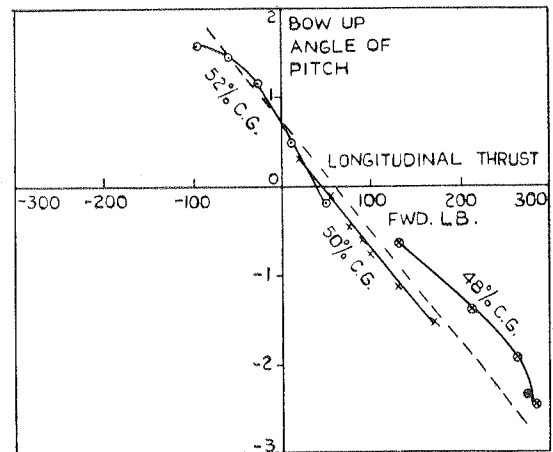


Figure 7. Pitch/thrust relationship with pitch control

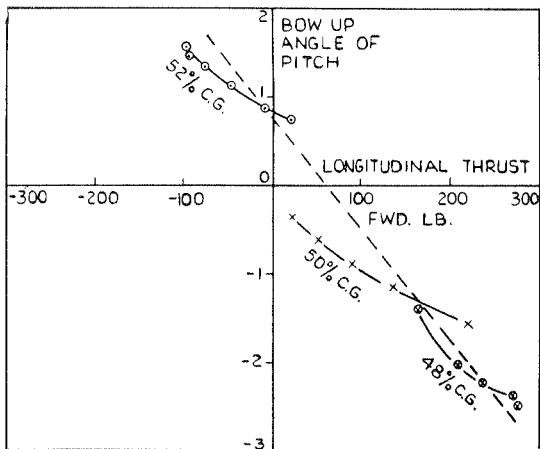


Figure 8. Pitch/thrust relationship with stability vane control

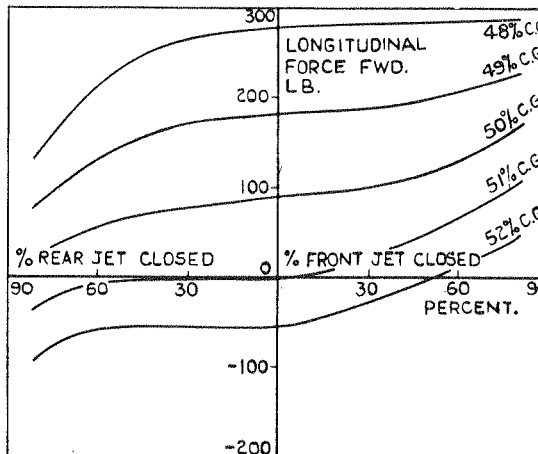


Figure 10. Effect of pitch control on longitudinal force

pitch was 0.75% Cp shift per degree when level but this increased to more than double this value as the angle increased. The craft is also stiffer in pitch when either the front or the rear jets were closed. Full control movement gave a rotation of 1.8° and a change of fore and aft thrust of 150 lb as will be seen in Fig. 4. When the craft was level there was a forward thrust of 50 lb due to the fixed vanes; if this was to be balanced out the craft had to be trimmed 0.6° bow up.

Similar curves for the whipstaves control are given in Figs 5 and 6. The central curves with the vanes vertical are the same, within experimental error, as those in Figs 3 and 4 but it will be seen that the outer curves are substantially different. Full control movement only gave a 1.1° change of angle but a 180 lb change of thrust when the craft was approximately level.

In Figs 7 and 8 thrust is plotted against angle and the mean slope is found to be 80 lb per degree (W tan  $\alpha$  for a weight of 4,560 lb is 81 lb per degree). The pitch control had fairly small secondary effects but it will be seen that whipstaves movement gave 175 lb per degree.

The actual effects of the pitch and whipstaves controls are shown in Figs 9-12.

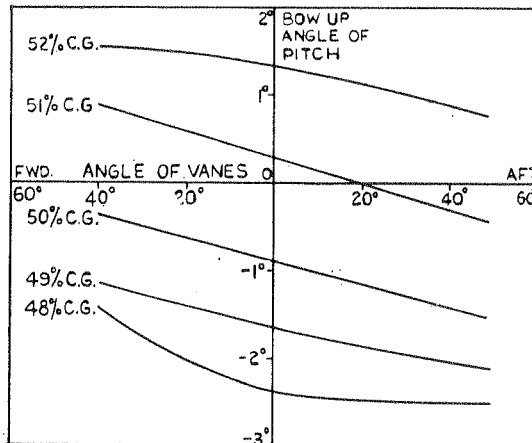


Figure 11. Effect of stability vane angle on pitch

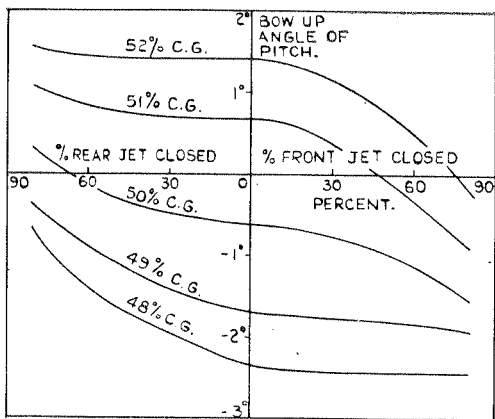


Figure 9. Effect of pitch control on pitch

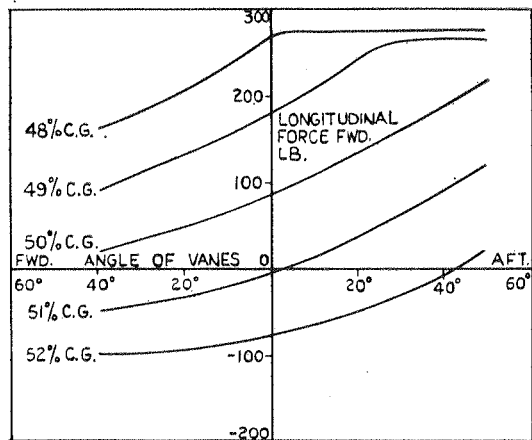


Figure 12. Effect of stability vane angle on longitudinal force

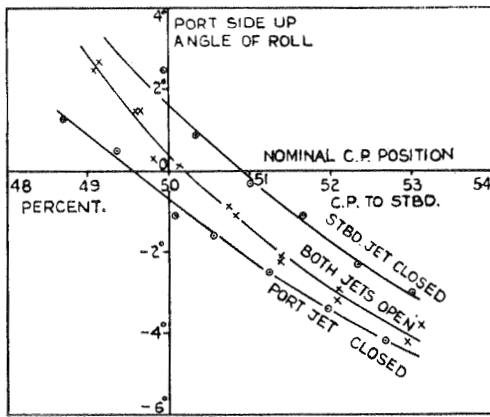


Figure 13. Roll of craft with CP movement and roll control

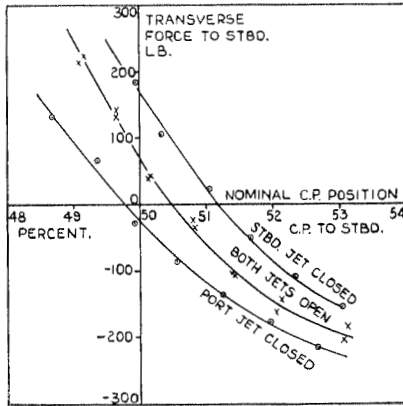


Figure 14. Change of transverse force with CP movement and roll control

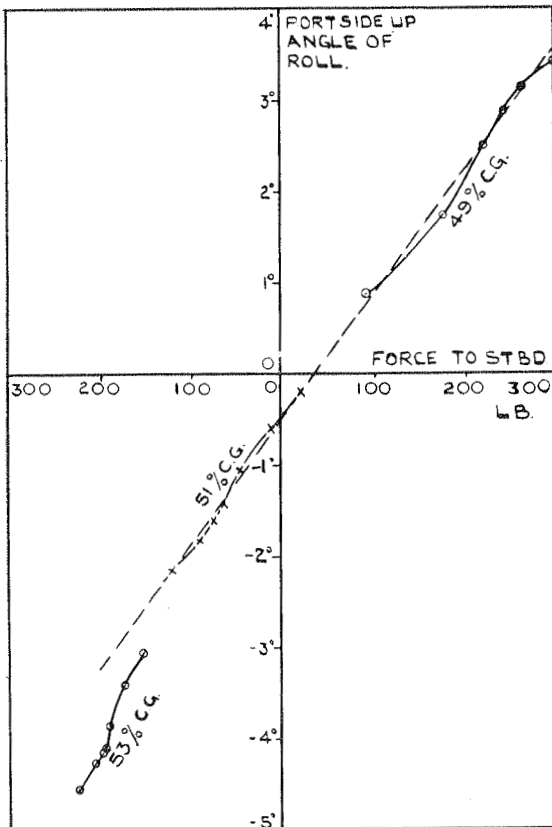


Figure 15. Roll/thrust relationship with roll control

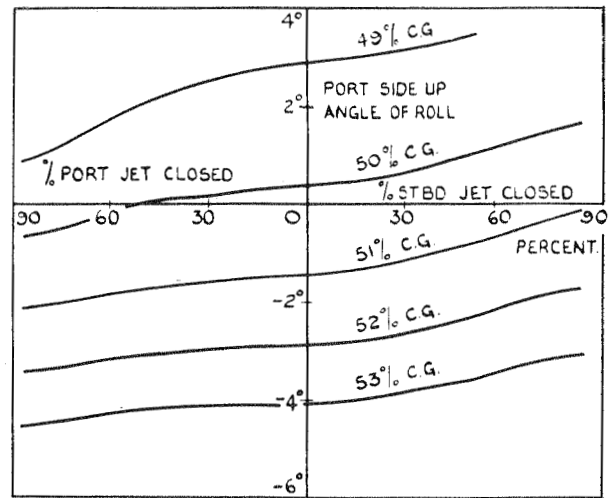


Figure 16. Effect of roll control on roll

Similar tests were made in roll. In spite of the stability jets the stiffness in roll was only 0.5% Cp shift per degree when the craft was level. Full control movement gave a rotation of 2.2° and a change of sideways thrust of 180 lb. When the craft was level there was a force of 40 lb to starboard which was probably due to the swirl induced by the fans. Fig. 15 gives a mean slope of 75 lb per degree of roll. The effects of the roll control are given in Figs 16 and 17.

The yaw forces were measured during these tests but, due to their small magnitude and the greater errors that were inherent in measuring them, the results were not satisfactory.

5. Conclusions

The test results bore out the subjective experience of the drivers that the control forces were very limited. The hover height achievable by CC2 was also less than had been hoped and this aggravated the control problem. CC2-001 has now been modified so as to have an improved hovering performance and the controls have also been substantially redesigned; a further test programme is to be undertaken on the modified craft.

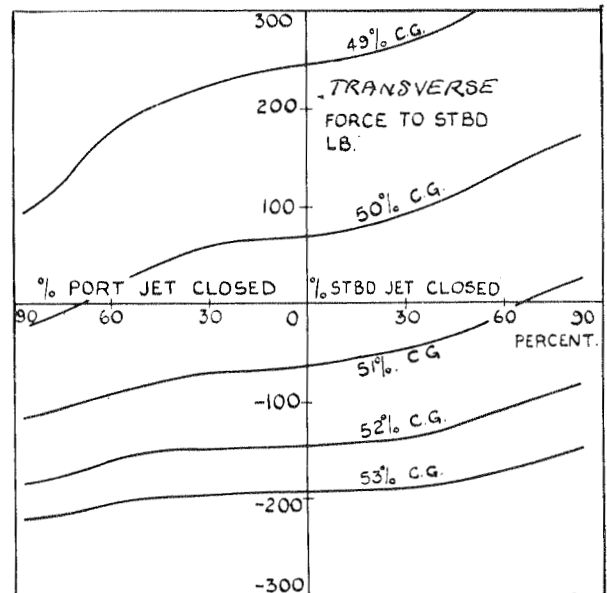


Figure 17. Effect of roll control on transverse force

# Effect of Forward Speed On a Two-Dimensional Ground-Effect Machine

by

A. A. West  
University of Wales



A. A. West

## Introduction

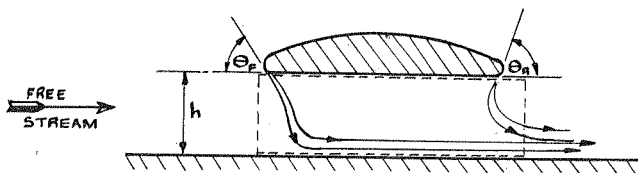
The material presented in this paper is part of a preliminary study which was undertaken to determine the feasibility of supporting a unique vehicle by Ground Effect Support at high forward speeds and to investigate the possibility of utilising the momentum of the ground effect curtain in the generation of thrust.<sup>1</sup> At the time that the investigation was initiated (1961) there was little information available on the effects of high forward speed on GEM's and it was decided that a two-dimensional study would be the most fruitful.

## Derivation of the Forward Speed Parameter

The flow around a two-dimensional GEM at forward speed can be characterized by one of the following regimes, Fig. 1:

- Subcritical, in which part of the front jet is deflected over the top surface of the GEM
- The Critical forward speed at which the front jet is just deflected under the GEM
- Supercritical, in which part of the free-stream air passes under the base of the GEM. In this regime the flow around the GEM is similar to that around a two-dimensional Jet Flap Wing out of ground effect.

At the Critical forward speed it is assumed that the free-stream stagnation pressure acts on the front jet curtain and that the free-stream static pressure acts on the downstream side of the rear jet curtain.



Applying the Momentum Theorem to the control volume shown and assuming that there are no mixing losses:

$$\begin{aligned}
 P_{\infty.c} h &= M_F (1 - \cos \theta_F) \\
 &+ M_R (1 + \cos \theta_R) \\
 &+ P_{\infty.c} h \quad (1)
 \end{aligned}$$

Assuming that the momentum flux issuing from the front and rear jets is the same, i.e.  $M_F = M_R = \frac{1}{2} M_T$  and that the front and rear jet angles are the same  $\theta_F = \theta_R$ , equation (1) may be written as:

$$(P_{\infty.c} - P_{00.c}) h = M_T \quad (2)$$

Now defining the forward speed parameter;

$$\Phi = \left( \frac{V}{V_c} \right)^2 \quad (3)$$

Assuming the free-stream airflow is incompressible,

$$\begin{aligned}
 \text{from (3)} \quad \Phi &= \frac{\frac{1}{2} \rho V^2}{\frac{1}{2} \rho V_c^2} \\
 &= \frac{q_{\infty}}{P_{00.c} - P_{\infty.c}} \quad (4)
 \end{aligned}$$

$$\text{from (2) and (4)} \quad \Phi = \frac{q_{\infty} h}{M_T}$$

## Model and Facilities

The model was two-dimensional of 10.5 in span and 7.5 in chord as shown in Fig. II. Air was supplied independently to the front and rear chambers and during the tests jet velocities up to 300 ft/sec were used. Aerodynamic forces on the model were measured on a six-component mechanical balance. Two different groundboards were used in this series of tests and a schematic model installation is shown in Fig. III.

## Results and Discussion

From Fig. IV it can be seen that the total lift acting on the model for a typical test increases smoothly with forward speed. For a three-dimensional the total lift may increase or decrease with forward speed, depending on the forward speed.<sup>2,3</sup>

Incidentally, the effect of the groundboard boundary layer is clearly seen from this figure; the height of the model above the groundboard and the total momentum flux were the same for both runs.

Fig. V shows that the aerodynamic lift coefficient increases rapidly with increasing forward speed in the subcritical regime, reaches a maximum around the Critical forward speed, and thereafter decreases slowly with increasing forward speed in the supercritical regime. It is believed that this graph justifies the use of the chosen forward speed parameter, although the significance of the aerodynamic lift coefficient is now somewhat suspect.

Fig. VI presents typical results in which the total drag is less than the profile drag but is none-the-less still a drag force.

From Fig. VII it can be seen that the thrust recovery coefficient is dependent on the ratio of free-stream to jet velocity, and also on the flow regime. It will be noted that values of the thrust recovery coefficient greater than unity are obtained. It is suggested that this is due to the airflow over the top of the model being entrained by the rear jet as shown in Fig. 1(c).

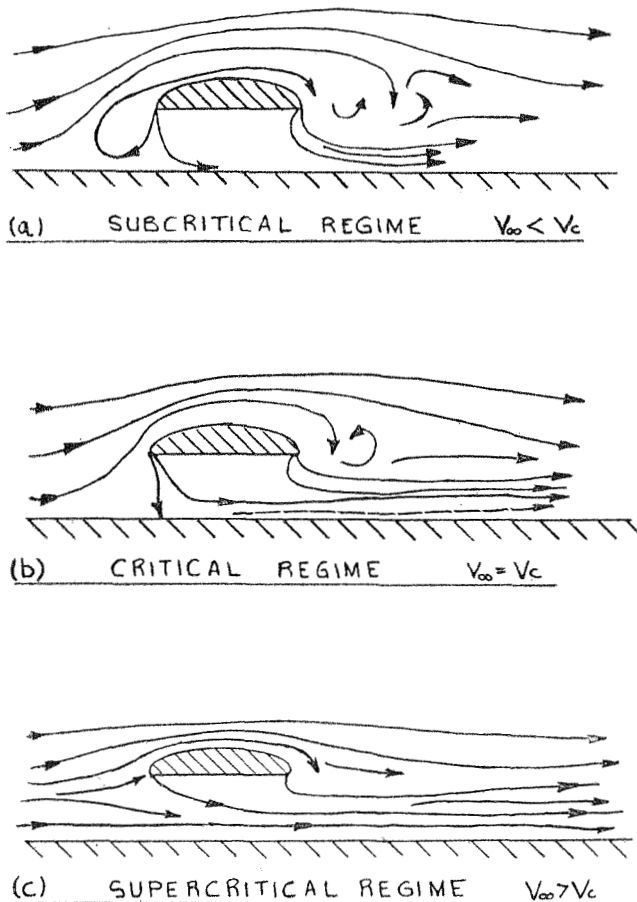


Figure 1. The effect of forward speed on the airflow around a two-dimensional GEM

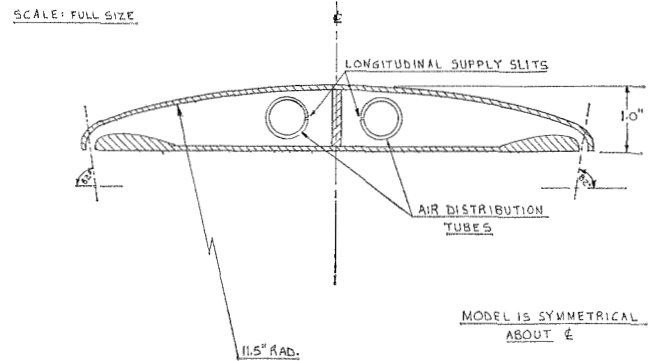


Figure 2. Section through model

References

1. A. A. West. "The Effect of Simulated High Forward Speed on a two-dimensional Ground Effect Support." Department of Aeronautical Engineering, Rensselaer Polytechnic Institute TR.AE.6304.
2. T. M. Harris, J. H. Davies and A. J. Alexander. "Some Tests on a Circular Ground Effect Machine with Forward Speed." The College of Aeronautics, Cranfield. CoA Note 133.
3. Norman K. Walker. "Some Notes on the Lift and Drag of Ground Effect Machines." Presented at the National Meeting on Hydrofoils and Air Cushion Vehicles, co-sponsored by IAS and US Navy. 17th-18th September, 1962.

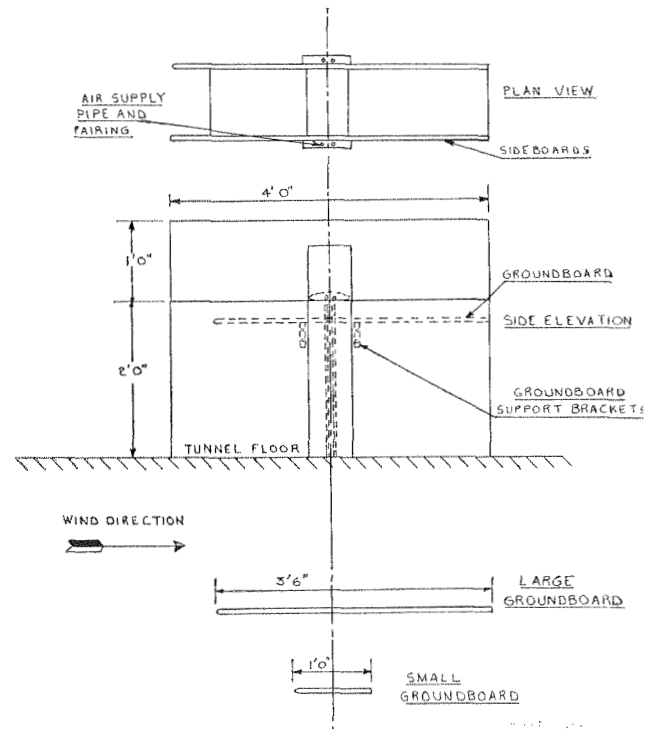


Figure 3. Schematic drawing of model installation

**Symbols**

- $C'_L$  aerodynamic lift coefficient =  $\frac{L'}{q\infty S}$
- $C_R$  thrust recovery factor =  $\frac{D_0 - D}{M \cdot 1/T}$
- D drag
- h height of model above groundboard
- l nozzle length = length of exposed model span
- L total lift
- $L_H$  lift at zero forward speed
- $L^2_H$  aerodynamic lift =  $\frac{L - L_H}{H}$
- M total momentum flux per unit length of model span =  $m V_j$
- $\dot{m}$  total mass flow rate of air supplied to front and rear jets per unit length of span
- p pressure
- q dynamic head =  $\frac{1}{2}\rho V^2$
- S exposed model plan area
- V velocity
- $V_j$  jet velocity calculated assuming the air in the chambers is expanded isoenergically and isentropically down to the free-stream static pressure
- $\Theta$  jet angle (see Fig. II)
- $\rho$  air mass density
- $\Phi$  forward speed parameter =  $\frac{q\infty h}{M \cdot 1/T}$

**Subscripts**

- c critical condition [see Fig. I(b)]
- F front jet
- O no air supplied to the nozzles
- R rear jet
- $\infty$  wind tunnel free-stream condition

**Superscript**

- o stagnation condition

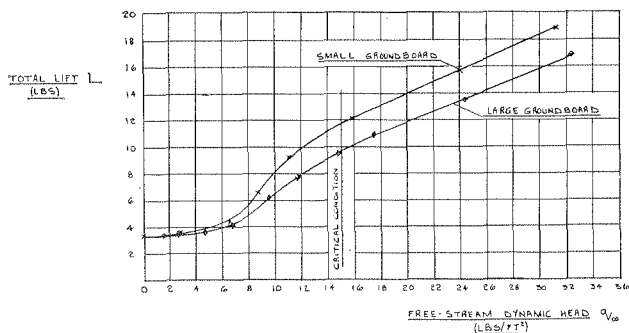


Figure 4. Total lift — free-stream dynamic head

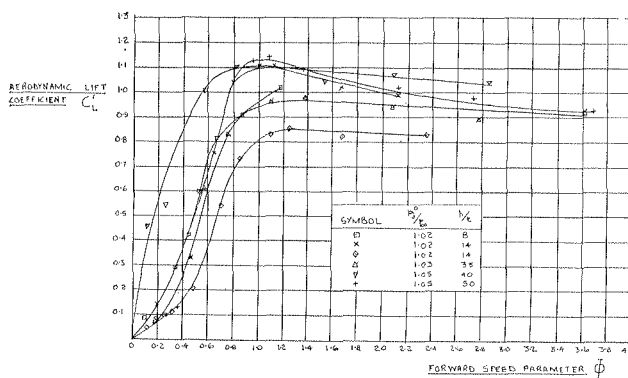


Figure 5. Aerodynamic lift coefficient — forward speed parameter

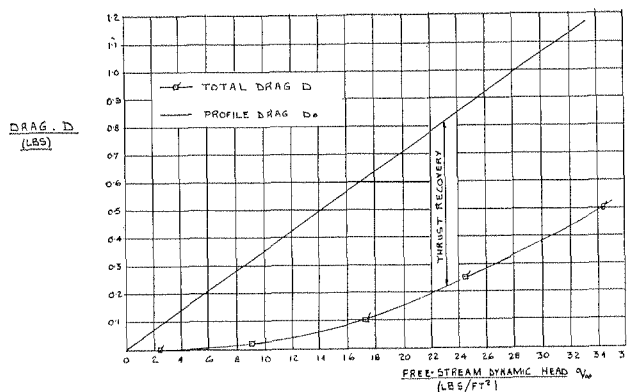


Figure 6. Drag — free-stream dynamic head

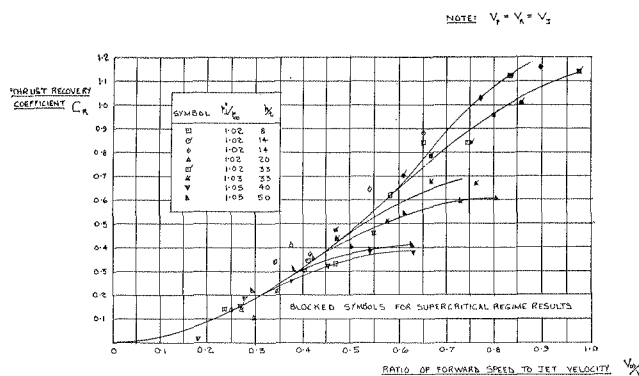


Figure 7. Thrust recovery coefficient — ratio of forward speed to jet velocity

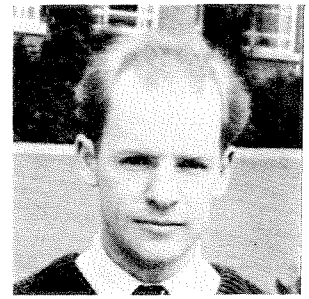
\* This paper was presented to the Research Symposium on Air Cushion Craft held in the Department of Engineering, University College of Swansea, from July 21st to July 23rd, 1964

# THE EFFICIENCY OF JET CURTAINS

by

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RESEARCH in this field at Queen's University has now been in progress for about two years. The object of this research was to determine the properties of an annular jet impinging on the ground, consequently a study of the parameters likely to affect the properties and efficiency of such a jet has been made.

The test rig used in these investigations is a two-dimensional representation of an annular jet. The basic layout of the original rig is shown in Fig. 1. This has been modified slightly since then due to effects discussed later. The air supply is taken from a Keith-Blackmann-Tornado centrifugal blower and passed through a settling chamber of section 7.5 x 19 in to a contraction. The contraction reduces the cross-section to 12 x 1.5 in respectively. Nozzles are attached to the contraction to give a uniform flow the same as the contraction end cross section. The range of nozzle angles currently available is 15°, 30°, 45°, 60° and 90° measured from the horizontal. The nozzle is attached to a pressure box in which the ground board can be moved to control the base height above the ground. The effective annulus diameter can be varied by inserting a dummy end wall.

Details of tests made with this original rig are given in Table 1, for which the index is given below:

Test	Nature of Tests (Original Rig)
1	Cushion or support pressure measurements
2	Pressure distribution along the ground
3	Visualisation of flow patterns
4	Total head traverses across the jet at the exit
5	Flow separation in the 30° nozzle
6	Yawmeter traverses
7	Hot wire traverses
8	Flexible curtains

## 1. Cushion or Support pressure measurements

The distribution of static pressure over the base board, representing the undersurface, was measured using flush static tappings.

The cushion pressure is designated to be the constant value the pressure reached within the cushion. The extent of the constant pressure region varied with nozzle angle and base height, the effect of base height predominating. With the limited range of base heights available in the original pressure box the condition where the static pressure varied along the entire length of the undersurface, was never reached. This

condition was achieved with the modified pressure box.

A typical set of results obtained from these early experiments is shown in Fig. 4. It came to notice that these cushion pressures were lower than those measured in other similar rigs and so a reason was sought. If we take a closer look at the sort of flow pattern one obtains from this particular nozzle layout it can be seen that there is a large suction over the extension of the base outboard of the nozzle. This is caused by the entrainment of air along the jet boundaries. This reduced pressure outside the jet curtain gives a lower cushion pressure for the same pressure rise across the jet, than would be obtained if the pressure outside the jet were atmospheric. These conclusions were borne out by the results of later tests.

It was because of this effect that the extension of the base outboard of the nozzle was removed.

That the jet induces a flow in the cushion can be deduced from the decrease in static pressure as the nozzle exit is approached. There is presumably a circulation of air within the support region. This circulation may be of the form of a single vortex or a series of smaller vortices. This aspect will require further study to discover the exact manner of circulation.

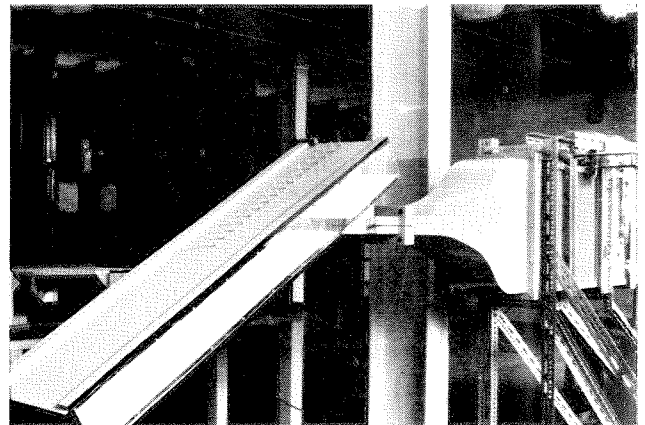


Figure 1. Original Test Rig

## 2. Pressure Distribution along the ground

These measurements were made to explore the flow in the jet region. A typical plot of these results is given in Fig. 5. It will be seen that there is a stagnation point in each case, the position of which does not vary appreciably with base height. There is, however, an outboard movement of the stagnation point as the nozzle becomes nearer the vertical. Moving the end wall of the box towards the jet to reduce the effective annulus diameter had some effect on the pressure distribution as mentioned previously.

The presence of a stagnation point implies some inexactitude in theories assuming that all of the flow along the ground in the region of the jet is in the outward direction. The accom-

panying analyses go some way towards a more exact theory.

## 3. Oil flow patterns

The nature of the flow in the neighbourhood of the jet was determined by taking oil flow patterns for the various combinations of  $\theta$  and  $h$ . Standard oil flow techniques were used. The results were very interesting and can be seen in Figs 6-9.

During the formation of these flow patterns the flow separation from the inside wall of the 15° and 30° nozzles was clearly visible. Separation also occurred in some cases where  $\theta$  was 45°.

The inflow along the base overhang is also visible.

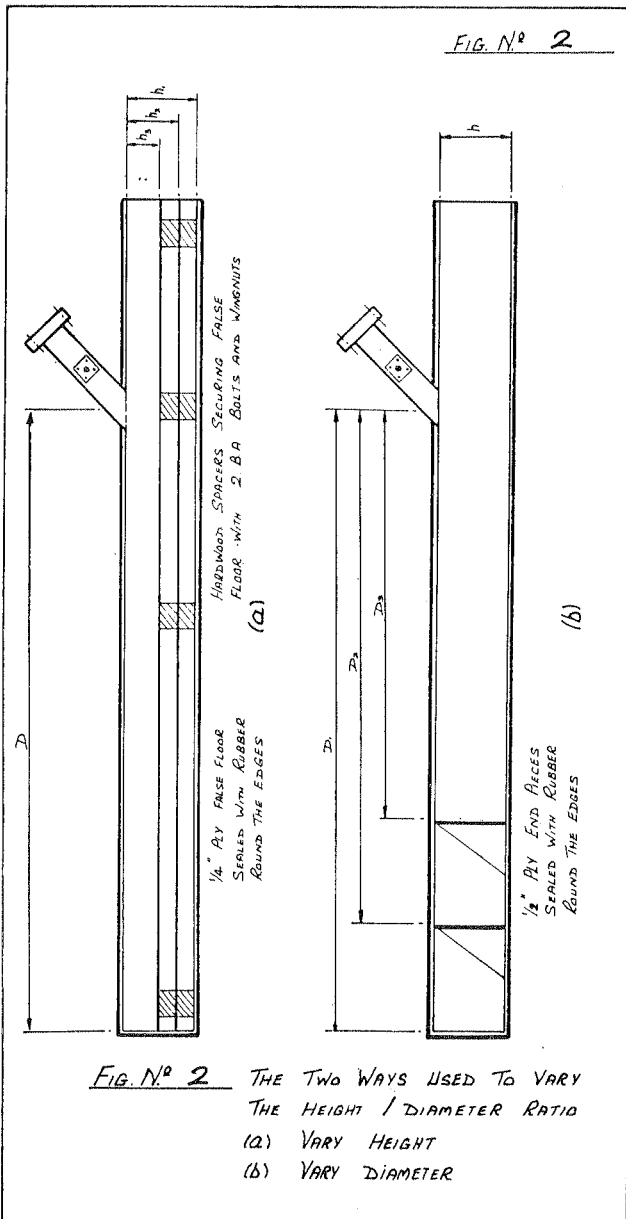


FIG. N<sup>o</sup> 3

DETAILS OF TESTS MADE  
 (SEE INDEX FOR NOTATION)

NOZZLE ANGLE DEGREES	BASE HEIGHT INCHES	ANNULUS DIAMETER INCHES	JET THICKNESS INCHES	TESTS MADE										
				1	2	3	4	5	6	7	8			
+15	2.0	72	1.5	x	x									
	3.0	72	1.5	x	x									
	4.0	72	1.5	x	x									
	4.0	60	1.5	x	x									
	4.0	48	1.5	x	x									
+30	2.0	72	1.5	x	x									
	3.0	72	1.5	x	x									
	4.0	72	1.5	x	x									
	4.0	60	1.5	x	x									
	4.0	48	1.5	x	x									
+45	2.0	72	1.5	x	x									
	3.0	72	1.5	x	x									
	4.0	72	1.5	x	x									
	4.0	60	1.5	x	x									
	4.0	48	1.5	x	x									
+90	2.0	72	1.5	x	x									
	3.0	72	1.5	x	x									
	4.0	72	1.5	x	x									
	4.0	60	1.5	x	x									
	4.0	48	1.5	x	x									

x INDICATES WIRE GAUZE ACROSS NOZZLE EXIT.  
 # INDICATES AIR FILTER INCORPORATED.

FIG. N<sup>o</sup> 3. TESTS MADE.

FIG. N<sup>o</sup> 4

$h/D = 0.0417$   $t/h = 0.500$   
 ATMOSPHERIC PRESSURE = 29.608" MERCURY  
 ATMOSPHERIC TEMPERATURE = 74°F  
 REFERENCE PRESSURE = 69.00 m/m WATER  
 JET TOTAL HEAD  $H_0 = 15.4$  c/m SLOPED ALCOHOL  
 1 c/m SLOPED ALCOHOL = 6.22 m/m WATER

NOZZLE ANGLE  $\theta = -45^\circ$

STATIC PRESSURE TUBE N <sup>o</sup>	STATIC PRESSURE c/m SLOPED ALCOHOL	STATIC PRESSURE lb / ft <sup>2</sup>	$\Delta P$ So. ft / lb	PRESSURE LIFT lb.
1	10.70	13.62	3.0	2.25
2	10.70	13.62	2.0	1.71
3	10.70	13.62	2.0	1.71
4	10.70	13.62	2.0	1.71
5	10.70	13.62	2.0	1.71
6	10.70	13.62	2.0	1.71
7	10.70	13.62	2.0	1.71
8	10.70	13.62	2.0	1.71
9	10.70	13.62	2.0	1.71
10	10.70	13.62	2.0	1.71
11	10.70	13.62	2.0	1.71
12	10.70	13.62	2.0	1.71
13	10.70	13.62	2.0	1.71
14	10.65	13.60	2.0	1.70
15	10.60	13.53	2.0	1.69
16	10.60	13.53	2.0	1.69
17	10.50	13.40	2.0	1.68
18	10.45	13.32	1.5	1.25
19	10.40	13.28	1.0	0.83
20	10.30	13.15	1.0	0.82
21	10.25	13.08	1.0	0.82
22	10.15	12.95	1.0	0.81
23	10.00	12.75	1.0	0.80
24	9.95	12.70	1.0	0.80
25	9.90	12.62	1.0	0.79
26	9.90	12.62	1.6	1.26

CUSHION PRESSURE  $P_c = 12.62$  lb/ft<sup>2</sup>

TOTAL PRESSURE LIFT = 37.71 lb.

FIG. N<sup>o</sup> 4. TYPICAL SET OF RESULTS TO MEASURE CUSHION PRESSURE AND JET TOTAL HEAD (WITHOUT GAUZE)

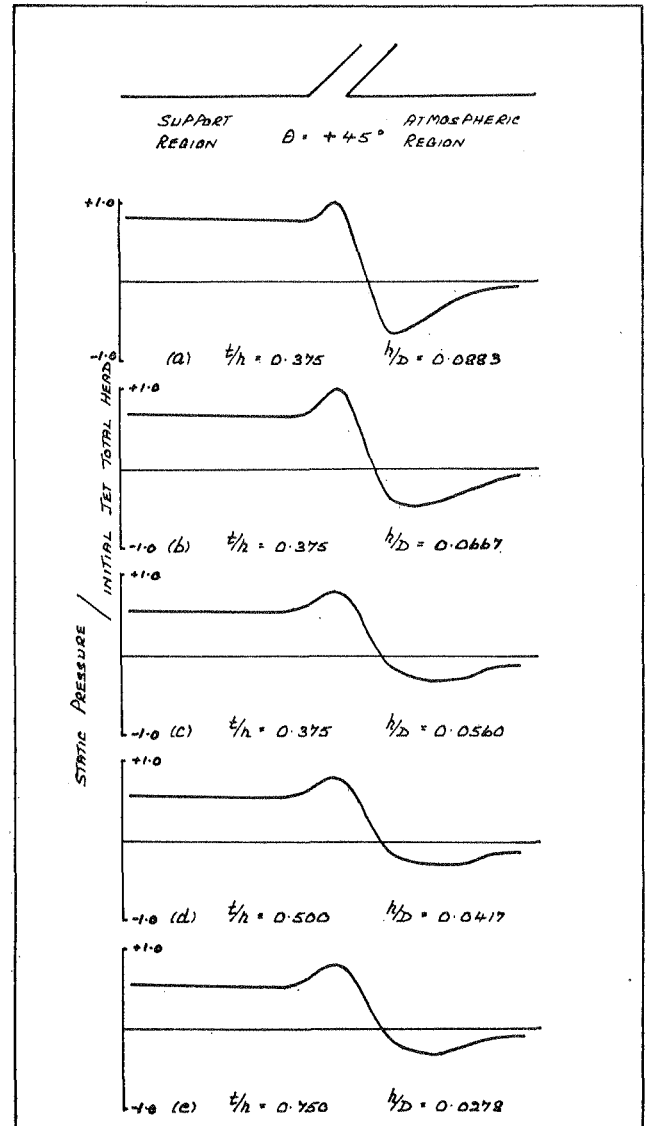
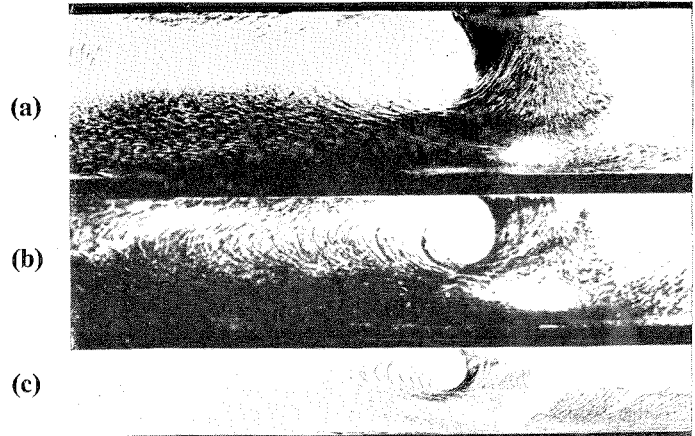


FIG. N<sup>o</sup> 5. STATIC PRESSURE VARIATION ALONG THE GROUND THROUGH THE JET WITHOUT GAUZE



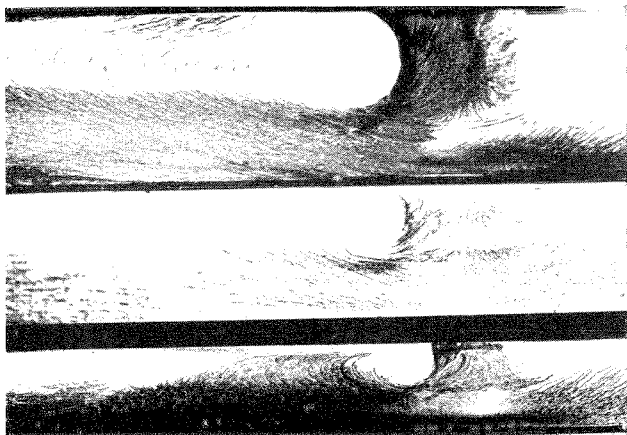
$h/t = 2.667$  (a)  
 $h/t = 2.000$  (b)  
 $h/t = 1.333$  (c)

Figure 6. Flow patterns  $\theta = 15^\circ$



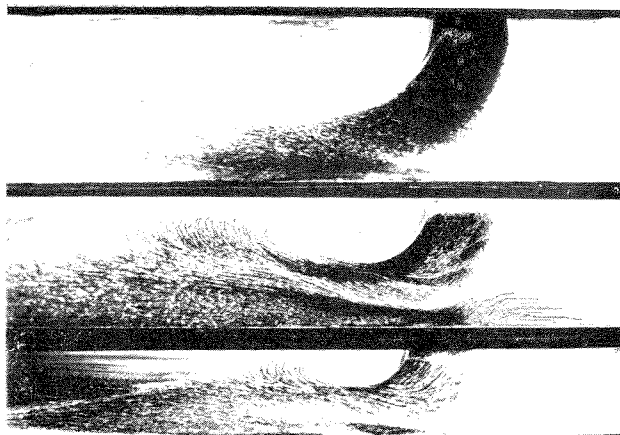
$h/t = 2.667$  (a)  
 $h/t = 2.000$  (b)  
 $h/t = 1.333$  (c)

Figure 7. Flow patterns  $\theta = 30^\circ$



h/t = 2.667 (a)  
 h/t = 2.000 (b)  
 h/t = 1.333 (c)

Figure 8. Flow patterns  $\theta = 45^\circ$



h/t = 2.667 (a)  
 h/t = 2.000 (b)  
 h/t = 1.333 (c)

Figure 9. Flow patterns  $\theta = 90^\circ$

4. Total head traverses across the jet at exit

The energy remaining in the jet was determined by taking  $\int \frac{1}{2} \rho V^2 ds$  across the jet at the end of the box as shown in Fig. 10. The integration was made only in the region where there was flow out of the box. The static pressure was already equal to that of the atmosphere so in effect  $\int \frac{1}{2} \rho V^2 ds$  becomes  $\int \frac{1}{2} \rho V^3 ds$ . This was compared with the initial energy content of the jet  $\int \frac{1}{2} \rho V_0^3 ds$  and expressed as a percentage of the initial energy content in Fig. 11. One would expect the energy losses to increase as the radius of curvature of the jet decreases, i.e. as the height decreases and the nozzle angle becomes nearer the vertical. This trend is followed approximately for the  $90^\circ$  and  $45^\circ$  angles but the results for the  $30^\circ$  and  $15^\circ$  angles did not fit in with this general pattern and indicate less loss of energy. This is thought to be a false indication brought about by the overhang and further tests are being made with the modified rig to check this anomalous result.

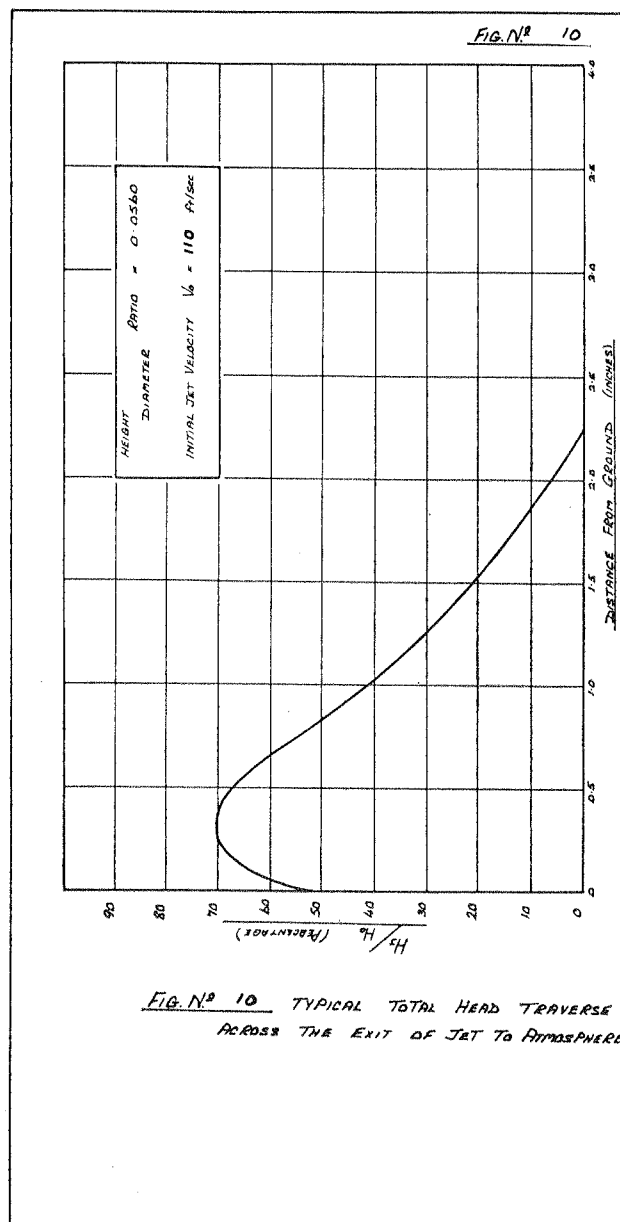


FIG. NO. 10 TYPICAL TOTAL HEAD TRAVERSE ACROSS THE EXIT OF JET TO ATMOSPHERE

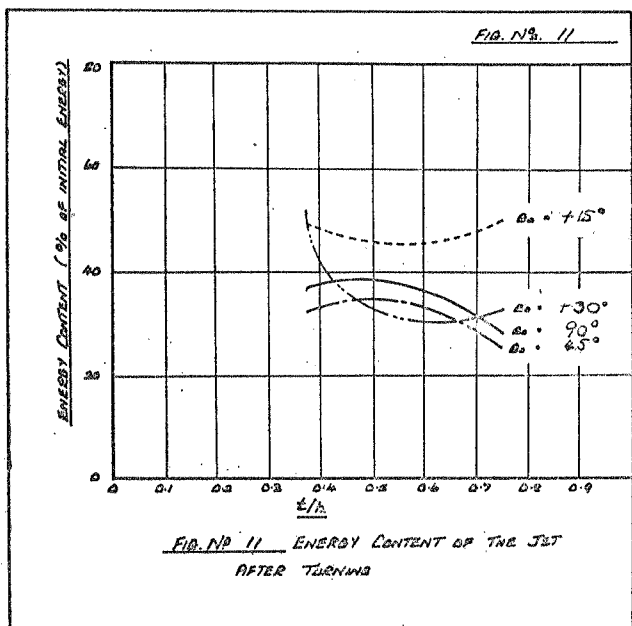
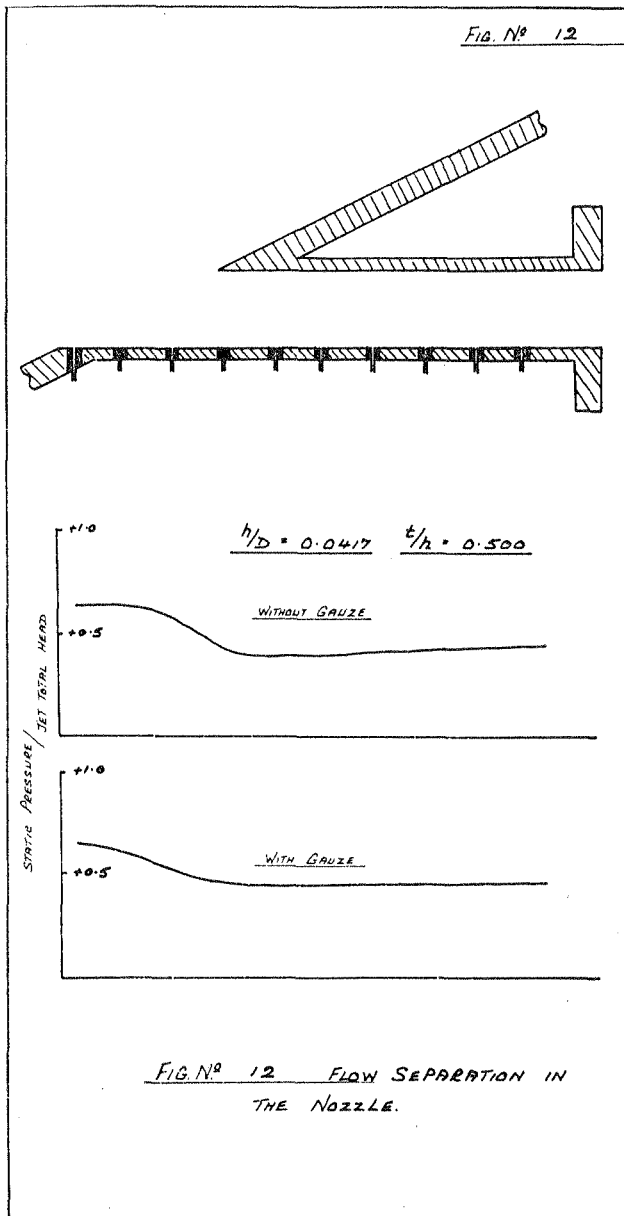


FIG. NO. 11 ENERGY CONTENT OF THE JET AFTER TURNING



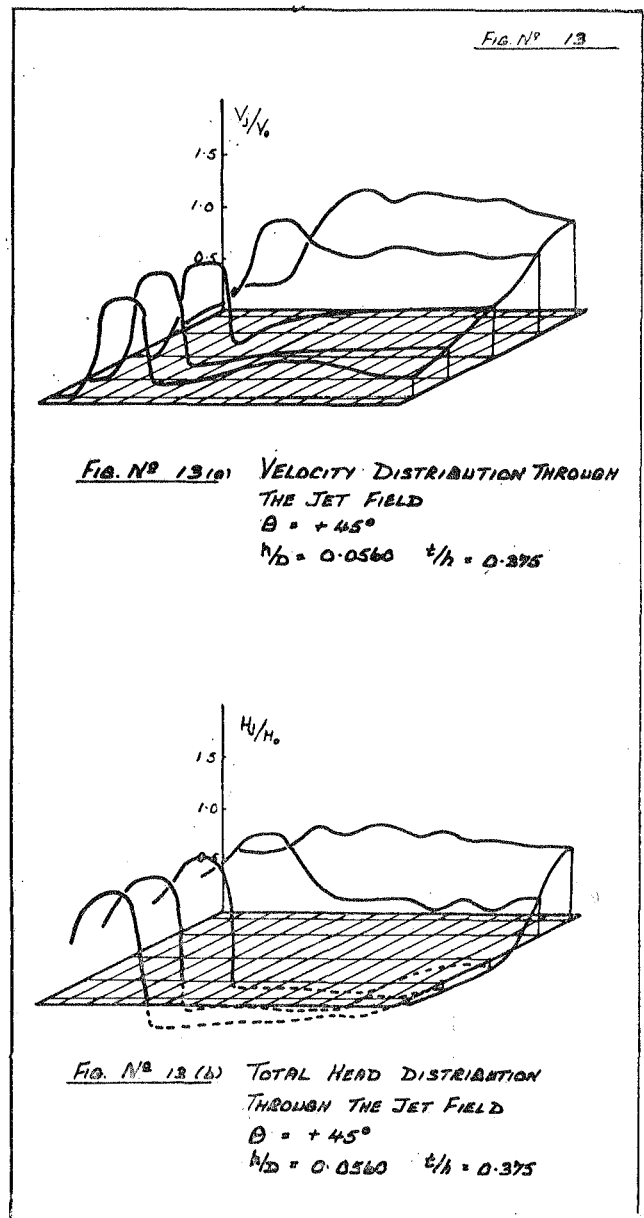
### 5. Flow separation in the 30° nozzle

It seemed likely that separation in the nozzle involved some loss in cushion pressure and therefore warranted investigation. Measurements were confined to the 30° nozzle which had given flow patterns typical of those in which separation had been detected.

Static pressure distributions along the inside wall of the nozzle were measured, a typical set of readings being shown in Fig. 12. It will be seen that there is a region of constant pressure (approximately cushion pressure) extending some 3 in inside the inner wall of the nozzle. This is presumably the region of separated flow.

### 6 and 7. Yawmeter and Hot wire measurements

In order to explore the flow in the jet and particularly to measure the extent to which air from either side of it was entrained, hot wire and yawmeter measurements were made at various positions in the jet flow region. The yawmeter served to determine both the direction of the flow and the total pressure at each point; the hot wire gave the mean velocity. The results were plotted to give an impression of a three-dimensional diagram displaying the distribution of total pressure and velocity over the whole region. Fig. 13 shows a typical result.



The total pressure was measured above atmosphere and plotted as a fraction of the initial total pressure in the nozzle. Similarly, the jet velocity is plotted as a fraction of the initial jet velocity.

It will be seen that the total pressure in the region outside the jet and close to the extension of the base board was below atmospheric pressure. The static pressure would therefore be even lower. Consequently, this extension of the base would be an undesirable feature in a hovercraft and would reduce the overall lift.

### 8. Flexible Curtains

Since the losses in the jet could be partly attributed to entrainment of the surrounding air it seemed reasonable to attempt to prevent this mixing by fitting a flexible curtain on one or both sides of the jet. The curtains were attached along one side only as shown in Fig. 14 and so were free to find their own shape. On test all such curtains were unsuccessful in increasing cushion pressure and inclined to flap violently and disintegrate. However, this latter defect would not necessarily arise in a three-dimensional case. The purpose of these floating curtains was to prevent mixing and should not be confused with the restrained but flexible skirts which have been successfully used to increase the operating height of current hovercraft.

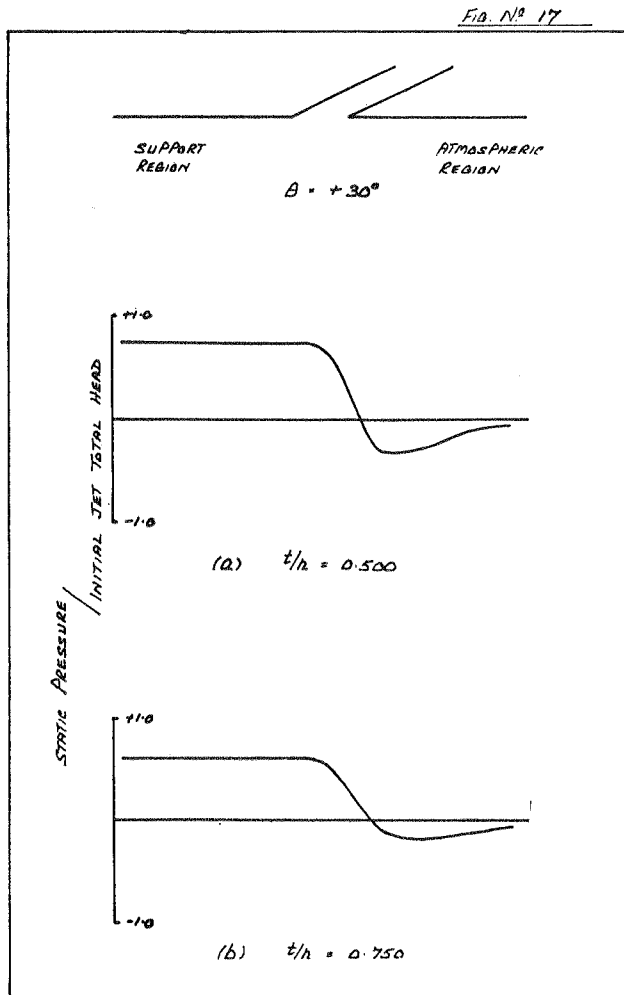
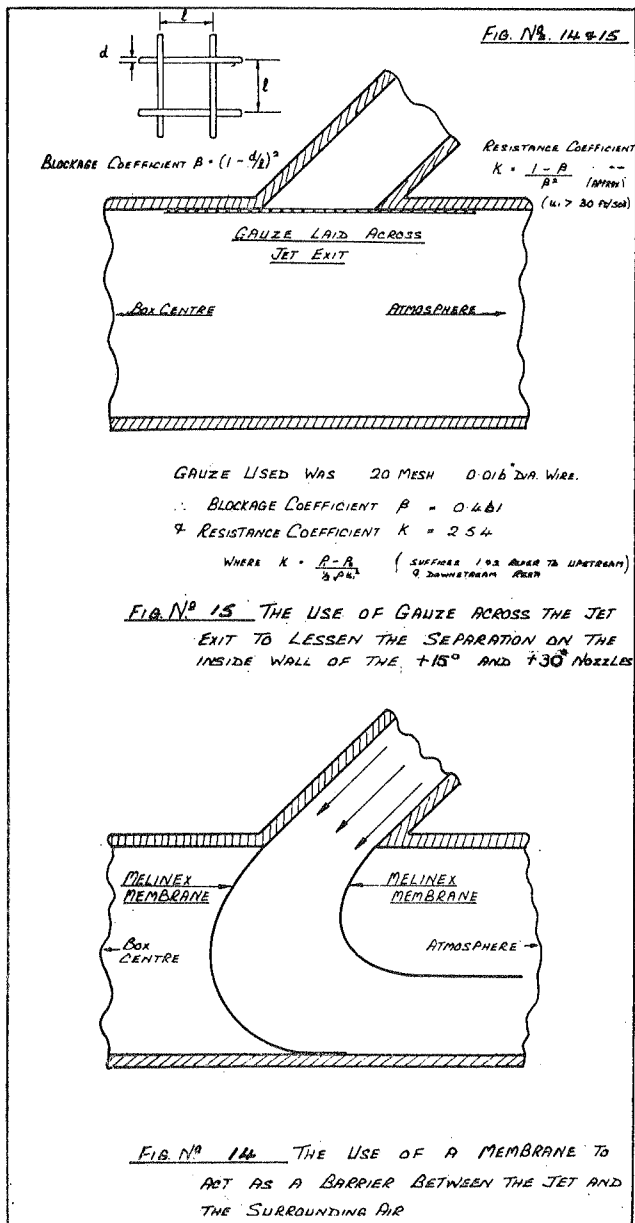
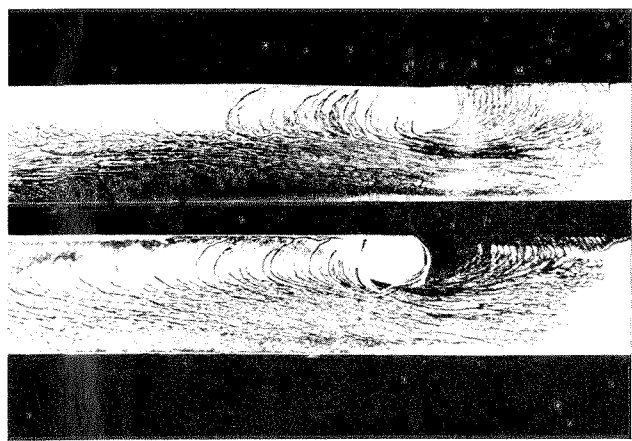


FIG. N<sup>o</sup> 17. STATIC PRESSURE VARIATION ALONG THE GROUND THROUGH THE JET WITH THE GAUZE ACROSS THE JET EXIT.



(a)  $\theta = 30^\circ$   $h/t = 2.000$   
 (b)  $\theta = 15^\circ$   $h/t = 2.000$

Figure 16. Flow patterns (with gauze)

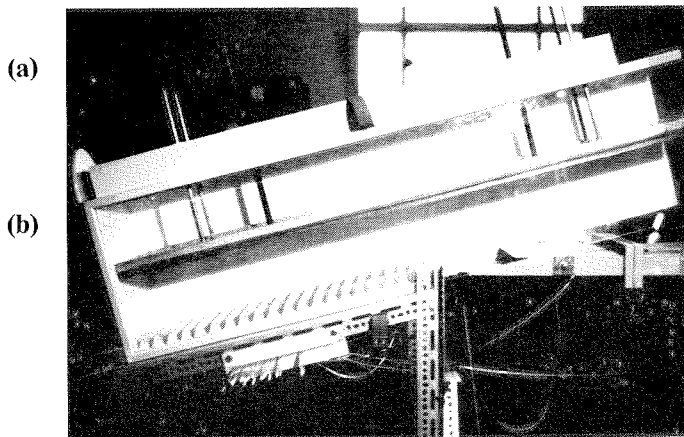
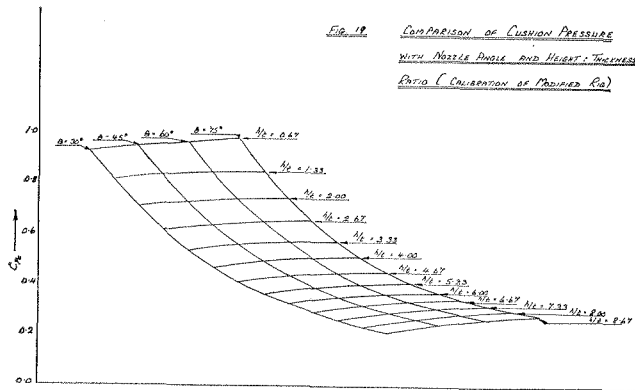


Figure 18. Modified test rig



### Gauze Effects

These tests were made to try and reduce the extent of the flow separation from the nozzle wall. The gauze was placed in a position as shown in Fig. 15, and proved effective in inhibiting separation in the nozzle. This can be seen from Fig. 16.

It seemed desirable, however, to investigate other effects it had been observed to have upon the flow.

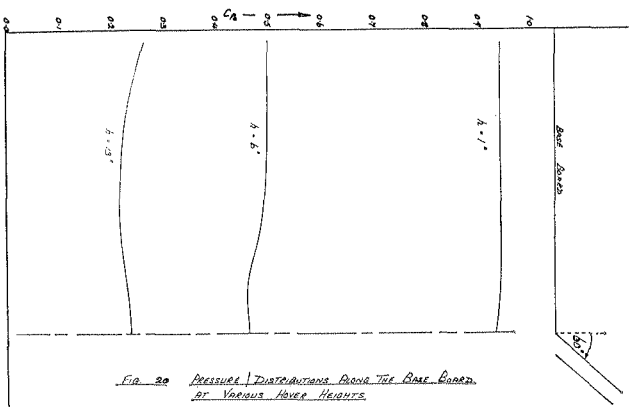
When the flow patterns were made with the gauze in position, there did not appear to be a stagnation point on the ground. Measured pressure distributions along the ground seemed to confirm this result (Fig. 17).

The cause of this phenomena is still a matter for speculation. Although the primary effect of the gauze is to promote more uniform flow by offering most resistance where the velocity is high it has a secondary effect of deflecting the stream. From the work of Cowdrey & Simmons<sup>1</sup> it can be deduced that the gauze actually used would have deflected the flow outwards through 5° to 10° in the cases investigated. This would not seem sufficient to alter the geometry of the flow enough to eliminate the stagnation of the inner-jet streamline.

Adding the gauze did not materially change the cushion pressure for a given energy input from which it follows that reduced losses in the turning process must have offset the losses arising from the resistance of the gauze itself. Further tests using gauzes of varying blockages could possibly explain this phenomena.

At this stage a new pressure box was constructed. It was designed to suit the existing contraction but to be more easily used, and have a larger range of base heights, the overhang outboard of the jet exit was removed as previously stated. The present rig is shown in Fig. 18.

Cushion pressures measured using this rig have increased and the calibration results are shown in Fig. 19. These measurements were obtained using a smooth base board. From the variation of static pressure along the base it can be deduced that there is a flow within the cushion. The severity of this flow increases as the base height increases as can be seen from Fig. 20. Tests are being made at present to see how base board roughness affects the flow within the cushion. This is being done by attaching strips of wood of triangular cross-section to the base board, the degree of roughness being varied by altering the size of the wooden strips.



Simple momentum analyses of the jet flows were investigated and are given in the Appendices.

The programme of future tests is given below.

### PROPOSED RESEARCH PROGRAMME FOR THE JET CURTAIN TEST RIG

1. The nozzle angles will be varied as follows:

30° 45° 60° 90°

measured as shown in Fig. 21. The value of  $h/t$  will be continuously variable between  $\frac{1}{2}$  and 10. The first tests will be made to ascertain whether the values of cushion pressure measured correlate with the exponential theory and other test data. There will be no overhang outboard of the nozzle exit which remains at a constant thickness of 1.5 in. These tests will be of the nature of a calibration of the new rig.

2. Fences will be attached to either side of the nozzle exit to study their effect on the entrainment flows. These flows will be made initially at values of  $h/t = 2$  and 8 but there is the possibility of extending this range if any interesting phenomena are found. The size of the fence can be varied as well as the shape.

3. The contraction angle of the nozzle will be varied to study the effect on separation of jet from the nozzle walls. Initially straight walls will be used.

(N.B.—Since this programme was compiled Burgess of Southampton University has informed me that he has eliminated separation with a 10° converging nozzle). Both converging and diverging nozzles will be studied.

4. The nozzle will be extended as shown in Fig. 22 and a study made of the flows within the cushion and along the edges of the jet. The value of  $h/t$  will initially be 3 with  $h/h$  ranging from 0 to 8.

5. Nozzle extensions with different exit geometries will be studied (Fig. 23). The conditions will be similar to section 4, but the parameters can be varied easily if this should prove to be worthwhile.

### Measurements :

The base pressure will be measured throughout the cushion region both on the undersurface of the box and on the ground board.

Static and total pressures in the jet will be measured to give the distribution of each across and along the jet. These measurements will be of particular importance where the exit geometry is altered.

Flow visualisation will be attempted wherever possible.

### THEORETICAL ANALYSIS OF JET CURTAIN

It is now well known that the pressure difference across a jet curtain depends upon the inclination of the jet, the ratio  $h/t$  and the fraction of the jet mass flow which flows into or out of the cushion. The cushion pressure is also dependent upon the amount of air entrained both from outside and in the cushion itself. An attempt has been made to build up a theoretical analysis of a two-dimensional jet curtain, taking these effects into account, for comparison with experimental results. (Appendix I.)

As a first step the entrainment of the air on either side of the jet was neglected, but allowance made for varying amounts of flow into the cushion region. Such a flow is relevant to the stability of hovercraft both as regards vertical movement and angular displacement about horizontal axes. Accordingly, it has been computed in some detail, with results given later. Attempts have also been made to take entrainment into account, since the fact that measured cushion pressures are always significantly less than those calculated from potential flow must indicate that entrainment is always present. However, this problem is complex and no very satisfactory solution has been obtained. It will probably be necessary to adopt a semi-empirical method based on assumptions suggested by experimental results.

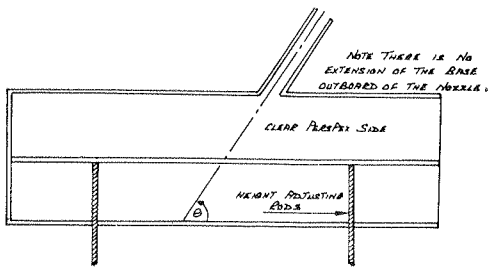


FIG. 21 GENERAL LAYOUT

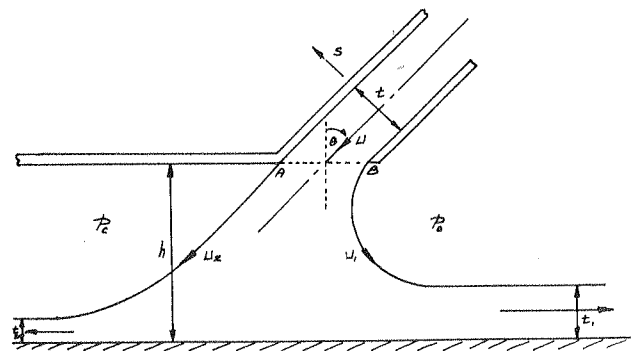


FIG. 24 FLOW MODEL USED IN ANALYSIS OF THE BIFURCATED JET

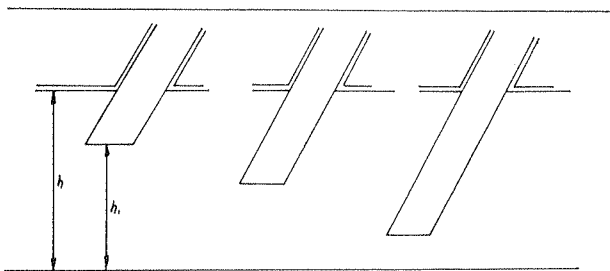


FIG. 22 VARIABLE LENGTH EXTENSIONS

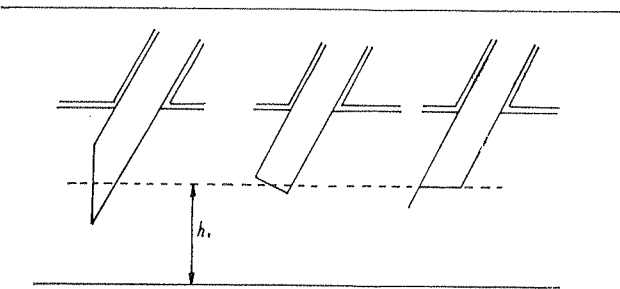


FIG. 23 VARIABLE GEOMETRY EXTENSIONS

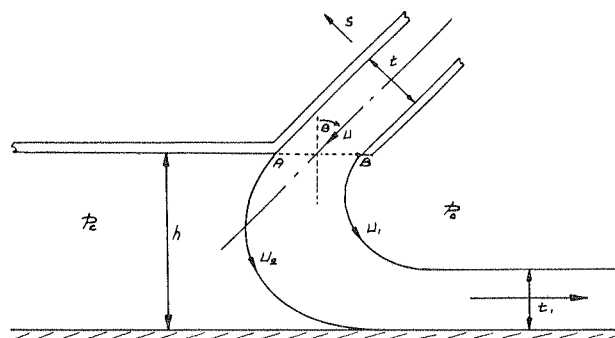


FIG. 25 ZERO INFLOW CASE (I.E.  $\lambda = 0$ )

The flow model used in the analysis of the bifurcated jet without entrainment is shown in Fig. 24. For the special case of zero flow into the cushion the flow is shown in Fig. 25. The same analysis applies. In either case it is assumed that the air entering has constant total pressure and emerges as a parallel stream along A' B'. It is further assumed that the velocity at points between A and B varies linearly between  $U_2$  and  $U_1$ . These assumptions were suggested by the experimental results already obtained. The third case investigated is shown in Fig. 26. In this there is an outward flow under the jet curtain, such as must arise when a hovercraft is descending, or for part of the periphery, when it is inclined to the horizon. It is assumed that there is no mixing between the two streams and that both have become parallel and uniform at B'. The result of the computation is given in Fig. 27 and the method of analysis is outlined in Appendix II.

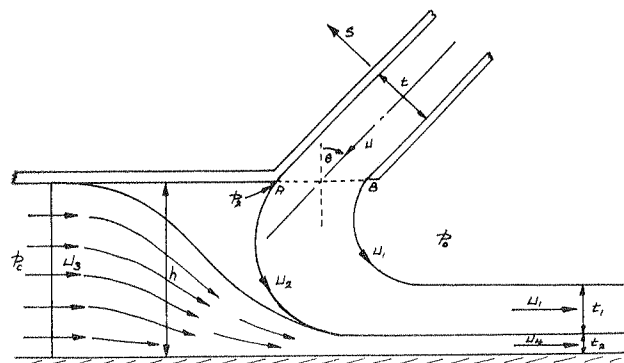


FIG. 26 MODEL USED IN ANALYSIS OF OUTWARD FLOW UNDER THE JET CURTAIN

$\lambda_1$  AND  $\lambda_2$  ARE THE TWO ROOTS OF EQUATION 9. IN APPENDIX II.

JET ANGLE $\theta$ (DEGREES)	$x = H/\lambda a$	$h/t$	$\lambda_1$	$\lambda_2$
30	1.5	2.0	7.77	-22
30	2.0	2.0	8.74	-22
30	3.0	2.0	9.09	-22
30	1.5	4.0	13.87	-22
30	2.0	4.0	15.90	0.74
30	3.0	4.0	16.61	1.510
30	1.5	6.0	19.85	0.81
30	2.0	6.0	22.95	2.02
30	3.0	6.0	23.98	3.20
45	1.5	2.0	8.02	-22
45	2.0	2.0	8.91	-22
45	3.0	2.0	9.24	-22
45	1.5	4.0	14.16	-22
45	2.0	4.0	16.11	0.53
45	3.0	4.0	16.81	1.31
45	1.5	6.0	20.19	0.47
45	2.0	6.0	23.17	1.80
45	3.0	6.0	24.24	2.94
60	1.5	2.0	8.05	-22
60	2.0	2.0	8.99	-22
60	3.0	2.0	9.32	-22
60	1.5	4.0	14.21	-22
60	2.0	4.0	16.20	0.44
60	3.0	4.0	16.88	1.24
60	1.5	6.0	20.68	0.46
60	2.0	6.0	23.27	1.70
60	3.0	6.0	24.28	2.90

FIG. 27 COMPUTED VALUES OF  $\lambda$  FROM EQUATION 9. IN APPENDIX II.

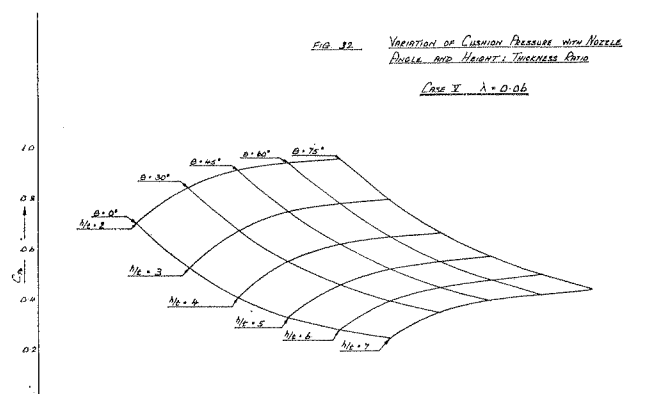
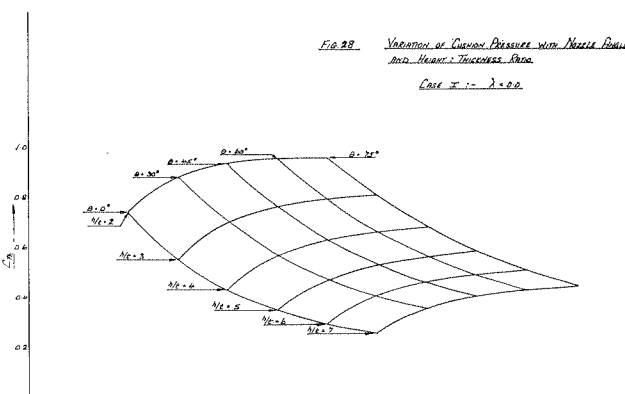
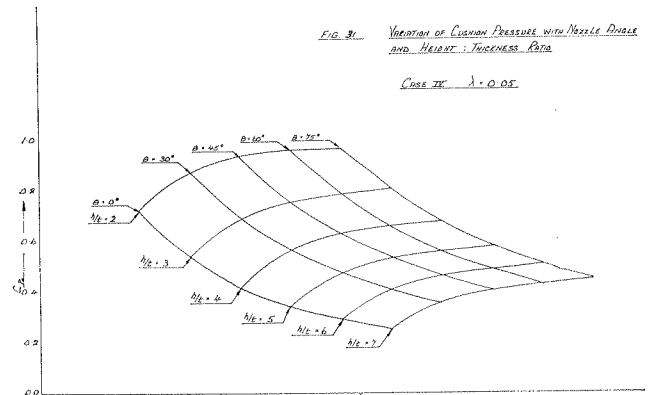
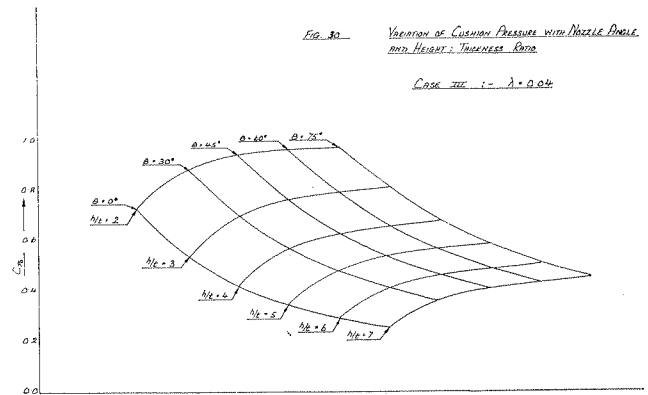
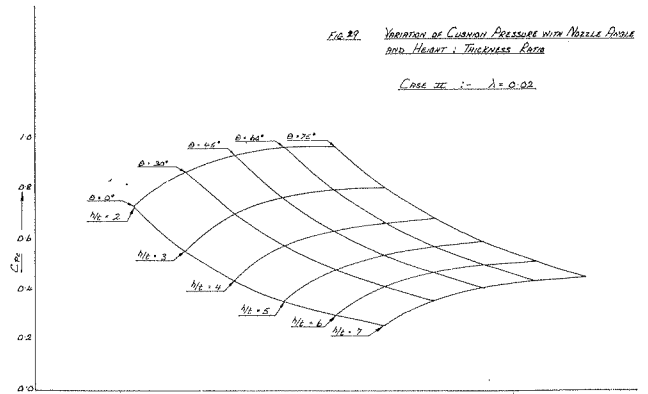
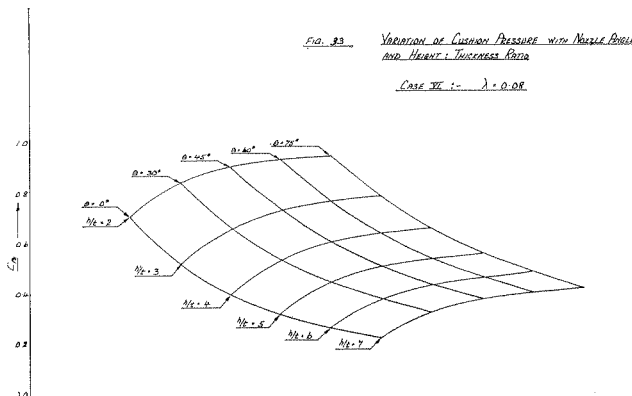


FIG. 23. Variation of Cushion Pressure with Nozzle Angle and Height: Zero Incidence  
Case No. 1:  $\lambda = 0.02$



### APPENDIX I

The flow model used in this analysis is shown in Fig. 24. For the particular case of hovering flight over level ground at zero incidence there will be no crossflow within the cushion, hence  $\lambda = 0$ . This case is shown in Fig. 25. The existing test rig is capable only of the zero incidence configurations but the incidence cases have been computed for comparison. When the base is at incidence the angle  $\Theta$ , in the analysis, represents the angle the centreline of the nozzle makes with the base, plus the angle of incidence,  $\alpha$ .

$$\Theta = \Theta' + \alpha$$

where  $\Theta'$  is normally termed the nozzle angle.

Assume a linear velocity variation from  $u_1$  to  $u_2$  along BA and let  $\lambda$  be the fraction of the jet flowing into the cushion.

$$\text{Then } u_2 t_2 = \lambda \left[ \frac{u_1 + u_2}{2} \right] t \quad (1)$$

$$u_1 t_1 = (1 - \lambda) \left[ \frac{u_1 + u_2}{2} \right] t \quad (2)$$

Momentum entering the control area across AB

$$= \int_0^t \rho u^2 \cdot ds. \quad (3)$$

$$\text{where } u = u_1 + \frac{s}{t} (u_2 - u_1) \quad (4)$$

Momentum in the jet

$$\begin{aligned} &= \int_0^t \rho \left[ u_1^2 + 2 \frac{s}{t} (u_2 - u_1) u_1 \right. \\ &\quad \left. + \frac{s^2}{t^2} (u_2 - u_1)^2 \right] \cdot ds. \\ &= \left[ \rho u_1^2 s + \rho \frac{s^2}{t} (u_2 - u_1) u_1 \right. \\ &\quad \left. + \frac{\rho s^3}{3t^2} (u_2 - u_1)^2 \right]_0^t \\ &= t \rho \left[ u_1^2 + u_1 u_2 - u_1^2 + \frac{1}{3} (u_2 - u_1)^2 \right] \\ &= \frac{1}{3} \rho t \left[ u_1^2 + u_1 u_2 + u_2^2 \right] \quad (5) \end{aligned}$$

It is also assumed that the static pressure across each section of jet emerging along the ground is constant, so applying the momentum theorem to the control area for the direction  $\longrightarrow$

$$\begin{aligned} &\rho u_1^2 t_1 - \rho u_2^2 t_2 + \frac{1}{3} \rho t (u_1^2 + u_1 u_2 + u_2^2) \sin \theta \\ &= (p_c - p_0) h = \frac{1}{2} \rho h (u_1^2 - u_2^2) \quad (6) \end{aligned}$$

From equations (1), (2) and (6)

$$\begin{aligned} &(1 - \lambda) \frac{(u_1 + u_2)}{2} u_1 t - \lambda \frac{(u_1 + u_2)}{2} u_2 t + \frac{1}{3} t (u_1^2 + u_1 u_2 + u_2^2) \\ &\quad \times \sin \theta \\ &= \frac{1}{2} h (u_1^2 - u_2^2) \end{aligned}$$

or

$$\begin{aligned} &(1 - \lambda) (u_1^2 + u_1 u_2) - \lambda (u_1 u_2 + u_2^2) + \frac{2}{3} (u_1^2 + u_1 u_2 + u_2^2) \\ &\quad \times \sin \theta \\ &= \frac{h}{t} (u_1^2 - u_2^2) \end{aligned}$$

$$\text{Let } \frac{u_1}{u_2} = x$$

$$(1-\lambda)(x^2+x) - \lambda(x+1) + \frac{2}{3}(x^2+x+1) \sin \theta$$

$$= \frac{h}{t}(x^2-1)$$

Collecting terms

$$x^2 \left[ 1 - \lambda + \frac{2}{3} \sin \theta - \frac{h}{t} \right] + x \left[ -2\lambda + \frac{2}{3} \sin \theta \right]$$

$$+ \left[ \frac{2}{3} \sin \theta - \lambda + \frac{h}{t} \right] = 0 \quad (7)$$

$$\text{Now } C_{p_c} = \frac{p_c - p_o}{\frac{1}{2} \rho u_1^2}$$

$$= \frac{\frac{1}{2} \rho u_1^2 - \frac{1}{2} \rho u_2^2}{\frac{1}{2} \rho u_1^2}$$

$$= 1 - \frac{u_2^2}{u_1^2}$$

$$= 1 - \frac{1}{x^2} \quad (8)$$

Equation (7) has been solved for values of the three parameters,  $\theta$ ,  $\lambda$  and  $\frac{h}{t}$  listed below

$$\theta = 0, 30, 45, 60, 75 \text{ degrees}$$

$$\lambda = 0.00, 0.02, 0.04, 0.05, 0.06, 0.08$$

$$\frac{h}{t} = 2, 3, 4, 5, 6, 7$$

The values of  $C_{p_c}$  computed from equations (7) and (8) are shown in Figs. 28-33. It should be noted, however, that the input power varies with  $x$ .

$$\text{In fact, input} = \int_0^t H \cdot u \cdot ds.$$

$$= \int_0^t \frac{1}{2} \rho u_1^2 \cdot u \cdot ds.$$

$$= \frac{1}{2} \rho u_1^2 \int_0^t \left\{ u_1 + \frac{s}{t} (u_2 - u_1) \right\} ds.$$

$$= \frac{1}{2} \rho u_1^2 \left[ u_1 s + \frac{s^2}{2t} (u_2 - u_1) \right]_0^t$$

$$= \frac{1}{2} \rho u_1^2 \left[ \frac{u_1 + u_2}{2} \right] \cdot t$$

$$= \frac{1}{4} \rho u_1^3 \left[ 1 + \frac{1}{x} \right] t \quad (9)$$

Hence the input power increases as  $x$  decreases i.e. as  $\lambda$  increases. Hence the fall-off of cushion pressure for increasing  $\lambda$ , keeping the power input constant, is more rapid than indicated by the curves.

\* \* \*

## APPENDIX II

### Flow under the Jet curtain.

#### Continuity.

$$u_3 h = u_4 t_2 = \lambda \frac{(u_1 + u_2)}{2} t \quad (1)$$

$$u_1 t_1 = \frac{(u_1 + u_2)}{2} t \quad (2)$$

Bernoulli.

$$\begin{aligned} p_c + \frac{1}{2} \rho u_3^2 &= p_o + \frac{1}{2} \rho u_4^2 \\ &= p_2 \\ &= p_o + \frac{1}{2} \rho u_1^2 - \frac{1}{2} \rho u_2^2 \quad (3) \end{aligned}$$

Consider Momentum balance.

$$\begin{aligned} \rho u_1^2 t_1 + \rho u_4^2 t_2 + \frac{1}{3} \rho t (u_1^2 + u_1 u_2 + u_2^2) \sin \theta \\ - \rho h u_3^2 \\ = (p_c - p_o) h \quad (4) \end{aligned}$$

or

$$\begin{aligned} \rho u_1^2 t_1 + \rho u_4 \lambda \frac{(u_1 + u_2)}{2} t + \frac{1}{3} \rho t (u_1^2 + u_1 u_2 + u_2^2) \sin \theta \\ - \rho u_3 \lambda \frac{(u_1 + u_2)}{2} t \\ = (p_c - p_o) h \end{aligned}$$

$$\text{Now } \frac{1}{2} \rho u_4^2 - \frac{1}{2} \rho u_3^2 = p_c - p_o \quad (5)$$

and from (3) and (5)

$$\begin{aligned} \frac{1}{2} \rho u_4^2 &= \frac{1}{2} \rho u_1^2 - \frac{1}{2} \rho u_2^2 \\ u_4 &= \sqrt{u_1^2 - u_2^2} \quad (6) \end{aligned}$$

Equation (4) becomes

$$\begin{aligned} \rho \frac{(u_1 + u_2)}{2} t + \rho \lambda \frac{(u_1 + u_2)}{2} t \sqrt{u_1^2 - u_2^2} \\ + \frac{1}{3} \rho t (u_1^2 + u_1 u_2 + u_2^2) \sin \theta - \rho \lambda^2 \frac{(u_1 + u_2)^2}{4} \frac{t^2}{h} \\ = \left( \frac{1}{2} \rho u_4^2 - \frac{1}{2} \rho u_3^2 \right) h \end{aligned}$$

$$\text{R.H.S.} = \frac{1}{2} \rho h \left[ u_1^2 - u_2^2 - \lambda^2 \frac{(u_1 + u_2)^2}{4} \frac{t^2}{h^2} \right]$$

or

$$u_1 \frac{(u_1 + u_2)}{2} + \lambda \frac{(u_1 + u_2)}{2} \sqrt{u_1^2 - u_2^2}$$

$$\begin{aligned} + \frac{1}{3} (u_1^2 + u_1 u_2 + u_2^2) \sin \theta - \lambda^2 \frac{(u_1 + u_2)^2}{4} \frac{t}{h} \\ = \frac{1}{2} \frac{h}{t} \left[ u_1^2 - u_2^2 - \lambda^2 \frac{(u_1 + u_2)^2}{4} \frac{t^2}{h^2} \right] \quad (7) \end{aligned}$$

$$\text{Let } x = \frac{u_1}{u_2}$$

$$\begin{aligned} \frac{(x^2 + x)}{2} + \lambda \frac{(1+x)}{2} \sqrt{x^2 - 1} + \frac{1}{3} (x^2 + x + 1) \sin \theta \\ - \lambda^2 \frac{(1+x)^2}{4} \frac{t}{h} \\ = \frac{1}{2} \frac{h}{t} \left[ x^2 - 1 - \lambda^2 \frac{(1+x)^2}{4} \frac{t^2}{h^2} \right] \\ 4(x^2 + x) + 4\lambda(1+x)\sqrt{x^2 - 1} + \frac{8}{3}(x^2 + x + 1)\sin \theta \\ - 2\lambda^2(1+x)^2 \frac{t}{h} \\ = \frac{h}{t} \left[ 4x^2 - 4 - \lambda^2(1+x)^2 \frac{t^2}{h^2} \right] \quad (8) \end{aligned}$$

Collecting terms in  $\lambda$

$$\begin{aligned} -\lambda^2 \left[ 2(1+x^2) \frac{t}{h} - (1+x)^2 \frac{t}{h} \right] + \lambda \left[ 4(1+x)\sqrt{x^2 - 1} \right] \\ + \left[ 4(x^2 + x) - 4 \frac{h}{t}(x^2 - 1) + \frac{8}{3}(x^2 + x + 1)\sin \theta \right] = 0 \end{aligned}$$

or

$$\begin{aligned} \lambda^2 \left[ (1+x^2) \frac{t}{h} \right] - \lambda \left[ 4(1+x)\sqrt{x^2 - 1} \right] \\ - 4 \left[ (x^2 + x) - \frac{h}{t}(x^2 - 1) + \frac{2}{3}\sin \theta(x^2 + x + 1) \right] = 0 \quad (9) \end{aligned}$$

This has been solved for

$$x = 1.5, 2.0, 3.0$$

$$\frac{h}{t} = 2, 4, 6$$

$$\theta = 30^\circ, 45^\circ, 60^\circ$$

#### REFERENCE

1. Measurements of the Aerodynamic Forces Acting on Porous Screens. R & M 2276. Cowdrey and Simmons.

# SUMMARY OF THE MODEL TESTS FOR SIMPLE RAM WING KAG-3

by

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## 1. WIND TUNNEL TESTS

### 1.1 Models and Apparatus

Tests were done in the low speed wind tunnel of Tokyo University Aeronautical Institute; the usual wind speed is about 40 m/sec, and the diameter of the open throat test section is 2.00 metres.

The size of models were one tenth of KAG-3, that is, the float length of the models is 0.5 metres. For the ground effect, we used a wooden plate to do experiments as quickly and cheaply as possible. The boundary layer on the wooden plate would cause some inaccuracies, especially when the model was very close to the ground plate. Another kind of error happened in the closest case; the ground plate was deflected downward (about 2-3 mm) by cushion pressure, and it made the clearance between model and ground somewhat larger with wind than without wind. In spite of the above inaccuracies, we tried to estimate the cruising performance of KAG-3. For KAG-3 at cruising condition, the lowest points of the floats are under the water surface ( $h < 0$ ), whereas in the wind tunnel test  $h$  is zero at least. In order to do  $h = 0$ , we used soft rubber built in the ground plate just below the model floats; we confirmed that slight contact of the float with the soft rubber caused no error.

Wind tunnel models are shown in Figs 1 to 9, and in many photographs.

Wing "WA" and "WB" (Fig. 1, photo 7)

These models were used in the first tests. They have the same thickness (11.75%), but "WB" are more cambered than "WA". We selected the aspect ratio of 1.2 and 0.8 for both sections. Size (or geometry) of thin end-plates "Po" is represented by angle  $\gamma$ .

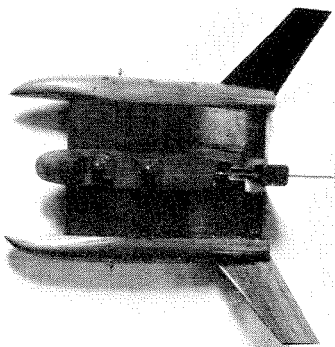


PHOTO. 1.  
 $W_D F C_{ET} V_{35}$

PHOTO. 2.  
 $W_E P_O$

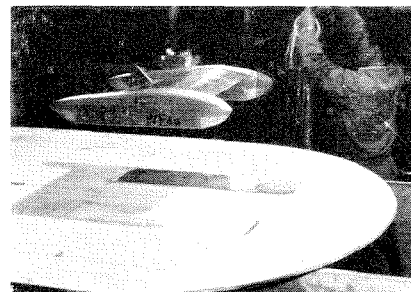


PHOTO. 3.  
 $W_E F_{do}$

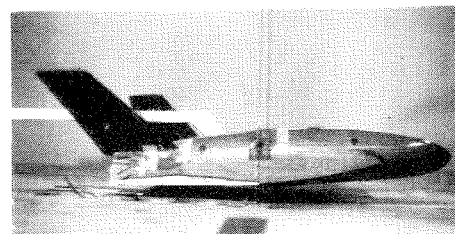
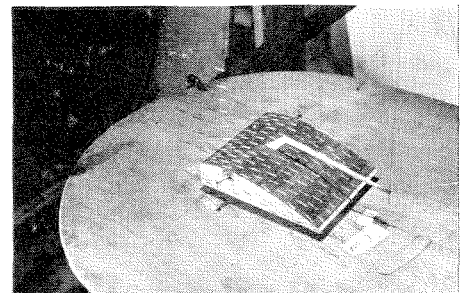


PHOTO. 4.  
 $W_E F_{SP} T_{V35}$

PHOTO. 5.  
 $W_C P_O \quad h/c=5\%$   
 $\alpha_w = \gamma = 8^\circ$



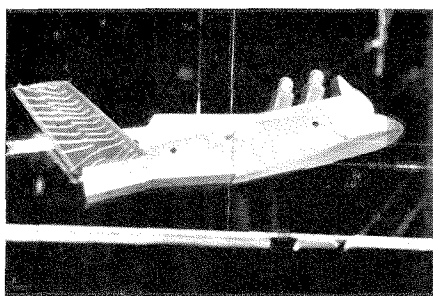


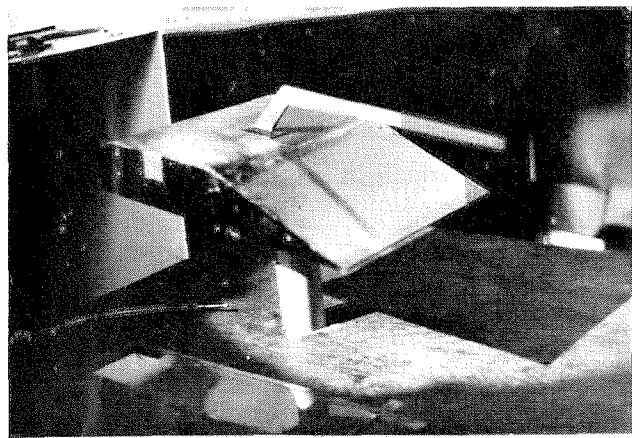
PHOTO.6.  
 $W_E F C_D E T_{V35}$   
 $\eta/c = 20\%$ ,  $\alpha = 0^\circ$

Wing "Wc" (Fig. 2, photo 5)

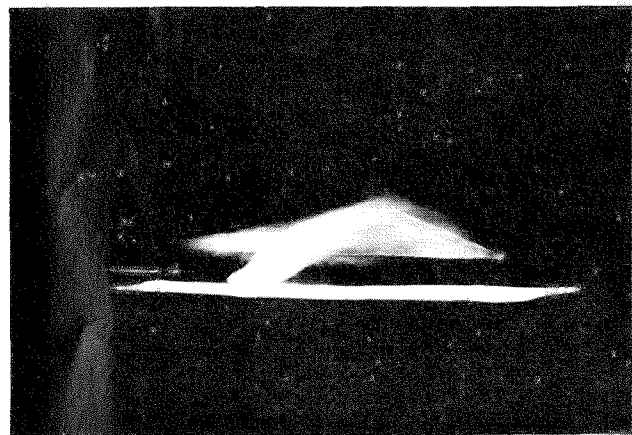
The first tests showed that the flow on the upper wing surface could easily be separated off with ground effect. Thus we chose thin cambered wing section NACA 6409 whose aspect ratio is 0.75.

Wing "Wd" (Photo 1)

This was made by reducing the span of "Wc" from 300 mm to 240 mm, thus we obtained the aspect ratio 0.6 and the area 0.096 m<sup>2</sup>.



d)  $\gamma = 5^\circ$



b)  $\eta/c = 5\%$   $\alpha = \beta = 0^\circ$

PHOTO.7.  $W_B P_O$

Wing "WE" (Fig. 3)

This wing has chord length of 358 mm and span of 268 mm, so that the aspect ratio is equal to that of "Wc" and the area is equal to that of "Wd".

Thin end-plates (Fig. 3, photo 2)

"Po" is of the simplest type. "P1" is of elevated trailing-edge type. "Pr" is of float-like type. "P" and "Pr" have the same height of the trailing edge, in the geometrical average.

Thick end-plates (Fig. 4, 5, photo 3)

"F" is the float similar to that of KAG-3, except the rear end is not faired.

"F<sup>d-15</sup>", "F<sup>d15</sup>", "F<sup>d15sp</sup>" and "F<sup>d30</sup>" have straight keel line, constant dead rise angle and both ends faired. Their thickness is the same as "F" (50 mm). "F<sup>d15sp</sup>" means

"F<sup>d15</sup>" with float bottom spoilers (see Fig. 5), and "F<sup>d15sp</sup>" means "F<sup>d15</sup>" with float bottom spoiler (see photo 9). These spoilers were intended to reduce suction force on the float bottom.

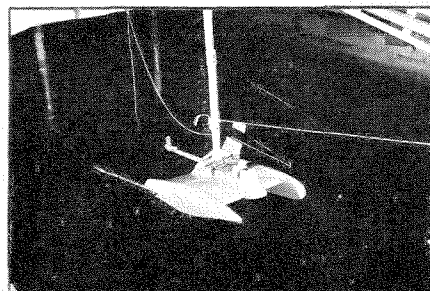
Tails (Fig. 6, 7, photo 1, 6)

"T<sup>HU</sup>" and "T<sup>HL</sup>" were fitted horizontally nearly within the main wing span, on the elongated tail-boom. "Tc" is a combination of a horizontal and separated Vee-tail, and also mounted on the elongated tail-boom. "T<sup>v35</sup>" is a separated

Vee-tail type, whose dihedral angle is 35°; fitted on the float directly. "Tr" is a combination of a horizontal tail (outside the main wing span) and vertical one. The sections of all tails are NACA 0009 in the free stream direction.

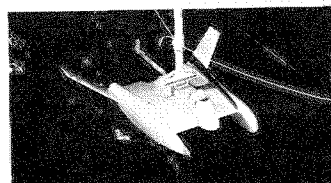
Cabins (Fig. 8, 9, photo 1)

"CA" and "Cb" are side-by-side, whereas "C" and "Cd"



$\alpha = 0$

$\alpha = 2 \text{ M/SEC.}$



$\alpha = 5 \text{ M/SEC.}$

PHOTO.8.  $W_B F C_C T_{V35}$   $1/10$  MODEL.

are tandem types. "CD" is similar to the cabin of KAG-3, except the rear part is not faired.

Engine (Fig. 9)

"E" is a very simplified substitute of the engine.

Notes:

Each model will be represented in a simple manner as follows:

Example 1:

"W FT" = A model consisting of main wing WE, float E v35 "F" and tail "T".

Example 2:

KAG-3 = W F' C' ET

primes on F and CD mean the additional fairings.

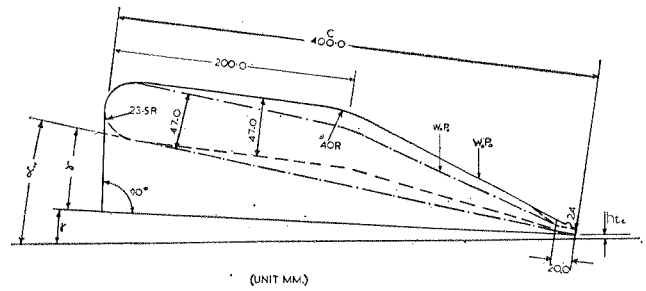


FIG. 1 GEOMETRY OF MODELS "WB" AND "WB2"  $\gamma = 5.913 \text{ DEG.}$   $R = 0.8 \text{ L2}$

1.2 Aerodynamic Performances

1.2.1 Effect of end-plates

Fig. 10 shows the remarkable effect of the end-plates, which was also observed for aspect ratio 1.2 Model "WAPo"). We concluded that a GEW should have the end plates if the aspect ratio is small.

1.2.2 Effect of airfoil section

Fig. 11 shows that the model "WAP1" has lower L/D than that of "W P". We often observed that ground effect was apt to separate off the flow over the wing upper surface. Thus we have thought a thin cambered wing would be promising as a GEW.

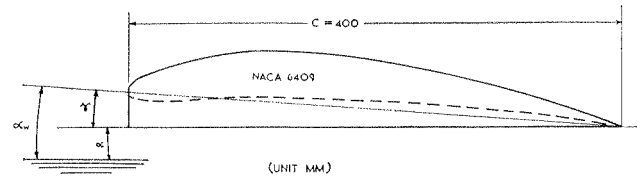


FIG. 2 GEOMETRY OF MODEL "WB1"  $R = 0.75$   $\gamma = 4.6810214 \text{ DEG}$

1.2.3 Effect of geometry of thin end plates

At first we consider the simple type "WPO", where size of the end-plate is represented by angle  $\gamma$ . Fig. 12 shows the smallest ( $\gamma = 5^\circ$ ) end-plate gives the largest lift drag ratio and slightly smaller lift. For larger end-plates, flow was separated off the wing upper surfaces and caused serious increase in drag. Fig. 13 shows similar trends for the thin cambered wing NACA 6409; namely  $\gamma = 4^\circ$  gives the largest L/D and the smallest lift.

Second, we compare "W P" with "W P1" and "W P", all of which have the same incidence of wing  $\alpha = 6^\circ$ .

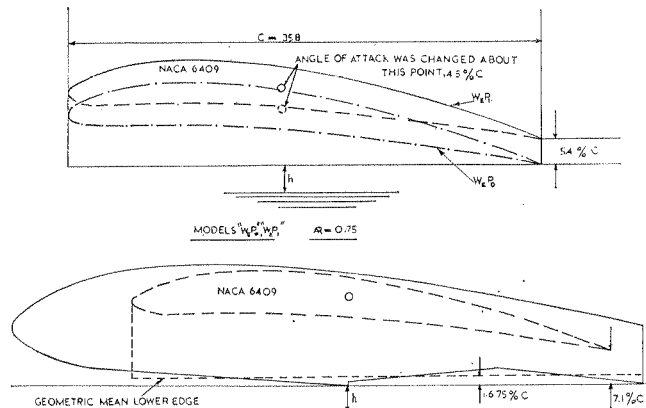


FIG. 3 THIN END PLATES "P1", "P", AND "P2" (THICKNESS 2mm)

Selection of  $\alpha = 6^\circ$  is related to many factors, such as

- larger lift coefficient
- larger lift-drag ratio

and higher leading edge from the ground surface (to prevent wave crests striking the wing leading edge). Trailing edge height of the model "W P" is 25.5 mm, which was

selected assuming that the vehicle should fly over a wave height of 5% float length, and that the trailing edge should not make contact with the waves. Trailing edge height of the model "W P" is 19.5 mm, which is equal to the mean height

of the model "W P". Fig. 14 shows the negligible differences between "W P" and "W P". The model "W P" has a larger (about 10%) drag than "W P" and "W P".

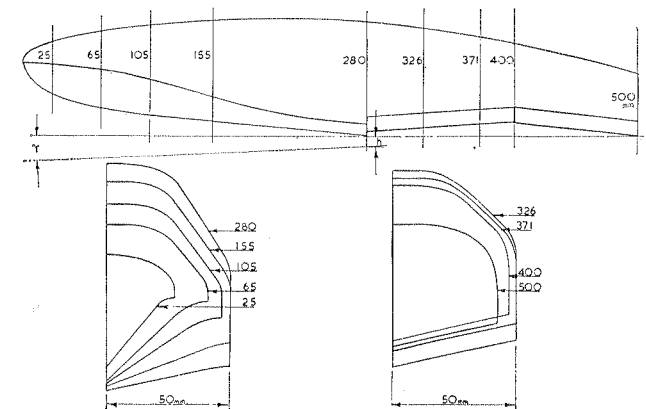


FIG. 4 GEOMETRY OF THE FLOAT "F"

1.2.4 Effect of geometry of thick end plates

Fig. 15 shows the lift difference between "W F" and "W P". The "W F" has somewhat lower lift than the "W P" at small  $h/c$ , but higher at large  $h/c$ . This is due to suction force between the float bottom and the ground. Fig. 16 shows the effect of float dead-rise angle; the model "W F" has largest lift and the models "W F" and "W F" have smallest lift. This is also due to the above

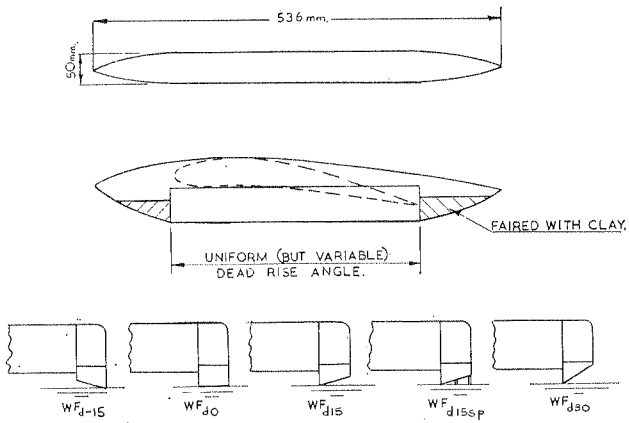
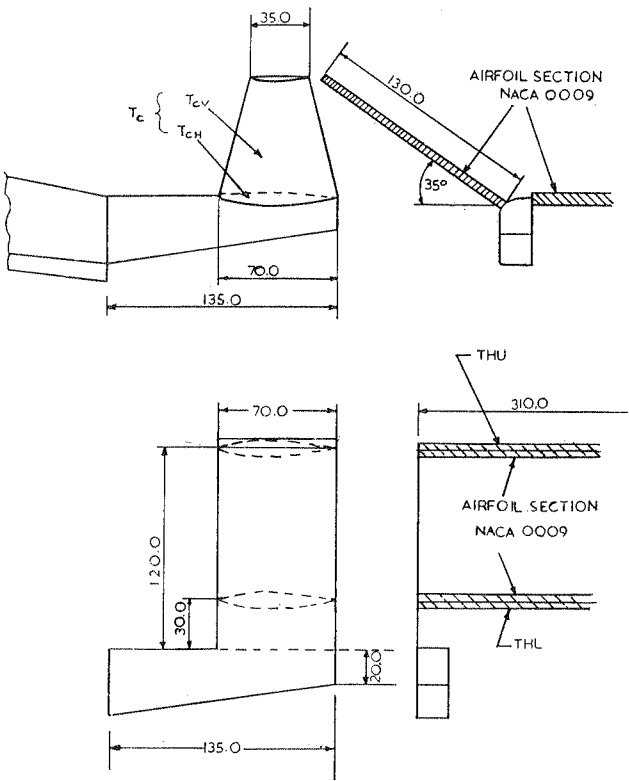


FIG. 5. GEOMETRY OF FLOAT WITH VARIABLE DEAD RISE ANGLE.



(UNIT MM)  
FIG. 6. GEOMETRY OF TAILS  $T_c$ ,  $T_{Hu}$  AND  $T_{Hl}$ .

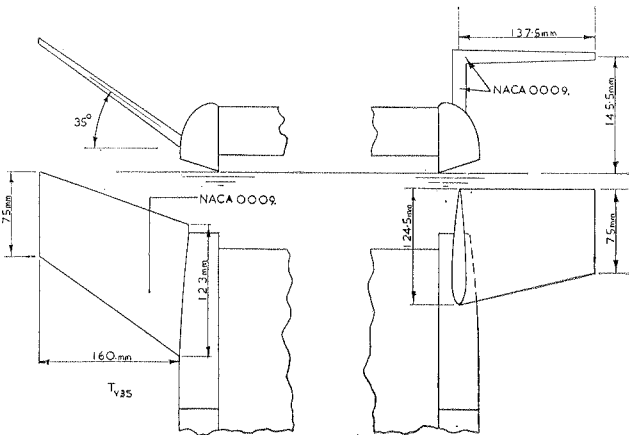


FIG. 7. GEOMETRY OF TAILS  $T_{v35}$  AND  $T_{v35p}$ .

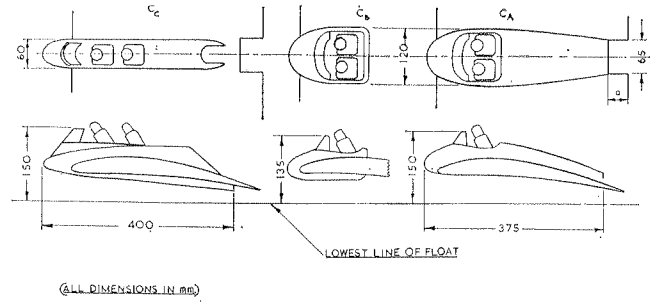


FIG. 8. GEOMETRY OF CABINS  $C_c$ ,  $C_p$ ,  $C_A$  AND  $C_c$ .

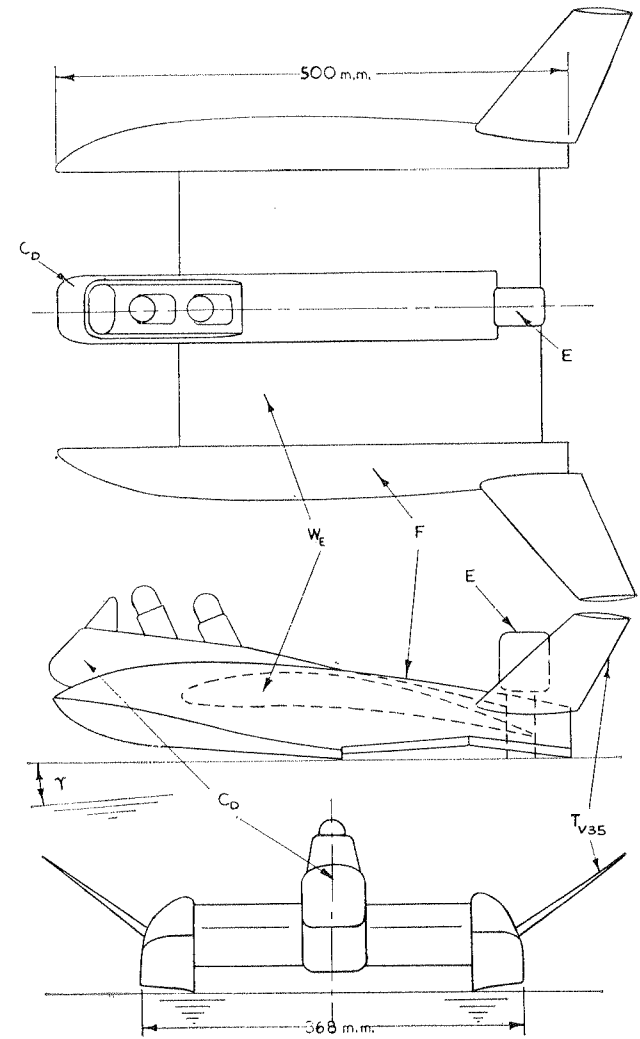


FIG. 9. GEOMETRY OF MODEL  $W_c F_c D_{ET_{v35}}$ .

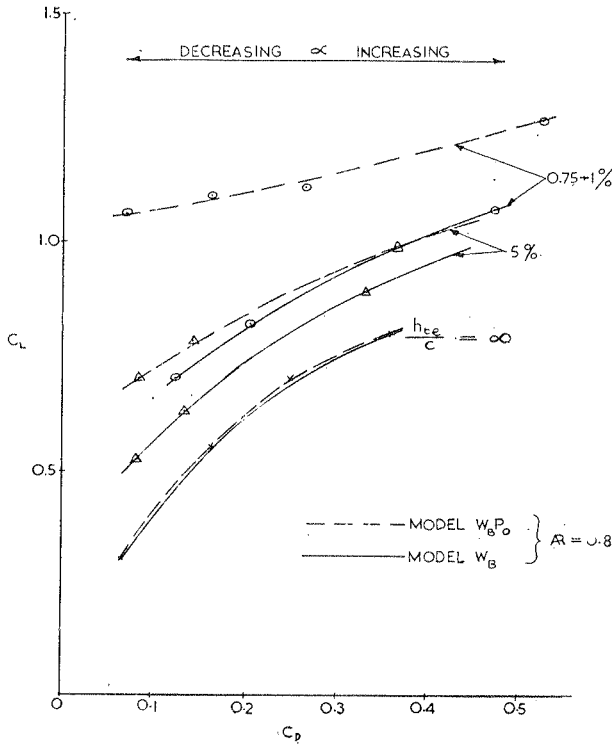


FIG.10 EFFECT OF END PLATES ON  $C_L$  VS  $C_D$

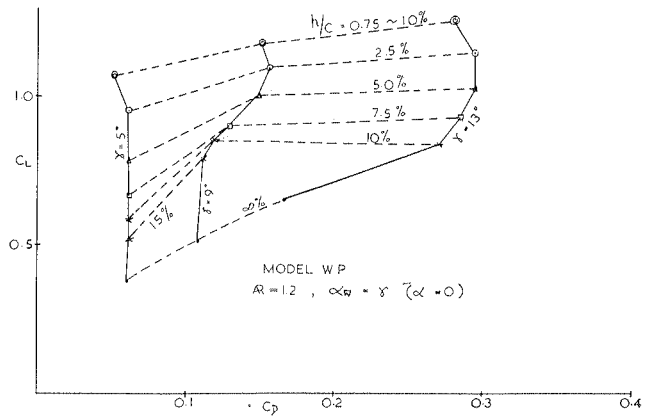


FIG.12. EFFECT OF END PLATE GEOMETRY ON  $C_L$  VS  $C_D$

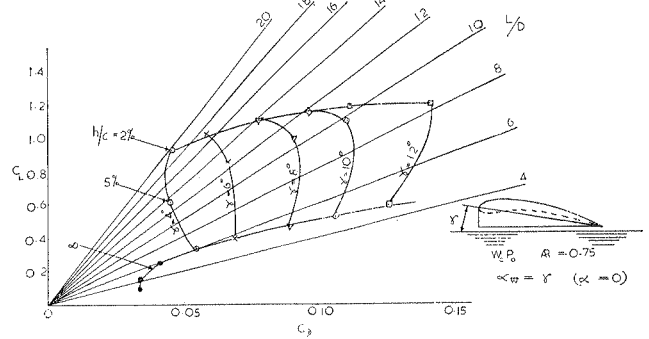


FIG.13. EFFECT OF END PLATE GEOMETRY ( $\gamma$ ) ON  $C_L$  VS  $C_D$

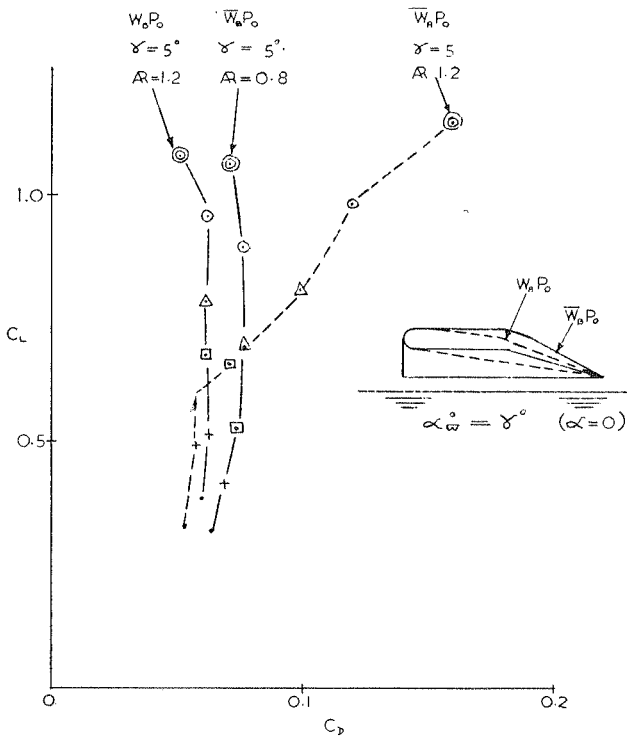


FIG.11 EFFECT OF AIRFOIL SECTION ON  $C_L$  VS  $C_D$

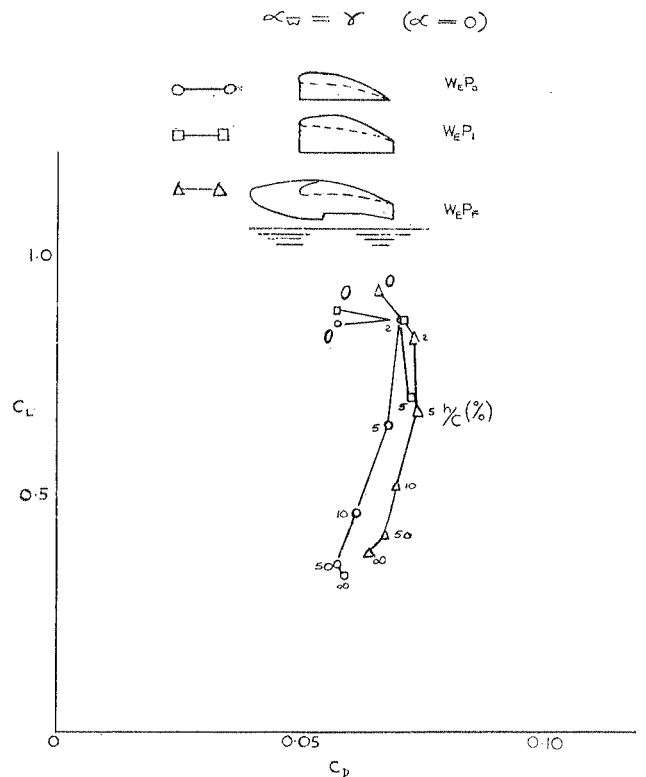


FIG.14. EFFECT OF THIN END PLATE GEOMETRY ON  $C_L$  VS  $C_D$

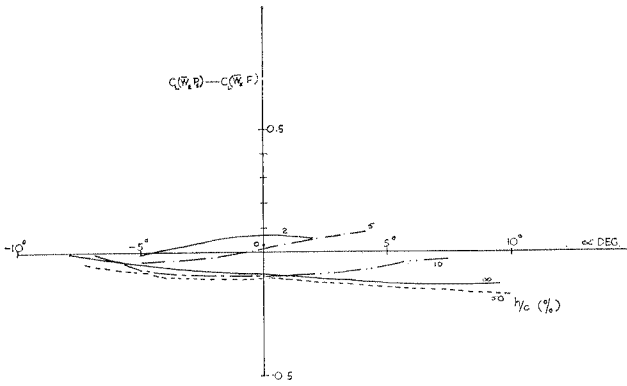


FIG. 15 EFFECT OF END PLATE THICKNESS ON LIFT COEFFICIENT

suction force. The models "W F<sub>E d30</sub>", "W F<sub>E d15</sub>", "W F<sub>E d0</sub>" and "W F<sub>E d-15</sub>" have smaller drag than model "W F<sub>E</sub>"; this may be owing to more refined geometry of the formers. Fig. 17 and 18 show a typical check of linearity on the diagrams C<sub>D</sub> vs C<sub>L</sub><sup>2</sup>, similar results being obtained for the other models. (We selected the pivot axis at 45% chord station to change the angle of attack, for all of the models.) The models with thin end-plate show nearly linear characteristics, whereas models with thick end-plate show somewhat non-linear characteristics. Thus we may conclude that the conventional induced drag formula C<sub>D</sub> ∝ C<sub>L</sub><sup>2</sup> is valid for GEW, only if some particular forces (such as suction force on the float bottom surfaces) do not exist. In order to estimate the ground effect we calculate "effective aspect ratio" defined by

$$AR_{eff} = \left[ \frac{C_L^2}{\pi(C_D - C_{Dp})} \right] \alpha = 0^\circ$$

at angle of attack 0°; see Fig. 19. Models "W P<sub>E F</sub>" and "W P<sub>E O</sub>" have effective aspect ratio of seven approximately

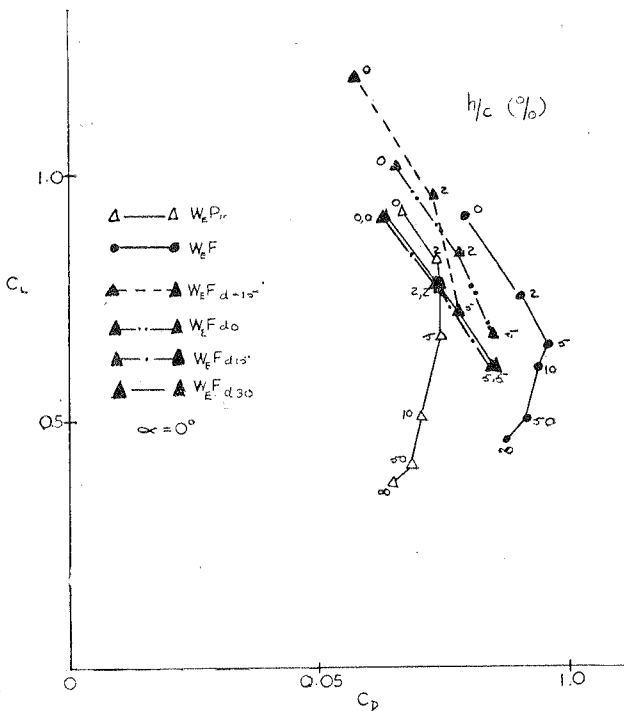


FIG. 16 EFFECT OF FLOAT DEAD RISE ANGLE ON C<sub>L</sub> vs C<sub>D</sub>

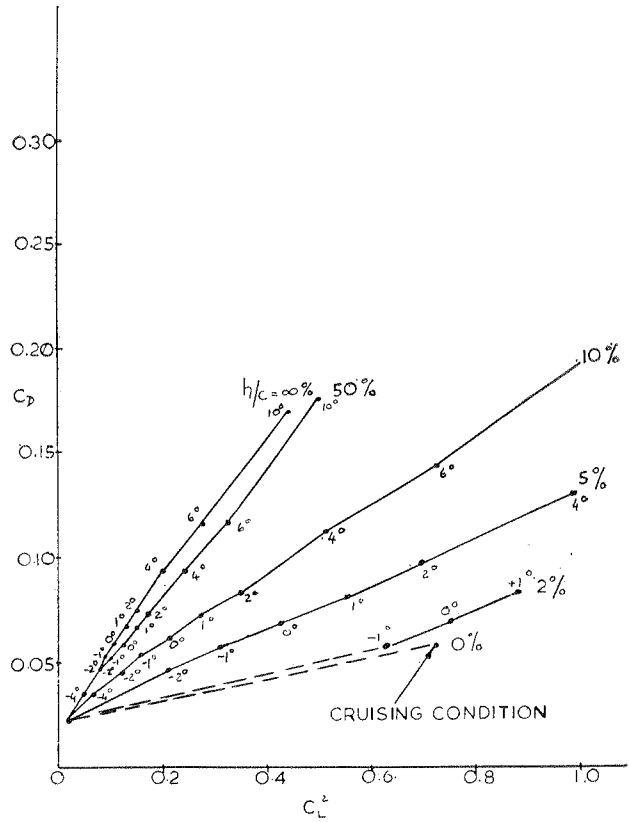


FIG. 17. CURVES OF C<sub>D</sub> vs C<sub>L</sub><sup>2</sup> FOR MODEL W<sub>E</sub> P<sub>0</sub>

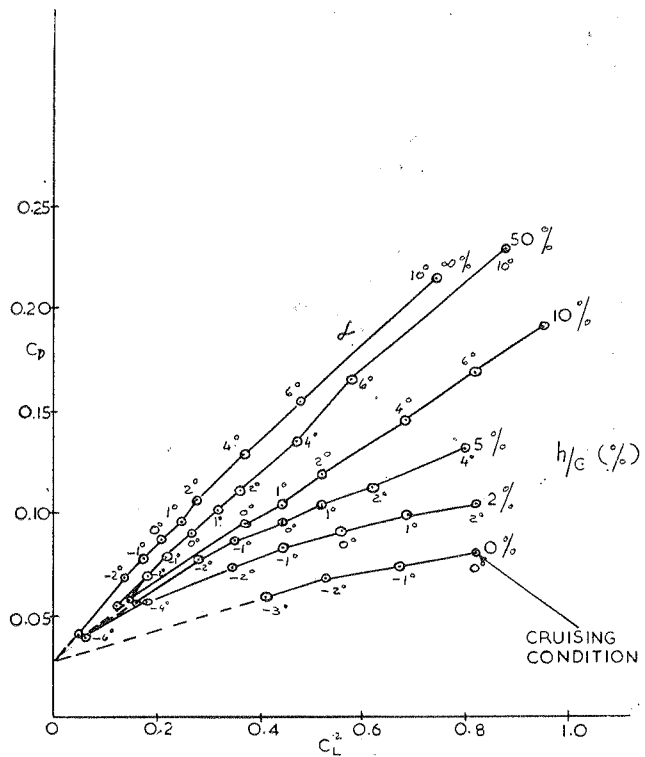


FIG. 18. CURVES C<sub>D</sub> vs C<sub>L</sub><sup>2</sup> FOR MODEL W<sub>E</sub> F

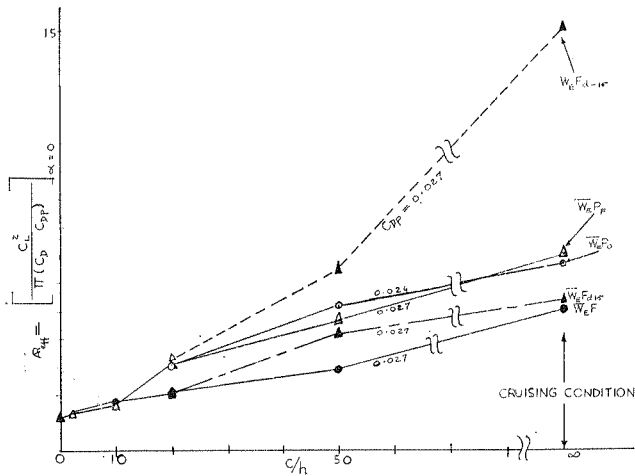


FIG.19 EFFECTIVE ASPECT RATIO OF VARIOUS MODELS  $\forall c/h$

and Models "W F" and "W F" have five approximately, whereas model "W F" has fifteen, in the limit of  $h$  tends to 0. These large differences, of course, result from the pressure on the float bottom surfaces.

1.2.6 Effects of canopy, engine and tails

Fig. 20 shows changes in lift and drag when the model becomes more and more complete from "W P" to "W F C E". The model "W F" becomes worse in both lift and drag, though the model "W F" recovers some parts of these losses. The canopy and engine increase drag, and canopy "C", side-by-side type in particular causes predominant drag.

Fig. 21 shows the contribution of the tails to  $C_L$  and  $C_D$  ( $C_L$  and  $C_D$  are defined on the area of main wing).

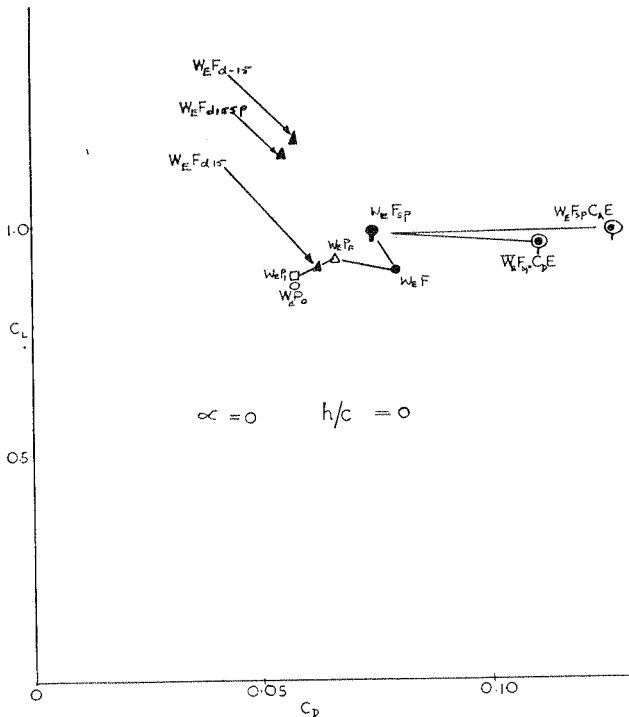


FIG.20  $C_D$  TRAVEL DUE TO CHANGE IN CONFIGURATION

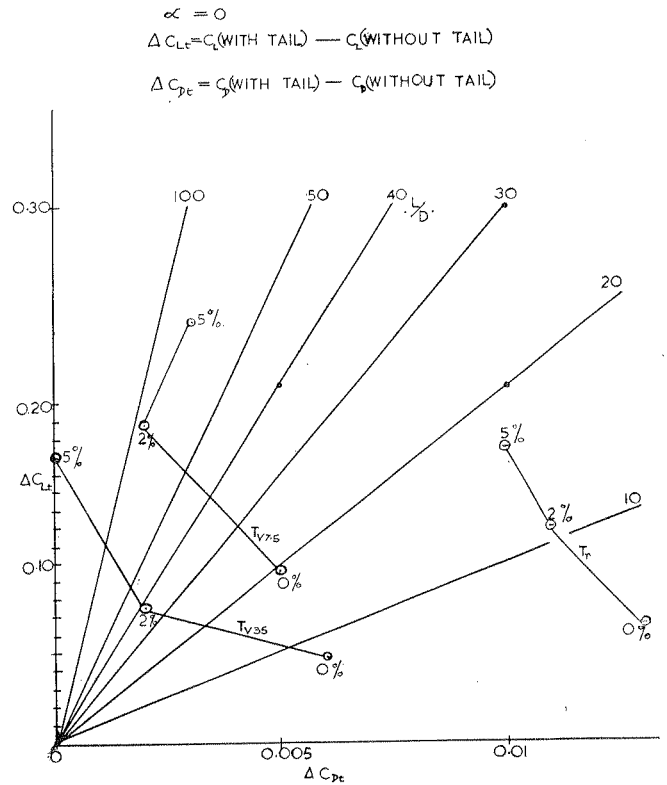


FIG. 21. EFFECT OF VARIOUS TAILS ON  $C_L \forall C_D$

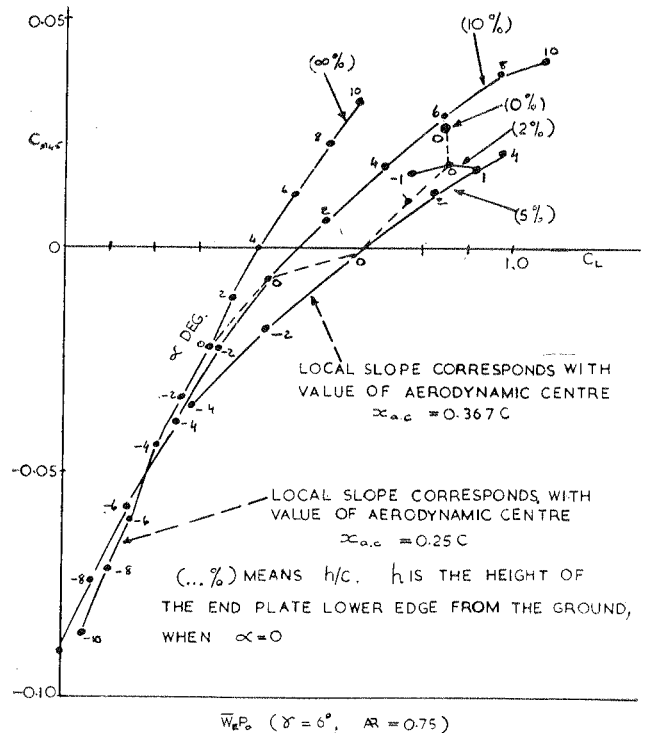


FIG. 22. EFFECTS OF HEIGHT AND INCIDENCE ON  $C_L \forall C_D$

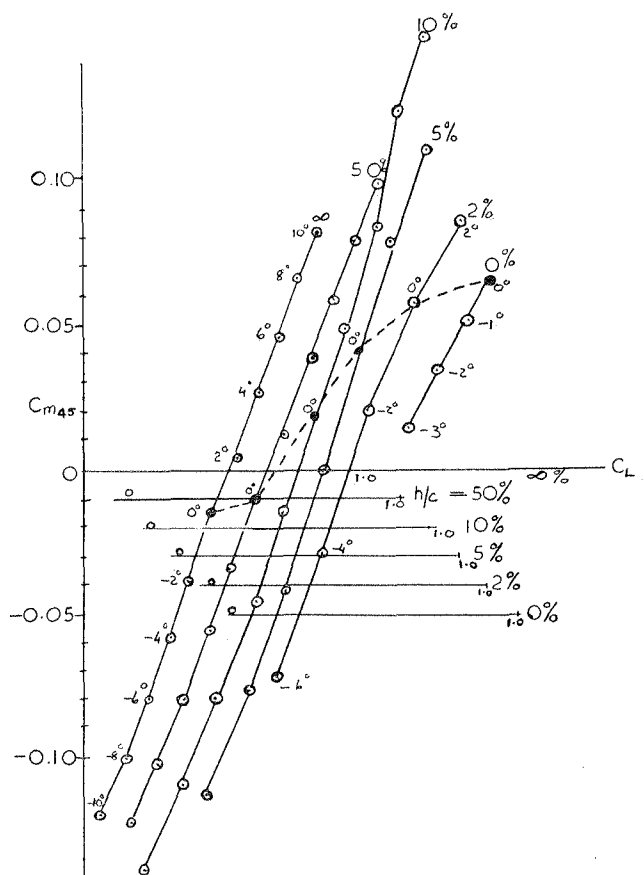


FIG. 23. EFFECTS OF THE GROUND HEIGHT AND ANGLE OF ATTACK ON  $C_{m45}$  vs  $C_L$  FOR MODEL  $W_E F$

The tail  $T_{v35}$  and  $T_{v7.5}$  give some favourable effect, especially in  $h/c$  of 2.5%, whereas tail  $T_I$  gives unfavourable effect. These facts may depend on the flow field produced by the main wing; as stated later, we observed trailing vortices outside the floats which gave complicated effects on the tail load.

1.3 Aerodynamic Stabilities

1.3.1 Pitching stability

(1) Pitching moment for "W P" and "W F"

Figs 22 and 23 show  $C_m$  vs  $C_L$  for the models "W P" and "W F" respectively.

We define the centre of pressure:  $X_{cp}/C = 0.45 - C_{m45}/C_L$   
 We define the aerodynamic centre:  $X_{ac}/C = 0.45 - \frac{\partial C_{m45}}{\partial C_L}$

where X means the distance aft from the leading edge of the main wing.

(2) Centre of lift ( $X_{cp}$ ) for tailless models

We find from Fig. 22 that  $X_{ac}$  of "W P" shifts rearward with ground effect, whereas  $X_{cp}$  shifts forward. Fig. 24 shows the  $X_{cp}$  vs  $C/h$ . There are negligible differences in  $X_{cp}$  for "W P", "W P" and "W P", whereas "W F" has much more forward  $X_{cp}$ . (The model "W F C E" has the

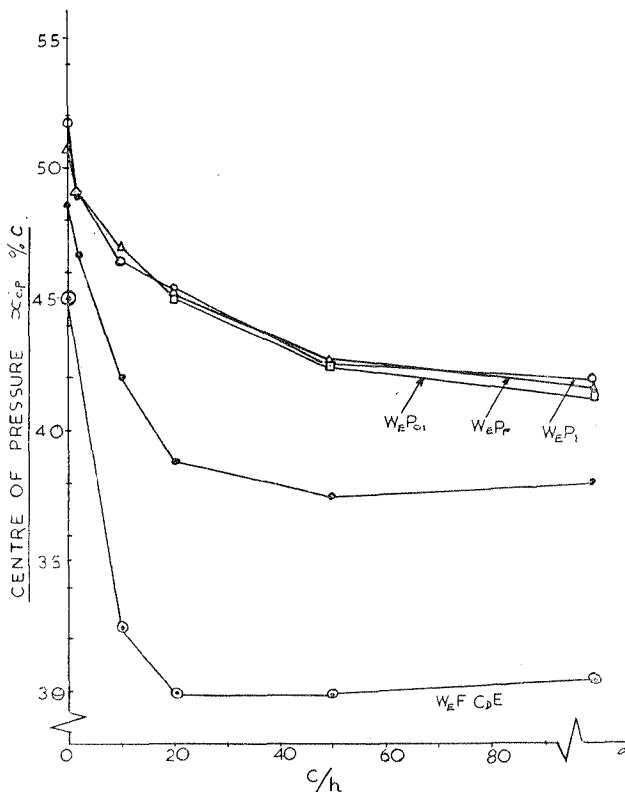


FIG. 24. EFFECT OF THE CONFIGURATION ON CENTRE OF PRESSURE LOCATION  $-2^\circ \leq \alpha \leq 2^\circ$

most forward  $X_{cp}$ . This is nonsense, because the direction of drag force due to canopy and engine is normal to that of the lift force.)

(3) Aerodynamic centre ( $X_{ac}$ ) for tailless models

Fig. 25 shows the  $X_{ac}$  vs  $C/h$ . The thickness of the floats makes  $X_{ac}$  shift forward and more unstable in pitch; it results from the suction force on the float bottom surface.

(4) Destabilizing effect of float thickness and stabilizing effect of the float bottom spoilers.

We measured the pressure distribution on the ground surface just under the float bottom. For "W F" there exists

considerable negative pressure, which moreover changes with angle of attack in a manner destabilizing the pitch mode. On the other hand, for "W F", we observed just the opposite.

Fig. 26 shows considerable destabilizing effect due to the float thickness, especially in small  $h/c$  (%). Fig. 27 shows stabilizing effect due to the float bottom spoilers.

(5) Effect of canopy and engine

We find that canopy and engine give some nose-up pitching moment, but negligible destabilizing effect.

(6) Stabilizing effect of various tails and its irregularities due to ground proximity

Fig. 28 gives  $C_{m45}$  vs  $\alpha$  for model "W F T". Ground effect increases instability, despite the forward shift of  $X_{ac}$

This fact results from remarkable increases of  $\frac{\partial C_L}{\partial \alpha}$

with ground proximity. In view of the results shown in Fig. 28, we decided to shift CG forward from 45% C to 40% C. Then simple calculation leads us to Fig. 29. Although the model is still unstable in pitch, we decided to take a risk and make KAG-3 similar to the model "W F C E T".

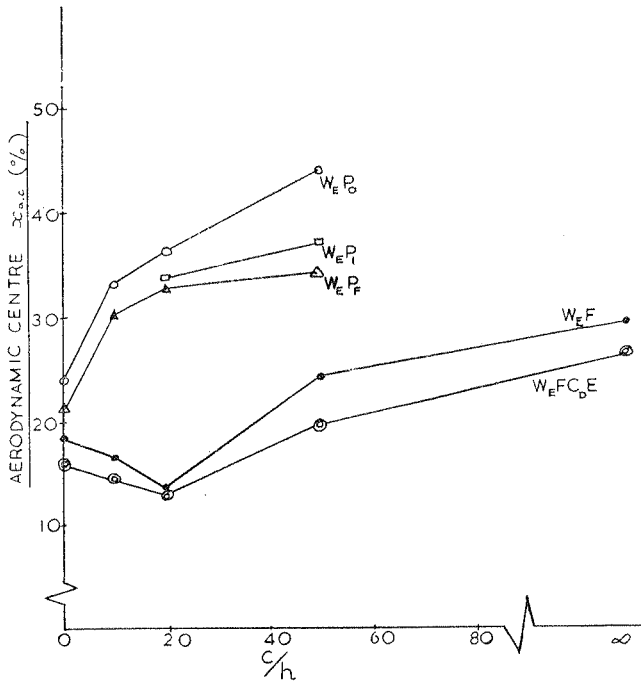


FIG. 25. EFFECT OF THE CONFIGURATION ON AERODYNAMIC CENTRE LOCATION  $-2^\circ \leq \alpha \leq +2^\circ$

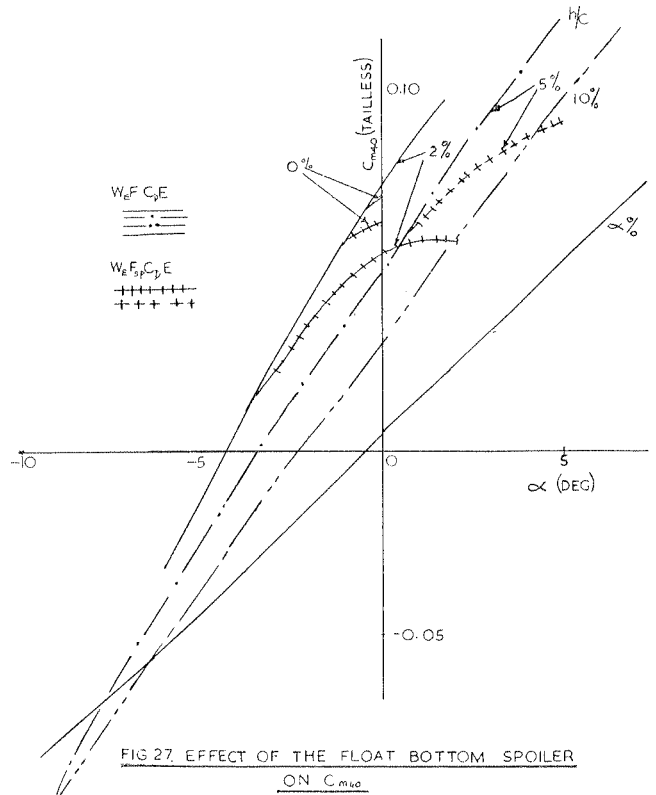


FIG. 27. EFFECT OF THE FLOAT BOTTOM SPOILER ON  $C_{m,0}$

with CG at 40% chord station. We did not have enough time to solve the stability problem completely through further model tests.

Now we will describe contributions of the tails to the pitch stability. See Fig. 30 for the tails T<sup>v35</sup>. Effectiveness of the tail is excellent for  $\alpha' \leq -2^\circ$ , but some sudden decreases in effectiveness occur as  $\alpha$  increases;  $\alpha = -2^\circ, -0.5^\circ, +3^\circ$  and  $+4^\circ$  for  $h/C = 0, 2, 5$  and  $10\%$  respectively. These strange changes embarrassed us seriously in designing KAG-3 and we made great efforts to find the physical meanings, as stated later. In order to improve the tail effectiveness, several kinds of tails were tested, the results of which are summarised in Fig. 31.

Contribution of a tail to the pitching moment coefficient is, theoretically:<sup>1</sup>

$$C_{mt} = \left( -\frac{q_t}{q_\infty} \cdot \frac{l_t}{c} \cdot \frac{S_t^*}{S} \cdot \frac{\partial C_{L_t}^*}{\partial \alpha_t^*} \cos^2 \Gamma \right) \times \left[ 1 - \frac{\partial \epsilon}{\partial \alpha} \right] \left[ \alpha + \alpha_{t_0} \right]$$

where

- $q_t$  = Dynamic pressure around the tail.
- $l_t$  = Tail length.
- $\Gamma$  = Dihedral angle.
- $S_t^*$  = Expanded area of the tail.

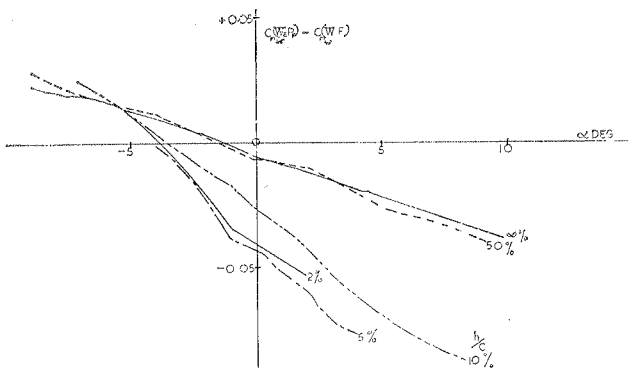


FIG. 26. DESTABILIZING EFFECT OF FLOAT THICKNESS

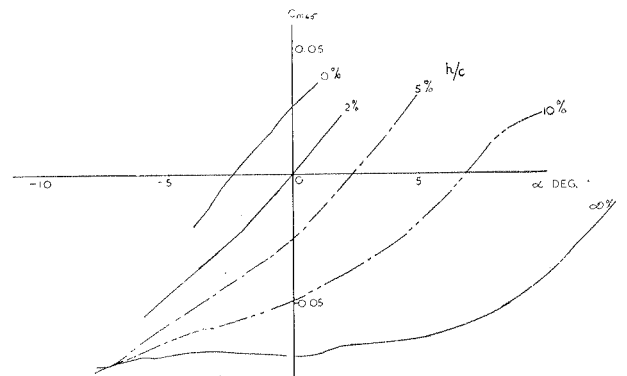


FIG. 28. PITCHING MOMENT COEFFICIENT OF THE MODEL  $W_E F T_{35}$

- C\* = Lift coefficient of the tail, measured in the direction perpendicular to the chord plane of each tail panel.
- α\* = Angle of attack of the tail, measured in the plane perpendicular to the chord plane of each tail panel, deg.
- ε = Downwash angle, deg.
- α = Angle of attack of the vehicle.

Therefore

$$\frac{C_{m\alpha}}{\frac{l_t}{c} \frac{S_t^* \cos^2 \Gamma}{s}} \approx -\frac{q_t}{q_\infty} (1 - \frac{\partial \epsilon}{\partial \alpha}) \left( \frac{\partial C_{L_t}^*}{\partial \alpha_t^*} \right)$$

means tail effectiveness per unit tail volume. (See Fig. 31) The tails "T<sub>cv</sub>", "T<sub>v35</sub>" and "T<sub>r</sub>" lie in the upwash field

produced by the main wing ( $-\frac{\partial \epsilon}{\partial \alpha} < 0$ ) whereas the tails "T<sub>HU</sub>" and "T<sub>HL</sub>" are in the downwash field ( $\frac{\partial \epsilon}{\partial \alpha} > 0$ )

So the former are more effective than the latter in  $\alpha \geq 0$ . But "T<sub>cv</sub>" shows seriously irregular characteristics for  $\alpha \geq 0$ , and "T<sub>v35</sub>" shows also some irregularity for  $\alpha \geq 0$ .

We suppose that tail "T<sub>r</sub>" may be the most suitable choice, although it is not adopted in KAG-3. Fig. 37 shows the static pressure measured on the tail-surfaces "T<sub>r</sub>".

observed sudden pressure decreases on the lower surface near the root, as  $\alpha$  increased. It is noteworthy that the pressure on the upper surface changed much more linearly than that of the lower surface, as  $\alpha$  increased. Therefore we can express this situation, that the lower surface is sucked down by something — trailing vortex produced by the main wing as stated later.

1.3.2 Side slip test

Fig. 33 shows the results of side slip test. When  $\beta$  increases  $C_L$  increases slightly,  $C_D$  (drag in the wind direction) increases remarkably and  $C_Y$  (side force) and  $C_l$  (rolling moment) increase linearly to considerable amounts.

The yaw mode is negligibly unstable and  $\frac{\partial C_l}{\partial \beta}$  shows positive dihedral effect. The influence of side slip on the pitching moment is negligibly small.

All of the data in Fig. 38 are related to  $\alpha = 0$ . Force data  $C_L$ ,  $C_D$  and  $C_Y$  changed nearly regularly, with  $\alpha$ , but moment data  $C_{m45}$ ,  $C_l$  and  $C_n$  changed in a complicated manner. This may be due to the complicated flow field near the tail surfaces.

1.3.3 Bank Test

Fig. 34 shows the results of bank test.  $C_L$  and  $C_D$  decrease a little while  $\frac{\partial C_l}{\partial \psi}$  shows the vehicle is stable in roll, only if the bank angle is small (less than 5°).

1.4 Flow-visualization tests

It is, of course, best to design so that  $\frac{\partial C_{mCG}}{\partial \alpha}$  is some negative value even in the possible deviations from the cruising conditions ( $\alpha = 0, h = 0, \beta = 0, \dots$ ). As shown in Fig. 34, however, we could not make the best design unless we used an extremely large tail-area or tail-length. It was thought that we should use as small tail-area or tail-length as possible, in view of reduction of structural weight.

The first device is to use "F<sub>sp</sub>" instead of "F" ("sp" means a longitudinal fin fitted on the float bottom after the

step, see photo 4); it really improved  $\frac{\partial C_m}{\partial \alpha}$  a for small h.

The second device is to use the Vee-tail outside of the float; these Vee-tail seem to lie in an upwash field produced by the main wing. Our forecast was valid for  $\alpha \leq 0$ , but there were sudden reductions of the tail effectiveness as  $\alpha$  increases into the positive range; it was surely beyond our forecast.

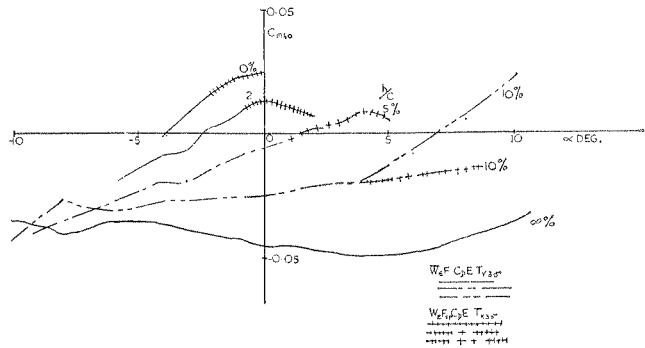
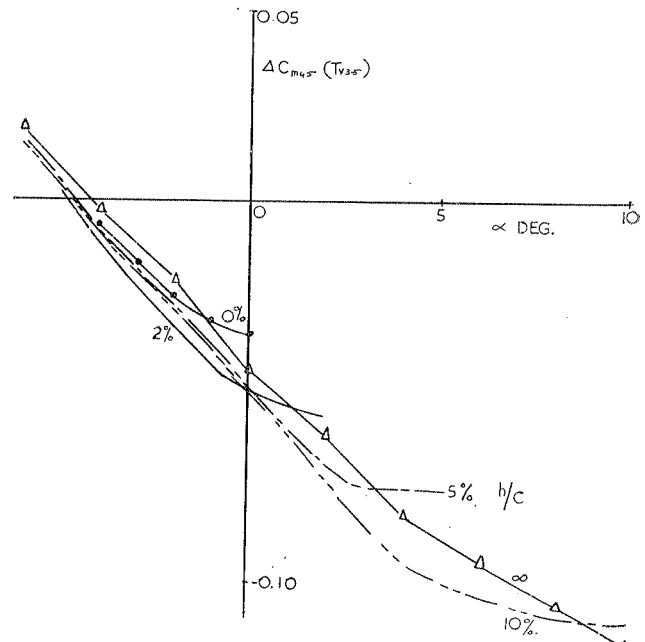


FIG. 29. PITCHING MOMENT COEFFICIENT OF THE COMPLETE MODEL WITH C.G. AT 40% CHORD STATION



$S_t^* = 0.016 \text{ m}^2$   
 $S_{\text{Heff}} (= S_t^* \cos^2 \Gamma) = 0.0107 \text{ m}^2$   
 $S_{\text{Heff}} \times l_t = 0.00195 \text{ m}^3$   
 $l_t S_{\text{Heff}} / CS = 0.0566$   
 $(l_t S_{\text{Heff}} / CS) = 0.1132$

FOR EACH TAIL (LEFT OR RIGHT)  
 FOR BOTH TAIL

FIG. 30 CONTRIBUTION OF THE TAIL SURFACES TO PITCHING STABILITY.

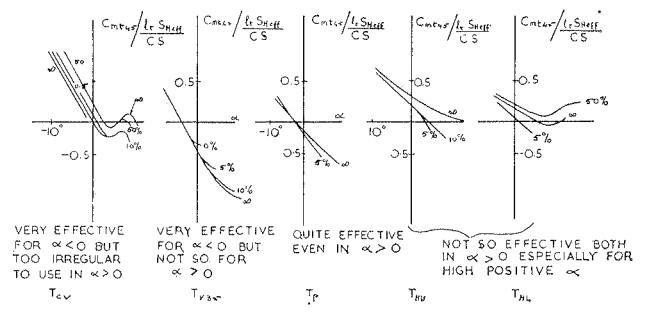


FIG. 31. PITCH STABILIZING EFFECTIVENESS OF VARIOUS TAIL CONFIGURATIONS.

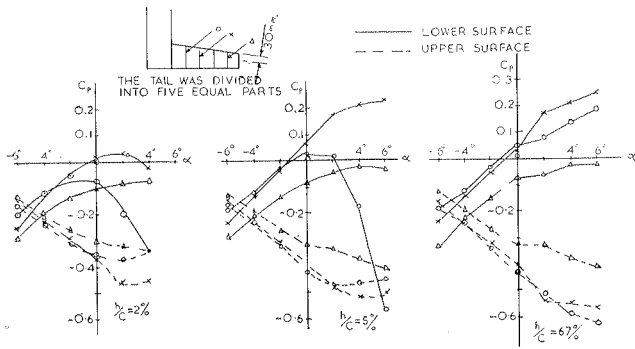


FIG. 32. PRESSURE DISTRIBUTION ON THE TAIL SURFACES  
MODEL  $W_p F T_{v35}$

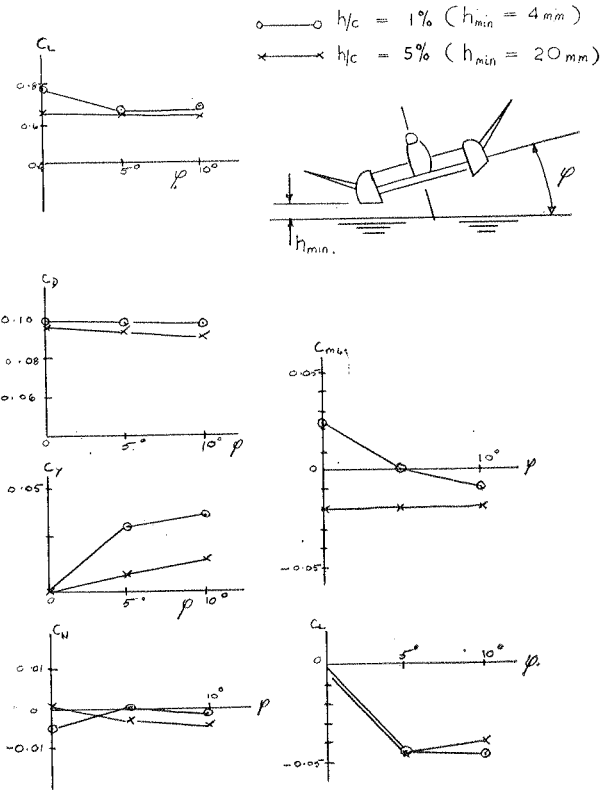


FIG. 34. BANK TESTS ON THE MODEL  $W_p F C_R E T_{v35}$

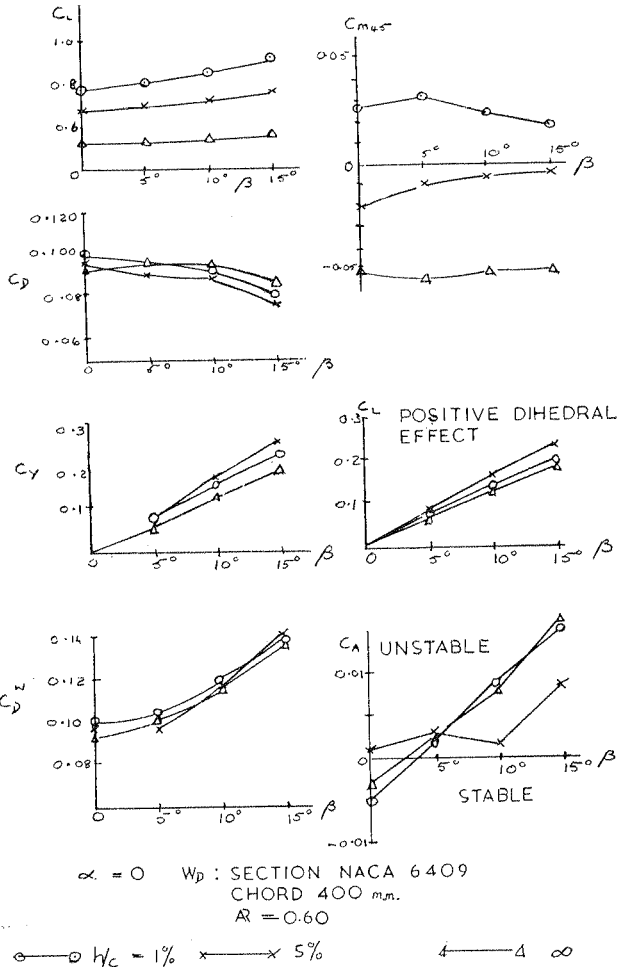


FIG. 33. SIDE SLIP TEST ON MODEL  $W_p F C_R E T_{v35}$

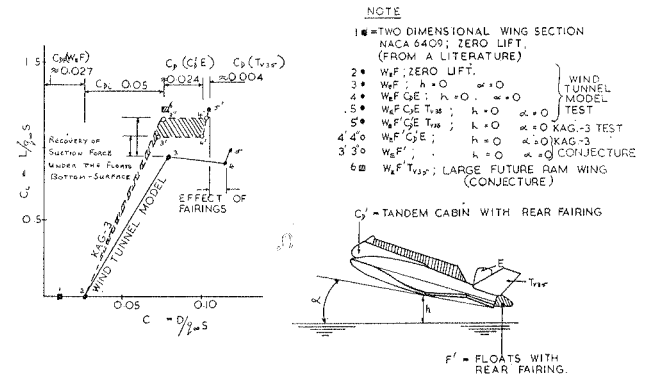
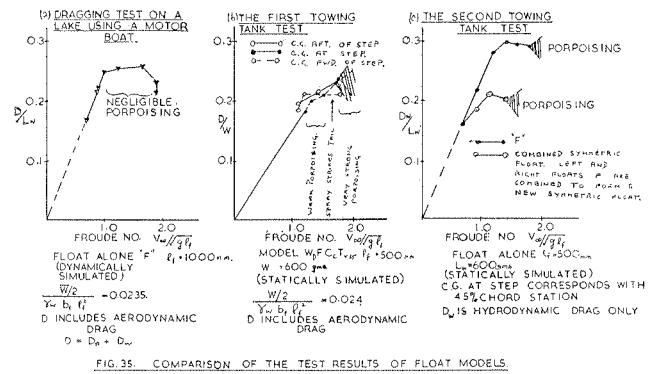


FIG. 36. COMPARISON OF PERFORMANCE BETWEEN THE WIND TUNNEL MODELS AND KAG-3

Pressure measured on both upper and lower tail surfaces made this phenomenon partly clear; the lower tail surface near the root seems to be suddenly sucked down, as  $\alpha$  increases (see Fig. 32). The tuft test visualized this phenomenon to some extent; we can find a strong downwash field concentrated only near the tail root (see photo 6). The next step was to elucidate the whole flow pattern near the tail by using smoke. First, for the model "W P", we found

B O

clear circulating flow field just outside the end-plate. (See photo 7). And second, for the model "W F" we found less

D

clear circulating flow field outside the float. Thus, we may conclude that:

GEW with end-plate (or side-floats) causes "outwash flow" passing through lowest edge of the end-plate; the outwash induces downwash along the end-plate, so circulating flow field is established just outside the end-plate. Although we observed the flow field qualitatively only, we suppose the circulating flow field is fairly localized like a separation vortex. Then it is very natural that the static pressure decreases remarkably in the circulating flow, or on a surface immersed in the circulating flow.

### 1.5 Concluding Remarks on GEW Aerodynamics

Our preceding wind tunnels tests, although they are somewhat preliminary, taught us many fresh phenomena, which are summarized below:

- (1) End-plates are very effective in order to get high lift-drag ratio at high lift coefficient, at least for the low aspect ratio GEW.
- (2) Suitable airfoil sections for GEW application may be thin cambered one, which resists the flow separation over the wing upper surface.
- (3) The geometry of the thin end-plates are, to some extent, insensible to aerodynamic performance and stabilities. For instances height of the wing trailing edge, forward extension of the end-plates hardly affect on the aerodynamics, when the gap between the ground surface and the end-plate lowest edges remains constant. We also confirmed the conventional induced drag theorem " $C_{Di}$  is independent of  $\alpha$ " for GEW with thin end-plates, at least when the angle of attack is changed about the axis at nearly mid-chord.
- (4) The geometry of the thick end-plates has remarkable influences on the GEW aerodynamics. When the bottom surface of the thick end-plates has "positive" dead-rise angle (which serves as a "diverging nozzle" for the out-flow), some serious negative pressure is generated and both lift and stability are considerably lost. We also found that the induced drag theorem  $C_{Di} \propto C_L^2$  is not valid for GEW with thick end-plates.
- (5) Some bulky bodies, such as cabin, on the wing upper surface may cause a serious drag increment, because of the accelerated flow there.
- (6) There exists a strong circulating flow, outside of each end-plate, somewhat similar to the separation vortex at the sharp leading edge of a delta-wing. Therefore, we must take special care in designing tail-stabilizers extending outside of the main wing span.
- (7) For aspect ratio of the main wing: Though our wind tunnel tests of GEW are limited within the low aspect ratio from 1.2 to 0.6, we found that the higher aspect ratio wings have better L/D. But we think we should not select the wing aspect-ratio in the aerodynamic viewpoint only. For instance, a vehicle should have a sufficient handling quality when passing through the entrance of existing harbours, or when moving in a harbour. These are especially important for the short range transportation, which usually connects somewhat small harbours. Dipping of the end-plate into a wave will result in serious situations, when the wing span is large; the vehicle might be tossed about and some structures might be damaged. The low-aspect-ratio GEW can avoid the above difficulties,

and moreover may have some additional merits. The end-plates can serve as side-floats, which support the whole vehicle weight in the power-off condition, and which may trim the vehicle attitude through hydrodynamic lift on the float bottom, and they may also house some useful loads. It is worthwhile to note that some sort of air cushion concept will be more easily applicable to a low-aspect-ratio GEW than to large aspect ratio GEW if it is necessary to improve take-off performance.

Thus in my opinion, practical use of GEW will start with low-aspect ratio, nearly one, whose overall L/D must be at least superior to that of both hydrofoil and Hovercraft.

## 2. TOWING TANK TEST OF KAG-3 MODELS

### 2.1 Design Philosophy of the Floats

The first point is the decision to adopt the side-float type of vehicle. The reason for this may be explained as follows:

- (1) The side-floats serve to trim the vehicle attitude, especially in the roll mode, throughout the speed range.
- (2) For the central-float type, the lower surface of the main wing will be washed with water spray caused by the central-float. This may bring some difficulties, such as increase of water friction drag and some structural considerations with regard to the wing lower surface.

The second point is width of the floats. It is natural that the width of the floats should be as small as possible, in order to minimize the normal wave impacts at high speeds. On the other hand, the hump drag at low speed becomes smaller with wider float beam. For the experimental vehicle KAG-3 only, we decided to reduce the hump drag rather than the wave impacts. So we used the following criterion on flying boat hull:

$$0.02 \geq \frac{W}{\gamma_w b_f l_f^2}$$

(non-dimensional)

Where  $W$  is the load carried by the float at rest,  $\gamma_w$  is the specific weight of the water,  $b_f$  is the float beam and  $l_f$  is the float length.

The third point is selection of the dead-rise. We avoided choosing one that would cause the water spray to contact the wing lower surface (e.g. "negative dead-rise"), even though the aerodynamic advantages would be great (see Fig. 19). Thus we adopted a pair of floats each of which is a half-body shape and has "positive dead-rise".

Geometry of the float tested is shown in Fig. 4.

### 2.2 Test results

We conducted the towing tank tests twice, both of which were just preliminary. The speed obtained was at most 6 m/sec, corresponding to the Froude number  $\frac{V}{\sqrt{gl_f}}$  of 1.8 even with one-tenth scale models. But we could find the hump drag, which happened at  $\frac{V}{\sqrt{gl_f}} = 1.4$ . At  $\frac{V}{\sqrt{gl_f}} = 1.7$  or higher, most tests were prevented by porpoising motion, because we had not enough time to make dynamically similar models and apparatus for the towing tank tests. In view of the preliminary characteristics the most essential parts of the test will be quoted below.

Fig. 35 (b) and (c) shows the test results of the models "W F C T" and floats alone respectively; in the former, the hump drag/weight is about 0.22 and in the latter about 0.3. There exists a large difference. Fig. 35 (a) shows the test results which were obtained with one-fifth scale models (floats alone) pulled by a motor boat on a lake. Here the hump drag/weight is about 0.25.

We, thus, could not forecast the hydrodynamic performance through the models at  $\frac{V}{\sqrt{g|f|}}=1.8$ . But fortunately many

previous tests for flying boat hulls showed that the drag-weight ratio hardly changes in the speed range from  $1 \times V$  hump to  $2 \times V$  hump, if there is no porpoising motion.

### 3. COMPARISON BETWEEN MODEL TESTS AND KAG-3

Measured drags<sup>2</sup> of KAG-3 were 74, 63 and 55 kg at the air speed of 80, 90 and 105 km/hr respectively. We assumed roughly that the overall drag of the vehicle is written as:

$$D = \left( W - \frac{1}{2} \rho V_a^2 S C_L \right) \left( \frac{D}{L} \right)_w + \frac{1}{2} \rho V_a^2 S C_L \left( \frac{D}{L} \right)_a$$

and that hydrodynamic drag-lift ratio  $(D/L)_w$  aerodynamic drag-lift ratio  $(D/L)_a$  and aerodynamic lift coefficient  $C_L$  are three unknown constants. Then we have

$$\left. \begin{aligned} C_L &= 1.24 \\ (L/D)_a &= 11.48 \\ (L/D)_w &= 5.66 \end{aligned} \right\} \text{for one crewman and } 80 \leq V_a \leq 105 \text{ Km/hr (*)}$$

These values are much superior to those of the model tests. Aerodynamic refinements, such as the cabin fairing and float rear fairing, should naturally reduce aerodynamic drag and  $(D/L)_a$ , but the reasons of higher  $C_L$  and higher  $(L/D)_w$  are still not clear.

Note: The above values (\*) were obtained without float bottom spoilers, because some overwater trials with float bottom spoilers caused severe porpoising motion and moreover resulted in lower maximum speed. Therefore, most of the overwater trials of KAG-3 were conducted without float bottom spoilers.

It is my present conjecture that water spray produced by the floats may considerably prevent the cushion air outflowing, and reduce the aerodynamic suction force on the float bottoms to a negligibly small value. The higher value of  $(L/D)_w$  may be due to the lower pitch angle than that of the towing tank tests. The reason for the lower pitch angle of KAG-3 is still not clear.

Fig. 36 shows a rough comparison of aerodynamic performance between KAG-3 and wind tunnel models. We assumed that the effective aspect ratio of "WF" overwater was approximately 7.5, then we obtained  $C_{Di}^E = 0.05$  for  $C_L = 1$ . The assumption  $AR_{eff} = 7.5$  seems not to be visionary, when we come back to Fig. 19 and take account of the recovery of suction loss on the float bottom.

The same value of  $C_{Di}^E$  can be obtained assuming that  $AR_{eff} = 5.0$  for "WF" from Fig. 19 and  $C_L = 0.9$ , and that the additional lift  $\Delta C_L = 0.2$  is obtained without additional induced drag, owing to the favourable effect of water spray.

In a larger vehicle we can conceal the canopy and engine in the wing, floats or other streamlined bodies, and then we may obtain the performance marked with

6



### 4. CONCLUSIONS

Wind tunnel tests and towing tank tests of KAG-3, experimental vehicle of simple ram wing, are summarized. Although they are somewhat preliminary, they taught us many fresh phenomena which have hardly been met in conventional aeroplane tests.

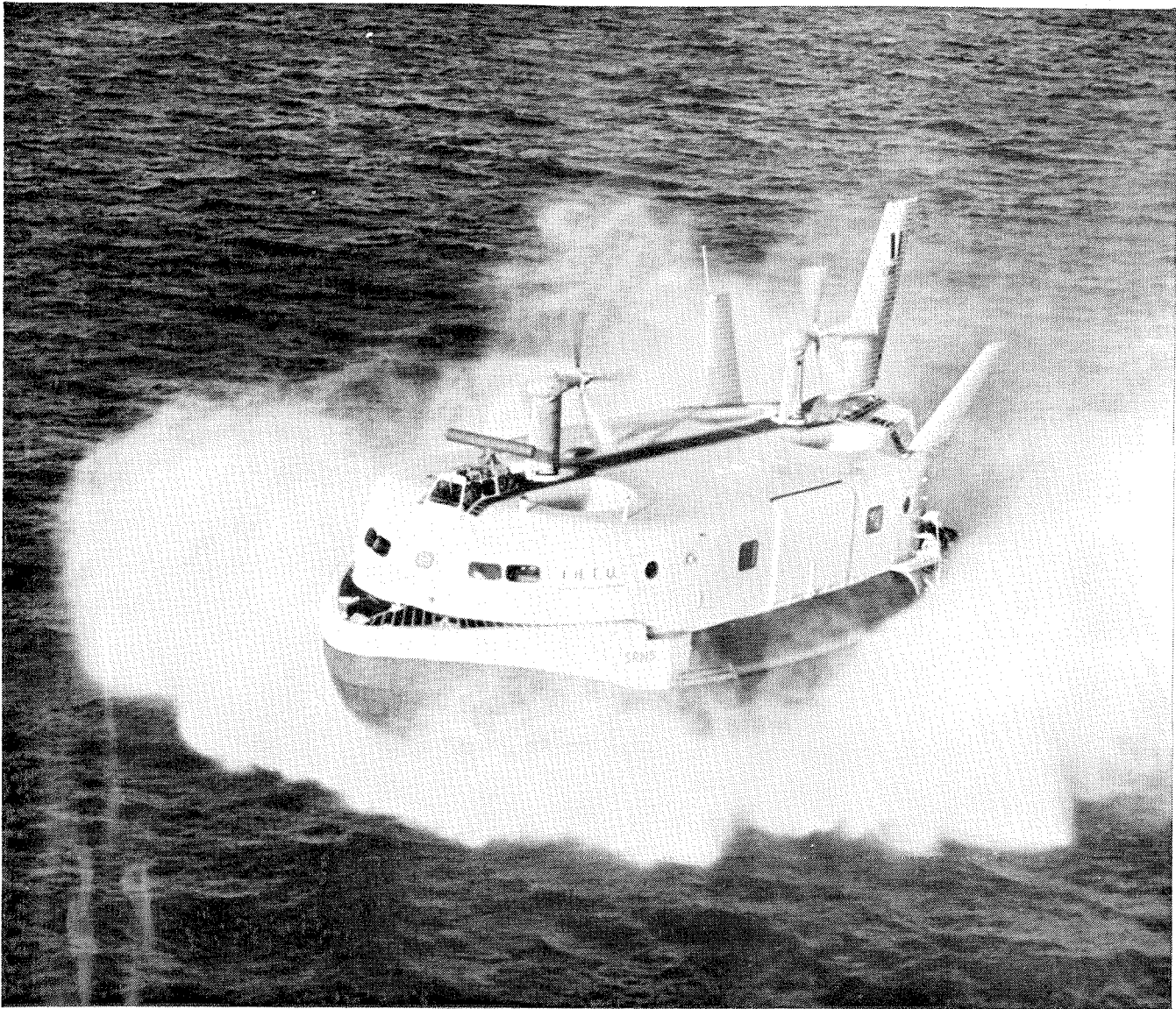
Concluding remarks on GEW aerodynamics were presented in Section 1.5. Design philosophy of the floats was concisely described in Section 2.1. Comparison between model tests and KAG-3 was given in Section 3. For larger vehicles we may obtain lift coefficient of nearly 1.20, lift-drag ratio of nearly 16, even if a main wing of a low aspect ratio, about 0.75, is used.

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- (1) P. E. Purser and J. P. Campbell, Experimental verification of a simplified Vee-tail theory and analysis of available data on complete models with Vee-tails. NACA Report No 823, 1945.
- (2) S. Ando, J. Miyashita and K. Terai. Design philosophy and test results of two-seated experimental simple ram-wing with side floats. *Kawasaki Review*, No 14, March 1964, pp 3-34 (in Japanese).

### SYMBOLS

C	=	Chord length of main wing.
h	=	Height of lowest edge of end-plate, from the ground surface, when $\alpha = 0$ , see Figs 3, 4.
$\alpha$	=	Angle of attack of "models", degree. See Figs 1, 2, 4.
$\alpha_w$	=	Angle of attack of main wing, degree. See Figs 1, 2.
	=	End-plate angle, degree. See Figs 1, 2.
	=	$\alpha_w = \gamma$ means $\alpha = 0$ .
AR	=	Aspect ratio of main wing.
C	=	Drag coefficient, $D / \infty q S$ .
$C_D$	=	Drag force, in the direction of model centre-line.
$q_\infty$	=	Free-stream dynamic pressure.
S	=	Area of main wing.
C	=	Lift coefficient, $L / q_\infty S$ .
$C_{m45}$	=	Pitching moment coefficient about 45% chord point of main wing, $M_{45} / (q_\infty S C)$ .
X <sub>c.p.</sub>	=	Location of centre of pressure, where $C = 0$ .
X <sub>a.c.</sub>	=	Location of aerodynamic centre, where $\frac{\partial C}{\partial \alpha} = 0$ .
C	=	Pressure coefficient, $(p-p_\infty) / q_\infty$ .
l <sub>t</sub>	=	Tail-length, distance from CG to aerodynamic centre of tail.
S <sub>Heff</sub>	=	Effective area of the horizontal tail (expanded area) $\times [\cos(\text{dihedral angle})]^2$ .
C <sub>l</sub>	=	Rolling moment coefficient (rolling moment) / $q_\infty S b$ .
C <sub>n</sub>	=	Yawing moment coefficient (yawing moment) / $q_\infty S b$ .
b	=	Span of main wing.
$\beta$	=	Angle of yaw, degree.
$\psi$	=	Angle of bank, degree.
b	=	Width of float. See Fig. 4.
l <sub>f</sub>	=	Length of float. See Fig. 4.
"WP"	=	See Fig. 1.
"W <sup>A O</sup> P"	=	See Fig. 1, photo 7.
"W <sup>B O</sup> P"	=	See Fig. 2, photo 5.
"W <sup>C O</sup> P"	=	See Fig. 3, photo 2.
"W <sup>E O</sup> P <sub>1</sub> "	=	See Fig. 3.
"W <sup>E</sup> P"	=	See Fig. 3.
"W <sup>E F</sup> P"	=	See Fig. 4.
"W <sup>E</sup> F", "WF", "WF", "WF", "WF"	=	See Fig. 5, photo 3.
d-15, do, d15, d15sp, d30	=	See Fig. 5, photo 3.
"T", "T", "T"	=	See Fig. 6.
C <sub>HU</sub> , C <sub>HL</sub>	=	See Fig. 6.
"T"	=	See Fig. 7, photo 1.
v35	=	See Fig. 7.
"T"	=	See Fig. 7.
"C", "C"	=	See Fig. 8.
"C <sup>A</sup> ", "C <sup>B</sup> "	=	See Fig. 8, photo 1.
"C"	=	See Fig. 9.
"C <sup>D</sup> "	=	See Fig. 9, photo 1.



## Bristol Siddeley power for Air Cushion Vehicles

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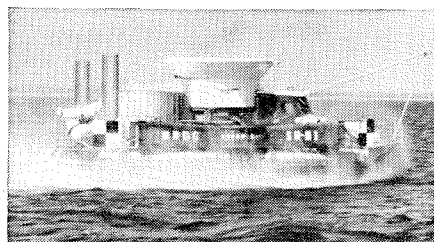
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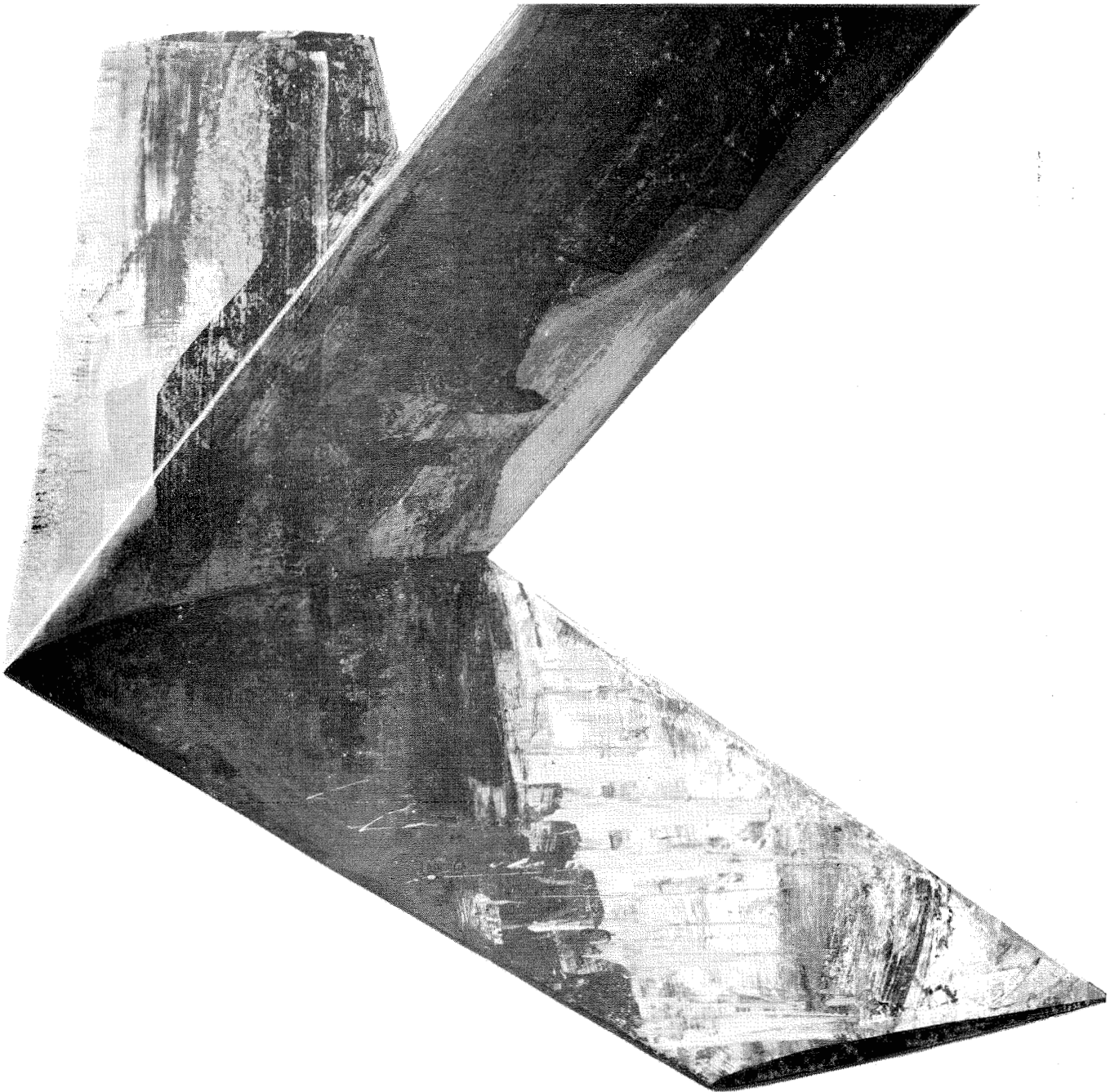
*The Westland SRN 2 powered by four Nimbus engines.*



*The Westland SRN 1 uses a Viper gas turbine.*



*The Westland SRN 5 uses a Gnome engine.*



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