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THE CASPAR ACV RESEARCH PROJECT REPORT NO. 3 - ON THE DRAG OF AIR CUSHION VEHICLES OVERLAND

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FOREWORD

This paper is presented as a progress report, examining the present status of the subject.

The intention is to put the present state of "Caspar" skirt/terrain interaction research programme before those working in this field, to act as a focus for discussion.

The theory advanced is tentative, and much of the experimentation reported is preliminary, so it should be regarded as a Working Paper, and not in any sense as a definitive treatment of the subject.

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1. INTRODUCTION

The resistance to motion of ACVs has been discussed at some length, notably by Trillo (Reference 1) who cites a considerable list of references, and by Waters et al, (Reference 2), but this discussion is almost entirely concerned with the overwater operation of ACVs.

Trillo does indeed state (p. 77, Reference 1) that:-

> "Wetting drag is a drag component accounting for the forces arising from contact with water of those parts of the hovercraft normally above the water surface. In this term is included spray impact drag, skirt drag in the form of induced wave drag, form drag and skin friction drag of skirt areas actually running through the water, and craft drag arising from increase in craft weight due to water taken on board the various surfaces."

He adds that (in 1971):-

> "No satisfactory method yet exists for the prediction of wetting drag. A common approach at the moment to determine wetting drag is simply to obtain total drag figures by measurement and to deduct from these the components which are calculable with reasonable accuracy. This method is obviously very approximate and there are usually doubts concerning several of the increments of drag, but it is conceivable that along these lines an empirical method could evolve when sufficient data have been accumulated for various craft."

As Trillo defines it, "wetting drag" includes the friction of the skirt in its passage through or over the waves which it encounters, and Trillo's subsequent discussion makes it clear that he considers this to cover skirt drag over land.

In Reference 2, Waters et al give a general treatment of drag very similar to Trillo's, but do add coefficients of friction between reinforced PVC (sometimes used as a skirt material) and concrete or grass. However, their treatment applies only to a "bag" skirt in contact with smooth ground, and also appears greatly oversimplified.

The general problem of the drag of an ACV, wearing any specified type of skirt, over terrain of any specified character (texture, microrelief, porosity, and vegetation cover), at any speed, cushion pressure, and lift airflow,

does not appear to have received any treatment further than that referred to above.

The above generally accepted framework of ACV drag calculation, as set out in References 1 and 2, will therefore be examined briefly, to see how it needs to be amplified to cover the overland case in a more satisfactory manner.

2. ACCEPTED CURRENT THEORY OF ACV DRAG

The current treatment of ACV drag, as set out for example in References 1 and 2, considers the resistance to motion under the following headings. These are set out for completeness for the overwater case, with a friction term overland added. It will be discussed in subsequent paragraphs which terms may be neglected overland.

The total drag of an ACV is composed of the sum of:

a. Aerodynamic Profile Drag
b. Momentum Drag
c. Induced Wave Drag
d. Wetting Drag (Trillo's nomenclature)

This includes:

1. the viscous friction of skirt on or in water
2. the drag of underwater appendages (skegs, propeller bearings, sidewalls, etc.)
3. Spray momentum drag
4. Skirt friction on ground
5. Trim changes due to drag, which in turn alter the drag.

Examining these terms in detail:

a. Aerodynamic Drag

Properly this term should include skin friction drag, but this is usually negligible in the ACV case.

The Profile (or Form) Drag is calculated as:

Drag = $\frac{1}{2}\rho V^2 A C_D$, where ρ = Atmospheric Density kg/m^3

(Drag in newtons)

V = Relative Air Speed of Vehicle m/s

A = Frontal Area m^2

C_D = Drag Coefficient

For values for the Drag Coefficient, Trillo quotes:

SRN-2	[Very well streamlined, with lift fan inlets in the aft wall, to reduce flow detachment.] C_D = .25
SRN-5	[A "typical" propeller-driven hovercraft.] C_D = .38
Car bodies	vary from C_D = .30 to .90
Surface Effect Ship	[A "well streamlined" model.] C_D = .50

Further data may be found in Reference 3. At the 5 m/s speeds of heavy AC transporters this term may often be neglected, but at higher speeds it must be accounted for, overwater or overland.

b. Momentum Drag [of Lift Air]

The lift system of an ACV takes air on board, and accelerates it to the forward speed of the vehicle. The momentum added to the lift air must therefore be accounted for, as a form of drag.

The lift air is assumed to exit through the hover-gap equally all round the vehicle, with no resultant thrust. Some writers (e.g. Waters in Reference 2) suggest a greater efflux aft, leading to a recovery of 30% of the momentum drag energy in thrust, and hence a 70% coefficient in the momentum drag estimation, but others (e.g. Trillo, Reference 1) disagree, and prefer to account for any deliberate cushion air bleeds separately. The present writer agrees with Trillo, and it is suggested that no such reduction of the momentum drag term should be accounted.

The Momentum Drag is calculated as:

Drag = ρQV, (Drag in newtons)

where ρ = Atmospheric Density kg/m^3

Q = Lift Airflow Rate m^3/s

V = Relative Airspeed
of Vehicle m/s

Again, at the low speeds of heavy AC transporters, this term can often be neglected, but at higher speeds it must be accounted for, over land or water.

c. Induced Wave Drag

This is the drag produced by the creation of a wave system on the water surface surrounding the vehicle. Its calculation is well known in the naval architecture of displacement ships, and it assumes that the ACV with the bubble of air beneath its cushion acts as a displacement hull, until planing speed is reached.

Since this is well known, and further since it is clearly not applicable to the present overland study, it will not be further discussed.

d. Wetting Drag

"Wetting drag" as Trillo describes it, includes a number of subheadings, which will now be examined separately.

d.1. "Viscous friction of skirt on or in water"

An interesting simplified treatment of this term is given by Waters in Reference 2. If an ACV is moving over a flat water surface with a hovergap h, there is no contact and this term is obviously close to zero, representing only the viscous shear of the lift air acting as a lubricant.

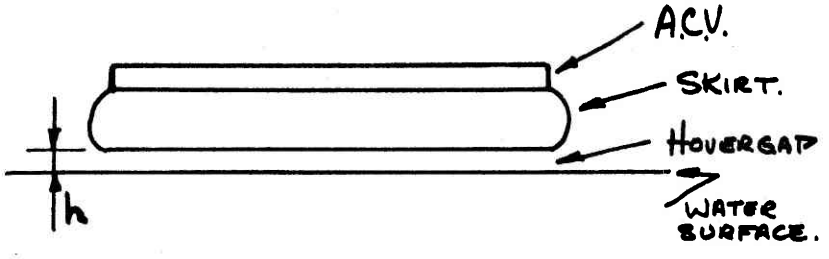


FIG. 1.

However, if the water surface is roughened by waves (assumed for simplicity to be sinusoidal) then some part of the skirt will either be submerged, or deflected and lie flat on top of the water surface. [Shaded portions in Figure 2.]

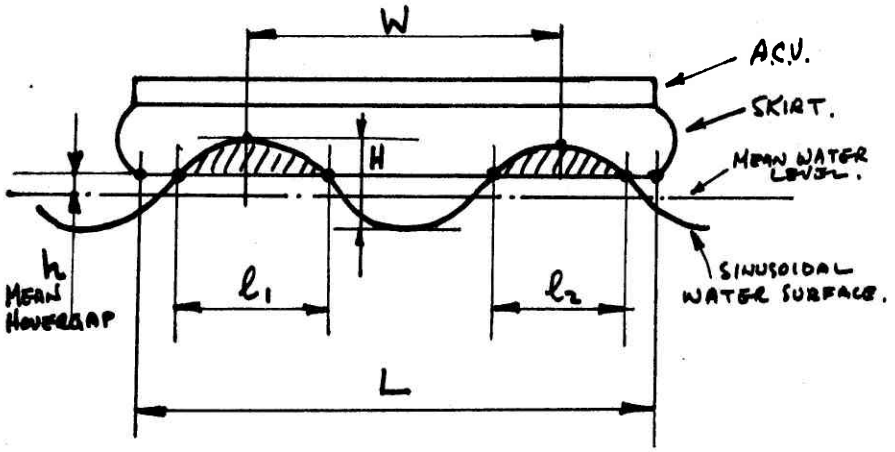


FIG. 2.

In this case, a length ($\ell_1+\ell_2$ etc.) of skirt, out of the total skirt length L will be in contact with the water, and ($\ell_1+\ell_2$ etc./L) will be related to hovergap h, mean wave height H and wavelength W of the sinusoidal waves in a simple manner.

Waters derives this simplified treatment in Reference 2, but since it is clearly only of overwater application the details will not be repeated here. However, it seems likely that a closely similar interaction occurs over rough ground, and this will be discussed at length in a later section of this note.

d.2. Drag of underwater appendages

This term describes the drag due to underwater propeller brackets, skegs, the keels of sidewall craft, etc.

It is obviously not applicable to overland vehicles, except that it could be used, with appropriate modifications, to account for the drag of the lightly loaded wheels sometimes used to keep AC trailers on course behind their

towing vehicle. In this case automotive technology would be used to calculate the rolling friction of wheels on the terrain in question.

d.3. Spray momentum drag

This is completely analogous to the lift air momentum drag discussed above (heading "b") but is the drag due to accelerating to vehicle speed the spray which lands on the deck etc. of the vehicle while in motion. While not directly applicable to overland vehicles, it could be considered to account for the drag caused by vegetation, snow and mud "rollers", or rocks being collected and rolled along beneath the skirt. The writer has observed this process many times, with objects as large as railroad ties, rocks, and tree stumps. This will be discussed in more detail in a later section of this note.

d.4. Skirt friction on ground

This heading is quoted from Ref. 2., in which Waters gives an extremely simplified treatment, considering a part of the skirt as sliding flat on flat ground, and calculating simple sliding friction for the relevant materials. He quotes the coefficients of friction of reinforced PVC (a material sometimes used for light skirts in warm or temperate climates) over concrete as 0.4, and grass from 0.45 to 0.6.

This analysis applies mainly to the bag skirts commonly fitted to small ACVs, depends on an area of contact which is critically dependent on vehicle trim fore and aft (see following section) and assumes a flat terrain surface. In the present writer's view, it represents an oversimplified case, and this drag would be better treated after the manner outlined in Section d.1. above. In any case, this subject is explored in much greater detail in following sections of this report dealing with experiments on HEX-1 and HEX-3, which latter has a bag skirt.

d.5. Trim changes due to drag

Since the drag of an ACV occurs at various points on the structure, and the relative contributions of the various drags outlined

above change with speed, nature of terrain etc, the line of action of the resultant total drag will change, and will usually be below the thrust or tow line. A nose-down moment on the vehicle will therefore usually result. From a knowledge of the fore-and-aft pitch stiffness of the vehicle, the attitude or trim while in motion can be calculated. This, with a given hoverheight, will in turn determine the position and extent of the areas of skirt contacting the terrain, and thus giving rise to frictional drag.

In summary it may be said that current theory, so far as it applied to overland ACV operation, describes the drag as being composed of:-

1. Aerodynamic profile drag
2. Lift air momentum drag
3. Friction of skirt on ground
4. Drag of guide-wheels on ground
5. Momentum drag of picked-up débris
6. It is noted that trim changes may alter drag
7. If the vehicle is climbing or descending a slope, the resolved part of its weight down the slope must clearly be accounted for.

Items 1, 2, 4 and 7 above may be calculated with acceptable accuracy from existing data.

Items 1 and 2 may be neglected at low speeds.

Item 6 depends on an assessment of all the other items, and an iteration.

Items 3 and 5 have so far received little attention, owing to a general preoccupation with marine ACV technology, and little data are available. It is therefore proposed to examine these items of skirt/terrain interaction in some detail.

3. DRAG DUE TO SKIRT/TERRAIN INTERACTION

Skirt/terrain interaction will be considered as being composed of three elements, so far as drag is concerned;-

1. Material friction
2. Deformative work of skirt on terrain
3. Deformative work of terrain on skirt.

3.1 Material Friction

This is taken to mean the sliding friction of skirt material over terrain, and does not include snagging or gross deformation over obstacles.

The laws of "poorly lubricated" friction, (Ref. 4), state that:-

a. For low pressures, the friction is directly proportional to the total normal force between the surfaces.

b. Friction does not depend on the area in contact, so long as the total normal force remains constant.

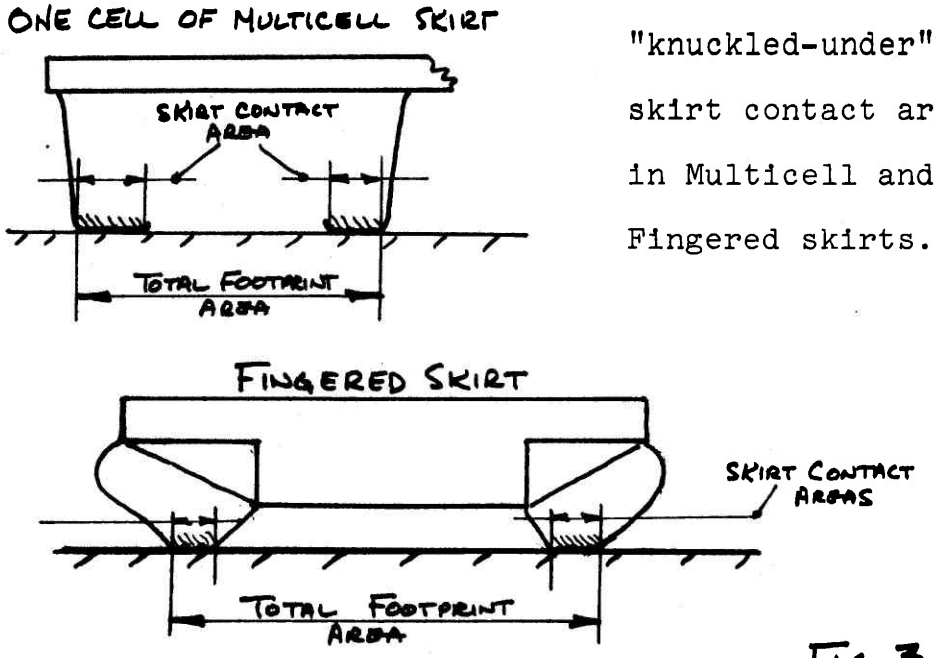
c. At very low speeds, friction remains constant. As velocities increase, friction decreases.

d. A greater force is required to start motion from rest than to maintain motion.

"Poorly lubricated friction" is described as the friction between two rough surfaces separated by a film of lubricating fluid thin enough that the asperities on the two surfaces protrude through it and interfere with each other. This appears to be a process on the microscopic scale, closely analogous to the ACV skirt moving over rough terrain viewed on a much larger scale. For a good discussion of the friction process, Ref. 5 should be consulted.

The laws of "well lubricated" friction are somewhat different, and describe the behaviour of surfaces separated by a relatively thick layer of lubricant fluid. The friction is then due to the shearing of the fluid, which in the case of the ACV is air. This in fact describes the near-zero ground friction of an ACV at full non-contacting hover over a smooth surface, and has little relation to the immediate point of discussion.

Considering the above laws, it becomes necessary to estimate how much of the vehicle's weight is acting through those parts of the skirt actually in sliding contact with the ground, so that the frictional force may be calculated. It appears that this frictional force will not increase with speed.



Diagrams showing "knuckled-under" skirt contact areas in Multicell and Fingered skirts.

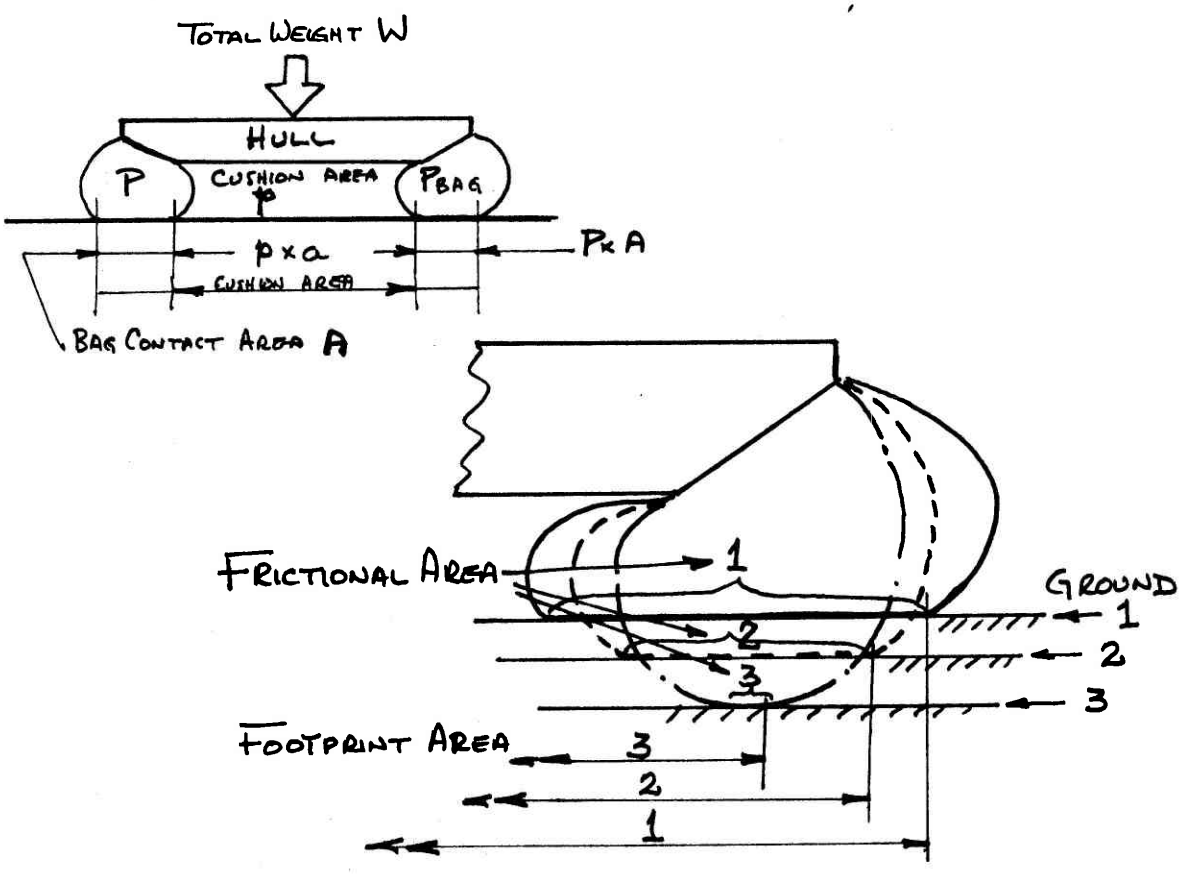
FIG. 3.

Cushion pressure may be assumed uniform within the skirt, so the total downward force on the knuckled-under part of the skirt which is in sliding contact with the ground will be $F = \frac{\text{Vehicle Total Weight} \times \text{Skirt Contact Area}}{\text{Total Footprint Area}}$. Owing to the essentials of skirt geometry, while the vehicle total weight remains constant, if the cushion pressure is increased then the footprint area will decrease and the craft rise, while reducing the degree of knuckling-under, until the craft reaches full hover. After this no further cushion pressure rise will occur, and hovergap will increase with lift airflow.

The proportion of total weight which acts through the knuckled-under skirt will therefore reduce, as cushion pressure is increased, until it becomes zero at full hover. However, even at full hover, rough ground or non-level trim may cause some parts of the skirt to knuckle-under locally although full-hover airflow has been established with excess hovergap under other parts of the skirt.

The plain "bag" skirt presents an essentially similar case, although with the added complication that the pressure in the bag (P) is higher than that in the cushion area (p). If the ratio of bag pressure to cushion pressure is r, then it follows that:-

$$W = PA+pa = (rA+a)p.$$



STATES OF INFLATION OF A BAG SKIRT Fig. 4.

The diagram shows that at constant weight, increasing pressure is accommodated by reduction of total footprint area due to change of shape of the bag skirt as it inflates up to the limit at which it achieves line contact only with the ground, and then rises into full hover.

At the same time, it shows that the area of skirt in frictional contact, and therefore the proportion of total weight borne by this area, decreases with increasing cushion pressure, thus showing that the frictional drag should decrease with increase of cushion pressure. This situation is complicated by the pressure distribution under the bag when any air escapes under it, causing the bag to adopt a complex nozzle-like contour, and also by local contact due to corrugated ground or imperfect vehicle trim, as in the previous cases.

In general it may be concluded that there will be a frictional component of drag, which will reduce to zero as the cushion pressure is raised to the full-hover value. This component will obey the laws of "poorly lubricated" friction, with a high static value, and a lower moving value which probably falls with increasing speed. The

magnitude of this component could be estimated from a knowledge of the appropriate skirt/terrain coefficients of friction and vehicle total weight, if the area of skirt contact could be defined. This area is difficult to predict in any given case, owing to ground roughness and trim changes of the vehicle.

The coefficient of friction of vegetation is also most difficult to define and measure. For example, certain grasses possess very rough hairy leaves, but their high coefficient of friction may temporarily be drastically reduced (by a factor of two or three) by the lubrication of morning dew.

As a guide, Ref. 2 quotes coefficients of friction between reinforced P.V.C. skirt material and various surfaces as:-

Concrete — μ = .4
Wet grass — = .45
Dry grass — = .6

These figures are quoted with strong reservations, as examples of the data at present available.

3.2 Deformative work of skirt on terrain

In this connection, the skirt is considered to be a quasi-rigid object forcing its way over ground and vegetation, which are deformed temporarily or permanently to let the skirt pass. In order to do this, a force must be exerted on the obstacles to distort them, either elastically if they subsequently recover (e.g. bent grass blades) or to shear them if they do not (e.g. brittle twigs or lumps of mud). The skirt is to some extent deformed, in the sense that its bottom edge is likely to be raised above its undeflected height, so the obstacles have to be bent down to this level or sheared off at this height. This occurs as each skirt element passes a given obstacle in the elastic case. In the shearing case the first skirt element may do all the work, leaving no resistance to the passage of later elements of the skirt, or later skirt edges may shave the obstacle down to a slightly lower height. In the elastic case it is unlikely that the recovering plant stem will return any of the deflection energy to the skirt as it passes.

In any case, the drag force F (newtons) due to this shearing or deforming is seen to be:-

F = Force to bend/shear one obstacle × obstacle density (number/m^2) × Number of skirt edges repeating the process.

This term is not dependent on vehicle speed. However, it must be realised that as each obstacle is sheared or bent, it is momentarily given a velocity proportional to that of the skirt which has forced it before it. The weight of material broken off in unit time must therefore be considered in the evaluation of "Momentum Drag of picked up débris," in Section 4 following.

The influence of cushion pressure and lift airflow on terrain-deforming drag will vary greatly according to the terrain. In the case of hard unbreakable ground, there will obviously be no deformation. If this ground is covered with loose material (gravel, small rocks, etc.) then this will be shifted, but the drag will be momentum drag as noted above. It is not until the vehicle traverses ground whose asperities can be sheared off that deformation drag is caused. It is clear that the less skirt depth is scrubbing the ground, the less damage it will cause, and once it has come to full hover and is only contacting the occasional taller peak, even less shearing will occur. At lift airflows high enough to hoist the skirt entirely clear of the ground, obviously the terrain deforming drag will be zero.

However, when vegetation is present it is most unusual for an ACV to hover high enough to clear it, or to appreciably alter the depth of vegetation in contact with the skirt, so the variations of vegetation deformation drag with cushion pressure or lift airflow is probably negligible, except in the unusual case of hovering over a putting green.

One may therefore conclude that terrain deformation by the skirt does cause a drag force, which does not vary with speed but is proportional to the shear strength of terrain asperities or vegetation, to the density (number per unit area) and possibly to the number of skirt elements under the vehicle.

Lift airflow or cushion pressure may have a limited influence on this drag component, and the débris caused by this process must have its added momentum accounted for, as an added drag.

3.3 Deformative work of terrain on skirt

Under this heading is included only the elastic temporary deformation of the inflated structure, against

the pressure differential across it and the tensile stresses generated by its inflated form. Actual ripping of the material cannot be a continuous process (not for long, anyhow) and is not considered here.

As a purely arbitrary description, when the drag force on the vehicle rises and falls reasonably smoothly with its passage over an obstacle, the process is here described as "Drag", whereas when the force increases to a peak as the obstacle stretches the skirt into a local bag around it, from which it escapes only by a sudden slipping or by a tensile skirt failure, it is called "Snagging". This latter is dependent on skirt geometry, and although highly undesirable, is difficult to avoid.

Returning to the continuous "drag" process, this is now considered as the movement of an elastic inflated structure over obstacles in a quasi-rigid terrain. To a reasonable approximation, the skirt material may be considered non-elastic, and without inherent stiffness or inertia. These assumptions will not hold true at high speed, in very large sizes, or in very high pressure skirts of unusually tough material, but they will enable a wide range of useful cases to be studied.

The reaction between skirt and obstacles is therefore that between the obstacle and a tensile member, connected through an inflated structure acting as a pneumatic spring to the vehicle hull. The limit is reached when the line of action of the tensile force becomes a straight line from obstacle to hull and the elasticity of the skirt material comes into play, but this is in fact the "snagging" case which is not being considered.

Within this limit, the force against which the obstacle deflects the skirt is therefore that of an extremely "soft" tension spring. Since reasonable skirt deflections do not greatly compress the air within the skirts, the force remains approximately constant irrespective of extension, producing the effect of a "dashpot" rather than of an orthodox "spring".

The tension force of this spring is directly proportional to the pressure difference across the various surfaces of the skirt structure which maintain its inflated shape. The drag due to the passage of each obstacle is therefore constant during its engagement with a skirt element, and depends on skirt inflation pressure above atmosphere, whatever the form of the skirt.

It is interesting to notice that in Ref. 6, Liston makes a clear distinction between drag when the relatively flexible fingers of a BHC skirt are deflected by normal obstacles, and the much higher drag when the much stiffer bag supporting the fingers is distorted by very large obstacles. This suggests that such a skirt could be described as two "dashpots" of different rates in series.

When the skirt is deflected by an obstacle it will therefore distort under constant force until it is sufficiently deflected for the hem to slip over the obstacle. The extent of this deflection depends on the extent of the obstacle above the bottom edge of the approaching skirt, and on the geometry of the skirt structure.

The number of obstacles causing drag at any instant therefore depends on the density of obstacles (number per unit area) multiplied by a factor depending on the number of skirt elements (in the same way as was shown in the previous section) also multiplied by a factor depending on obstacle size and skirt geometry (which control the distance of advance over which each obstacle acts before the skirt slips clear).

The drag force is therefore found as the product of this "Number of Obstacles" term and the force generated at each interaction, which was seen to be proportional to the skirt inflation, - or cushion, - pressure. To a first approximation, under the simplifying assumptions stated, speed is not a factor. This limitation is not so serious as might be thought, since at the present state of the art, ACVs are unlikely to be driven at high speed over rough terrain, while over smooth terrain this term will not be too significant although higher speeds can be attained.

3.4 Summary of skirt/terrain interaction drag

As was pointed out at the beginning section 3, skirt/terrain interaction drag is composed of three elements;

1. Material friction
2. Deformative work of skirt on terrain
3. Deformative work of terrain on skirt.

Material friction depends upon:-

a. Skirt configuration

b. Vehicle total weight

c. Coefficient of friction (skirt/particular terrain)

d. Cushion pressure and lift airflow. Friction will reduce with increase of these quantities.

e. Vehicle trim.

f. Vehicle speed. Friction will probably fall slightly (from maximum static value) with increase of speed.

Deformative work of skirt on terrain depends upon:-

a. Density (number/unit area) of terrain asperities.

b. Shear strength of terrain asperities.

c. Skirt configuration.

d. Lift airflow and cushion pressure may have a limited influence.

e. Speed will not affect this drag force.

Deformative work of terrain on skirt depends upon:-

a. Density (number/unit area) of obstacles.

b. Obstacle geometry.

c. Skirt configuration.

d. Skirt inflation or cushion pressure.

e. Speed will not affect this drag, until it is high enough to give rise to dynamic phenomena.

Collecting this information, it appears that skirt/terrain drag will be greatly influenced by:-

a. Skirt configuration, both in the sense of the pattern and number of skirt edges brushing the ground, and of the stiffness of the inflated structure between hard hull and the bottom edge of the skirt.

b. Cushion and skirt pressure and lift airflow, both due to the amount of skirt brushing the ground or the height it is lifted off, and to the stiffness to the inflated structure.

c. Density and shear strength and geometry of terrain asperities. The coefficient of friction (skirt/terrain) will have some influence, but is a highly variable and unpredictable quantity. Vehicle total weight will also have some influence.

It appears that vehicle speed will have very little influence on the drag force.

4. MOMENTUM DRAG OF PICKED-UP DEBRIS

Although the escaping lift-air blows light débris up all around the vehicle, heavier débris rolls up in front of the skirt like a ship's bow wave, or is rolled along under the skirt.

Heavy wet snow or mud is formed into a roller and pushed along by the bow skirt. This has been observed by the writer in front of the near-vertical multicell skirt, and has been reported to him (Ref. 7) in the case of the 45° sloped fingered skirts of HDL type.

Heavy discrete obstacles, if not anchored very firmly, are captured and rolled along under the skirt, with multicell and also HDL skirts. The writer has observed a 15-ton multicell ACV moving at walking speed capture half a dozen railroad ties laid in long grass as obstacles, and carry them along under it. The 3-ton ACV Caspar rolled up large balls of loose forest vegetation under its skirts, and the 120/240 ton ACT-100 (HDL skirt) rolled 45-gal. oil drums, 3 ft. drainpipes, and 6 ft. terratire under it during tests when these were tied down as obstacles.

Finally, when vegetation or terrain asperities are broken off or thrown flat, these too are momentarily accelerated to vehicle speed.

The Momentum Drag Force of such collected material is simply calculated, as:-

$$\text{Drag (newtons)} = MV,$$

where M = mass of material collected per second (kg/s),

V = Vehicle speed (m/s).

In addition to this, it should be proper also to account for the frictional drag of the material, if it is scrubbed along the ground under the vehicle, or the rotating momentum of a rigid body such as a rock, which is set into rolling motion.

5. CASPAR PROGRAMME - EXPERIMENTS ON DRAG (1974 SEASON)

This section will deal specifically with drag experiments on the research ACV "Caspar". Other drag tests in the same programme are described in the following section on the Spectra II HEX-3, while experiments on Caspar on other subjects such as stability are reported elsewhere.

The only experiments in this series in which a coherent body of data has been accumulated deal with the lift/drag performance over a "Forestry" track. A track 10 meters wide and 60 meters long was cut through a waterlogged forest area. Trees up to 15 meters high were felled and hauled out, leaving 0.5 meter high stumps, while the ground cover of creepers, weeds, leaves, twigs, etc. was left intact. The soil was of very deep soggy black leaf mould, richly penetrated by tree roots. The pictures in Fig. 5 illustrate this.

Caspar (see Ref. 8), with its Build 1 Multicell skirt, was hauled to and fro over this track at quite low speeds by a logging winch and a truck-mounted winch. On the measured runs the steel cable (about 80 meters long) was attached to the nose of Caspar by a strain gauge element, whose output was recorded on chart by a pen recorder in the cabin. Lift airflow and an array of cushion pressures were also recorded on another channel of the chart, via transducer and Scanivalve.

Typical towload recordings are shown in Fig. 6, with notes added, and the results of three representative sets of experiments are plotted in Fig. 7.

The results are plotted on the system laid out in "Caspar Research Project Report No. 1, Programme and Basic Data", TR3/74, pages 19 and 26. Lift airflow and drag are presented in non-dimensional form as:-

$$\text{Tow Coefficient} \equiv \frac{\text{Drawbar Pull}}{\text{Total Weight}} \times 100\%.$$

Both forces are measured in newtons, and the Tow Coefficient is non-dimensional.

$$\text{Lift Air Coefficient} \equiv \frac{Q\sqrt{P_c}}{A_{UW}} \times \sqrt{\frac{\rho}{2}}$$

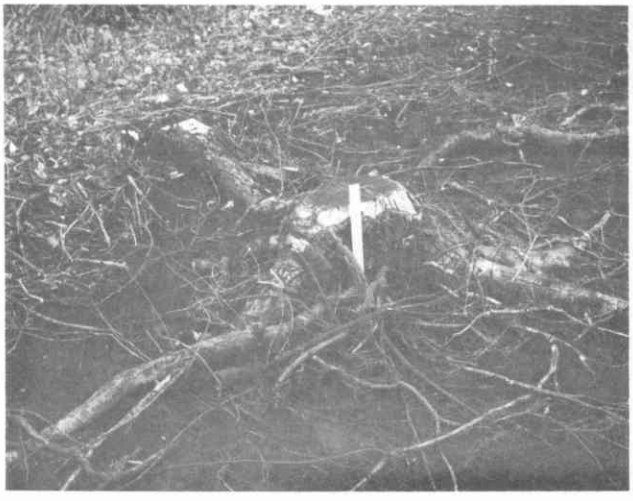
TERRAIN ON ACV TEST SITE - FOREST TRACK

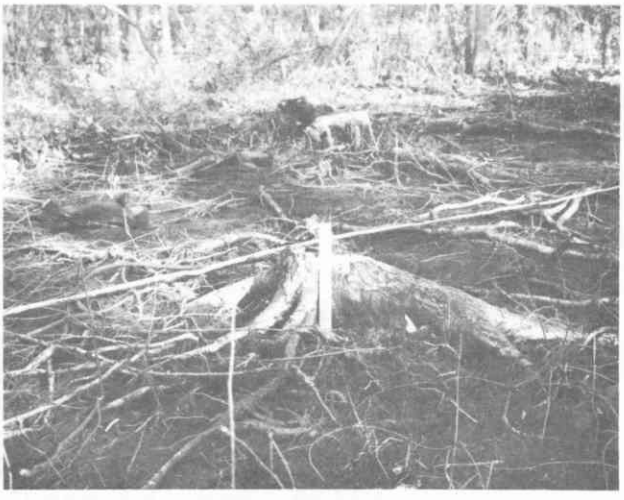


Undisturbed After 20 passes



"Caspar" Hovering





Typical Tree Stumps

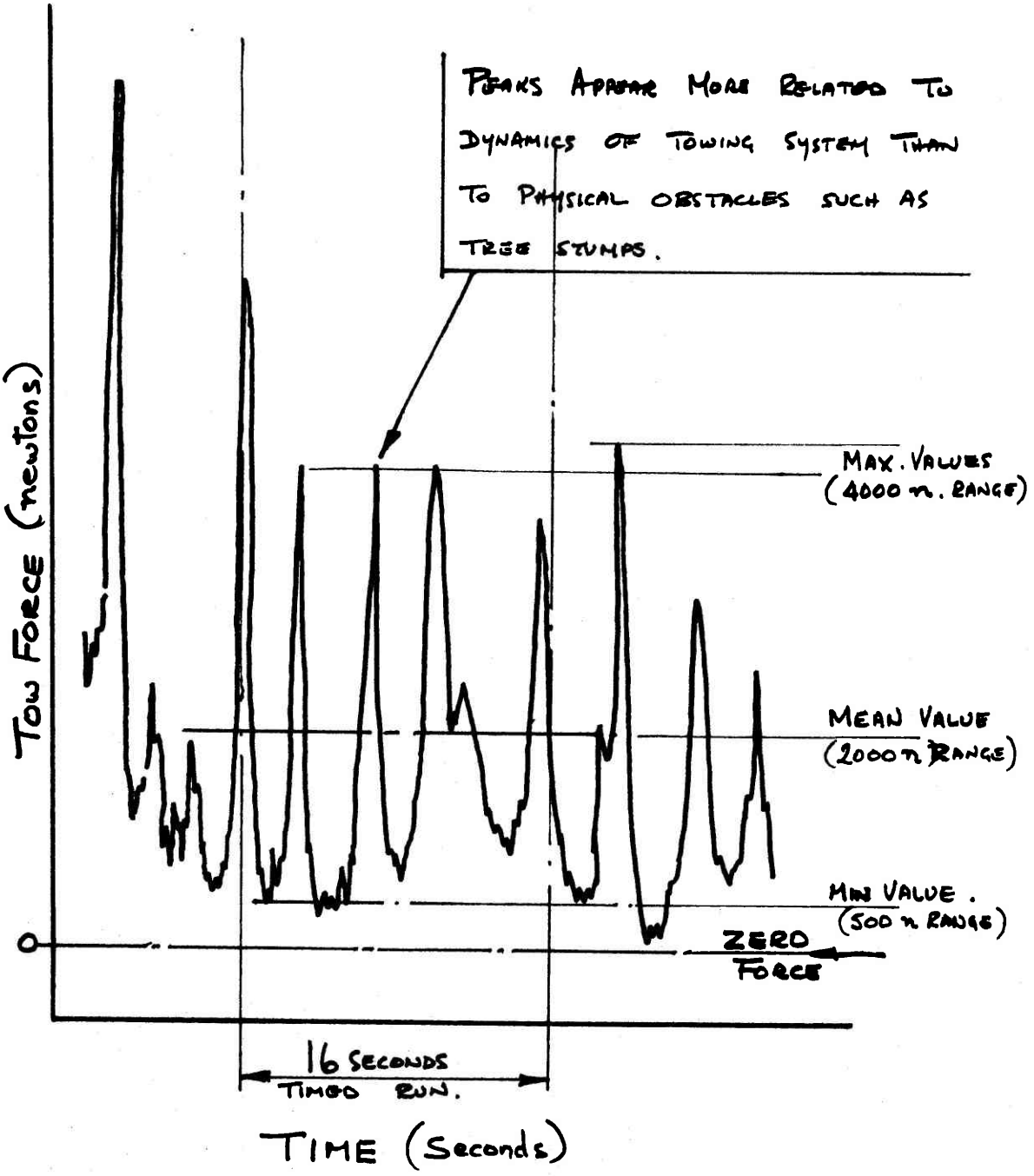




Pit full of Stones Obstructions in track

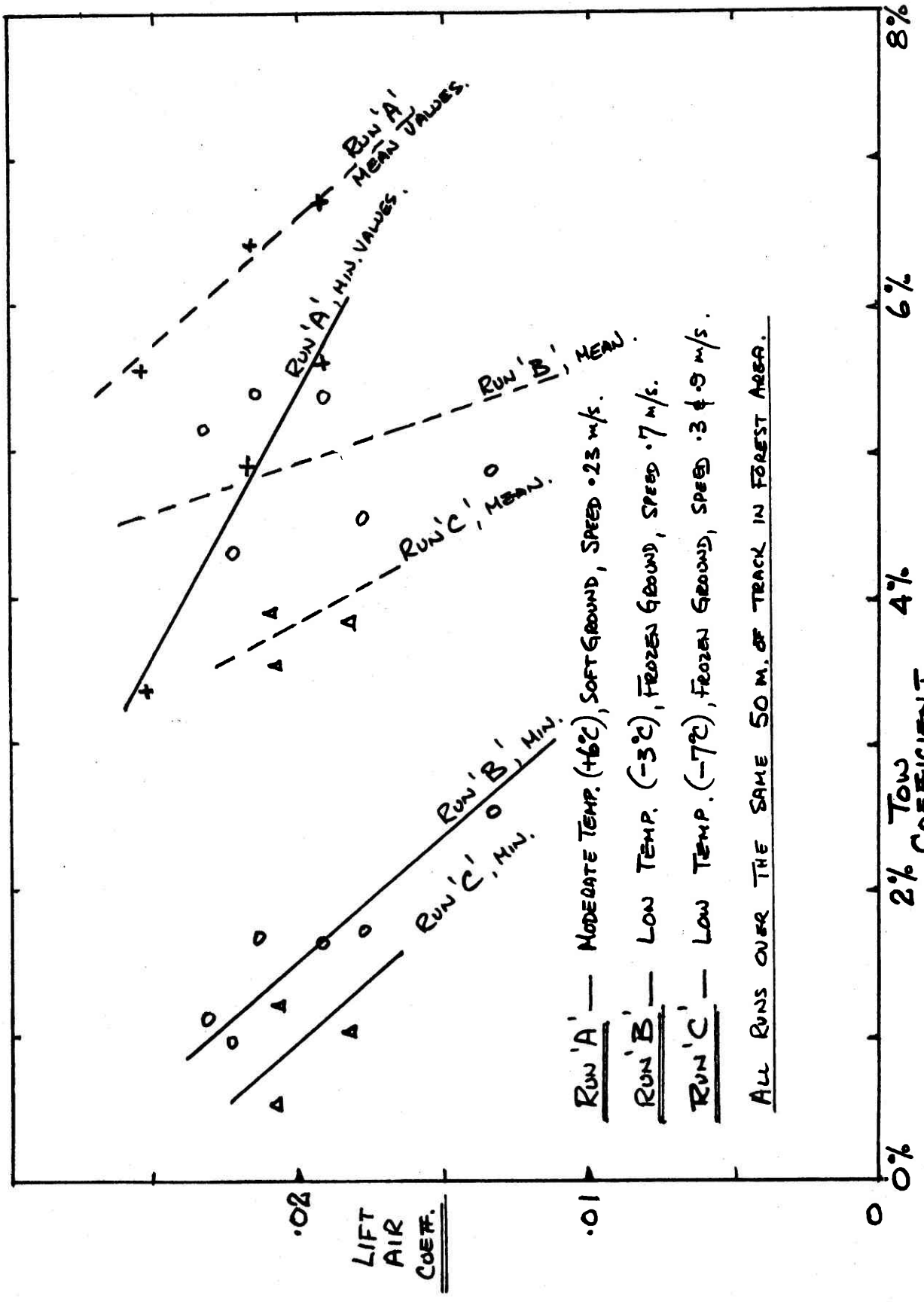
The scale seen in the pictures is 1.0 ft. (0.3 meters) long

Fig. 5



TYPICAL STRAIN-GAUGE RECORD OF TOW-FORCE, CASPAR HEX-1 ON FOREST TRACK, WITH MULTICELL SKIRT, 27-XI-1974.

Fig. 6.



TOW COEFF. VS. LIFT AIR COEFF. — HEX-1 (MULTICELL SKIRT) ON FOREST TRACK.

FIG. 7.

where Q = Lift Airflow m^3/s

P_c = Cushion Pressure n/m^2. (Gauge Press.)

Auw = Total Vehicle Weight n.

ρ = Air Mass Density (at current conditions) kg/m^3.

This formula is similar to Trillo's C_{QC} (Ref. 1) and assumes the length/beam ratio of 2:1, which is true for "Caspar".

The results in Fig. 7 are all of experiments in which the towing speed was less than 1 m/s, so no correction has been made for aerodynamic or momentum drag. Since the terrain was flat, no gradient correction was necessary. The drag of picked-up debris was accepted as an essential part of the forest-track operation being studied, and no attempt has been made to separate it.

In each of the three sets of experiments, Fig. 7 plots both the "Mean" and "Minimum" drag values, shown for example in Fig. 6. In interpreting these recordings, a description of the vehicle's behaviour is essential. As the long steel tow cable tightened, the vehicle would move forward, gathering a little speed. The tow force at this instant included the accelerating force. The vehicle would then catch its skirt on a stump, and "hang up" momentarily, with a sharply increasing tow force. When this overcame the hang-up, the vehicle would surge ahead, let the tow-line fall slack, and usually yaw off course. As it slowed up, it would be abruptly jerked back on course by the towline, with a momentary peak load, surge ahead to a slack cable, be pulled back on course with a jerk, and so on.

It is considered by the writer that a value somewhere between the "minimum" and the arithmetic "mean" shown on Fig. 6 is most properly used to express the average drawbar pull over this terrain, although the "maximum" value might be of interest to a designer stressing the tow attachment gear in a vehicle.

This transient character of the tow force recordings makes it clear that some steadier method of towing the vehicle on test must be evolved.

The second striking feature of Fig. 7 is that although the points measured on any one day are reasonably disposed on a line, the lines of points for experiments on three separate days over the same track are widely separated.

The track apparently suffered little erosion after the first few passes (before any of these test points were taken) and subsequent examination showed no skirt damage. All results were corrected to standard atmospheric conditions. It therefore appears that some drastic change in skirt/terrain interaction took place between the three sets of runs, as the airflow coefficients are consistent.

It does not seem that the skirt material suffered any great change between the runs. In any case, it would be expected to stiffen as the temperature fell, leading to higher drag figures. Figure 7 shows lower drag at lower temperatures.

It therefore appears that the nature of the track has changed. In this case, the skirt was not shearing vegetation or lumps of soil, except in the first few passes, which do not concern these results. The only remaining factor seems to be a lower coefficient of sliding friction over frozen soil and vegetation than over the same terrain when moist, which incidentally suggests that the frictional component of drag was very large in these tests. It may be remarked here that protruding tree stumps showed definite amounts of black rubber deposit, scraped off the skirt, after 10 passes or so. A similar occurrence over stony tracks after repeated passes was reported to the writer by Mr. Rapson of HDL.

These considerations add a further arguement to the necessity of improving the test technique, by preparing some standard form of test track on which repeatable results can be obtained, while admitting the wide variation of drag in the field.

6. EXPERIMENTS ON DRAG WITH VEHICLE HEX-3 (1974)

A Spectra II ACV was drastically modified and fitted with simple instrumentation to measure lift airflow and the drawbar pull required to tow it under controlled conditions. The vehicle is identified as HEX-3.

A calibration of the lift airflow metering system over a smooth flat concrete floor gave data relevant to the present discussion, and subsequent towing experiments over various terrains gave further interesting data.

The vehicle has a cushion area of approximately 2.2 m. long and 1.6 m. wide, a total unballasted weight (with driver) of 470 kg., and it is fitted with a simple bag skirt. During these experiments it was towed on a 10 m. cable from a truck, and speeds were measured by stopwatch over measured tracks 20 m. and 60 m. long. The tracks sloped slightly uphill to help stop the vehicle after the run, but the uphill component has been analysed out of the tow force figures. At the higher speeds, momentum drag and aerodynamic drag are also subtracted.

6.1 Static lift airflow experiments

HEX-3 was run at various lift-engine speeds, at three total weights, and the lift airflow and cushion pressure were measured. Bag pressure is held at approximately 1.2 times cushion pressure in this vehicle. A summary of the experimental data follows.

It will be noted that in the dimensions quoted below, the cushion area is given only approximately since it is difficult to define the actual area of cushion under a bag skirt, as the edges of the cushion area are not precisely defined under the curved lower surface of the bag. There is no "edge" of the skirt as there is in a Multicell or Fingered type. This point is discussed following the table of results.

Vehicle - HEX-3

Tests over smooth level concrete floor.

Cushion area approximately 2.9 m × 1.6 m [= 4.6 m^2].

Point	AUM	Lift	Cushion Press.	Cushion Area	Lift Airflow	Lift Air Coef.	Hovergap h
	kg.	RPM	n/m^2	m^2	m^3/s	-	cm.
1	467	4000	956.5	4.80	2.67	.0140	.76
2	467	4500	989.1	4.64	3.13	.0167	.86
3	467	5000	1031.2	4.45	3.58	.0195	.97
4	467	5500	1068.6	4.30	4.14	.0229	1.09
5	513	5000	1118.0	4.51	3.60	.0186	.94
6	383	5000	870.0	4.33	3.92	.0238	1.14

In this table, the Cushion Area has been calculated from the accurately measured total mass (AUM), and the cushion pressure, measured by a static probe flush in the vehicle hull underside and connected to a manometer. With proper precautions, this method has been shown to be trustworthy by many other experiments.

The main point of interest in these results is that they show that changes of bag and cushion pressure alter the cushion area by an appreciable amount (a 10% area change). Since the concrete ground does not change its flat surface, and since it is thought unlikely that the bag could expand or contract its periphery enough to make this change, it would seem that the only explanation is that the bag alters its cross-section with bag pressure. It must assume a more "pointed" shape and thus decrease the total footprint area as the bag pressure increases, or as the vehicle weight increases (thus increasing cushion pressure at the expense of lift airflow). This is in fact in complete aggreement with the theory outlined previously in Section 3.1.

This relationship is illustrated in Figs. 8 and 9. The cushion area was calculated as:-

$$\text{Area} = \frac{\text{Total Weight (n)}}{\text{Cushion pressure } (n/m^2)}$$

from the measured weight and pressure. Using this area, and assuming that the length/beam ratio of 2:1 still holds, the effective periphery was calculated. This and the measured lift airflow enabled the hovergap h to be calculated.

6.2 Towed trials over short grass, at various lift airflows and weights

HEX-3 was towed on a 10 meter nylon line behind a truck over short springy grass, about 10 cms. high. Lift

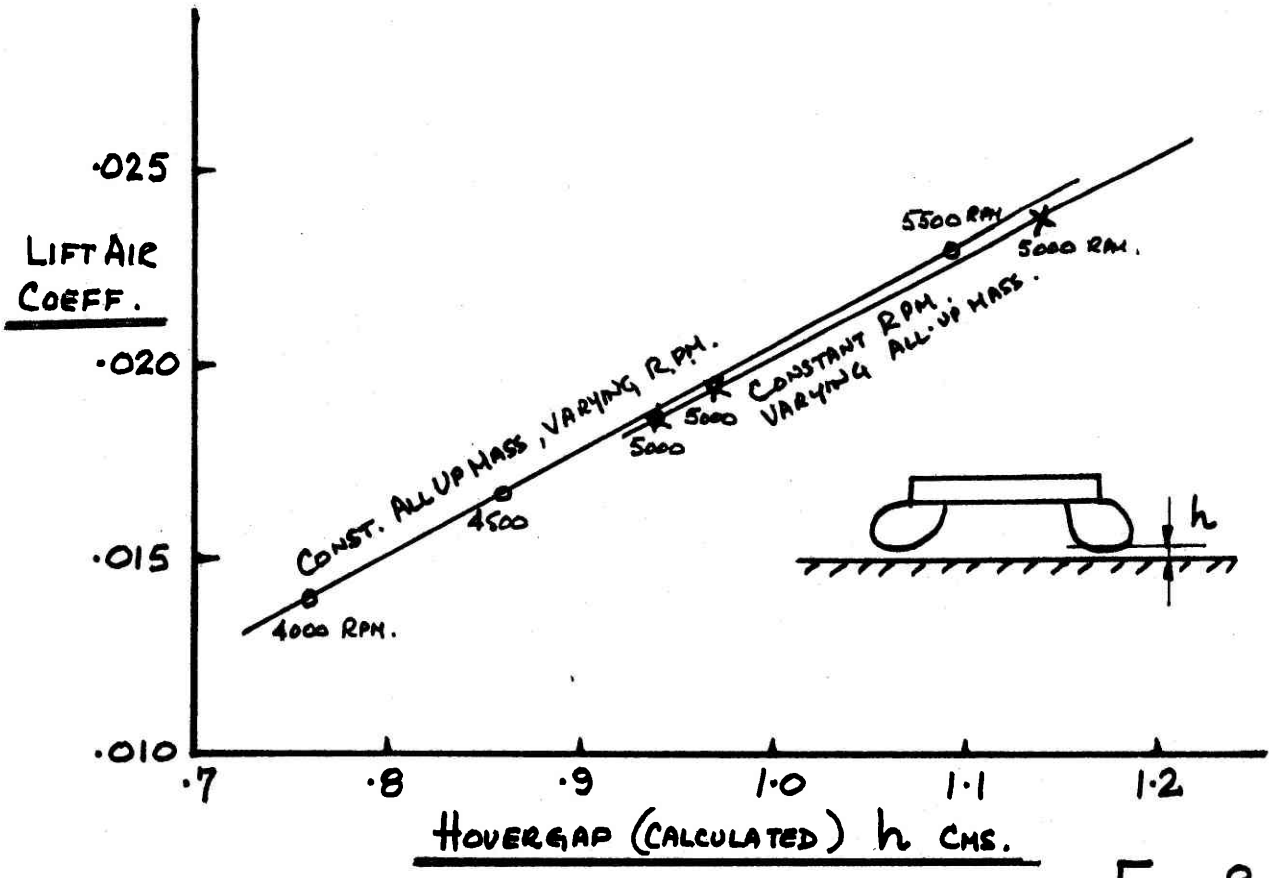


Fig. 8.

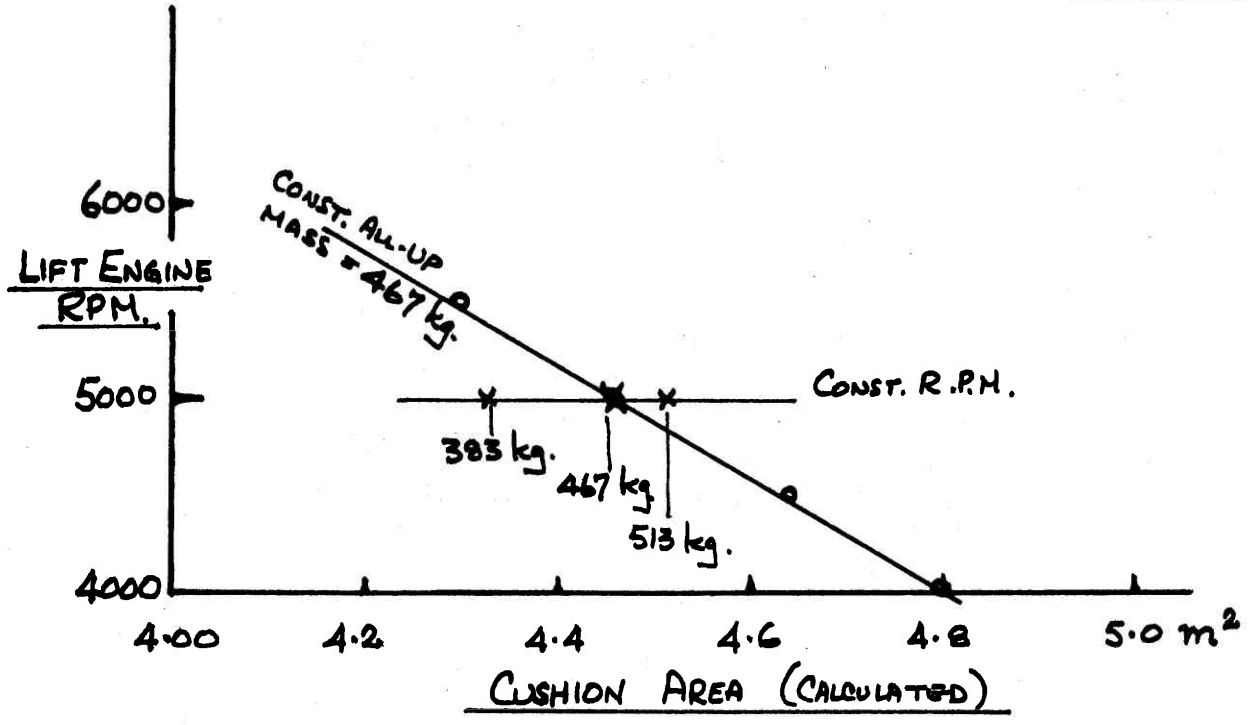


Fig. 9.

HEX-3 STATIC HOVER EXPERIMENTS

[SIMPLE BAG SKIRT OVER SMOOTH CONCRETE]

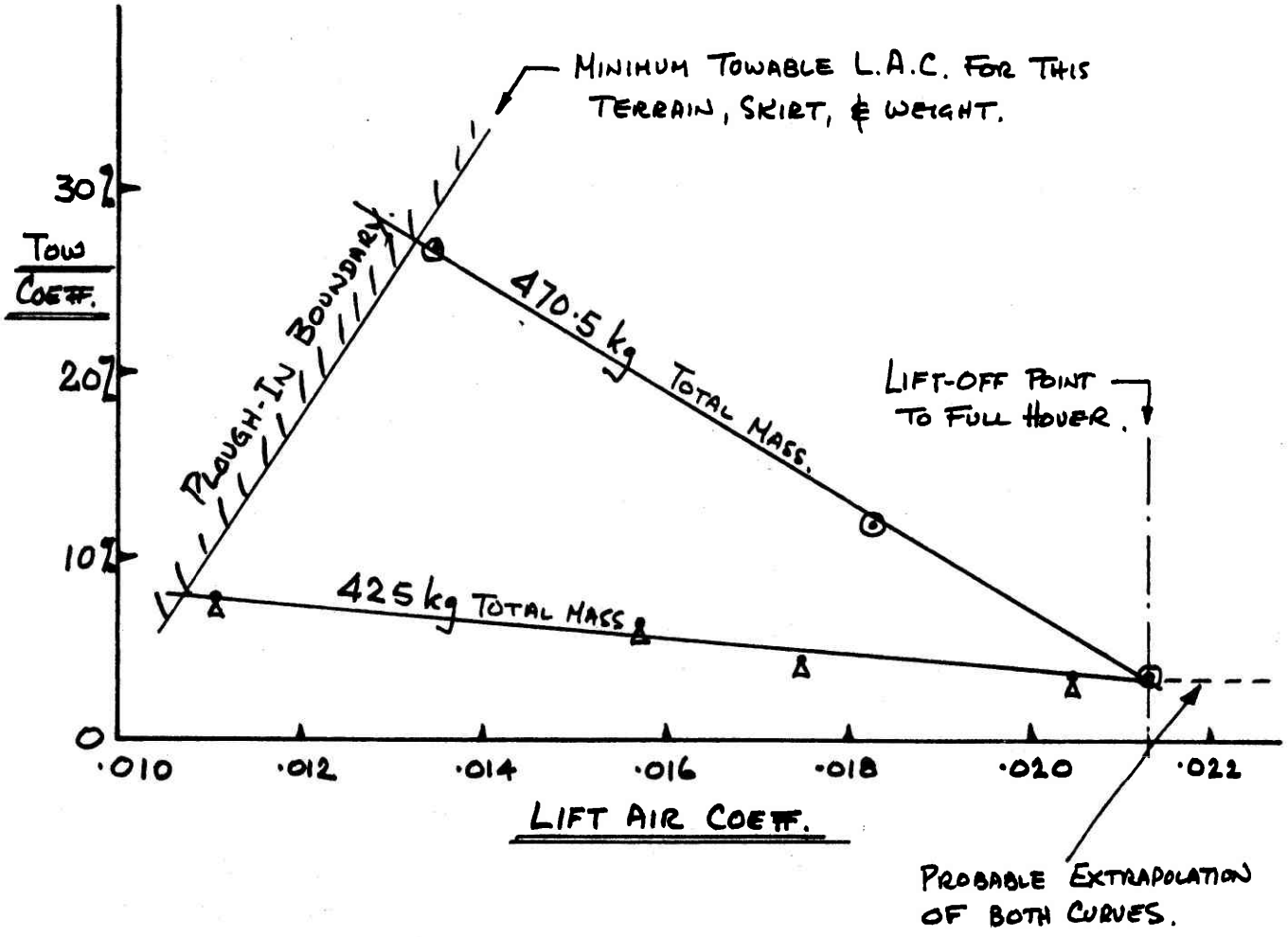
airflow was measured using a manometer on the ground, temporarily connected to the vehicle's probes while hovering at the set RPM before the run. It was assumed that at this constant lift engine RPM, the lift airflow remained constant during the run. Tow force was measured by a hydraulic cylinder in the tackle connecting the towline to the ACV, and was read off a pressure gauge by the driver. This system had been calibrated with weights.

The ACV was towed, over the range from maximum attainable lift airflow to the minimum flow at which towing was possible. At this low flow the friction was high, and acted at skirt-bottom level. The tow force was applied at deck level, which resulted in a nose-down pitching mement. This forced the nose-down, increasing the local skirt friction at the nose, and in the limit causing a "plough-in" such as is well known in marine operations. This sometimes reached the stage of lifting the tail off and swinging it round wildly while the nose stayed "dug-in". This behaviour is not peculiar to the bag skirt; exactly similar performance was met by the writer, while carrying out early trials of the C-105 with an underinflated Multicell skirt, in the self-propelled mode over long grass. It was much reduced when the grass was lubricated by heavy dew.

The HEX-3 was run at two values of total weight during these tests by adding two 23 kg weights at the CG of the vehicle for one series of runs. It is most interesting that the curves describing these two series of runs are separated, but converge at what appears to be the full-hover condition. It is unfortunate that 5500 rpm was the engine/blower speed limit, so that no higher airflows could be obtained. The results of these tests are plotted in Fig. 10.

6.3 Towed trials over flat sandy soil with sparse vegetation at a range of speeds and two attempted lift airflows

HEX-3 was towed, as in the over-grass trials described above, over flat sandy ground with sparse weedy growth up to 20/25 cms high. The experiment was beset with problems; the short track available made it difficult to eliminate acceleration effects, it was difficult to read the dragmeter at higher speeds, and the higher lift airflow test was abandoned owing to sand choking the engine air filter. The vehicle threw up such a cloud of dust that engine RPM at full throttle fell to 50% in 10 minutes. This cycle was repeated after cleaning the filter. The vehicle was therefore fitted with air intake trunks above the dust region, and further experiments carried out on a much longer and less dusty track.



HEX-3 TOW TESTS OVER GRASS (10 CMS HIGH)

AT 1·5 m/s SPEED.

FIG. 10.

Only the results of the low lift-airflow experiment are presented in Fig. 11.

6.4 Towed trials over a deteriorated concrete airfield runway, at constant weight and lift airflow, over a range of speeds

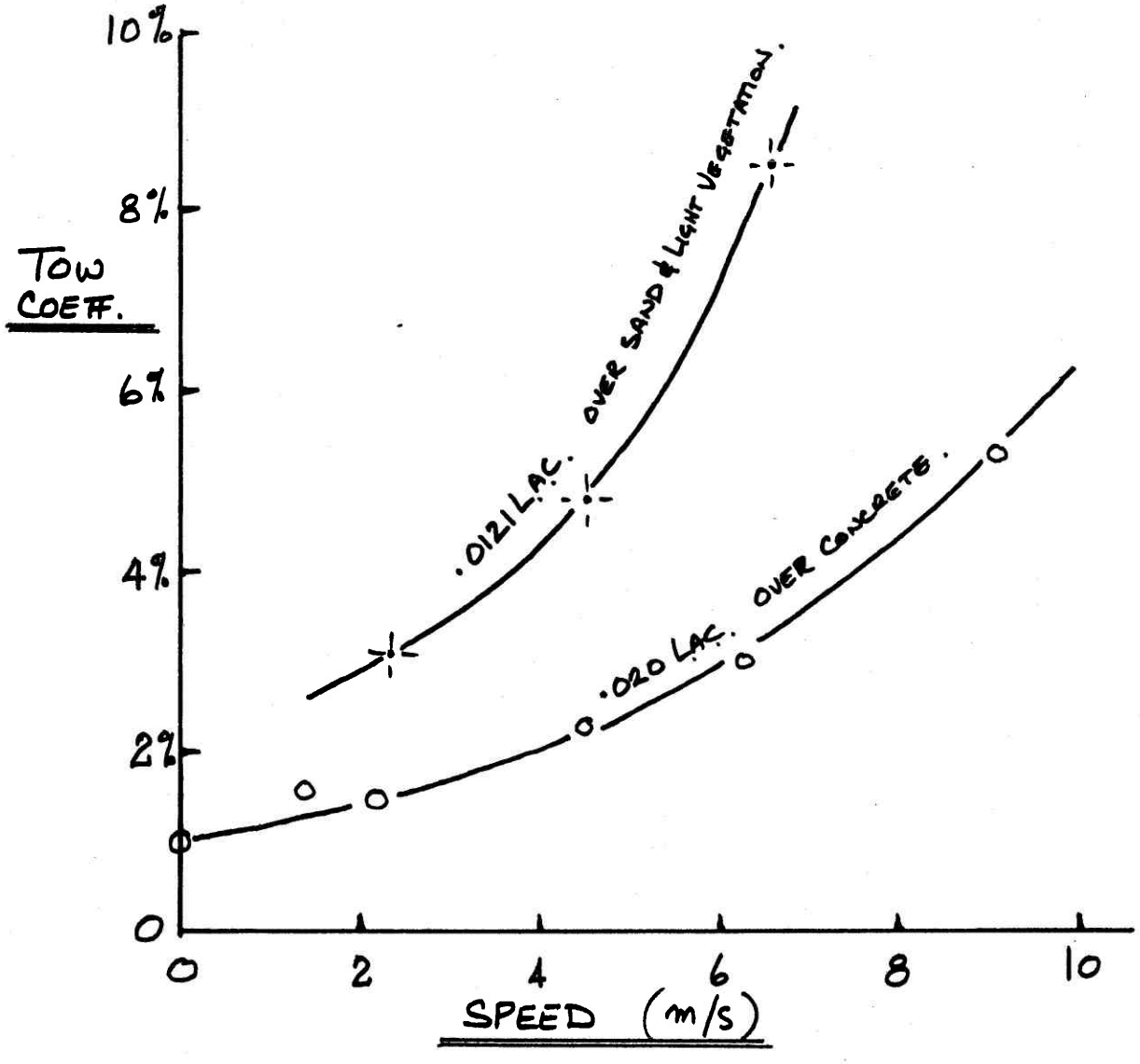
HEX-3 was towed as above over a long concrete runway, with a rough deteriorated surface. Ample distance was available to set up steady conditions before the 30 m. timed section was entered. Results are shown in Fig. 11.

Over this surface, the lift airflow used gave practically free hover, and the vehicle drifted freely when stationary before the run. Further runs should be made at lower lift airflows, although the abrasion of bag on runway might be severe. This in itself would be of interest, with some study of the relation between abrasion, lift airflow, and speed.

The low friction value at this lift airflow was vividly demonstrated during the deceleration phase of the higher speed runs, when the ACV actually got ahead of the tow-truck, travelling broadside on. Lower lift airflows and the resulting higher drag should of course lessen this problem.

In future tests it might be interesting to eliminate the trim changes due to the nose-down moment caused by the tow rope, and also avoid possible collisions with the tow truck by running the ACV up to speed using its own propulsion system, and then allowing it to coast through the test section after cutting the thrust throttle. A film of the vehicle passing markers at set intervals (say 2 m. steps) would allow its deceleration to be measured without interference, hence giving the total drag force, over the whole speed range. This approach could be compared with the results already obtained to check their correlation.

This technique is discussed in detail in Reg. 6, (see also Appendix to the present report), and in Ref. 9.



THESE FIGURES HAVE BEEN CORRECTED FOR AERODYNAMIC, MOMENTUM, & SLOPE DRAG.

HEX-3 TOW TESTS OVER SAND & CONCRETE AT VARIOUS SPEEDS.

FIG. 11.

7. GENERAL DISCUSSION

On the basis of the theoretical consideration in Sections 2, 3, and 4, it appears that systematic data on overland ACV drag must include information on:-

Vehicle dimensions,
Skirt configuration,
Lift airflow and atmospheric conditions,
Drag force, and
Terrain description.

Very few such complete data are available, and those known to the writer are summarised in this report, and its appendix. This information is presented in one graph in Fig. 12.

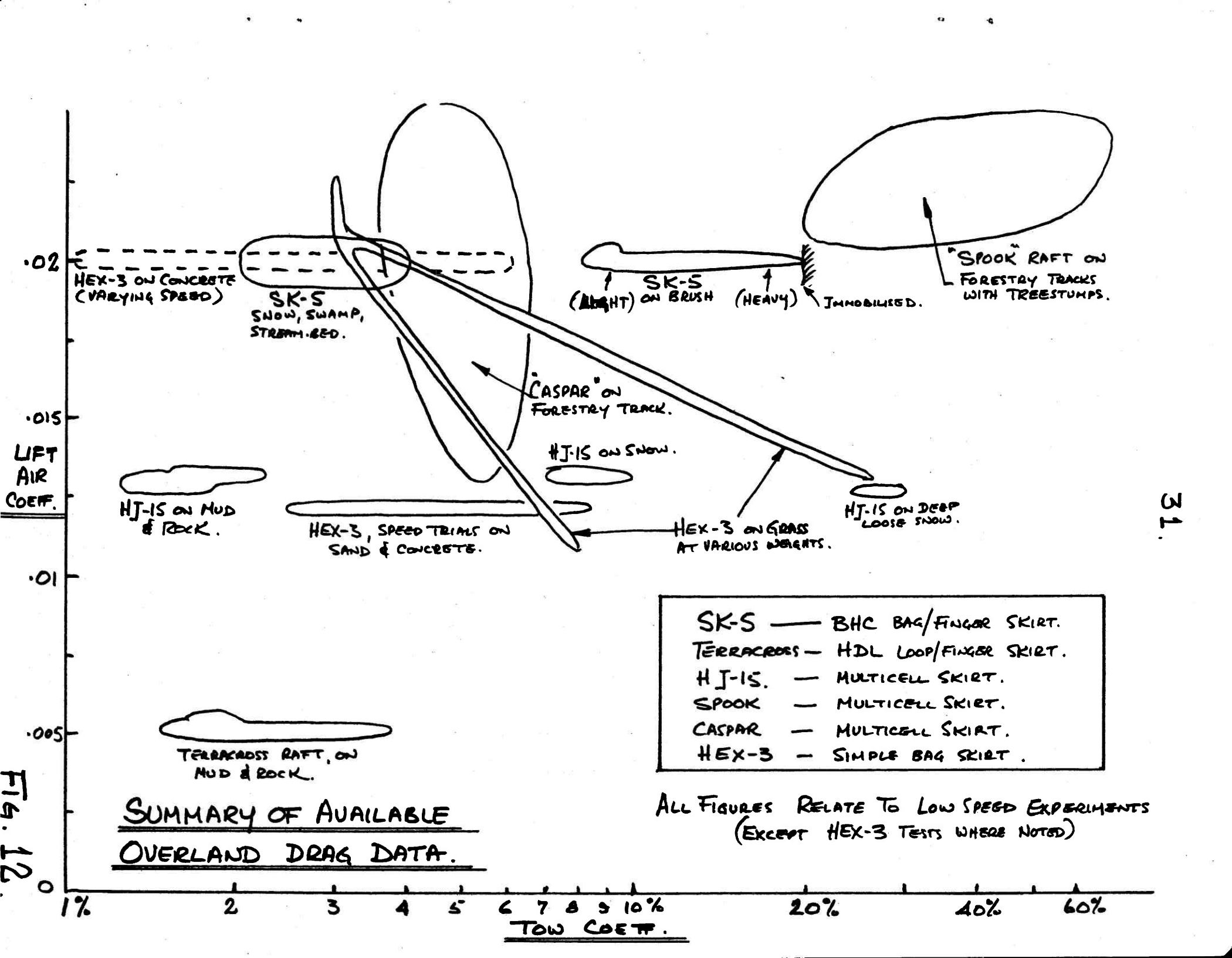
The techniques of measuring ACV drag are in urgent need of improvement.

Most attempts at drag measurement so far have been by the measurement of tow force fluctuation while the vehicle is towed at approximately constant speed by a tractor or a winch. Neither towing mechanism has been satisfactory. It is possible that a study of ship-tank towing methods, where the model is towed by a massive guided carriage, relative to which its reaction is measured, might be fruitful. Such a method might reduce the "wandering" of the ACV, and the spurious fluctuations of the recordings.

Over relatively smooth ground, the free deceleration methods discussed in Refs. 6 and 9 appear to open a promising avenue of approach.

The experiments on Caspar, SPOOK, and on the CRREL SK-5 all show an unacceptable spread of results over nominally the same terrain. Since even the passage of an ACV over some terrain modifies it (by selective erosion, crushing vegetation, etc.) then successive runs will clearly not give identical results, and since no two "natural" tracks are identical, a quandary results.

It appears essential that some tests are run over "real" terrain, to determine ability to traverse it (as a GO-NO GO result) and to measure the wear inflicted on the skirt by the terrain, and vice versa. However, it also appears necessary to run tests over a synthetic "standard rough terrain," which will give drag comparable to the real case, but which will be easily described, and remain constant through a whole programme.



SUMMARY OF AVAILABLE OVERLAND DRAG DATA.

ALL FIGURES RELATE TO LOW SPEED EXPERIMENTS (EXCEPT HEX-3 TESTS WHERE NOTED)

FIG. 12.

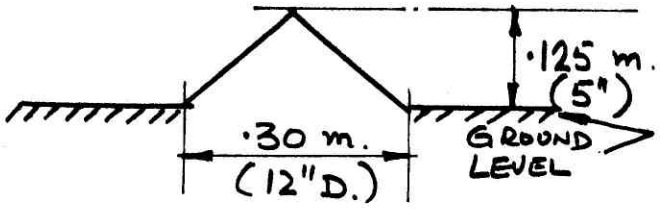
It therefore appears necessary to construct a test track, of perhaps 300 m length, of some wear-resistant material such as concrete. The track would have provision for attaching standard roughness elements, such as the cones examined in an early stage of the Caspar programme (Fig. 13). This track should enable repeatable drag measurements to be made.

An improvement in the quality of the drag recordings might be obtained by towing the ACV through a straingauge/dashpot system, while guiding it by some kind of carriage analogous to that used in a ship-model tank. The carriage itself could be towed along the test track by a winch.

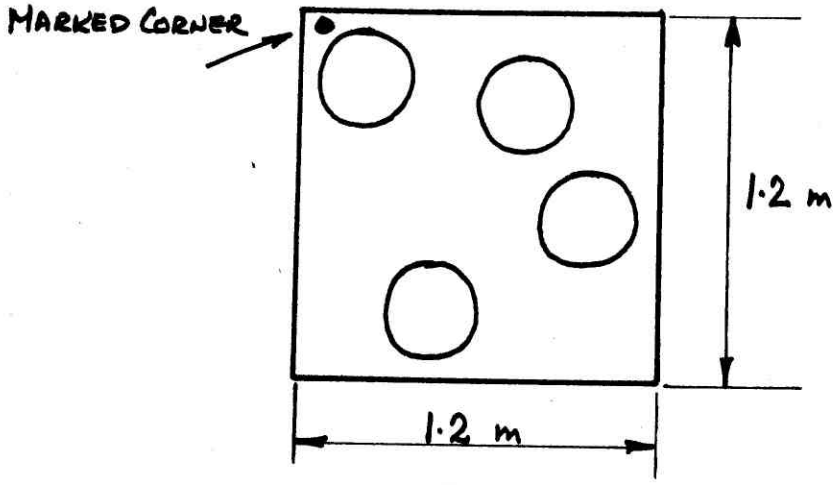
On smoother terrain, a version of the deceleration technique should be studied, in conjunction with aerodynamic drag measurements on models of the test vehicle.

In the meantime, this report summarises the best existing data known to the writer, and lists the sources from which these data have been gathered.

PROFILE OF CONE.



SPACING OF CONES ON PATTERN UNIT.



ARRANGEMENT OF UNITS ON TRACK [BY ROTATING PATTERN 90° CLOCKWISE AT EACH SUCCESSIVE REPETITION.]

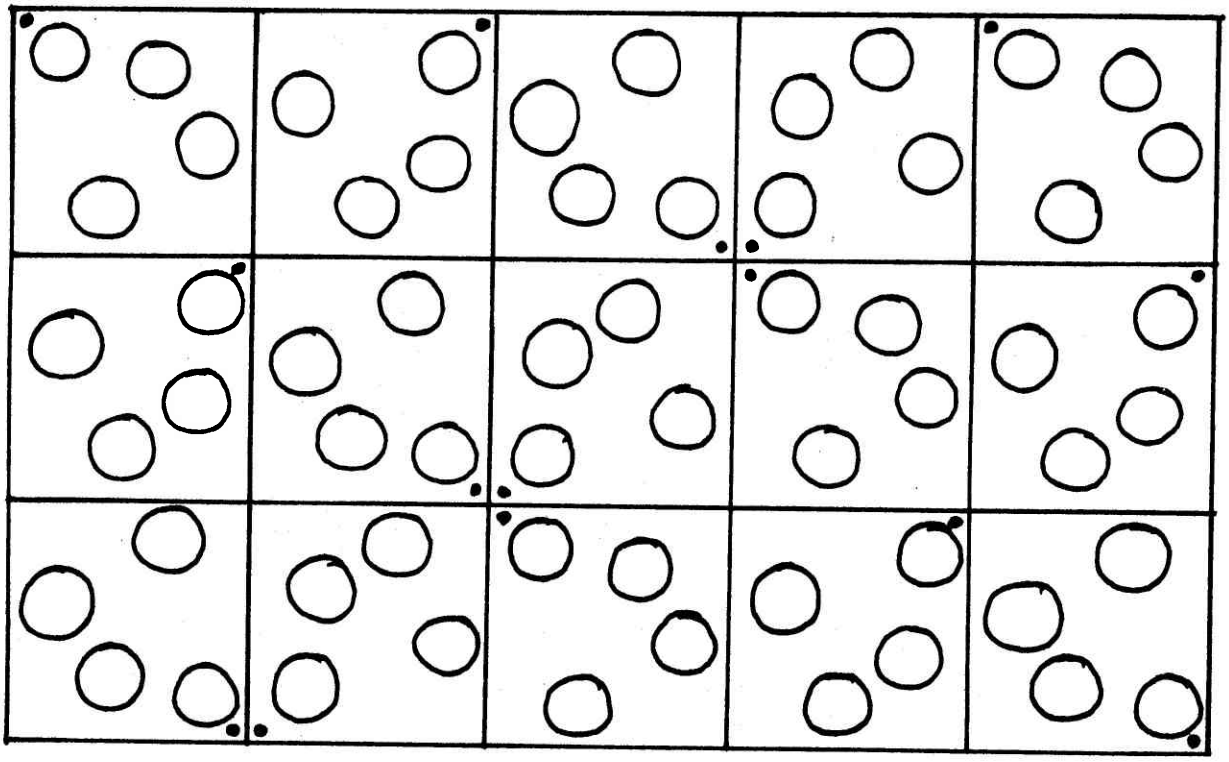


FIG. 13.

SYNTHETIC ROUGH TERRAIN.

"CASPAR" TRAVERSED A 3×8 UNIT SAMPLE SEVERAL TIMES [JAN 1974]

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9. APPENDIX

An attempt is here made to collect the available experimental data on overland ACV drag, and to present it in a consistent form.

The minimum required data are:-

Vehicle dimensions, including total vehicle weight

Skirt type

Lift air flow (at specified atmospheric conditions)

Drag force

Terrain description.

None of the published data known to the writer include all this information, but in a number of cases it has been possible to make an acceptable estimate of the missing factors. The writer acknowledges gratefully the sources from which the data have been drawn, and assistance from Mr. R.G. Wade in estimating certain lift airflows.

9.1 ACACT/TDA/HydroQuébec Trials at Baie Comeau (Ref.10)

Two ACV rafts were towed over a variety of St. Lawrence North Shore terrain in Summer 1973 by various tug vehicles. A straingauge link in the towbars enabled some tow coefficient data to be collected. The terrain is described briefly in a table in Ref. 10, along with representative Tow Coefficient figures. No measurement of lift airflow was made, so in the present analysis manufacturers' data have been used to estimate this. Discussions with makers and operators suggest that the machines were not operated at much less than full throttle, so these figures are likely to be as realistic as can be hoped from commercial fan data. One must remember also that the trials were organised to obtain field operating experience and data, so that the collection of scientific data was only a secondary activity.

The following section is extracted from Ref. 10:-

"Towing Resistance

Towing resistance was recorded at Ragueneau and at L.E.T.E. over nominally flat concrete test tracks. The values shown in the table below have been derived from dynamometer recordings made at Ragueneau, and L.E.T.E., Orleans using the NRC dynamometer. Mean values and standard deviations

are taken from short runs over flat terrain of semi-uniform surface characteristics.

NO.	DATE	LOCATION	TOWING FORCE (LBS)	STD. DEV.	RAFT ALL-UP WEIGHT (LBS)	DRAG COEFF.	TERRAIN
HoverJak							
H-2	11-09-73	Ragueneau	698	155	30,000	0.023	Sandy road
H-3	11-09-73	Ragueneau	532	97	30,000	0.016	Dry mud
H-4	11-09-73	Ragueneau	343	68	30,000	0.011	Dry mud
H-5	18-10-73	LETE	600	33	34,000	0.018	Flat rock, dry
H-6	18-10-73	LETE	481	109	34,000	0.014	Flat rock, dry
H-7	18-10-73	LETE	187	95	34,000	0.005	Concrete, dry
H-8	25-10-73	LETE	60	18	34,000	0.002	Concrete, dry
Terracross:							
T-1	4-09-73	Ragueneau	930	130	50,000	0.019	Wet mud
T-2	4-09-73	Ragueneau	1,114	286	50,000	0.022	Dry Mud
T-3	4-09-73	Ragueneau	1,348	297	50,000	0.027	Varying: wet to dry
T-4	4-09-73	Ragueneau	1,373	435	50,000	0.027	
T-6	4-09-73	Ragueneau	1,831	245	50,000	0.037	Dry mud
T-7	4-09-73	Ragueneau	767	155	50,000	0.015	Water or mud
T-8	4-09-73	Ragueneau	1,419	369	50,000	0.028	Mud
T-9	4-09-73	Ragueneau	1,739	371	50,000	0.035	Churned marsh
T-10	1-11-73	LETE	916	226	30,000	0.018	Wet flat rock

After inspection, the recorder traces were divided in sections covering movements over approximately uniform terrain. Mean traction values, as well as the standard deviation were calculated for each section."

From the same reference, data on the two rafts are extracted to permit Lift Air Coefficient calculations to be made, as follows:-

In the absence of other data, it will be assumed that the figures relate to Standard Day barometric conditions.

Hoverjak Raft

Cushion Area	= 58 m^2
Total Vehicle Weight	As indicated in table
Of this, 2% is carried on wheels	$\therefore$ 98% is taken on cushion
Design point Lift Airflow (356 H.P.)	= 47.2 m^3/s

Terracross Raft

Cushion Area	= 49.7 m^2
Total Vehicle Weight	As indicated in table
Of this, 7% is carried on wheels	$\therefore$ 93% is taken on cushion
Design point Lift Airflow (196 H.P.).	= 20 m^3/s

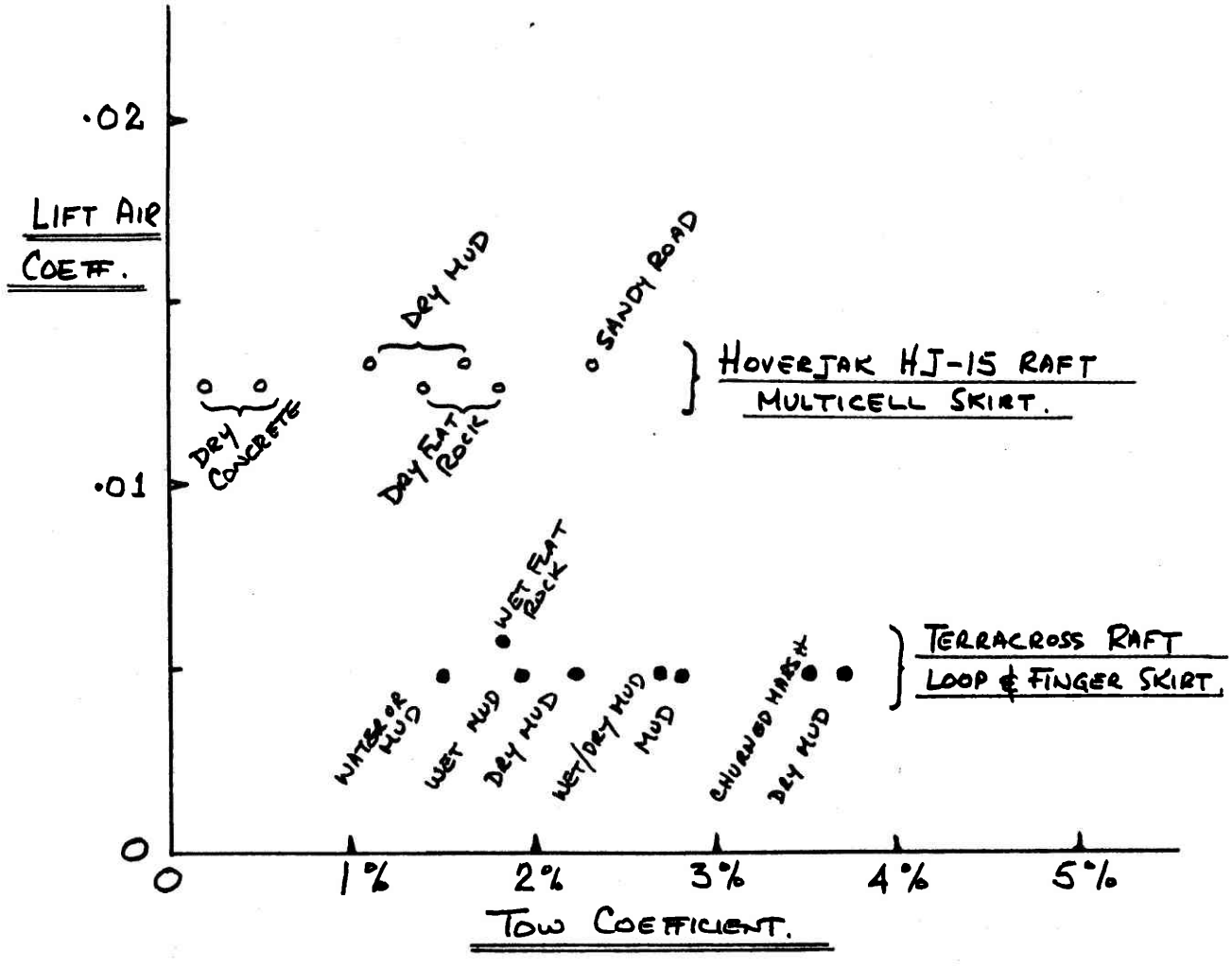
A "standard day" barometer is assumed, so that Air Density = 1.23 kg/m^3. Hence, a continuation of the previous table may be constructed:-

Test No.	Total Wt. on Cushion (newtons)	Cush. Press. (n/m^2)	Lift Air Coeff. (Non-dim.)	SKIRT TYPE
HOVERJAK - Cush. Area = 58 m^2, Q = 47.2 m^3/s				MULTICELL
H 2, 3, 4	130830	2256	.0134	
H 5 - 8	148268	2557	.0126	
TERRACROSS - Cush. Area = 49.7 m^2, Q = 20 m^3/s				HDL LOOP/FINGER
T 1 - 9	206925	4164	.0049	
T 10	143548	2888	.0059	

The results of these trials are plotted in Fig. 14 at the end of this section. From statements in Ref. 10, it is believed that these data were taken at forward speeds around 1.8 m/s (4 m.p.h.).

9.2 Tests over Snow, at Orangeville Airport

In the Winter of 1973/74, a HoverJak AC raft of the same type as discussed in the previous section, was towed over snow. A variety of snow conditions was met, from unbroken glazed crust to drifts of light fluffy snow up to 1 meter deep. Towing was by a Bombardier tracked vehicle on which no measurements were made, and by helicopter (a Vertol 44 with twin rotors driven by a total of about 1100 H.P.). Some estimate of tow load was possible in the latter case, and the Lift Air Coefficient could be estimated as in the previous section.



DRAG DATA — BAIE COMEAU TRIALS

[FROM REF. 10.]

ALL AT APPROX 1·8 m/s. SPEED.

FIG. 14.

a. Glazed Snow Surface

When the raft was towed by helicopter over glazed snow surface, the tow force was so low that the towline (approximately 50 meters long) hung in a slack loop, and the raft (total weight of about 140,000 n) slid along on cushion at speeds up to 15 m/s. This implies a Tow Coefficient of 0.5% or less, probably closer to 0.1%. It was interesting to observe that the raft, of about 140,000 newtons (16 tons) total weight, was able to slide over the glazed snow surface without breaking the 5 mm ice sheet on top of the snow.

b. Shallow Loose Snow over Glazed Base

When the raft was towed through deeper drifts the tow load rose to high values. In the worst case observed, the helicopter appeared to be in about a 30° nose-down attitude, on a taut towline, and the pilot estimated a 10,000 lb. tow force (maximum permitted for the helicopter) which is equivalent to a Tow Coefficient of 30%. This was in an area where the fluffy snow had drifted about 1.5 meters deep.

Throughout these trials the raft was operating at full lift airflow, which may be estimated roughly as a Lift Air Coefficient of .013, except possibly in the glazed snow surface, where somewhat lower airflow may have been used.

The above figures are extremely rough, and are reported simply because they represent the only over-snow quasi-quantitative data known to the auther.

9.3 Experiments over Various Terrains, with a Bell SK-5 (SRN-5) at the U.S. Cold Regions Research and Engineering Laboratory

In Ref. 11, Liston describes various tests in which an SK-5 (with BHC fingered skirt) was towed over various terrains, including water, by vehicle or boat. A strain-gauge was used to attach the towline to the towing vehicle, which introduces errors, and Liston says of the whole set of tests:-

"Even though the skirt drag numbers obtained in this test appear to be in the right "ball park," it is suggested that the technique is not correct. The towline is an obvious source of error; and the tests

were confined to locations negotiable by a vehicle of some sort. It would seem better to measure changes in speed while moving over the surface of interest with zero propulsive force. It is possible that relationships between skirt drag and speed could be obtained for any surface of interest. This requires more faith in the equations describing aerodynamic and momentum drag than is possessed by the writer. However, if skirt drag at low speeds is adequate, the measurement of deceleration and subsequent computation of drag is straightforward and should produce reliable and accurate results. This technique was applied to subsequent tests at Fort Greely, Alaska."

Reference 11 should be studied in detail, for a very interesting description and discussion of these tests.

No attempt was made to measure lift airflow on these tests, so corresponding SRN-5 operating data were consulted, at the total vehicle weights and turbine r.p.m. stated by Liston in Ref. 11. From this, it is estimated that the Tow Coefficients tabulated below were measured at a Lift Air Coefficient of .021, and at "Very Low Speed," so that aerodynamic and momentum drag could be neglected.

Drag Experiments at CRREL (U.S.) - Ref. 11

Vehicle - Bell SK-5 (SRN-5)

Total Weight of Vehicle during experiments 67,000 newtons (15,000 lb.)

Cushion Pressure = 1400 n/m^2

Cushion Area = 48.3 m^2

Speed = "Very Low"

Lift Air Coefficient = .021 approximately

	Surface	Tow Coefficient
1.	"Grassy dry surface"	1.1%
2.	"Marsh, live mat over water"	1.5%
3.	"Marsh with dense brush"	3.1%
4.	"Marsh with thin brush"	1.9%

(From 3-4 the resistance of dense brush is deduced to equal 1.2% in this particular case. Liston also notes that he estimates that dense brush of about half the

height of the inflated skirt would immobilise the ACV. Whether this is due to porosity or simple drag he does not say.)

5. "Shallow water below hump speed (at 10 m.p.h.)" 6.3%

6. "Deep water below hump speed (at 10 m.p.h.)" 3.6%

7. "Deep water above hump speed" 2.8%

These figures are plotted in Fig. 15

In a second report (Ref. 6) Liston describes further experiments with the same vehicle in Alaska. In these experiments the drag was measured by driving the vehicle under its own power to the entry of a set course. At this point the propeller pitch was set to zero thrust, and the deceleration of the vehicle measured on the marked course. This gave a measure of the drag, after aerodynamic drag had been corrected out analytically. Since the method often relied on the measurement of time or distance to standstill after entering the course at measured speed (usually 5-8 m/s), it implied a constant drag force, irrespective of speed, although it is argued in the report that in some cases the drag appeared to be dependent on speed. However, the error appears relatively small in most of the cases discussed.

Measurements of lift airflow were not made during these tests, but it has been assumed by the present writer that the lift airflow was roughly equal to that deduced for the previous SK-5 tests. Liston's conclusions from his experiments are most detailed and interesting, and should be studied in full (Ref. 6, pages 26-28). An extremely short summary is given below, together with a table of results extracted from Table III of this reference. The reference also gives clear photographs and descriptions of the various terrains.

SKIRT DRAG TABLE [FROM TABLE III, REF. 6]

SURFACE	LIFT AIR POWER %	INITIAL SPEED	TOW COEFFICIENT %
Smooth concrete and snow	91	-	0.0
Rough hummocky snow, hard glazed surface	91	-	0.2
Light brush on rough ground	83	would not move	25.0
	89	7.2 m/s	7.5
	91	8.3	9.2
Swamp grass, tufts in water	83	3.3	0.6
	89	6.6	2.0
	91	7.6	3.4
Rock strewn creek bed, graded level	83	5.2	3.0
	89	5.2	2.6
	91	6.3	2.0
Rock strewn creek bed, left rough	83	2.0	2.2
	89	2.7	1.4
	91	2.8	1.2

Data for Bell SK-5, total weight for test = 58,100 newtons.

(Loop & Finger BHC skirt)

These figures are also plotted in Fig. 15

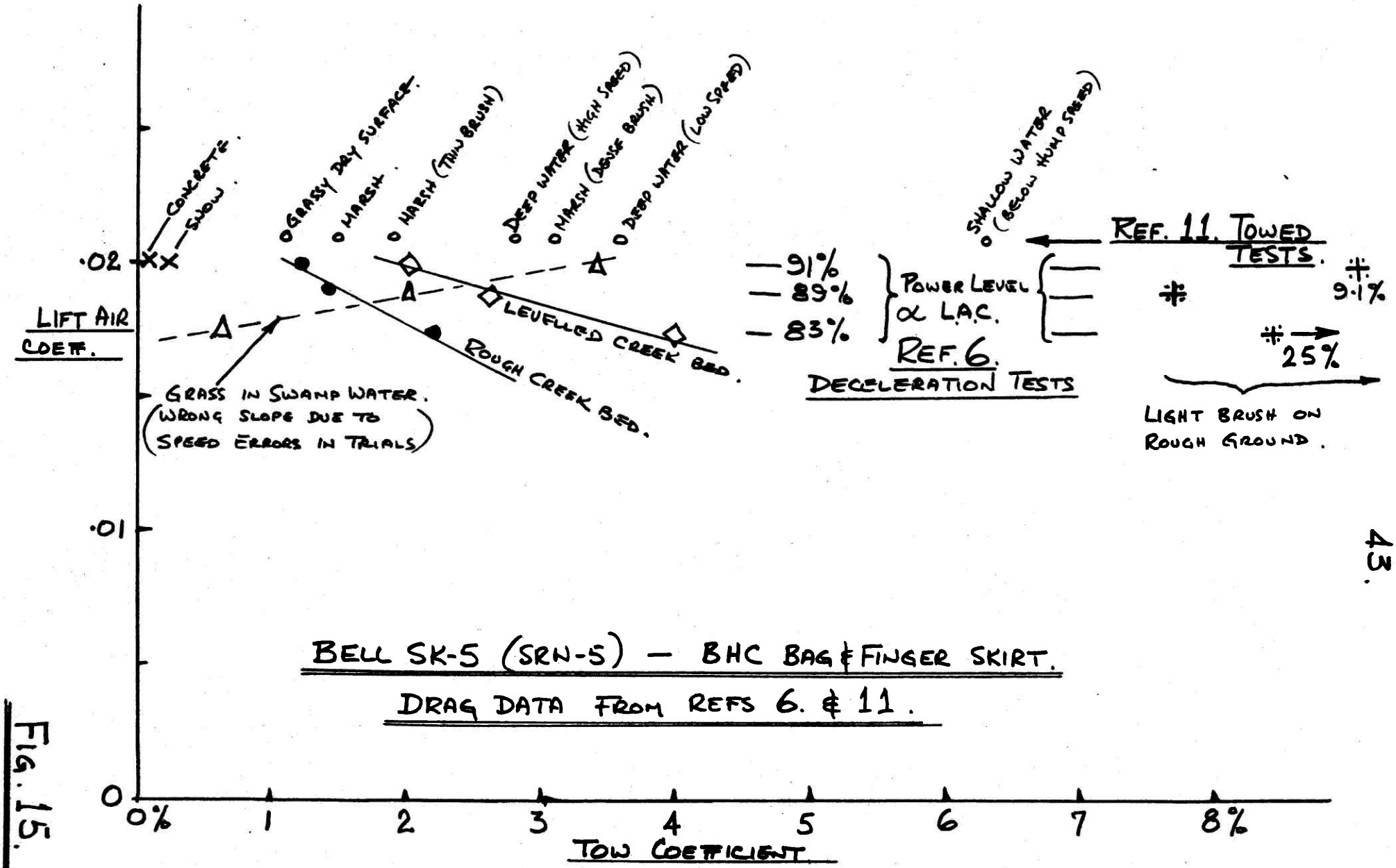
Liston's conclusions may be summarised in an extremely brief and simplified form as follows, although his full discussion in Ref. 6 should be consulted.

a. Drag is strongly dependent on surface material.

b. Drag is not directly related to surface roughness.

(c. Wear is not necessarily related to drag. The nature of the surface material is important.)

d. Skirt drag is only dependent on vehicle speed when the deformation of skirt or terrain is rate-sensitive. (Liston distinguishes between the easily deformed fingers and the less easily deformed bag, in relation to whether obstacles are high enough to deform the bag. This consideration is specific to bag-and-finger skirts.)



BELL SK-5 (SRN-5) — BHC BAG & FINGER SKIRT.

DRAG DATA FROM REFS 6. & 11.

Fig. 15.

e. Drag is related to hovergap in the sense that at large gap there is zero contact and zero drag, at zero gap there is full contact and high drag, and at any gap giving partial or transient contact over rough ground there is some intermediate drag. The data available do not permit a more precise relation to be stated.

9.4 Experiments on "Forestry" Terrain with the "SPOOK" AC Raft

In Refs. 12, 13 and 14, Silversides et al give detailed accounts of tests carried out by the Forestry Division of the Department of the Environment, and their Petawawa field site.

These tests were of a most detailed nature, with careful drag measurements and excellent descriptions of the terrain and the effects on it of the ACV. The SPOOK was a towed AC raft 6 m × 3 m, of about 20,000 newtons weight, and had a Multicell skirt, with 8 jupes inside a peripheral skirt. Unfortunately lift airflow was not measured.

Various tests are described, including a number over several arrays of synthetic "tree stumps" of specified heights. However, the results most relevant to the present discussion are summarised in the table in Appendix II of Ref. 13, which is summarised below. This shows the tow coefficients required to pull the SPOOK at a series of total weights round a track, which is carefully described (with photographs) in Ref. 13. The track was over fairly level ground, and was typical cut-over forest land, with ground-cover and light slash lying among tree stumps, creating both extreme roughness including snags, and also very high "porosity" to reduce the effectiveness of the lift air supplied.

The drag measurements recorded are the most complete available, and are of particular interest. They were measured by straingauging the girder holding the ball-hitch on the tug vehicle, an articulated Timberjack tractor. The SPOOK was clamped to this ball-hitch by a rigid 'A' frame. This allowed recording of tow loads (positive and also negative as the SPOOK tried momentarily to override the tractor) and also side loads, as the SPOOK tried to veer off course against the restraint of the 'A' frame.

The present writer would criticise this system, as while it undoubtedly measures the interaction at the tow-hitch with great precision, much of the fluctuation is due

to the highly irregular motion of the tractor rather than of the SPOOK. Since it is well-known that an ACV has a smoother motion over obstacles than a wheeled vehicle, the writer feels that this system will give a large spurious magnification of tow load fluctuations. A suitable analytical method should give a mathematically valid mean tow force, but the physical validity of this is open to discussion, and the meaning of the peak values requires interpretation. Similar criticisms also apply although in lesser degree, to the winch and towline method. With a long springy towline, the ACV is apt to hang back until an excessive tension breaks it loose. It then surges ahead, to an almost no-load state, and coasts slowly until the towline again tightens to the breakout value.

There is no simple way to measure ACV drag over non-homogeneous terrain, and an evaluation of this problem is of urgent importance.

The table from Appendix II of Ref. 13, referred to above, is presented below in modified form. Only the positive tow loads are given, and these are shown as non-dimensional Tow-Coefficients, to conform with other data in the present Note. Negative tow force (override) and side loads are not given here, but a full study of Ref. 13 is recommended. The average of values for Blue and Yellow tracks of Ref. 13 is given, and the Standard Deviation of the tow loads has been converted to a percentage of the average load for each run to non-dimensionalise it. It indicates either terrain roughness or tug/ACV elastic interactions, the writer is not at this point prepared to say which.

SPOOK AC RAFT EXPERIMENTS OVER FOREST TERRAIN (REF. 13)

RUNS	TOTAL VEHICLE WT. (newtons)	TOW COEFFICIENT	STD. DEVIATION (% OF MEAN DRAG)
8 & 9	20,500	39%	39%
4 & 5	22,700	18%	57%
6 & 7	24,900	34%	34%
10 & 11	27,200	23%	52%
12 & 13	29,400	51%	21%
		Avg. 33%	41%

The lift airflow was not measured in these tests, but the lift engine, fans, ducting, and skirt were essentially identical with those of Caspar (Build 1). It is believed

that the SPOOK raft was operated at full lift power during these trials. Using Caspar data, the Lift Air Coefficient is therefore estimated at between .028 and .022, depending on the total weight at each test point.

The results are plotted in Fig. 16. It must be realised that these tests were over extremely severe terrain, over which the high drags recorded seem not unreasonable.

FORESTRY TERRAIN TRIALS – "SPOOK" A.C. RAFT

TOWED BY TIMBERJACK TRACTOR ON RIGID LINK.
AT APPROX 2 m/s. SPEED.
MULTICELL SKIRT. (REF. 13.)

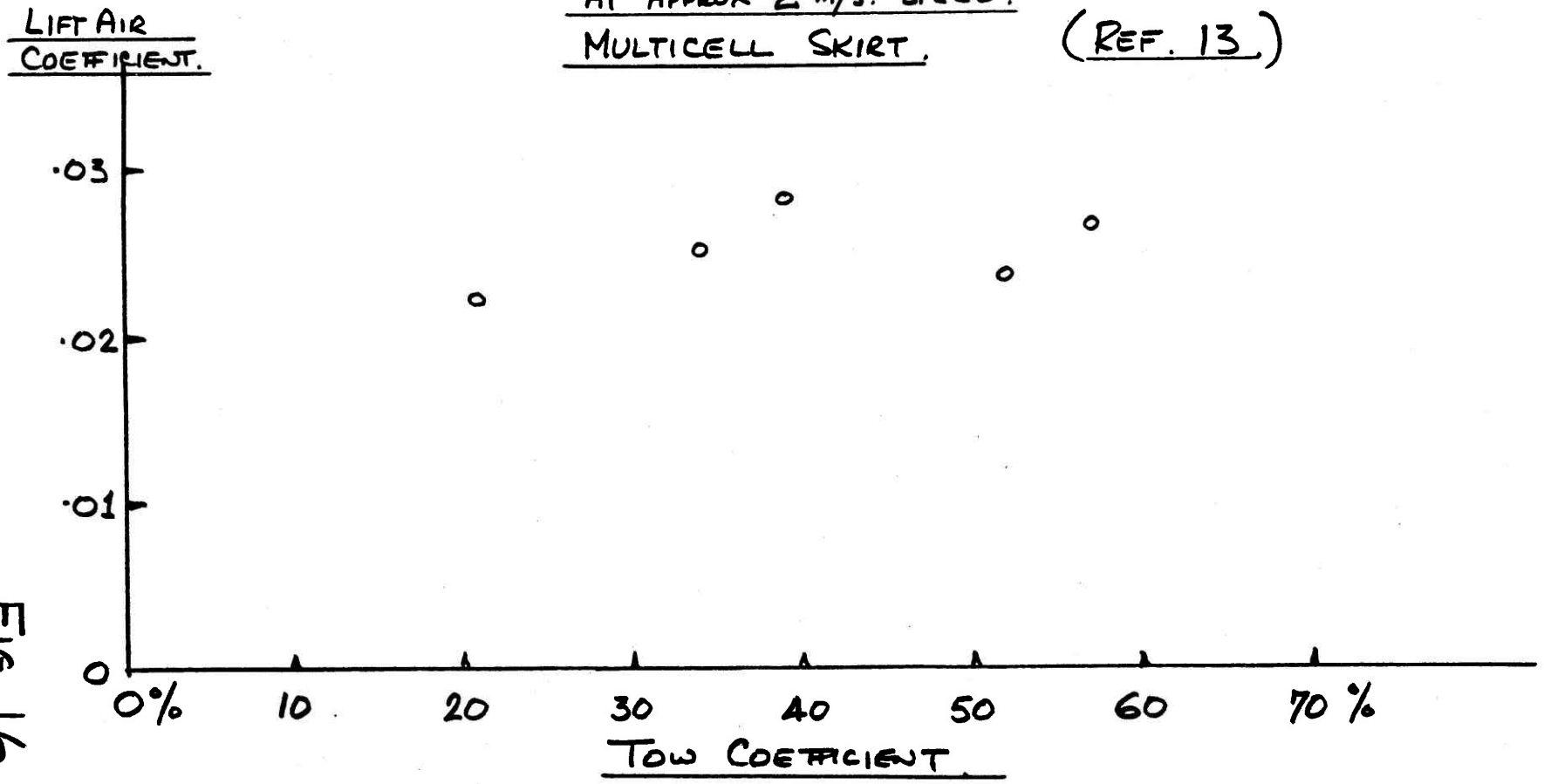


FIG. 16.