GROUND EFFECT MACHINE RESEARCH AND DEVELOPMENT IN THE UNITED STATES

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Ground effect machine (GEM) investigations in the United States have grown at an astonishing rate since early 1957. At present they involve some 40 commercial firms, laboratories, etc., and represent an increasingly significant investment of capital and engineering manpower. These investigations are thus far largely exploratory in nature. They represent a considerable variety of approaches, both as to types of ground cushion phenomena employed, and vehicle applications envisioned. The various ground cushion concepts are reviewed, in terms of elementary principles of fluid mechanics. All of the concepts are shown to give direct relationships between vehicle performance and vehicle size/height ratio. GEM developments are therefore expected to tend ultimately toward large ocean-going vehicles operating very close to the surface. Some of the outstanding advantages and problems of the various ground cushion concepts are discussed, but present knowledge does not support strong opinions as to which of the concepts will prevail.

SYMBOLS

S	Base area in square feet
h	Height above surface in feet
C	Perimeter of the base in feet
l	Vehicle length in feet
b	Vehicle beam in feet
G	Nozzle width in feet
θ	Normal jet discharge angle in degrees (see Figs. 1 and 3)
β	Tangential jet deflection angle in degrees (see Fig. 3)
Δp	Effective cushion (base) pressure in pounds per square foot gage
ρ	Mass density of air in slugs per cubic foot
ρ_w	Mass density of water in slugs per cubic foot
V_j	Average jet velocity at discharge feet per second
V_e	Full-expansion velocity, in feet per second, of cushion air (velocity cushion air would attain if allowed to expand to atmospheric pressure)

V_0	Free-stream velocity in feet per second
q_0	Free-stream dynamic pressure in pounds per square foot ($q_0 = \frac{1}{2}\rho V_0^2$)
L	Total lift in pounds
L_0	Aerodynamic lift in pounds (lift contributed by pressure distribution associated with external flow field)
D_{ram}	Ram drag (momentum drag) in pounds
D_f	Parasite drag in pounds
T_j	Thrust component of jet reaction
D	Net drag in pounds ($D = D_{ram} + D_f - T_j$)
C_{L0}	Aerodynamic lift coefficient ($C_{L0} = L_0/qS$)
C_{Df}	Parasite drag coefficient ($C_{Df} = D_f/q_0S$)
P_c	Cushion-system power in pound-feet per second
P_p	Propulsion-system power in pound-feet per second
P	Total power ($P = P_c + P_p$)
M	Figure of merit $M = \left(\frac{1}{2\sqrt{\rho}} \frac{L}{P} \sqrt{\frac{L}{S}}\right)$
$\mho$	Nondimensional velocity parameter $\left(\mho = \frac{V_0}{\sqrt{L/(\rho S)}}\right)$
M_w, $\mho_w$	Same as M, $\mho$, but with ρ_w substituted for ρ
η_A	Augmentation efficiency
η_d	Duct efficiency
η_p	Compressor efficiency
η_{int}	Internal efficiency
η_F	Propulsive efficiency
D_c	Discharge coefficient
E	Energy ratio (ratio of maximum kinetic energy flux in system to power dissipation)
k_p	Effective pressure recovery factor $\left(k_p = \frac{\Delta p}{\frac{1}{2}\rho V_e^2}\right)$
D_e	Equivalent diameter $D_e = 4\,\frac{S}{C}$

INTRODUCTION

Just over three years ago, in early 1957, a report [1] by the NACA of experiments with a ground effect phenomenon sparked one of the most unique engineering and technical movements of modern U.S. history, a movement which appears to be still gathering momentum. A recent article in the technical press reported some forty firms now actively engaged in some form of ground effect machine (GEM) investigations, financed by government support nearing the ten-million-dollar mark plus an even larger investment of private funds.

Numerous economic and psychological reasons have been advanced to account for this remarkable growth of GEM activity. Certainly a major factor is the fascinating simplicity of the basic ground cushion concepts. The most casual technical training affords qualitative understanding of the basic ground cushion principles, and innumerable arrangements of readily available mechanical components which can produce a ground cushion come easily to mind. It is not really surprising that so many individuals should have felt the urge to put something together and putter around with it a bit. Even so, it may take something more to explain the scope and vigor of GEM activity—and the financial investment which it represents—at a time when the GEM's place in the transportation field is still highly uncertain.

This same simplicity of the ground cushion concept occasioned many a remark of surprise, in those early days of 1957, that "someone hadn't thought of it before." Of course, it turned out that someone had, notably, Kaario of Finland, Weiland of Switzerland, Cockerell of England, and Frost of Canada. Even in the U.S., a rather astonishing number of GEM models and vehicles of various types were soon found to be already in existence in widely scattered back yards, basements, and garages. Nevertheless, nearly all of the many GEM programs now in progress in the U.S. can be traced to the NACA report of 1957 and to the subsequent government activity which it inspired.

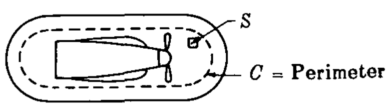
Equally as interesting as the volume of GEM work now in progress is its diversity. At least seven different ground cushion concepts, with almost countless combinations and variations, are under serious study. Sizable independent programs are being devoted to studies of engines, compressors, ducting problems, and structural design considerations. While in itself one of the most interesting aspects of the U.S. GEM picture, this diversity makes a comprehensive review of GEM research and development impractical. The present paper will be confined to a review of seven of the more significant vehicle concepts, in terms of simple fluid mechanics principles, with sketchy indications of the present stage of development and prospects of each. Sources of more detailed information will be given wherever possible.

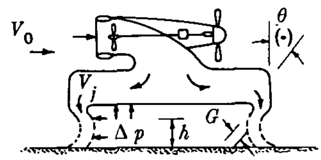
THE GROUND CUSHION CONCEPTS

Seven ground cushion concepts have been chosen as representing, either directly or in combination, most of the basic ideas under active consideration in the U.S. Several of these concepts are at a rather primitive stage of development. In the analyses which follow, an attempt is made to reduce the various concepts to their lowest common denominator, in order that their similarities and distinctions will be readily apparent. To this end, the analyses follow what is termed, throughout this paper, "simplified ideal theory." This entails assumptions of inviscid, incompressible flow, liberal application of the one-dimensional flow approximations, and neglect of aerodynamic pressures and forces induced by the external flow field. It might be argued with some justice that these analyses should be termed "over-simplified ideal theory." Certainly, there is a deplorable lack of rigor, and the results are obviously not directly applicable to engineering problems. Nevertheless, it is believed that the essential features of the basic principles involved are retained in the results; and that the useful purposes of providing clear understanding and meaningful comparisons are served. In the case of the most highly developed concept, the air curtain, an engineering analysis (still highly simplified) will also be given, and compared to experimental results, to illustrate the relation between the simplified ideal theory and physical reality.

SIMPLE AIR CURTAIN

The air curtain (or "annular jet" or "peripheral jet") concepts have received by far the most attention and serious study. They are correspondingly the furthest advanced, in terms of practical understanding and engineering data. The simple air curtain is illustrated in Fig. 1. As in all the ground cushion concepts, the major source of lift force is the ground





Simplified Ideal Theory:

Hovering		Cruise	
$L = \Delta pS$	(1-1)	$D_{ram} = \rho V_j GC V_0$	(1-6)
$\Delta ph = \rho V_j^2 G(1 - \sin\theta)$	(1-2)	$P_p = D_{ram} V_0$	(1-7)
$P_c = V_j GC(\frac{1}{2}\rho V_j^2 + \frac{1}{2}\Delta p)$	(1-3)	$P_c = V_j GC(\frac{1}{2}\rho V_j^2 + \frac{1}{2}\Delta p - q_0)$	(1-8)
$M \equiv \frac{1}{2\sqrt{\rho}}\frac{L}{P_c}\sqrt{\frac{L}{S}}$	(1-4)	$\mathcal{V} \equiv V_0 / \sqrt{\frac{L}{\rho S}} = \sqrt{\frac{2}{C_L}}$	(1-9)
$\boxed{M_{opt} = \frac{S}{hC}}$	(1-5)	$\boxed{\left(\frac{LV_0}{P}\right)_{opt} = 2\frac{S}{hC}\frac{\mathcal{V}}{\sqrt{1+\mathcal{V}^2}}}$	(1-10)

Fig. 1. Simple air curtain

cushion itself, a region of positive gage pressure trapped between the vehicle and the ground. With the air curtain types, this ground cushion is generated and contained by a jet of air exhausted downward and inward from a nozzle at the periphery of the base. With the simple air curtain, the resultant jet reaction force is vertical, and propulsion must be provided by a separate device (shown schematically in Fig. 1 as a propeller).

Hovering

The jet reaction force contributes to the lift, but this contribution is small compared to the cushion lift, so long as the vehicle is near the ground. The lift is approximated by the product of cushion pressure times base area:

$$L = \Delta pS \ . \tag{1-1}$$

The cushion pressure also reacts against the air curtain with a force which must balance the momentum change within the curtain. This relationship is approximated by

$$\Delta ph = \rho V_j^2 G(1 - \sin\theta) \tag{1-2}$$

where the jet discharge angle θ is taken, by convention, to be negative for the inward-inclined jet sketched in Fig. 1.

The power required is the product of jet volume flow rate times compressor pressure rise, approximated by

$$P_c = V_j G\, C\left(\frac{1}{2}\rho V_j^2 + \frac{1}{2}\Delta p\right) \tag{1-3}$$

where the compressor pressure rise equals the jet total pressure and is the sum of mean dynamic pressure (approximated by $(1/2)\rho V_j^2$) and mean static pressure (approximated by $(1/2)\Delta p$).

Hovering performance is expressed by the dimensionless figure of merit,

$$M = \frac{1}{2\sqrt{\rho}}\frac{L}{P}\sqrt{\frac{L}{S}} \tag{1-4}$$

which provides a direct indication of the important lift/power ratio L/P, and a direct comparison with the ideal shrouded propeller or helicopter (with fixed figures of merit, outside ground effect, of 1.0 and $\sqrt{1/2}$, respectively). Combining Eqs. (1-1) through (1-4), gives

$$M = (1 - \sin\theta)\,\frac{\sqrt{\frac{G}{h}(1 - \sin\theta)}}{1 + \frac{G}{h}(1 - \sin\theta)} \cdot \frac{S}{hC}$$

which has a maximum value (when $G/h = 1/2$, $\theta = -90°$) of

$$M_{opt} = \frac{S}{hC}\,. \tag{1-5}$$

A more thorough analysis (see Ref. 3, for example) gives slightly different values for optimum nozzle width ratio G/h and jet angle θ, but almost exactly the same result for optimum figure of merit M_{opt}. Practical design limitations, internal losses, etc., will limit actual vehicles to about $M = 0.6\ S/hC$.

The ratio S/hC is called the size/height ratio. The initiate to the GEM field will find that a few minutes devoted to firmly fixing the size/height ratio and its geometric meaning in his mind will be well spent. This ratio is of predominant importance in virtually all considerations of all types of ground effect machines. The size/height ratio may be thought of as an area ratio, between the "cushion area" S of the vehicle base and the "curtain area" hC of an imaginary peripheral screen sealing in the ground cushion. Or, it may be thought of as a length ratio. Noting that, for a circular plan form, the quantity S/C is equivalent to one-fourth the diameter, $S/hC = D_e/4h$, where D_e is the "equivalent diameter" of the plan form.

Cruise

When the simple air curtain vehicle moves horizontally in forward flight, two modifications to the hovering equations occur. First, a "ram" drag D_{ram} equal to the air mass flow rate through the peripheral nozzle times the forward velocity, is experienced by the vehicle;

and the propulsion system must expend energy at the rate $P_p = D_{ram} V_0$ to overcome this drag (Fig. 1, Eqs. (1-6), (1-7). Second, while the cushion power P_c is still the product of air volume flow rate times compressor pressure rise, the required pressure rise is now reduced by the amount q_0 of the free-stream dynamic pressure recovered by the inlet (Eq. (1-8), Fig. 1).

The cruise performance is expressed by the dimensionless "equivalent lift/drag ratio" LV_0/P (Both the range of the GEM and its direct operating cost per ton-mile are directly proportional to the equivalent lift/drag ratio.). Combining Eqs. (1-7) and (1-8) with (1-1) and (1-2) and solving again for optimum G/h ($= 1/2\ (1 + \mho^2)$) and θ ($= -90°$) gives

$$\left(\frac{LV_0}{P}\right)_{opt} = 2\,\frac{S}{hC}\,\frac{\mho}{\sqrt{1+\mho^2}} \qquad (1\text{-}10)$$

where $\mho$ is the dimensionless velocity parameter $V_0/\sqrt{L/(\rho S)}$.

Since optimum nozzle width ratio G/h decreases with increasing forward velocity, Eq. (1-10) represents an envelope curve for possible designs (or possible settings of an adjustable-nozzle design).

Equation (1-10) describes a curve which rises asymptotically to the value $2\ S/hC$ as the forward velocity increases without limit. Consideration of the parasite drag will, of course, cause the equivalent lift/drag ratio to fall below this simplified ideal solution and to peak out at some value of $\mho$ corresponding to the "optimum cruise speed." This, and other practical considerations, will be discussed further when a simplified engineering analysis of the air curtain vehicle is presented in a later section of this paper. It may be said here that actual vehicles of the simple air curtain type will probably be limited to equivalent lift/drag ratios of about $0.7\ S/hC$, at optimum cruise speeds corresponding roughly to $\mho = 1.0$.

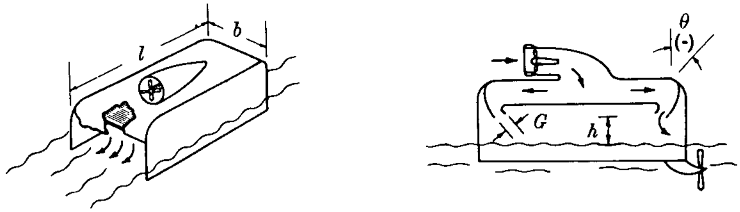
More detailed information on the simple air curtain is found in Refs. 2 to 5.

AIR CURTAIN WITH SKEGS

If the GEM is to operate exclusively over water, and at moderate speeds, a substantial power saving is effected by the use of side plates, or skegs, which extend into the water as sketched in Fig. 2. The equations are exactly the same as for the simple air curtain except that the air curtain is furnished to only the portion $2b$ of the total perimeter $2b + 2l$. Both the figure of merit and the equivalent lift/drag ratio are hence improved in proportion to the factor $1 + l/b$ (Fig. 2, Eqs. (2-1), (2-2)).

In practice, of course, the drag on the submerged portion of the skeg becomes very significant at high speeds. The exact breakeven point between the simple air curtain and the air curtain with skegs depends on the roughness of the water surface (which determines the minimum skeg submersion necessary to effect a seal). It is generally felt, however, that the application of submerged skegs is confined to speeds below 50 knots.

A compromise between the simple air curtain and the air curtain with skegs is also being studied wherein side plates extend below the base part way to the water, with air curtains issuing from nozzles at the lower extremities of the side plates. The total curtain



Simplified Ideal Theory:

Equations same as for air curtain, except that power is furnished to only the portion ($2b$) of the perimeter ($2l + 2b$)

Hover		Cruise	
$M \equiv \frac{1}{2\sqrt{\rho}} \frac{L}{P} \sqrt{\frac{L}{S}}$			
$\boxed{M_{opt} = \frac{S}{hC}\left(1 + \frac{l}{b}\right)}$	(2-1)	$\boxed{\left(\frac{LV_0}{P}\right)_{opt} = 2\,\frac{S}{hC}\,\frac{\upsilon}{\sqrt{1+\upsilon^2}}\left(1 + \frac{l}{b}\right)}$	(2-2)

Fig. 2. Air curtain with skegs

area is $2\,bh + 2\,lh'$ (where h' is the clearance of the side plates above the water) as compared to $hC = 2\,bh + 2\,lh$ for the simple air curtain. The simplified ideal theory performance is hence

$$M_{opt} = \frac{S}{hC}\,\frac{1 + \frac{l}{b}}{1 + \frac{l}{b}\cdot\frac{h'}{h}}$$

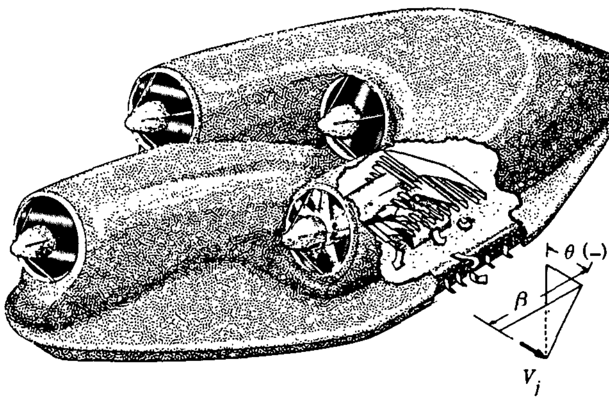
$$\left(\frac{LV_0}{P}\right)_{opt} = 2\,\frac{S}{hC}\cdot\frac{\upsilon}{\sqrt{1+\upsilon^2}}\cdot\frac{1 + \frac{l}{b}}{1 + \frac{l}{b}\cdot\frac{h'}{h}}\,.$$

The proponents of this compromise believe that the side plates, because of their low frontal area, can be designed to survive occasional high-speed impacts with higher-than-average waves.

More detailed information on the air curtain with skegs is found in Refs. 6 and 7.

INTEGRATED AIR CURTAIN

The integrated air curtain provides for propulsion by directing the peripheral jet at a rearward-inclined angle, so that the net resultant jet reaction force is inclined forward from vertical. This system is illustrated in Fig. 3. Vanes in the peripheral nozzle deflect the jet exhaust rearward through the tangential jet deflection angle β. If the vehicle has a



Simplified Ideal Theory:

Cruise	
$V_0 = V_j \sin\beta$ (ram drag = thrust)	(3-1)
$L = \Delta p S$	(3-2)
$\Delta p h = \rho V_j^2 G (1 - \sin\theta) \cos^2\beta$	(3-3)
$P = P_c = V_j G C \cos\beta \left(\frac{1}{2} \rho V_j^2 + \frac{\Delta p}{2} - q_0 \right)$	(3-4)
$\mathcal{V} \equiv \dfrac{V_0}{\sqrt{L/(\rho S)}} = \dfrac{\tan\beta}{\sqrt{\frac{G}{h}(1 - \sin\theta)}}$	(3-5)
$\boxed{\left(\dfrac{L V_0}{P}\right)_{\text{opt}} = 2 \dfrac{S}{hC} \mathcal{V}}$	(3-6)

Fig. 3. Integrated air curtain

slender plan form, with pointed bow and stern, so that the entire peripheral nozzle lies nearly parallel to the direction of flight, then the rearward velocity component produced by tangential deflection is, at all points along the nozzle exit, nearly equal to $V_j \sin \beta$. The thrust component of jet reaction is hence mass flow times $V_j \sin \beta$, and equals the ram drag (mass flow times V_0) when

$$V_0 = V_j \sin \beta \; . \tag{3-1}$$

The base pressure and jet momentum relationship is modified from the simple air curtain case (Eq. (1-2)) as follows: The effective nozzle area per unit nozzle length is reduced in proportion to $\cos \beta$, and only the fraction $\cos \beta$ of the jet momentum enters into reaction against the ground cushion (since the tangential component of jet momentum is unchanged as the jet curves outward). The equivalent relationship for the integrated air curtain is therefore

$$\Delta ph = \rho V_j^2 G \, (1 - \sin \theta) \cos^2 \beta \; . \tag{3-3}$$

The cushion power expression is the same for the simple air curtain (Eq. (1-8)) except for the modified effective nozzle area:

$$P_c = V_j G C \cos \beta \, (\frac{1}{2} \rho V_j^2 + \frac{1}{2} \Delta p - q_0) \tag{3-4}$$

Combining, and solving for optimum nozzle width ratio G/h ($= 1/2$) and jet angle θ($= -90°$) gives for the equivalent lift/drag ratio

$$\left(\frac{LV_0}{P}\right)_{opt} = 2 \frac{S}{hC} \mho \; . \tag{3-6}$$

Comparison of this equation with Eq. (1-10) for the simple air curtain shows that the results are equivalent at very low speeds, but the integrated air curtain becomes vastly superior at high speeds. Close examination of the integrated air curtain equations (Fig. 3) will reveal that the power required, compressor pressure rise, internal air mass-flow rate, and optimum nozzle width are all independent of speed. In practice, all of these advantages are somewhat diluted (but not negated) by the effects of parasite drag and internal losses. The best design practice might be to provide sufficient tangential jet deflection to counteract the ram drag, plus a separate propulsion system to counteract the parasite drag. This and other practical considerations are discussed further in the simplified engineering analysis of air cushion performance presented in a later section of this paper. It may be said here that actual air cushion vehicles will probably be limited to equivalent lift/drag ratios of the order of $0.9\, S/hC$, at optimum cruise speeds corresponding roughly to $\mho = 1.0$.

More detailed information on the integrated air curtain is found in Refs. 4 and 5.

WATER CURTAIN

In principle, a ground cushion can be contained by a peripheral jet of water in just the same manner as by a jet of air. This concept is represented schematically in Fig. 4. Air is pumped to the base of the vehicle until the ground cushion is established, at which point equilibrium is reached between the change of momentum within the water curtain and the

Simplified Ideal Theory:

Equations same as for air curtain (neglecting gravity) except that water density appears instead of air density.

Hovering	Cruise
Simple Water Curtain	
$M_w \equiv \frac{1}{2\sqrt{\rho_w}} \frac{1}{P_c} \sqrt{\frac{L}{S}}$ (4-1) $\boxed{M_{w,\text{opt}} = \frac{S}{hC}}$ (4-2) $M_{\text{opt}} \doteq 29 \frac{S}{hC}$ (4-3)	$\boxed{\left(\frac{LV_0}{P}\right)_{\text{opt}} = 2 \frac{S}{hC} \frac{\mathcal{V}_w}{\sqrt{1+\mathcal{V}_w^2}}}$ (4-4) $\left(\frac{LV_0}{P}\right)_{\text{opt}} \doteq 2 \frac{S}{hC} \frac{\mathcal{V}}{\sqrt{0.0012+\mathcal{V}^2}}$ (4-5)
Integrated Water Curtain	
	$\boxed{\left(\frac{LV_0}{P}\right)_{\text{opt}} = 2 \frac{S}{hC} \mathcal{V}_w}$ (4-6) $\left(\frac{LV_0}{P}\right)_{\text{opt}} \doteq 58 \frac{S}{hC} \mathcal{V}$ (4-7)
Note remarks in text!!	

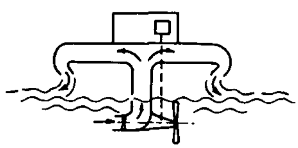


Fig. 4. Water curtain

reaction of the cushion pressure against the curtain. Gravity has a favorable effect on the water curtain in that the jet gains momentum as it falls from the nozzle to the surface; and it has an unfavorable effect on the pumping power, in that the water must be raised from the surface to the level of the nozzle. The problem is greatly simplified, and the essential character of the result is unchanged, if these effects are neglected. The equations for the water curtain then become identical with those for the air curtain (Figs. 1 through 3), except that water density ρ_w is substituted for air density ρ. The results, in terms of dimensionless parameters referred to water density (Fig. 4, Eqs. (4-2), (4-4), (4-6)), are exactly analogous to the air curtain results. However, when the parameters are referred to air density, it is apparent that, in principle, the water curtain enjoys a tremendous advantage. In the hovering case, and in the case of the integrated water curtain at cruise, the results (Eqs. (4-3) and (4-7)) show the water curtain doing the same job as the air curtain with 1/29 as much power required.

The trouble with this rosy picture becomes apparent when it is recalled that the optimum nozzle width G on which these results are based, is half the operating height h. A piping system large enough to supply such a nozzle, and filled with water, would weigh a staggering amount. It is obviously necessary to compromise in favor of a much, much thinner nozzle. In both of the cases cited, simplified ideal theory gives the power as proportional to the quantity

$$\left(\frac{1}{\sqrt{2\frac{G}{h}}} + \sqrt{2\frac{G}{h}} \right) .$$

The compromise to thinner nozzles thus destroys much of the theoretical advantage. (For example, if $G/h = 1/200$ instead of $1/2$, the power required is increased by a factor of five, leaving the water curtain with roughly a 6:1 theoretical advantage over the air curtain compared to the original 29:1 advantage.) Furthermore, experiments show that a thin water curtain provides an imperfect seal, so that air must be pumped into the cushion at a quite substantial rate to maintain the cushion pressure. This makes further serious inroads into the theoretical advantage. Just how much advantage is left, if any, is not quite clear at present. Certainly, the water curtain concept should not be discounted without careful study, and a vigorous study program is, in fact, underway.

More detailed information on the water curtain concept is found in Ref. 8.

PLENUM

The plenum is by far the simplest of the ground cushion concepts, both in principle and in physical embodiment. The plenum concept is represented schematically in Fig. 5. The vehicle has a recessed base. Air is simply pumped into the recess and allowed to leak out along the ground.

Hover

Neglecting internal velocities in comparison to the full-expansion velocity, V_e, gives

Lift $$L = \Delta p S \qquad (5\text{-}1)$$

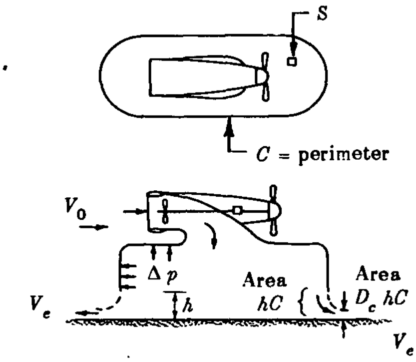
Cushion pressure $$\Delta p = \frac{1}{2} \rho V_e^2 \qquad (5\text{-}2)$$

Cushion power $$P_c = V_c D_c h C \Delta p \qquad (5\text{-}3)$$

Figure of merit $$M = \sqrt{\frac{1}{2}} \frac{1}{2D_c} \frac{S}{hC} \qquad (5\text{-}4)$$

where D_c is the discharge coefficient of the leakage flow, $D_c hC$ being the flow area at full expansion. Using a typical value of 0.61 for D_c gives

$$M = 0.58 \frac{S}{hC} . \qquad (5\text{-}5)$$



Simplified Ideal Theory:

Hovering		Cruise	
$L = \Delta p S$	(5-1)	$D_{\mathrm{ram}} = \rho V_e D_c h C V_0$	(5-6)
$\Delta p = \frac{1}{2} \rho V_e^2$	(5-2)	$P_p = D_{\mathrm{ram}} V_0$	(5-7)
$P_c = V_e D_c h C \Delta p$	(5-3)	$P_c = V_e D_c h C (\Delta p - q_0)$	(5-8)
$M \equiv \frac{1}{2\sqrt{\rho}} \frac{L}{P_c} \sqrt{\frac{L}{S}}$		$\mathcal{V} \equiv V_0 \Big/ \sqrt{\frac{L}{\rho S}} = \sqrt{2} \frac{V_0}{V_e}$	(5-9)
$= \frac{0.353}{D_c} \frac{S}{hC}$	(5-4)	$\boxed{\left(\frac{L V_0}{P}\right)_{\mathrm{opt}} \doteq 1.16 \frac{S}{hC} \frac{\mathcal{V}}{1 + \frac{1}{2}\mathcal{V}^2}}$	(5-10)
$\boxed{M \doteq 0.58 \frac{S}{hC}}$	(5-5)		

Fig. 5. Plenum

Cruise

The ram drag (mass flow times flight velocity), propulsive power, and cushion power (same as in hovering, except for effect of ram pressure recovery in inlet) are given by

$$D_{\mathrm{ram}} = \rho V_e D_c h C V_0 \tag{5-6}$$

$$P_p = D_{\mathrm{ram}} V_0 \tag{5-7}$$

$$P_c = V_e D_c h C (\Delta p - q_0) \cdot \tag{5-8}$$

Introducing the dimensionless velocity parameter

$$\mathcal{V} \equiv V_0 \Big/ \sqrt{\frac{L}{\rho S}} = \sqrt{2} \frac{V_0}{V_e} \tag{5-9}$$

and again using the value 0.61 for D_c gives

$$\frac{LV_0}{P} \doteq 1.16\,\frac{S}{hC}\cdot\frac{\upsilon}{1+\frac{1}{2}\upsilon^2}. \tag{5-10}$$

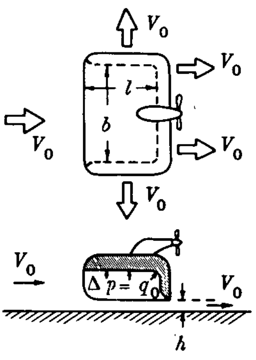
Compared with the corresponding air curtain results, the plenum concept falls considerably short, both as to figure of merit and (especially) equivalent lift/drag ratio. Nevertheless, it has its supporters among GEM investigators, because of its extreme simplicity. Of the GEM concepts, the plenum is the most compatible with cheap, lightweight, rugged construction.

More detailed information on the plenum concept is found in Refs. 9 and 10.

RAM WING

The ram wing is believed to be the oldest of the ground cushion concepts, having been introduced in Finland by Kaario as early as 1935. The ram wing concept is represented schematically in Fig. 6. The vehicle takes the form of a box with the bottom and front side removed. The basic ram wing has no hovering capability, but if it moves forward very close to the ground (so that velocities within the ground cushion are negligible), the ram pressure $\rho V_0^2/2$ builds up beneath the base, giving a lift force

$$L = \frac{1}{2}\rho V_0^2 S\,. \tag{6-1}$$



Simplified Ideal Theory:

Cruise	
$L = \frac{1}{2}\rho V_0^2\, lb$	(6-1)
$D_{ram} = \rho V_0\,(2lhD_c)\,V_0$	(6-2)
$P = D_{ram}\,V_0$	(6-3)
$\boxed{\left(\frac{LV_0}{P}\right)_{opt} \doteq 1.64\,\frac{S}{hC}\,\frac{1+b/l}{2}}$	(6-4)
$\upsilon \equiv \frac{V_0}{\sqrt{L/(\rho S)}} = \sqrt{2}$	(6-5)

Fig. 6. Ram wing

Only the air which leaks out at the tips contributes to the ram drag, since the air leaked out the rear recovers it original rearward momentum. Assuming the discharge coefficient D_c to be 0.61,

$$D_{ram} = \rho V_0\,(2lhD_c)\,V_0 \tag{6-2}$$

$$P = D_{\mathrm{ram}} V_0 \tag{6-3}$$

$$\frac{LV_0}{P} = 1.64 \frac{S}{hC} \frac{1 + \frac{b}{l}}{2} . \tag{6-4}$$

This elementary solution gives equilibrium flight at only one speed, corresponding to

$$\mho \equiv \frac{V_0}{\sqrt{L / (\rho S)}} = \sqrt{2} . \tag{6-5}$$

In practice, one of the other ground cushion concepts must be combined with the ram wing to maintain the ground cushion during acceleration to and deceleration from this equilibrium speed. For equilibrium at speeds higher than given by (6-5), the height h must increase until the cushion pressure falls to something less than the full ram pressure. Even at $\mho = 2$, the lift contributed by suction pressure induced on the upper surface of the wing (neglected by the simplified ideal theory) is significant, but it does not dominate the problem. At higher speeds this suction-pressure lift does begin to predominate, and the simplified ideal theory must be abandoned in favor of approaches along the line of conventional wing theory.

It is interesting to note, from Eq. (6-4), that the ram wing, like the conventional aircraft wing, gives much better performance with high aspect ratio, b/l.

There has been practically no development effort devoted to the ram wing in the U.S. However, several U.S. groups have recently begun study programs, and a rapid expansion of activity in this area is not unlikely.

Kaario's discussion of the ram wing concept is found in Ref. 11.

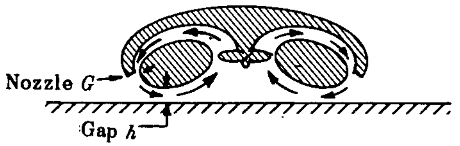
DIFFUSER-RECIRCULATION SYSTEM

From an academic point of view, the diffuser-recirculation system is perhaps the most interesting of all the ground cushion concepts. It is the only one which can, in principle, sustain a vehicle at a finite height above the ground without dissipating any power.

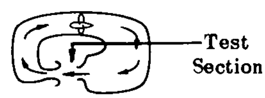
The diffuser-recirculation system is represented schematically in Fig. 7. A recirculating flow, rather like a standing ring vortex, is maintained within and under the vehicle. At the periphery of the base, the flow passes through a nozzle G, and is then exposed to atmospheric pressure until it passes through the gap h between the underside of the base and the rim. The static pressure at the gap h is thus essentially atmospheric. The geometry of the base and internal passages is so arranged that the highest velocity (and thus the lowest pressure) of the flow occurs at the periphery, where the flow is exposed to atmospheric pressure. The average static pressure under the vehicle is therefore higher than atmospheric, giving a net lift force on the vehicle. Under the assumption of inviscid flow, this is a closed system with no energy dissipation. Simplified ideal theory thus gives

$$M_{\mathrm{opt}} \equiv \frac{1}{2\sqrt{\rho}} \frac{L}{P} \sqrt{\frac{L}{S}} = \infty$$

$$\left(\frac{L\,V_0}{P}\right)_{opt} = \infty .$$



Diffuser-Recirculation Vehicle



Open-Jet Wind Tunnel

Simplified Ideal Theory:

Hover: $M = \dfrac{1}{2\sqrt{\rho}}\,\dfrac{L}{P}\sqrt{\dfrac{L}{S}} = \infty$

Cruise: $\dfrac{L\,V_0}{P} = \infty$

Wind Tunnel Analogy:

Hover: $M = \dfrac{E\,K_p^{3/2}}{2\sqrt{2}}\;\dfrac{S}{h\,C}$

Cruise: $\dfrac{L\,V_0}{P} = \dfrac{E\,K_p^{3/2}}{\sqrt{2}}\;\dfrac{S}{h\,C}$

Fig. 7. Diffuser-recirculation system

Most of the research and development effort in the diffuser-recirculation area is concerned with modifications and variations of the basic system described. The practical outlook for the basic diffuser-recirculation system is not encouraging, primarily because of the following considerations:

1. The geometric relationship between the nozzle G and gap h is rather critical. This relationship can be established properly only for a single operating height; and variations in h from wind and surface disturbances cannot be avoided. Particularly disconcerting is the occurrence of an unstable condition, wherein lift force decreases with decreasing height, at heights below the optimum.

2. In practice, as in theory, the performance is totally dependent upon efficient diffusion (deceleration and static pressure recovery) of the flow as it moves inward between the vehicle base and the ground. Irregularities in the surface over which the vehicle moves would make efficient diffusion impossible.

An interesting analogy can be drawn between the diffuser-recirculation vehicle and the open-jet wind tunnel, also sketched in Fig. 7. The wind tunnel is also a closed system in which the maximum velocity occurs at a section (the test section) where the flow is exposed to the atmosphere. The power dissipation of the wind tunnel would be zero with inviscid flow; and, like the vehicle, its actual performance depends upon an efficient diffusion process. Tunnel performance is often expressed by the "energy ratio" E, defined as the ratio of the kinetic energy flux through the test section to the power dissipation. Applying this terminology to the vehicle, taking the gap area hC as analogous to the test section area, gives

$$P_c = \frac{1}{2} \rho V_e^3 h \frac{C}{E}$$

$$L = \Delta p S = k_p \frac{1}{2} \rho V_e^2 S$$

where k_p is the effective pressure recovery factor. This gives

$$M \equiv \frac{1}{2\sqrt{\rho}} \frac{L}{P} \sqrt{\frac{L}{S}} = \left(\frac{k_p}{2}\right)^{3/2} \frac{S}{hC} .$$

Open-jet wind tunnels typically have energy ratios around 3.0. Using this value, and assigning (arbitrarily, and probably optimistically) the value of 0.7 to k_p would give

$$M \doteq 0.6 \frac{S}{hC}$$

as a rough estimate of actual hovering performance, under favorable conditions. This is the same as the estimated actual hovering performance of well-designed air curtain vehicles.

This numerical result is questionable, due to the assumptions employed. Of greater significance is the demonstration that, for the diffuser-recirculation concept, just as for all of the other ground cushion concepts, the performance is directly dependent on the size/height ratio, S/hC.

More detailed information on the diffuser-recirculation concept is found in Ref. 12.

SIMPLIFIED ENGINEERING ANALYSIS OF THE AIR CURTAIN VEHICLE

The foregoing "simplified ideal theory" analyses serve only to give mathematical expression to the basic ideas involved in the various ground cushion concepts. Comparisons between the various concepts on this basis are still only comparisons of ideas. Realistic comparisons of engineering merit will require not only more complete analysis, but a considerable background of systematic empirical information. Such comparisons are not possible at the present state of the art. More complete analyses of several of the concepts will be found in the references, but only in the case of the air curtain concepts is there a sufficient body of systematic experimental data to support a realistic assessment of the practical performance.

It would be superfluous to repeat here any detailed analysis of air curtain vehicle performance. It may be useful, however, to follow a simplified development, along the lines of the simplified ideal theory, but accounting, in an elementary way, for the most significant of the effects previously neglected. These are:

1. Internal losses, accounted for by a duct efficiency η_d, compressor efficiency η_p, and internal efficiency $\eta_{\text{int}} = \eta_p \eta_d$.

2. Base pressure loss, accounted for by an augmentation efficiency η_A.

3. Aerodynamic lift coefficient C_{L_0}, and parasite drag coefficient C_{Df}, produced by the external flow field.

4. Propulsion system losses, accounted for by the propulsive efficiency η_F.

Both tangential jet deflection β (Fig. 3) and separate-propulsion-system power will be accounted for. This is appropriate to a semi-integrated air curtain concept, wherein part, but not all, of the thrust is derived from the air curtain itself. The resulting equations will be reducible to the simple or integrated air curtain cases simply by setting β equal to zero, or setting air-curtain thrust equal to net drag, respectively.

The lift is approximated by

$$L = \Delta p S \ \boxed{+\ C_{L_0}\ q_0\ S} \tag{8-1}$$

(The box will be used to indicate modifications to the simplified ideal theory.)

The base pressure is approximated by

$$\Delta p = \rho\ V_j^2\ \frac{G}{h}\ (1 - \sin\theta)\ \cos^2\beta\ \boxed{\eta_A}\ . \tag{8-2}$$

The cushion power is approximated by

$$P_c = \boxed{\frac{1}{\eta_{int}}}\ V_j\ G\ C\ \cos\beta\left(\frac{1}{2}\rho\ V_j^2 + \frac{1}{2}\Delta p - \boxed{\eta_d}\ q_0\right). \tag{8-3}$$

The ram drag, parasite drag, and air curtain thrust are given by

$$D_{ram} = \rho\ V_j\ G\ C\ \cos\beta\ V_0 \tag{8-4}$$

$$D_f = \boxed{C_{Df}\ q_0\ S} \tag{8-5}$$

$$T_j = \rho\ V_j^2\ G\ C\ \cos\beta\ \sin\beta\ \boxed{\frac{2l}{C}} \tag{8-6}$$

where the factor $2l/C$ accounts for the fact that the tangential force component of each element of the air curtain lies tangential to the local periphery, not, in general, precisely parallel to the direction of flight.

The propulsion power is net drag times flight velocity, corrected for propulsive efficiency:

$$P_p = \frac{(D_{ram} + \boxed{D_f} - T_j)\ V_0}{\boxed{\eta_F}}\ . \tag{8-7}$$

Combining, and forming dimensionless ratios:

$$\frac{P_c}{L^{3/2}/\sqrt{\rho S}} = \frac{1}{\eta_{int}} \frac{\sqrt{(1 - \sin\theta)\frac{G}{h}\eta_A}}{2\,(1 - \sin\theta)\frac{S}{hC}\eta_A} \left[\left(\frac{1}{(1 - \sin\theta)\frac{G}{h}\eta_A \cos^2\beta} + 1\right)\right.$$

$$\left.\cdot\left(1 - \frac{C_{L_0}}{2}\mho^2\right)^{3/2} - \eta_d\mho^2\left(1 - \frac{C_{L_0}}{2}\mho^2\right)^{1/2}\right] \tag{8-8}$$

$$\frac{P_p}{L^{3/2}/\sqrt{\rho S}} = \frac{1}{\eta_F}\frac{D}{L}\mho \tag{8-9}$$

$$\frac{D}{L} = \frac{\sqrt{(1 - \sin\theta)\frac{G}{h}\eta_A}}{(1 - \sin\theta)\frac{S}{hC}\eta_A}\sqrt{1 - \frac{C_{L_0}}{2}\mho^2}\,\mho + \frac{C_{Df}}{2}\mho^2$$

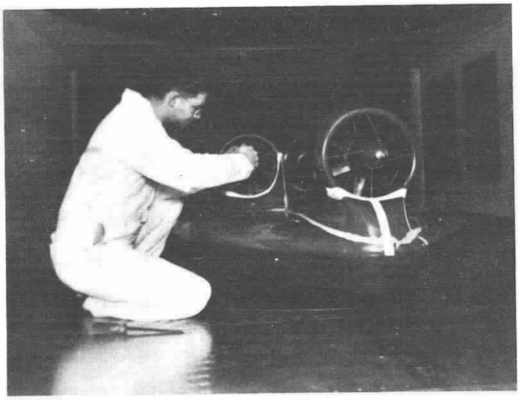
$$- \frac{\tan\beta}{(1 - \sin\theta)\frac{S}{hC}\eta_A}\left(1 - \frac{C_{L_0}}{2}\mho^2\right)\frac{2l}{C} \tag{8-10}$$

$$\frac{LV_0}{P} = \mho \bigg/ \left(\frac{P_c + P_p}{L^{3/2}/\sqrt{\rho S}}\right). \tag{8-11}$$

These last four equations form a system from which realistic estimates of air curtain performance (whether simple, integrated, or semi-integrated air curtain) can be made — if estimates of the parameters η_A, C_{L_0}, and C_{Df} can be obtained. The problem of providing a reliable basis for estimating these three parameters occupies much of the systematic GEM research now underway in the U.S. (The internal-, duct-, and propulsive-efficiency problems are, of course, age-old problems, not peculiar to GEM's, and highly developed techniques for dealing with them are available in the literature.) Some progress has been reported in the references. A good deal of additional progress can be expected in the immediate future.

It will suit our present purposes to side-step the question of how these estimates can be made, and to use, for our discussion, a source of data for which the necessary parameters have been evaluated to some reasonable degree of accuracy, experimentally. Such a source is Ref. 5, which presents data from wind-tunnel tests of the David Taylor Model Basin's Gem Model 448. This model represents the nearest approach to a realistic, practical GEM configuration for which laboratory-controlled performance test data are presently available.

Photographs of the model are presented in Fig. 8. The sketch in Fig. 3, used to illustrate the integrated air curtain concept, is also representative of the geometric arrangement



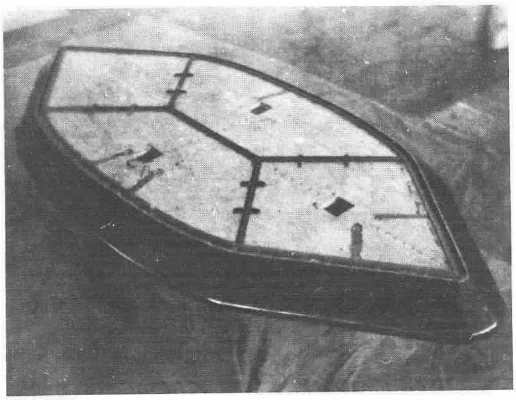


Fig. 8. DTMB GEM Model 448

and airflow path of Model 448. The four compressor nacelles are powered by calibrated electric motors. Several interchangeable sets of nozzle control vanes were employed to produce various tangential deflection angles β (see Fig. 3). The model is not equipped with an actual propulsion system, but propulsive power was accounted for in the test data reduction by arbitrarily assuming it to equal 1.25 DV_0 (i.e., $\eta_F = 0.8$). (It should be noted that, as explained in Ref. 3, the assumption $P_p = 1.25\ DV_0$ becomes unrealistic at low forward speeds. Nevertheless, it provides a convenient and reasonable basis for quick examination of the overall performance characteristics.) The performance parameters necessary for evaluation of Eqs. (8-8) through (8-11) vary slightly with changing test conditions, but it will suffice for our purposes to use the fixed set:

$$\eta_{int} = 0.57 \qquad \eta_A = 0.73$$

$$\eta_d \doteq 0.70 \qquad C_{L_0} = 0.42$$

$$\eta_F = 0.80 \qquad C_{Df} = 0.074 .$$

(These performance parameters reflect design features dictated by scale and by research utility considerations. A highly developed vehicle should have substantially improved internal and duct efficiency and parasite drag coefficient, perhaps 0.8, 0.9, and 0.04, respectively.) The pertinent geometric data for the model are:

$$
\begin{aligned}
S &= 20.50 \text{ square feet}\\
C &= 18.85 \text{ feet}\\
l &= 8.45 \text{ feet}\\
G &= 0.058 \text{ foot}\\
\theta &= -45^\circ .
\end{aligned}
$$

Performance calculations from Eqs. (8-8) through (8-11) are compared with experimental results in Fig. 9. The consistent agreement, over wide ranges of test conditions, strongly suggests that the very elementary considerations employed in the simplified engineering analysis correctly represent the major physical phenomena involved.

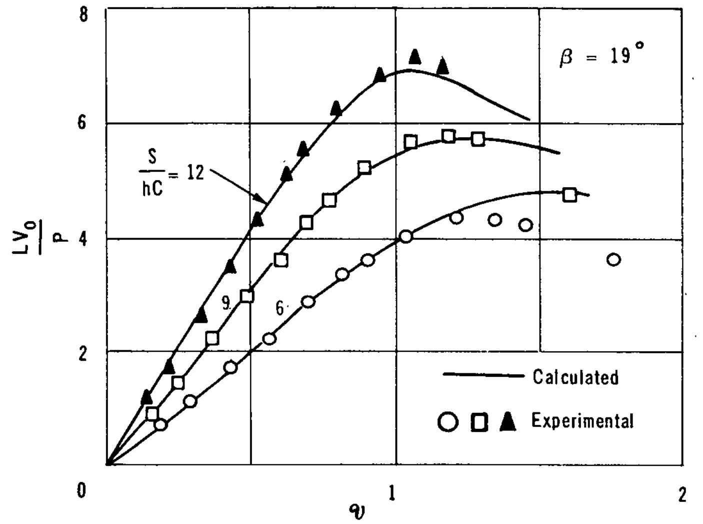
(It is not our purpose here to consider the detailed performance of the air curtain GEM. However, in passing, one should note: (a) the strong, almost linear dependence of the equivalent lift/drag ratio, LV_0/P, on size-height ratio, S/hC, shown in Fig. 9a, (b) the significant performance advantage indicated in Fig. 9b for the vehicle with controlled tangential deflection β of the air curtain, and (c) the further advantage indicated for such a vehicle, in Fig. 9c, in terms of the power-required distribution between cushion power and propulsive power. The total installed power required, if separate power sources are used for the cushion system and propulsion system, will be the sum of the maximum cushion power required and the maximum propulsion power required. This sum, especially for the simple air curtain ($\beta = 0$) is very much larger than the maximum total power required at any given instant.)

Having confirmed that the simplified engineering analysis gives a reasonable representation of the actual facts, we are in a position to examine the relationship between the simplified ideal theory and physical reality. It will be easiest to consider the simple air curtain ($\beta = 0$) for this purpose. For direct comparison, the appropriate form of simplified ideal theory is obtained from Eqs. (8-8) through (8-11) by setting

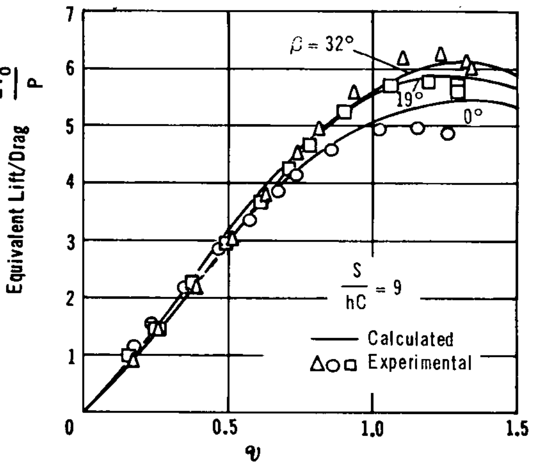
$$\eta_{int} = \eta_d = \eta_F = \eta_A = 1.0$$

$$C_{L_0} = C_{Df} = 0 .$$

The most important information one may hope to obtain from simplified ideal theory is a qualitative prediction of equivalent lift/drag ratio. The calculation of optimum equivalent lift/drag ratios from Eqs. (8-8) through (8-11) is rather laborious. However, as suggested by Ref. 4, and confirmed by Fig. 9, an excellent indication of effects on optimum performance is obtained by considering performance at $\mho = 1$. Figure 10 gives the result of such a calculation, starting with simplified ideal theory, and with successive curves which result from setting the performance parameters, in steps, to the values appropriate to Model 448. Each of the "real" effects gives a successively less optimistic performance prediction compared to the simplified ideal theory. At the end, the actual equivalent lift/drag ratio of Model 448 is very much lower than predicted by simplified ideal theory (about one-half), but the essential conclusion of the simplified ideal theory as to the nearly linear relationship between equivalent lift/drag ratio and size/height ratio is borne out.

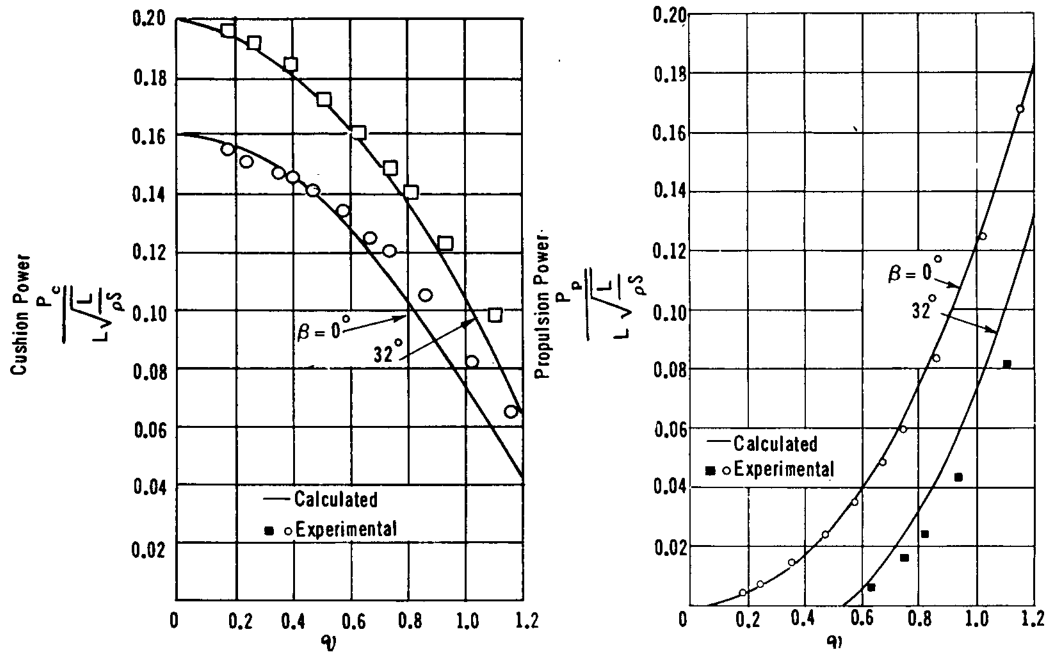


(a) Equivalent lift/drag versus speed



(b) Effect of β on equivalent lift/drag

Fig. 9. Comparison of "simplified engineering analysis" calculations with experiment



(c) Distribution of power between cushion and propulsion systems, $S/hC = 9$

Fig. 9. Comparison of "simplified engineering analysis" calculations with experiment (Cont'd)

Curve	η_F	η_A	η_{int}	η_d	C_{L_0}	C_{D_f}
A	1.0	1.0	1.0	1.0	0	0
B	0.8	1.0	1.0	1.0	0	0
C	0.8	0.733	1.0	1.0	0	0
D	0.8	0.733	0.57	0.70	0	0
E	0.8	0.733	0.57	0.70	0.42	0.074

Legend

$\beta = 0$ $\mathcal{V} = 1$

Calculated

(Equations [8-8] through [8-11]) { ——— / - - - -

Experiment (Reference 5) ●

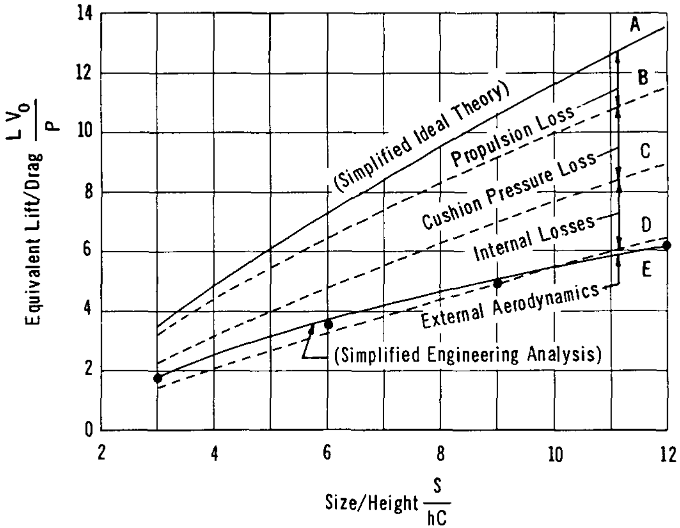


Fig. 10. Influence of "real" effects neglected by the simplified ideal theory

Similar demonstrations have been or could be made, from data available in the references, that the hovering performance (figure of merit) is also, experimentally, almost directly proportional to the size/height ratio in the cases of all the air curtain types, the water curtain type, and the plenum type. The hovering performance is less significant, in terms of vehicle usefulness; but this lends additional support to the essential conclusions of the simplified ideal theory.

RESUME

The simplified ideal analyses furnish valuable insight into the fundamental ideas of the air cushion concepts. They furnish, further, the invaluable information that all of the air cushion concepts have in common the property of rapidly improving performance with increasing size/height ratio. Unfortunately, they leave unresolved – as does also experience to date – the essential question: Which concept is best for which application?

The following remarks are in large part merely the author's opinions:

Air Curtain – Most thoroughly studied, and correspondingly best understood of the air cushion concepts; most logical choice for early applications.

Plenum – Simplest and cheapest to build but ranks low in performance; very poor prospects for favorable high-speed performance unless combined with another concept, such as ram wing.

Ram Wing – Interesting only in combination with some other concept to provide low-speed flight capability; requires much additional research to evaluate practical problems and merits; appears to have great potential, if stability and control problems prove tractable.

Diffuser-Recirculation System – Intriguing idea, but unlikely to prove practical.

Water Curtain – Falls far short of theoretical expectations, but may eventually prove advantageous for moderate-speed over-water applications; not amphibious

Skegs – (Previously considered in combination with air curtain, but equally suitable for combination with any of the other concepts.) Likely to prove advantageous for moderate-speed over-water applications; not amphibious.

THE GEM'S PLACE IN TRANSPORTATION

In every one of the ground cushion concepts considered, elementary analysis indicates a direct dependence of the performance on the size/height ratio. Except for the air cushion types, the available experimental evidence is rather limited; but every bit of data which is available tends to confirm this direct dependence. This alone is enough to identify the natural form and habitat of ground effect machines: very large vehicles operating very close to the earth's surface. Since land areas are, in general, topographically unsuitable for the operation of large, high-speed vehicles at low heights, this means ocean-going GEM's. A more specific idea of the sizes and heights involved is afforded by Fig. 11. For a GEM with $LV_0/P = 0.9\ S/hC$ (appropriate to a highly developed air curtain vehicle) the equivalent lift/drag ratio is plotted in comparison with existing aircraft, and the size is given for each of several operating heights. The argument implied in Fig. 11 is, of course, somewhat superficial. There is the possibility that one of the other ground cushion concepts will

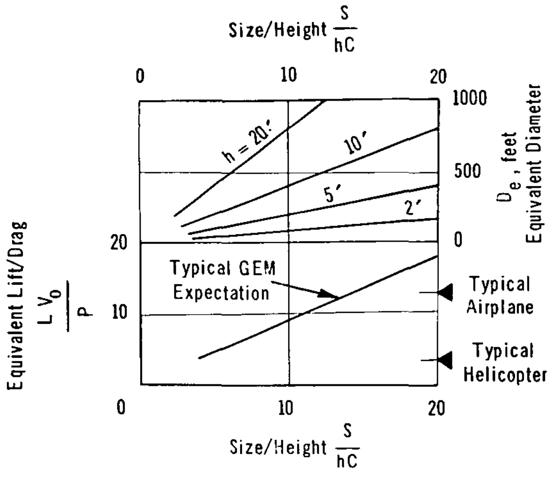


Fig. 11. The relationship between performance and size for a GEM

provide better performance than the air cushion. There is the possibility that a GEM can compete successfully, even with somewhat inferior lift/drag ratio, because of its more flexible load-handling abilities and terminal facility requirements. And there is the possibility that the GEM's apparent compatibility with nuclear power will, in future years, loom larger than the lift/drag consideration. Nevertheless, it would be necessary to stretch any or all of these possibilities rather far to avoid the conclusion that ocean-going GEM's will be very large vehicles indeed. As such, their development represents a very imposing economic undertaking, and, while a great deal of current GEM research and study is directed toward the ocean-going machine, it may be assumed that serious development efforts will await clarification of the present confused state of knowledge.

In the meantime, GEM applications will be made in "fringe" areas where special circumstances or special requirements make moderate-size GEM's attractive. The two main categories of such fringe areas are:

1. The limited application possibilities over flat inland areas and protected waters, where extremely low operating heights afford good performance for moderate-size vehicles. These include passenger and cargo ferries, emergency craft, sport craft, and swamp buggies.

2. Limited military application possibilities where requirements for speed, amphibious capability, and load-carrying ability outweigh the conventional economic performance criteria.

Early applications are likely to center around the air curtain concepts. Only in this area is the state of the art sufficiently advanced to permit rational design. Where the future will lead is anybody's guess.

Whatever form the GEM of the future takes, this much is certain: If energetic and enthusiastic activity count for much, the GEM's future in the U.S. should be very bright indeed.

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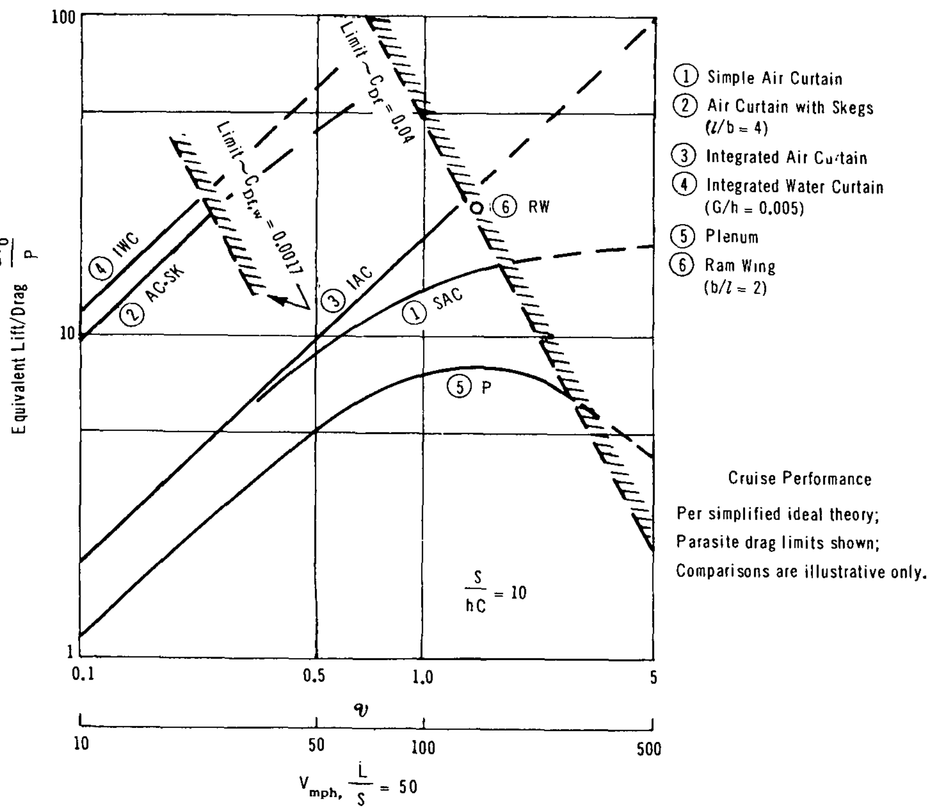
ADDENDUM

ILLUSTRATIVE COMPARISON OF THE GROUND CUSHION CONCEPTS

Direct comparisons between the various ground cushion concepts are very risky at the present state of the art. The simplified theory presented in the body of this paper neglects many factors, which may affect one concept more than another, and the degree of experimental understanding is by no means the same for all of the concepts. For this reason it was originally decided to avoid direct comparisons.

However, in retrospect it became apparent that direct comparisons would go far toward clarifying many of the points made. It was decided to present the comparisons shown in Fig. 12 after all. The reader is implored to accept Fig. 12 as merely illustrative of some of the distinctive characteristics of the different concepts, and to use it cautiously or not at all as a criterion of their relative practical usefulness.



The cruise performance curves for the six concepts shown are plotted directly from the simplified ideal theory. Special assumptions, such as length/beam ratio of 4 for the air curtain with skegs, and nozzle-width/operating-height ratio of 0.005 for the water curtain, are noted in the legend. The seventh concept, the diffuser-recirculation system, is omitted, since the dearth of practical experience makes it impractical to plot a curve of even illustrative value.

Also shown in Fig. 12 are performance limits imposed by parasite drag, under assumed parasite drag coefficients:

$$C_{Df} = \frac{D_f}{\frac{1}{2}\rho V_0^2 S}$$

$$C_{Df,w} = \frac{D_f}{\frac{1}{2}\rho_w V_0^2 S}.$$

The "simplified ideal theory" curves account for cushion power and momentum drag but ignore parasite drag. The "limit" curves account for parasite drag but ignore all other power requirements, as follows:

$$P_{\text{limit}} = D_f V_0$$

$$L \equiv \frac{\rho S V_0^2}{\mho^2}$$

$$\left(\frac{LV_0}{P}\right)_{\text{limit}} = \frac{2}{C_{Df}\mho^2} = \frac{2}{C_{Df,w}\mho^2} \cdot \frac{\rho}{\rho_w}.$$

The concepts which do not involve contact with the water (curves 1, 3, 5, 6) are assumed, for illustrative comparison purposes, to have parasite drag coefficients of $C_{Df} = 0.04$; the concepts which do involve water contact are assumed to have $C_{Df,w} = 0.0017$. (A calculation which included cushion power, momentum drag, and parasite drag would give a curve which followed closely below the "simplified ideal" curve at low speed, then peaked over and followed closely below the "limit" curve at high speed.)

The relative performance picture afforded by Fig. 12 should be interpreted as follows:

1. Within the no-water-contact family, the relationship between curves 1, 3, and 5 is probably in reasonable qualitative harmony with the facts. If lower S/hC or lower C_{Df} were assumed, the integrated air curtain would appear slightly better, compared to the simple air curtain; the plenum, slightly poorer. Curve 6, for the ram wing, is only a single point, since under the approximations used in theory, equilibrium flight occurs at only one speed coefficient, $\mho = \sqrt{2}$. If lower S/hC or lower C_{Df} were assumed, the ram wing could be made to appear superior to the other members of the no-water-contact family, by assigning it a higher aspect ratio b/l.

2. Within the water-contact family, the positions of curves 2 and 4 relative to each other are not meaningful, since they can be substantially changed or reversed by assigning a different nozzle-width ratio G/h to the water curtain and/or a different length/beam ratio l/b to the air curtain with skegs.

3. Between the two families, absolute performance comparisons are meaningless for the same reasons. However, the significant and valid point that the water-contact concepts are superior at low speeds, while the no-water-contact concepts are superior at high speeds, is very well illustrated. The exact degree of superiority, and speed range to which it applies, depends very heavily on the respective parasite drag coefficients. The values of C_{Df} and $C_{Df,\,w}$ used in Fig. 12 were selected arbitrarily, for illustrative purposes only.

DISCUSSION

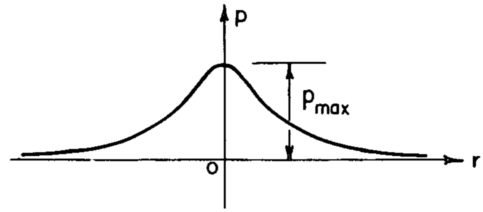
R. L. Weigel (University of California)

I do not want this to be construed as a criticism of Mr. Chaplin's paper: the subject he was given was extremely broad to cover. However, there is one important aspect that he did not touch upon and that is the wave resistance of this type of vehicle moving over the water surface. I have chosen this one aspect because I think it of general interest to naval architects and furthermore, as this meeting is dedicated to Sir Thomas Havelock, I think it is interesting that the technique used in predicting the wave resistance is due to Sir Thomas Havelock. Rather than considering a true ship, he considered a pressure disturbance moving over the surface of the water, and this is precisely the problem of the ground effect machine. Sir Thomas Havelock's main advance is that he considered a pressure area rather than a pressure point, and he formulated his problem in such a manner that numerical results could be calculated from the equations rather than just looking at the integrals and so forth. Furthermore, he even went so far as to calculate the resistance in almost the exact form that is needed to obtain the information for designing a ground effect machine. Sir Thomas Havelock considered a pressure disturbance something like that shown in Fig. D1 where pressure is measured vertically and the radius of the disturbance is measured along the abscissa, with axial symmetry assumed. Now, he chose one particular shape; however, tests that we have made have indicated that we can have quite irregular shapes such as a double hump shape and the resistance is practically the same as one obtains from this shape that Havelock assumed.*

Havelock's† numerical results are shown in Fig. D2. Very often in naval architecture we are dealing with the deep-water aspects and a Froude number based upon the length of the ship. If we deal in inland waterways we talk about a Froude number based upon the water depth. It turns out for ground effect machines we must consider both of these simultaneously. So we have a parameter which is the diameter of the pressure disturbance divided by the water depth. This is a dimensionless resistance which is a specific weight of water (ρg) times the resistance, and this is the wave resistance (R) divided by 2π times the diameter of the ground effect machine times the maximum pressure squared (that exists

* R.L. Wiegel, C.M. Snyder, and J.B. Williams, "Water Gravity Waves Generated by a Moving Low Pressure Area," Trans. Amer. Geophys. Union 39 (No. 2):224-236 (Apr. 1958).

† T.H. Havelock, "The Effect of Shallow Water on Wave Resistance," Proc. Roy. Soc. (London) A100 (No. A705):409-505 (Feb. 1, 1922).



D = Effective diameter of pressure area, feet.

d = Water depth, feet.

ρ = Mass density of water, slugs/ft.^{2}

g = Gravity, ft./sec.^{3}

R = Wave resistance, pounds.

p_{max} = Maximum pressure of pressure area, lbs/ft.^{2}

Fig. D1. A pressure disturbance on the water surface

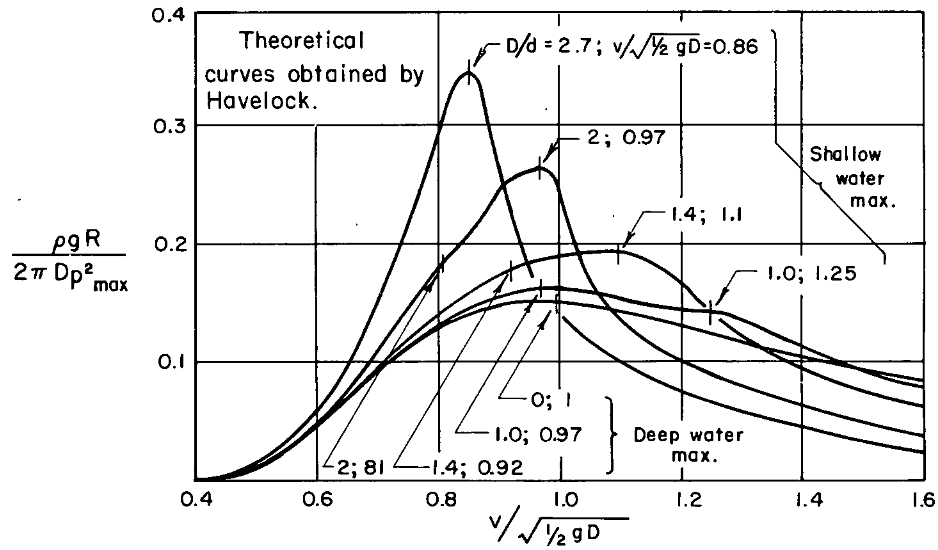


Fig. D2. Theoretical curves obtained by Havelock

in the base cavity). Then, for various values of the ratio of the diameter of the disturbance to the water depth we can get a series of curves as shown (Fig. D2); where the diameter is great compared with the water depth we have a shallow water resistance peak, where the diameter is small compared with the water depth we have the typical deep-water peak, and where we have intermediate values we have double peaks, the deep-water and the shallow-water peak, or shoulders. I think the thing of primary interest is just how great is the wave resistance due to a high-speed vessel of this sort. Using the results of Havelock I made several calculations just briefly to give you an idea. If we choose a craft that is large, that's the type the Navy is considering, the type that Mr. Chaplin mentioned, with the diameter of 300 feet, flying over the ocean at some relatively high speed (I have had to choose a speed of only 65 knots, which is low, but if I chose higher it would have been off these curves) the resistance will be lower than what I show here. If it is moving over water deep enough so that $D/d \approx 0$ (where d is the water depth), then $V/\sqrt{gD/2} = 1.6$, and $\rho gR/2\pi Dp^2_{max} = 0.085$. In very deep water it turns out that the horsepower that is utilized in wave resistance is only 12-1/2 hp, for a base pressure of 5 pounds per square foot, which is practically negligible, as we are talking about a craft with a 40,000- to 50,000-hp motor. It is almost unbelievable. The horsepower loss is dependent upon the square of the base pressure, so if you get up to the more modern concepts, which have a higher base pressure loading, and you go up to say 30 pounds per square foot the horsepower goes up to 440, and even this is only of the order of 1 percent. It is becoming appreciable but is still relatively small. In operating the GEM, it will move from deep water into shallow water as it is coming ashore and here is where we have to be careful. We can hit some of these "hump" speeds and for one combination which I picked at semirandom (I chose a water depth of 100 feet and a forward speed of 55 knots) the wave resistance can rise to over 1500 to 1600 hp. In general when we are operating over deep water at high speeds, the wave resistance will be negligible. The only time it will tend to become important is when one is bringing it in over relatively shallow water. The stopping of one of these vehicles is a major problem. Consequently this high resistance that one gets as one comes into shallow water probably will turn out to be very useful because I think that maybe for slowing a GEM we can make use of this shallow wave resistance.

In practice the peak pressure will be higher than the average base pressure on a GEM, and the power necessary to overcome wave resistance will be higher than the values mentioned, perhaps by a factor of almost two.

L. W. Rosenthal (Folland Aircraft Limited)

I would like to thank Mr. Chaplin for the very pleasant paper he presented, but I am going to be so ungracious as to suggest that it had the wrong title! I think perhaps it might well have been called "A Simplified Method of Comparing the Performance of Ground Effect Machines." During the whole of the Symposium, I have hoped that the hydrodynamicists would have discussed the position of the ground effect machine in the light of the conclusions that Mr. Chaplin had arrived at. When Mr. Oakley spoke, he did in fact suggest that attention had been given to the position of the ground effect machine, with the limitations that we know, in the marine transport pattern. Unfortunately, he did not develop this point. Mr. Van Manen, discussing the Crewe Eggington hypothetical project, quietly but firmly took it to pieces on the structure weight grounds, but he gave no constructive comment on what he would suggest instead. Mr. Newton followed this up by saying that the structural problem concerned with a large ground effect machine in a seaway needed investigation, but here again he gave no lead at all. Mr. Chaplin broadly touches on the place of the ground effect machine but his comments are based on a general parameter and not necessarily on the specialized uses to which we might be able to put the vehicle at the moment.

What I would like to suggest, if this is not ungracious again, is that possibly the hydrodynamicist and the naval architect are dragging their feet on this particular problem, or is it that no conclusions have yet been reached and we are looking for something or some information which does not yet exist.

Another point to which Mr. Chaplin made no reference in his assessment of the small machines, and this could hardly have been considered a secondary one, is the means of obtaining pitch and roll stability and the penalties associated therewith. I would like to

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ask if Mr. Chaplin would like to discuss these points in the light of the title of his paper "Research and Development of Ground Effect Machines in the United States."

J. L. Wosser (ONR, Washington)

After listening to all the papers on hydrofoils and associated subjects that have been delivered to date at this meeting, let me state that I am very impressed with the level of the work that has been done. There has been just this one paper presented in the area of ground effect machines (GEMs). Most of this was Mr. Chaplin's original work. It included a brief summary of some of the other things that have been done, but very brief. I would like to point out that as far as we in the United States are concerned, we consider the GEM state of the art stands about where that of the airplane did in 1904, or where you gentlemen with the hydrofoil boat were in 1930. We are just getting started in this field, research wise. However, there is a considerable research effort underway.

Within the Office of Naval Research we are supporting some 16 research tasks, all coordinated into an overall GEM research program. Our objectives in this area are not the far-out aims that Mr. Chaplin mentioned at the conclusion of his paper: the 600-foot transoceanic GEM. In order to get this type of research effort underway, we have more immediate aims. We are looking for the areas where the GEM's unique capabilities to travel over all types of surfaces (water, land, ice, snow, and mud) with equal facility can be utilized for military purposes. Now, this military approach is not the direction of the effort that is going on in England, and I am sure that Mr. Shaw will tell you about their commercial interests in a moment.

In addition to the work of the Office of Naval Research, extensive programs are being sponsored by Bureau of Naval Weapons, Bureau of Ships, and the Army Transportation Corps—all looking at their own areas of interest where the GEM has unique capabilities. The Army is particularly interested in overland vehicles that can travel over ice fields, mud flats, river deltas, etc., to open up these areas for future exploration or military operations. To give you a complete outline of the work that is being done would take too long. A thumbnail sketch would show that we have programs underway that will utilize more sophisticated approaches to some of the simplified theories you have heard presented today: viscous analyses of flow inside and external to the machines, propulsion and structural loads analyses, stability and control criteria, and ditching and flotation tests at the Seakeeping Basin here at Wageningen.

In conclusion, let me tell you a few of the things that have been achieved in the GEM area to date. During his talk Mr. Chaplin showed you some of the machines now in existence. Remember that we consider this thing to be in the period 1904 aircraft wise, or just starting out hydrofoil wise. In England, they have flown a GEM at 60 mph over the water on the Solent and successfully operated in eight-foot waves. In Switzerland, we watched a demonstration of a 30 × 30 foot-machine move over the water at 51 knots. The Curtiss-Wright Aircar has been officially clocked at 65 mph. At the present time, Mr. Carl Weiland, now working for the Reynold's Metals Company, is building a 90-mph machine at Louisville, Kentucky. This is supposed to be flying by Christmas (1960).

Yesterday I received a letter which I have already shown to Mr. Chaplin, so this will not come as any surprise. About two years ago at an Institute of the Aeronautical Sciences meeting in New York I met a Dr. Bertelsen. We discussed theoretical aerodynamics and GEMs for an hour and a half before I found out that he was an M.D., an obstetrician from

Illinois. He delivers babies and dabbles in aerodynamics on the side. So, with that as a background, these are abstracts from the letter I received from him yesterday: "Since I saw you in January 1960 at the IAS meeting, considerable work on Ground Effect Machines has obviously been done all over the world. We too have been busy. We now have what we consider to be the world's best Ground Effect Machine from the standpoint of control, hill climbing, stability and all around utility. We have a 200-hp, four-passenger flying machine in the chassis stage and have gotten well along in testing it. We get 12-inch altitude at 1600 lbs. gross weight, climb a 10-degree slope and go 50 mph over land or water. I feel that with all the theory and experimentation, we lead the world and challenge all comers in this category of small personal Ground Effect Vehicles."

R. A. Shaw (Ministry of Aviation, London)

It seems to me that you are mostly ship men here and therefore at a disadvantage in assessing the possibilities of what we call hovercraft in England and what you call ground effect machines in America. (What you call them on the continent, I have not yet discovered.) You are at a disadvantage because you look at them and you think, Reynolds' number, Froude's number—must explain it all this way.. It isn't really very helpful in working out an understanding of hovercraft or ground effect machines because, perhaps fortunately for everyone, the Froude number is not very important as far as ground effect machines are concerned, at least you soon get out of the regime in which it is important. Perhaps the particular case in which it will continue to be important is when your machine enters shallow water and does the transition from water to land. Apart from this, as ship people I feel that you are at a disadvantage because the problems of ground effect machines are largely the problems which have been studied by the aircraft industry in the past. Hovercraft certainly stand astride the two fields but a proper appreciation of ground effect machines and their future, I think, is easier for the aircraft people who rather rub their hands and say "jolly good, this is easy stuff," by comparison with the ship people who say "what a troublesome problem." It isn't really easy stuff because there are a lot of very curious things in it. What I wanted to bring home to you was that you couldn't assess it simply by ship standards. There are many subtleties in ground effect machines, and to give you an example, in a machine like the SRN-1, the British hovercraft, there was more power lost between the fan and the ducts than was used in the lifting and propulsion of the machine. This is just part of the problem of design, how to use your power effectively and efficiently in a novel way. People haven't got habits of thinking about hovercraft so they don't naturally choose a good solution. We have got to go through that process of finding good solutions and that's why people like Dr. Bertleson, who are following the example of the Wright Brothers and starting at the beginning, are just as likely at this stage to hit on a good solution as well-informed gentlemen at national establishments. In fact, we are in the pioneering stage and have to assess our progress in terms of that stage; it is 1904 as Col. Wosser said. But despite the fact that it is only 1904, or perhaps to be precise 1905, we are in England at the moment, building a 25-ton hovercraft capable of cruising at about 70 knots and carrying about 50 or 60 people several hundred miles. This is being achieved within a few years of the concept taking hold and within a year or 18 months of our first demonstration. By contrast, in the hydrofoil business, hydrofoils have been talked about for a generation and although they are now at the 80-ton stage, it has taken a generation to get there. With a background of aircraft experience it does look possible to get into the ground effect business in a matter of five years. I want to redress any influence which Mr. Chaplin's final statement might have on this audience in thinking that unless you got into the 600-foot or 10,000-ton class, ground effect machines have no place, by reinforcing what Col. Wosser said and that is you must not consider them in relation to conventional forms of transport on conventional routes.

You have got to think of the places you can't get to any other way, the marshes, the bogs, the ice flows, the out of the way places where you can't land an aeroplane. These are the places where I believe the hovercraft will really take root and where we shall gain the experience we need to allow us ultimately to build big ocean craft.

L. Landweber (Iowa Institute of Hydraulic Research)

The following comments were written before the contents of the present paper were known. That can be justified, however, by noting that these comments will serve as a bulwark to the title of Mr. Chaplin's presentation which they supplement by describing the work in this field that is being done at the Iowa Institute of Hydraulic Research. These comments were written by Lawrence R. Mack and Joachim Malsy:

Increasing interest in the possibilities of ground effect machines hasled many organizations in several countries to undertake basic studies of ground effect phenomena or studies of the means of practical utilization of these phenomena or both. During the past two years the Iowa Institute of Hydraulic Research, with the financial support of the Office of Naval Research, Contract Nonr 1509(03), has conducted both analytical and experimental investigations of the behavior of an annular-jet nozzle in proximity to solid and liquid surfaces. The results of the first year's work were presented at the Princeton Symposium on Ground Effect Phenomena in October 1959.* Since then a thesis describing an experimental study of an annular jet moving over water has been completed;† the results of this study, together with certain results for a stationary jet over land obtained preparatory to the over water experiments, are contained in a forthcoming report to the Office of Naval Research.‡ It is the intent of this discussion to summarize briefly these results.

A rigidly supported 7-inch-diameter annular nozzle discharging air vertically at different rates through a 1/8-inch gap was towed at different altitudes and speeds (including zero velocity) over initially quiescent water. Chosen combinations of these three variables led to 18 runs, for each of which the configuration of the water surface in the vicinity of the nozzle and the pressure distribution on the base of the nozzle were determined and plotted in the form of contour drawings.

The measurements of water-surface configuration were obtained by means of a capacitance wire and a point gage and were supplemented by stereo photographs as an aid in preparing contour maps. All stationary cases show a deep annular depression, caused by the impinging jet sheet, about 1.2 nozzle radii from the center line of the jet. The water surface under the nozzle base was considerably higher than what would, under the assumption of hydrostatic pressure distribution in the water, correspond to the pressure within the base cavity, a ridge at about 0.7 nozzle radius actually projecting above the still water surface. Forward speeds produced a considerable change in surface configuration from that of the static case. A forward ridge, or bow wave, was clearly discernible in all runs. With higher jet momenta and especially with higher speed, this bow wave seemed to split into two separate ridges, each situated in front of the nozzle about 45 degrees from the direction of

* Lawrence R. Mack and Ben-Chie Yen, "Theoretical and Experimental Research on Annular Jets over Land and Water," Proc. Symposium on Ground Effect Phenomena, Princeton, Oct. 1959, pp. 263-284. Also available as Reprint No. 164, State University of Iowa Reprints in Engineering.
† Joachim K. Malsy, "Experimental Investigation of an Annular Jet Traveling over Water," M.S. Thesis, State University of Iowa, Aug. 1960.
‡ Lawrence R. Mack and Joachim Malsy, "Experimental Studies of an Annular Jet," Iowa Institute of Hydraulic Research Report to the Office of Naval Research, Sept. 1960.

forward motion. At low velocities a half-moon-shaped depression, concave rearward, was beneath the front part of the base plate, the deepest parts being situated on either side of the nozzle center. This deep, very clearly visible depression moved to the rear with increasing speed and decreasing jet momentum. A high wave directly to the rear, which at times almost touched the nozzle, behaved similarly. In general, it can be said that all observed surface phenomena moved to the rear and became less pronounced in magnitude with increasing forward speed and decreasing jet momentum.

Base-plate pressures were measured at 14 piezometer holes, the number of locations being tripled for some runs by making two 45-degree rotations of the base plate, and isopiestic lines were drawn. In the stationary cases, especially for the higher altitude, a dip in pressure was noticed at about 0.7 nozzle radius, the same location as an elevation in the water surface. For all cases of forward speed the pressures were larger in the rear than in front, pressures at the center and extreme rear tending to be the highest. A roughly circular pressure valley at about 0.7 nozzle radius was clearly discernible, culminating in a saddle point between the two peak pressures. The high pressures to the rear and low pressures to the front combined to give nose-down pitching moments *acting on the base plate* for all cases of forward motion.

The total base-plate lift, and hence the lift-augmentation factor, for each run was obtained by integration of the pressure distribution. As expected, the augmentation factor was found to increase with decreasing altitude for all conditions. For the stationary runs the augmentation increased with decreasing jet momentum for a given altitude, in qualitative agreement with the theoretical predictions of Mack and Yen (first footnote) even though the surface-configuration data did not support certain of their assumptions. The numerical magnitudes of augmentation, however, were less than their idealized predictions. For constant altitude and jet momentum, forward speed, within the experimental range, improved the augmentation initially, then caused a decrease at still higher speed. This feature, particularly the increase of augmentation with increasing speed at low speeds, was more pronounced for the lower altitude tested. It thus appears that there is an optimum forward speed for each combination of altitude and jet momentum.

The same basic 7-inch annular nozzle, but with interchangeable mouthpieces, was also tested statically over a ground board. Discharge angles of 0, 15, and 30 degrees inward with a 1/8-inch annulus width were used, as were 0- and 15-degree angles with gaps of 5/16 and 1/2 inch. As expected, the 30-degree discharge angle gave the highest augmentation; no significant distinction in augmentation was noted, however, between the 0- and 15-degree angles. It was found that, within the gap range tested, the augmentation factor and the radial uniformity of pressure both increased with increasing gap width. This behavior of the former is in qualitative agreement with the theoretical prediction of Mack and Yen (first footnote, Fig. 1) within its range of validity (altitude less than the nozzle radius).

The results summarized herein of tests conducted at the Iowa Institute of Hydraulic Research on annular jets moving over water and stationary over land are described more fully in the report to the Office of Naval Research already referred to.

E. C. Tupper (Admiralty Experiment Works)

Mr. Chaplin did a very good job in condensing this research work into such a relatively short paper and I hate to suggest more work for him, but I would like to make two points.

First of all, I should like to emphasize how important it is that we should not progress too far with detailed experimental and theoretical work into the optimum form for resistance and propulsion alone. It may well be that many of the configurations so studied will prove quite unacceptable from the point of view of stability or seaworthiness. In my opinion, a broad, less detailed, study is first required into all aspects of design to determine the ranges of the principal dimensions which are likely to prove suitable for a balanced design.

Second, I would like to support Mr. Rosenthal's plea for some comments upon stability for the various configurations which have been discussed. This obviously is of prime importance in operation over waves as well as over calm water, and I would like the author's comments on whether passive stability may be adequate in some cases, or whether active stabilizing will always be necessary.

Harvey R. Chaplin

I will not reply at great length to the various comments, but will touch just a couple of the specific questions. About the optimum plan form for waves, certainly we don't have the answers on this yet but there is a program at the Netherlands Ship Model Basin underway now which will give answers having some bearing on this question and other programs within the United States too which are touching on this question. The plan form on which most of the recent air curtain research has been concentrated has been the plan form of the model which the photograph has shown, which is not too far distant from the ship forms and may not be totally unsuitable from the standpoint of possible wave impact. The stability question of course, is a very important question and it would be inexcusable not to cover the stability if we knew what to say about it. Again on the air curtain, a good bit is known about the stability; we know how to stabilize the machine, how to give it some natural stability, and we are close to knowing an answer to the question of whether it will be possible to have inherent stability or whether it will be necessary to have artificial stability. I personally feel that for the air cushion at speeds up to 100 knots it will be possible to have inherent stability without the black box. Beyond those two specific points, if I may abstract other comments en mass, they would add up to the fact that I have left an awful lot out and this is certainly true. I am afraid I cannot undertake to fill in very many of the gaps in the limited time that we have. Fortunately, some of the gaps were filled in by the commenters themselves and I thank them for that. Certainly the one thing that I shouldn't have left out is what was pointed out by Professor Wiegel, and this is the wave drag problem which bears on the person to whom the Symposium is dedicated. I certainly owe him gratitude for pointing out this inexcusable oversight. As to the title of the paper, I have to take my excuse from the fact that, as you know, in the scheme of things, the title and abstract of the paper were submitted some months in advance of the paper itself and as is often the case, the paper at the time it was submitted was quite a bit different from the way it was envisioned at the time the title was submitted.

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