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CASPAR ACV RESEARCH PROJECT
REPORT NO. 4
PROGRAM 1, THE MULTICELL SKIRT, A SUMMARY

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A SUMMARY

SUMMARY

The report summarises the present state of knowledge of the Multicell skirt, primarily with respect to its operation overland, insofar as it is understood in Canada. The discussion is written under a number of headings, dealing with:

(a) A description of the skirt system and its components;

(b) The stability of the vehicle as a whole, while stationary over a hard surface or over water;

(c) The way in which forward motion affects this stability; and

(d) The manner in which the structural stability of the individual cells of the skirt is determined, and in which this affects the vehicle's stability.

(e) The drag of the skirt system over various terrains is discussed.

(f) The system's ability to operate over obstacles is considered.

(g) Finally, the skirt is considered as an inflated structure, and its design, fabrication, and strength are examined.

From the designer's point of view, one may single out the influence of fan characteristic on vehicle roll and heave stability, and the influence of cell-feed configuration on the cell as an inflated structure. The connection between lift airflow quantity and drag (or propulsive power) and on skirt wear are also of great importance.

From the point of view of the pilot, probably the most important point brought forward is the vehicle stability, which is quite different from that of any other skirt system. It is shown that the vehicle has an extraordinarily stiff roll or pitch characteristic up to a large value of disturbing force, but that at a critical point it collapses without warning, and may be difficult to restore to level hover.

This critical point is greatly affected by lift airflow, so that the vehicle cannot well be operated at reduced lift throttle to increase drag and directional control. This is quite unlike the performance of a fingered or bag skirt, which is much "softer" in roll, and which is often "dragged" at reduced lift airflow to gain greater control during "tight" manoeuvering.

This behaviour would come as a shock to a pilot accustomed to the fingered or bag skirt systems.

The preceding comments on handling apply mainly to the overland case; over water the Multicell skirt behaves in a manner much more comparable to the fingered, segmented, or bag systems.

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CASPAR REPORT NO. 4

A DISCUSSION OF THE MULTICELL SKIRT

1. INTRODUCTION

The "CASPAR" program was initiated with the object of studying the behaviour of various types of skirt systems on ACVs, as they interacted with the types of terrain they were intended to operate over. This objective has been interpreted in a fairly broad manner, and the study includes not only direct experiments with HEX-1 (the original research ACV known as "Caspar") but also other experiments on the smaller HEX-3 and the analysis of any relevant data from other sources.

The systematic study of skirt-terrain interaction is such a complex subject that a thorough experimental program covering all aspects completely would be too unwieldy to contemplate. The experimental study has therefore been selective, attempting to cover a few situations which appeared to be crucial in the light of understanding which developed during the course of the program. As a result, a fair understanding of the Multicell skirt has been built up, based on a patch-work of specific experiments, fortuitous observations during other operations, engineers' insight, and reported data from other sources.

The simple Multicell skirt appears to be practically obsolete at the date of writing, but the basic cell technique appears in more sophisticated hybrid systems, so an understanding of the cell element and Multicell arrangement still appears to be of considerable value. This report is therefore presented, as the outcome of the first series of experiments in the CASPAR program, carried out over the period 1973 to 1975. (For data on the CASPAR program, and the research ACV HEX-1, see Ref. 1).

In order to avoid any misunderstanding, it will be clearly stated which data are derived directly from quantitative measurement,

which from qualitative tests, from observation of operation, and which from literature or discussion.

It is further stated at the outset that the basic patents on the Multicell skirt are held by SEDAM of France for M. Bertin, and that the construction and use of any skirts described here is liable to be covered by these or other patent rights.

2. GENERAL DESCRIPTION OF THE MULTICELL SKIRT SYSTEM

A very good discussion of the basic multiskirt system is given, (by M. Bertin himself) in Ref. 2.

The cell on which the system is built is a truncated cone of light flexible material, with an airfeed in the top (large diameter) and with the open bottom (smaller diameter) hovering a small distance (the "hovergap") above the terrain. (Fig. 1)

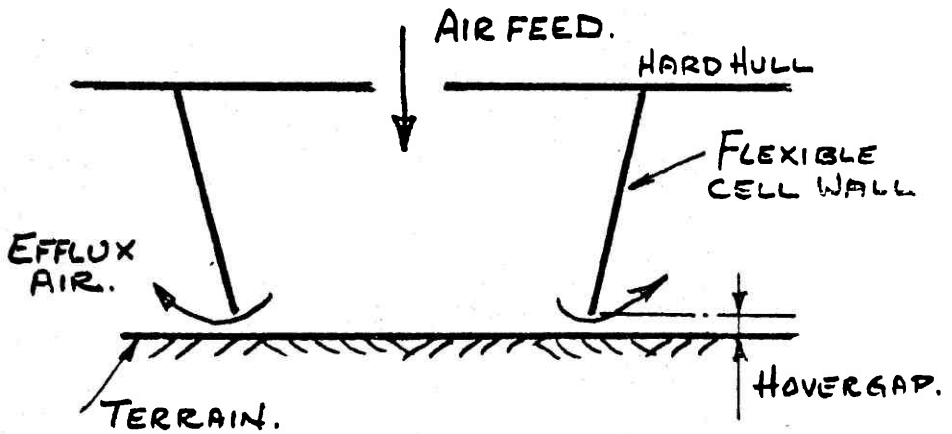


FIG. 1.

The air within the cell is quasi-stagnant, at "cushion pressure", while it escapes through the hovergap with a speed corresponding to a dynamic pressure equal to the pressure difference between cushion pressure and atmospheric pressure. The cell is maintained stiffly developed by this same pressure difference, exerting a peripheral (hoop) tension in the cell wall; and because the bottom diameter of the cell is smaller than the top, a vertical force is exerted downwards on the inside of the cell wall to keep it developed vertically.

The lift developed by the cell is equal to the base area ("foot-

print") times the cushion pressure. The vertical equilibrium is simple, the cell rises until the hovergap is large enough to allow the airflow supplied to the cell to escape through it at the velocity dictated, as described above, by the pressure difference between cushion and atmosphere.

The single cell has no stability in the pitch or roll sense. It is therefore used in groups of at least three cells under a vehicle, which is stabilised by the stability of the several cells each in the vertical (heave) sense, as the total vehicle rolls or pitches.

This is the "Multicell" system at its simplest, and unfortunately it has a poor load-carrying capacity. This is because the sum of the circular footprint areas of the cells which can be clustered under a given total vehicle planform is much smaller than the vehicle planform area itself. It is therefore usual to enclose the whole planform in some kind of "peripheral skirt", which gives maximum total "cushion area" for lift, but with zero roll stability, while a group of cells within this area give roll stability as previously described. The airfeed is usually within the cells, and the air escaping from under these fills the general cavity to increase the total lift, finally escaping through a second hovergap under the peripheral skirt. There may also be a small direct airfeed to the general cavity. This is the system usually referred to as the "Bertin system" in which the cells are often called "jupes".

Another system, the Aerojet "Pericell" describes the cells closely spaced all round the vehicle periphery, so tightly packed that they form a seal and hold the cushion pressure in the same way as the peripheral skirt of the Bertin system.

Further systems, developed in Canada by D. Jones, achieve similar results, but with improved performance over jagged terrain.

The present report is mainly concerned with the so-called Bertin system, of cells within a peripheral skirt, such as was installed under HEX-1 MKI, from a design by Jones. (See Ref. 1)

So much for the most simple view of the Multicell skirt. The simplicity is deceptive.

We will now discuss the various aspects of the system in detail.

The variables in the skirt system are as follows:

A. Geometrical

Diameter	D (top)
Diameter	d (bottom)
Height	H
Cone Angle	θ^0 (dependent on H, D, & d)
Material thickness	t
Hovergap	h

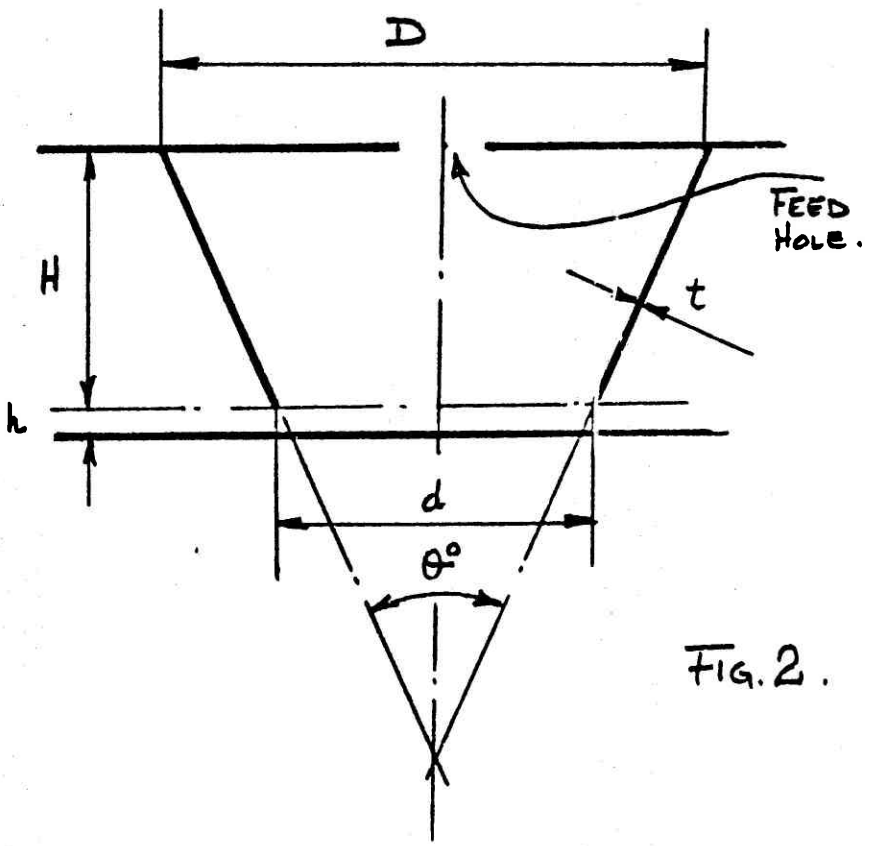


FIG. 2.

B. Aerodynamic

Feed hole dimensions and form
Airflow
Cell Pressure
General Cushion Area Pressure
Atmospheric Pressure
Blower (or rather air supply) characteristic

We shall examine how these large groups of variables affect some performance characteristics, mainly in the overland case.

3. VEHICLE STABILITY (STATIC)

(A) OVERLAND

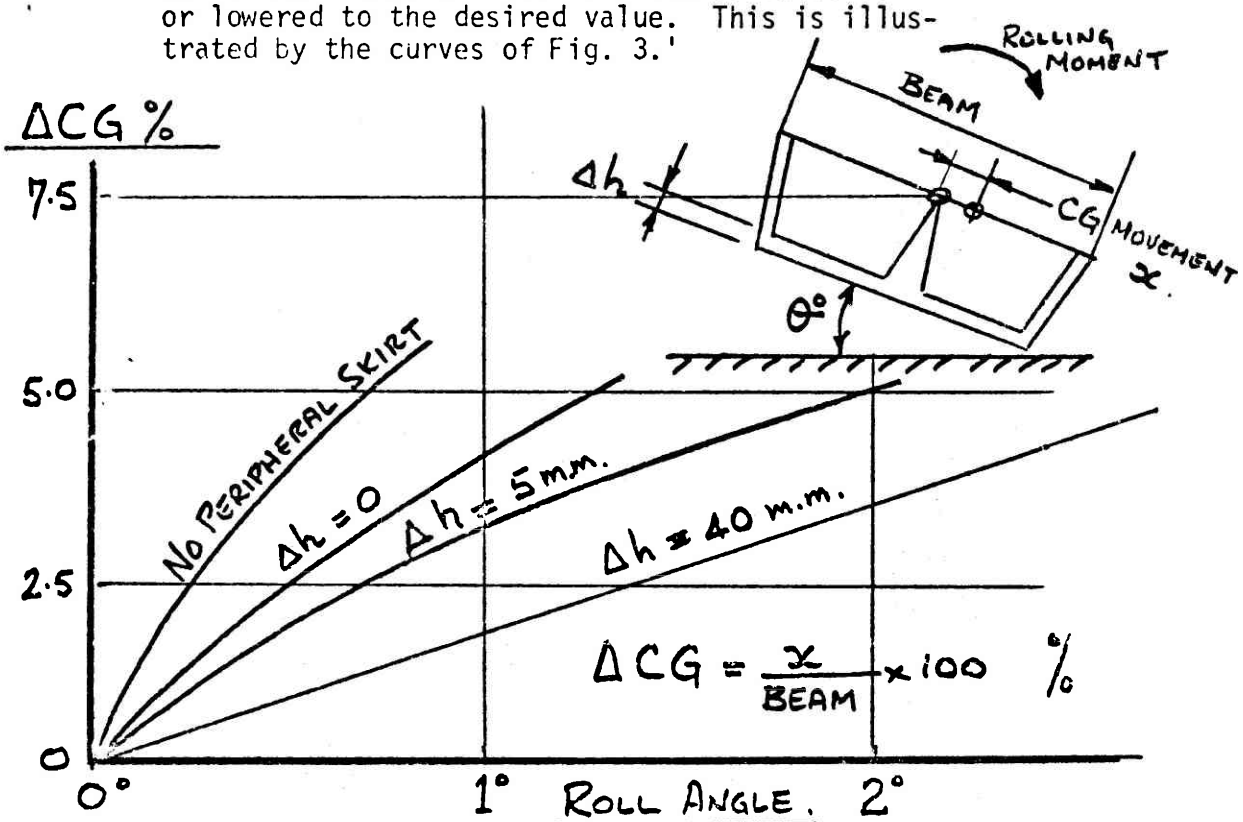
The stability of the stationary vehicle (in roll or pitch) is relatively easy to measure, and has therefore been studied extensively.

Roll (or pitch) stability is usually expressed in terms of ^{0}Roll/1% shift of CG, where the CG shift (or equivalent rolling moment) is given as a percentage of the total maximum hard-structure beam of the vehicle (or length, in the case of pitch instead of roll).

A clear but oversimplified explanation of the basic principle of roll stability is given by Bertin in Ref. 2, as follows:

> 'In the case of the multiple skirt system, if each inner skirt is supplied independently, the restoring torque can be as large as one chooses provided the slope of the compressor characteristic is properly selected. When the distance between the ground and one of the chambers is reduced, the air escape rate is reduced and the inner pressure increases. The opposite effect takes place (on the other side of the vehicle) where the distance is increased. A stabilizing torque develops immediately.
>
> Finally, adding a peripheral skirt to the multiple skirt system gives an even greater adaptability. By playing with the relative lengths of the peripheral skirt and the inner skirts - even in a small proportion from 1 to

3% in h/D - angular stiffness can be increased or lowered to the desired value. This is illustrated by the curves of Fig. 3.'



ROLL STABILITY OF BC-8 [FROM REF. 2.]

FIG. 3.

However, this appears to be an extremely simplified explanation, and only covers the first small deflection of the roll process. The addition of the peripheral skirt will be discussed later, at present we will speak of the simple vehicle with an array of cells without any peripheral skirt.

When this simple vehicle is rolled, by an applied moment, the skirt and stability go through four separate phases. The first is the one described by Bertin above, where the hovergap on one side of the vehicle reduces from the normal value down to zero, while that on the other side increases correspondingly from normal to about twice normal.

While the following discussion applies strictly to a single cell of an array, the loss of lift in one cell at a critical point will probably overload and collapse the remaining cells, leading to the general behaviour to be described.

In the case of HEX-1 MKI, operating at full lift over a polished concrete floor, with about a 1.5 cm hovergap, this phase was vividly illustrated by the vehicle "dancing", a gentle oscillation within this phase at a period of about 3 secs/per cycle and an amplitude of about $0^0 03'$ (1.0 cms/side). This was not accompanied by any similar pitch oscillation, although a heave of 0.2 cms was observed at shorter period (1/3 secs/cycle). This general instability occurred when the applied roll moment was zero, and was undamped.

The second phase of the roll involves the local "knuckling under" of the bottom edge of the skirt on the low side of the vehicle, and a corresponding increase of hovergap on the high side. This is more or less a stable state, and occurs within a definite range of applied rolling moment. In this range, roll is almost linearly dependent on applied moment.

The third phase occurs at higher values of applied moment, and the cell-wall develops creases some distance above the lower edge, often about halfway up. This phase is time-dependent, and seldom lasts long. In fact the second phase may progress into the third, typically in a matter of 5-10 minutes, and then speedily pass into the fourth phase, - the collapse phase. If the applied moment is removed during even the third phase, the cell is likely to redevelop and bring the vehicle back to even keel. However, after a very short time in the third phase, the cell usually crumples completely and collapses, to form phase four. Jones suggests that this behaviour may be critically dependent on cell cone angle. Removal of the applied moment may or may not permit redevelopment to bring

the vehicle back level. This may be because the CG of a rolled vehicle is itself shifted to the down-side, and thus the removal of the applied roll moment may leave the rolled vehicle itself exerting some roll moment on the suspension system.

It is unfortunately the case that the typical Multicell skirt ACV has a very thick hull, whose depth is occupied by lift air ducts. The engines and payload are placed on top of this hull, thus giving the vehicle a very high centre of gravity. Although the Multicell skirt is notably "stiff" in roll, the resulting vehicles are far less stable than they might be, due to this high CG.

It would appear perfectly feasible to use flexible air ducts (of skirt material) outboard of the hard hull, along each side. This could greatly reduce the hull thickness, hence lowering the CG and improving stability, while the air ducts could be collapsed and reefed to the sides to reduce vehicle width for transport.

As was described in Section 2 above, the (Bertin) Multicell system usually includes a peripheral skirt surrounding the cells (jupes), to increase the total lift. However, as Fig. 3 on page 8 shows, this combination of a group of cells (roll-stable) within a single large peripheral cell (roll-unstable), has a lower roll-stability than the simple group of cells.

The Bertin approach was stated in Ref. 2 to be that the general cushion area (between jupes and peripheral skirt) was fed with air from the efflux under the jupe edges. The pressure difference between jupes and cushion was controlled by cutting the jupes shorter than the peripheral skirt (by an amount Δh, in Fig. 3). The greater this pressure difference (i.e. the smaller Δh) the stiffer the roll characteristic, and the more firmly developed were the jupes. On the other hand, this stiffness was obtained by a reduction of cushion pressure, an overall loss of lift and hence skirt contact. The main argument against this way of controlling the pressure difference was the fact that travel over abrasive ground speedily wore off the bottom of the

peripheral skirt until Δh became effectively zero, after which all skirt and jupe hems wore down together.

A better system, devised by Jones, was to feed the cushion area by separate feed holes from the air duct, calibrated to give the desired pressure difference between jupes and cushion.

However, in both cases this system of feeding the cushion at a controlled rate and relying on it for about half the vehicle lift contributed to a poor characteristic of the system. As explained above, if sufficient roll moment is applied, the down-side skirts ultimately buckle, like Euler columns, and collapse. Removal of the rolling moment may permit the vehicle to rise again, but there is usually a hysteresis in this process. This is due to at least three factors.

Firstly, the vehicle's CG is displaced in the rolled condition, and causes a rolling moment itself, which remains after the applied roll moment is removed. In calculations of stability, this extra rolling moment must be accounted for at each roll angle observed, although at small roll angles it may be found to be negligible.

Secondly, the crumpled cell has something of the characteristics of the Euler Column. It has retained some inherent stiffness until it actually buckled. Once buckled, it has far less supporting power (to return from the rolled condition). This factor is at present arguable, owing to our imcomplete understanding of the support afforded by an inflated flexible structure, but this statement appears to be true in the light of current opinion.

Thirdly, when one side of the vehicle collapses at maximum roll, the up-side shows a large hovergap which allows lift air to blow off as fast as the calibrated cell and cushion feed holes will supply it. If the support was from simple cells, with no peri-

pheral skirt, then the down-side cells would be sealed by their collapse, and would roll the vehicle back level against the unsealed (atmospheric pressure and zero lift) cells blowing off on the up-side.

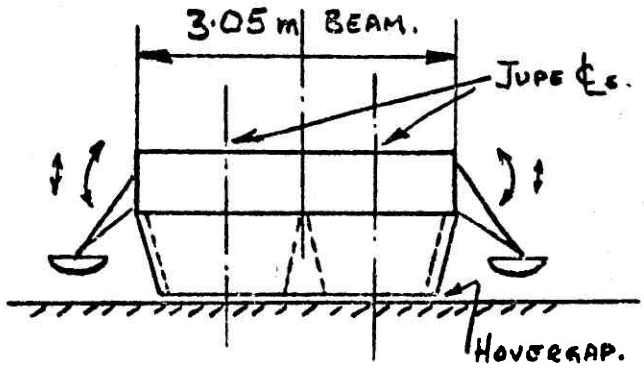
However, since the lift is now derived half from the cushion, and since the whole cushion area is blowing off freely through the excessive gap on the up-side, the down-side has only half its normal lift (i.e. that derived from the cells only). The down-side therefore has insufficient lift to roll it up again. This lift is even further reduced by the buckled condition of the cells. This is easily confirmed, since often an added weight on the up-side will reduce the gap that side to a small value, allow cushion pressure to rise, and the whole vehicle will rise into even keel.

Both Jones and Sullivan have developed analytical methods of predicting static roll stability, from which optimum cell/cushion pressure ratio may be determined.

A set of observations and calculations from a typical roll test on HEX-1 will help to confirm the descriptions given above.

Roll Test (4065-1600-1A) on 12-II-74

Vehicle HEX-1 (CASPAR) (see Ref. 1). Indoors, over polished concrete floor.



FRONT VIEW
CONDITION 1.

FIG. 4.

CONDITION 1

Time (from start of test)	3 minutes
Rolling Moment	= zero
Roll	= -0.2^0
Hovergap	= 1.5-2.0 cms Port Side
	= 0.5-1.0 cms St'b'd. Side
Live Roll	= (at hull corners) 1 cm amplitude, 3 secs period
Live Pitch	= (at hull corners) not detectable
Live Heave	= (at hull corners) 0.2 cms amplitude, 1/2 sec. period

Skirt Condition, stiff and stable.
(Rolling moment expressed as the moment which would be generated by the total weight of the vehicle about the vehicle centreline if the CG were shifted by the stated percentage of the total hardhull beam).

CONDITION 2

Time 17 minutes from start. Rolling moment = +0.5% CG Shift. Observations exactly as at Condition 1, except for Average Roll = $+0.2^0$. Live roll, pitch, and heave as before.

CONDITION 3

Time (from start of test)	25 minutes
Rolling moment	= +1.7% CG Shift
Roll	= $+0.5^0$
Hovergap	= 0.1-0 cms Port
	= 2.5-3.5 cms Stbd.
Live Roll	= Ceased, or at least heavily damped, owing to slightly touching skirt on down-side
Live Pitch	= Not detectable
Live Heave	= 0.1 cm (period undetermined)
Skirt Condition	= Stiff and stable

CONDITION 4

Time (from start of test) 40 minutes
Rolling moment = +4% CG shift
Roll = +0.95°
Hovergap = Touching and just crumpled - Port
2.5-3.5 cms - Stbd.
Across front & rear touching to 0.2 cms at centreline, with gap to Stbd. Increasing crumple to Port.

Slight stirring still, in Roll and Heave.
Skirt stiff and stable, all jupes fully extended, stiff, and stable, level with peripheral skirt hem on Stbd.

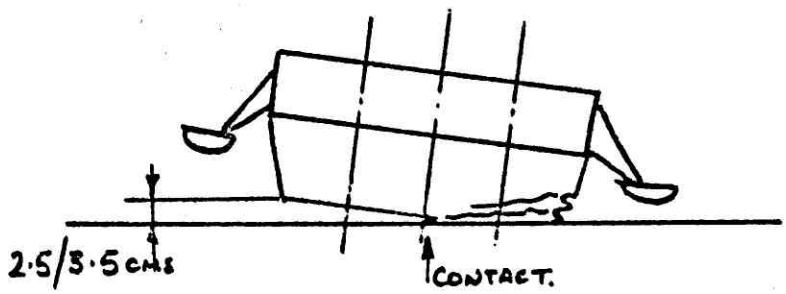


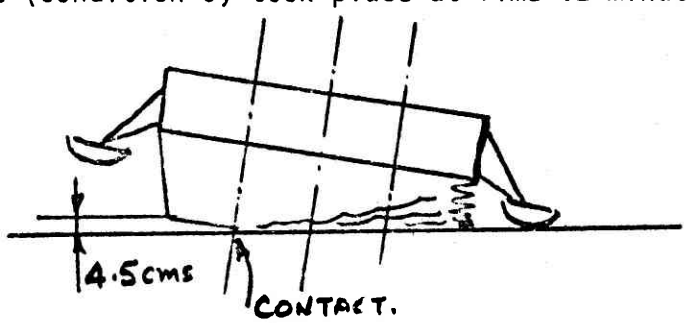
FIG.5.

CONDITION 4.

CONDITION 5

Time (from start of test) 50 minutes
Rolling Moment Set up at 5% CG shift

No apparent change from Condition 4. However, after about two minutes, while readings were being recorded, the vehicle suddenly rolled heavily onto the Port landing pads. This represents a 7.9° Roll, and by shifting the vehicle's high C of G, increased the Rolling moment to approximately 8.6% CG shift. The roll to this state (Condition 6) took place at Time 52 minutes.



CONDITION 6.

FIG.6.

In an attempt to level the vehicle, ballast was shifted to Stbd. At zero CG shift (i.e. normal balance) the vehicle showed no sign of recovery. Finally, at an opposite roll moment of about -5% CG shift, the vehicle stirred, lifted, and rolled over immediately onto the opposite (Stbd) landing pads.

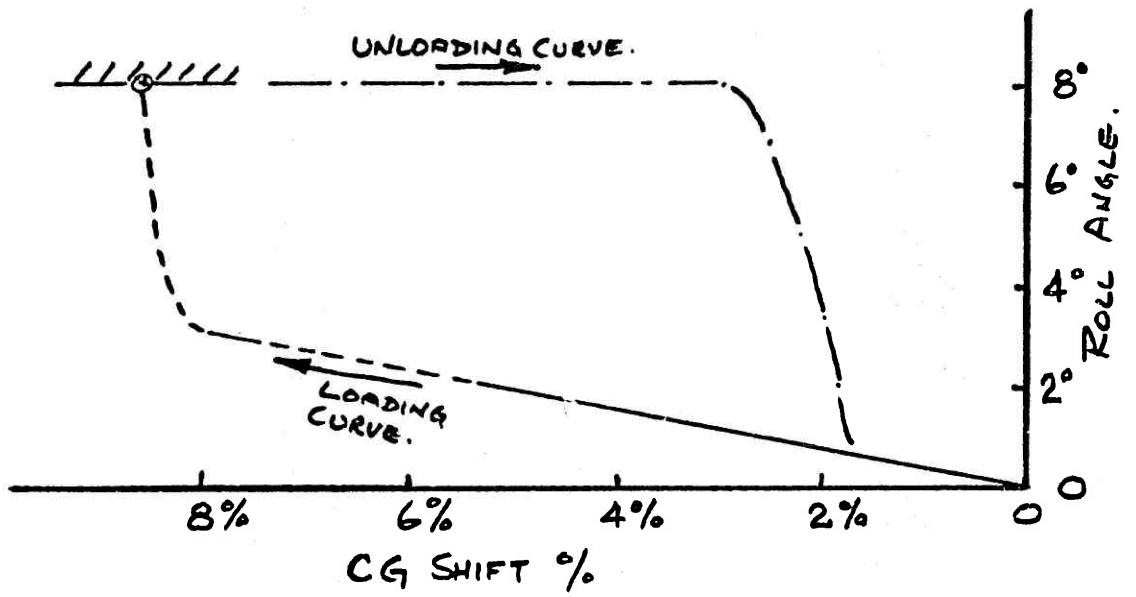
When the rolling moment due to the displacement of the high CG in the 7.9° rolled position was subtracted from the opposite roll moment required to recover the vehicle through the even keel position, the recovery curve of the skirt system could be plotted. This curve is shown in Fig. 8, and there is seen to be a considerable hysteresis between the roll and recovery curves, even after removing the effect of displacing the vehicle CG due to the roll.

This hysteresis has been reported by Jones, and also by Sullivan and Hinchey at UTIAS, who studied the subject in extreme detail on the UTIAS static model rig. This behaviour is closely repeatable, and occurs also to a much less extent in the British "open loop and finger" type of skirt.

OBSERVATIONS FOR STATIC ROLL TEST 406S-1600-1A, VEHICLE HEX-1

RDG. SET NO.	ROLL ANGLE (DEG.)	C. OF G. SHIFT (%)	AVERAGE SKIRT PRESS. ($N./m^2$)	TRUE INLET FLOW ($m^3/sec.$)		TOTAL INLET FLOW ($m^3/sec.$)
				RIGHT	LEFT	
1	-.2		$2.67 \cdot 10^3$	4.02	5.81	9.83
2	+.1	.70	$2.72 \cdot 10^3$	5.31	4.84	10.15
3	+.5	1.74	$2.69 \cdot 10^3$	6.70	4.06	10.76
4	+.95	2.73	$2.46 \cdot 10^3$	7.17	2.94	10.11
5	Observations not complete, owing to sudden collapse to Condition 6.					
6	+7.9	8.58	$2.23 \cdot 10^3$	6.93	2.49	9.47

Fig. 7.



ROLL CHARACTERISTIC OF MULTICELL SKIRT
[ROLL MOMENT DUE TO VEHICLE DISPLACEMENT SUBTRACTED TO PLOT THIS CURVE]

FIG. 8.

(B) EFFECT OF AIRFEED HOLES ON VEHICLE STABILITY

It appears from the foregoing discussion that a large part of the vehicle's roll or pitch stability is derived from the fact that the jupe away on the down-side is sealed by contact with the ground, and therefore develops its maximum possible lift by retaining full air supply pressure, while the jupes on the up-side are blowing off air through a large hovergap, and hence their pressure falls below supply pressure and their lift correspondingly falls. This generates a restoring moment due to the differential lift between the two sides of the vehicle.

In view of this, it is clear that stability depends critically on the air supply characteristic, in that if at the one extreme an infinite supply into the jupe was available, the large hovergap on the up-side would not drop the jupe pressure, and the restoring differential lift would not be achieved.

If at the other extreme the air supply was very limited, a small increase of hovergap would rapidly exhaust the air in the jupe with but little replacement, the pressure would drop rapidly, and a very high restoring moment would be generated.

In order to maintain the lift of the whole vehicle when traversing uneven or porous ground it is clearly necessary to have an ample supply of air to the whole skirt assembly, but the above argument shows that a high-loss restriction is needed at the entrance to each jupe to maintain roll or pitch stability. In order to minimise blower power, this loss should be as local to the jupe as possible, and the duct from the blower to this restriction should have as low a loss as possible.

These comments are illustrated by the results of static stability experiments on the first vehicles used in the CASPAR program, the "Grishkin" models. These were a series of models, all of about 2 square meters footprint area, each fitted with a different type of skirt, but all fitted with the same engine and lift blower system.

Two results from roll tests on Grishkin 2 (Multicell plus peripheral skirt) over flat concrete are given below, and show the effect of doubling the feed hole area. Vehicle roll is plotted against CG shift % (equivalent rolling moment) for a case using all four feed holes A-D in each jupe, and for a case with only holes A and C operating. It is seen that indeed the air supply (in the two hole case it is restricted to roughly half the flow of the four hole case), does indeed influence the roll stability to a tremendous extent, roughly doubling the applied moment needed to achieve a given roll, and greatly increasing the limiting roll before collapse occurs, in the case with the smaller air supply.

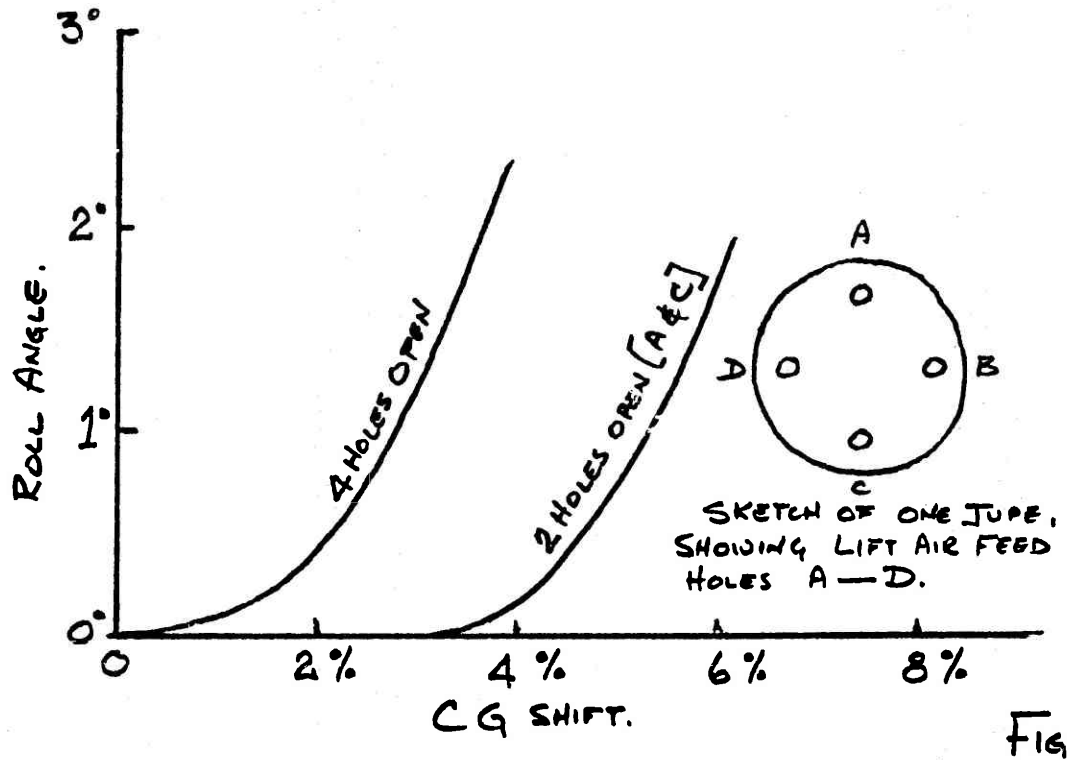
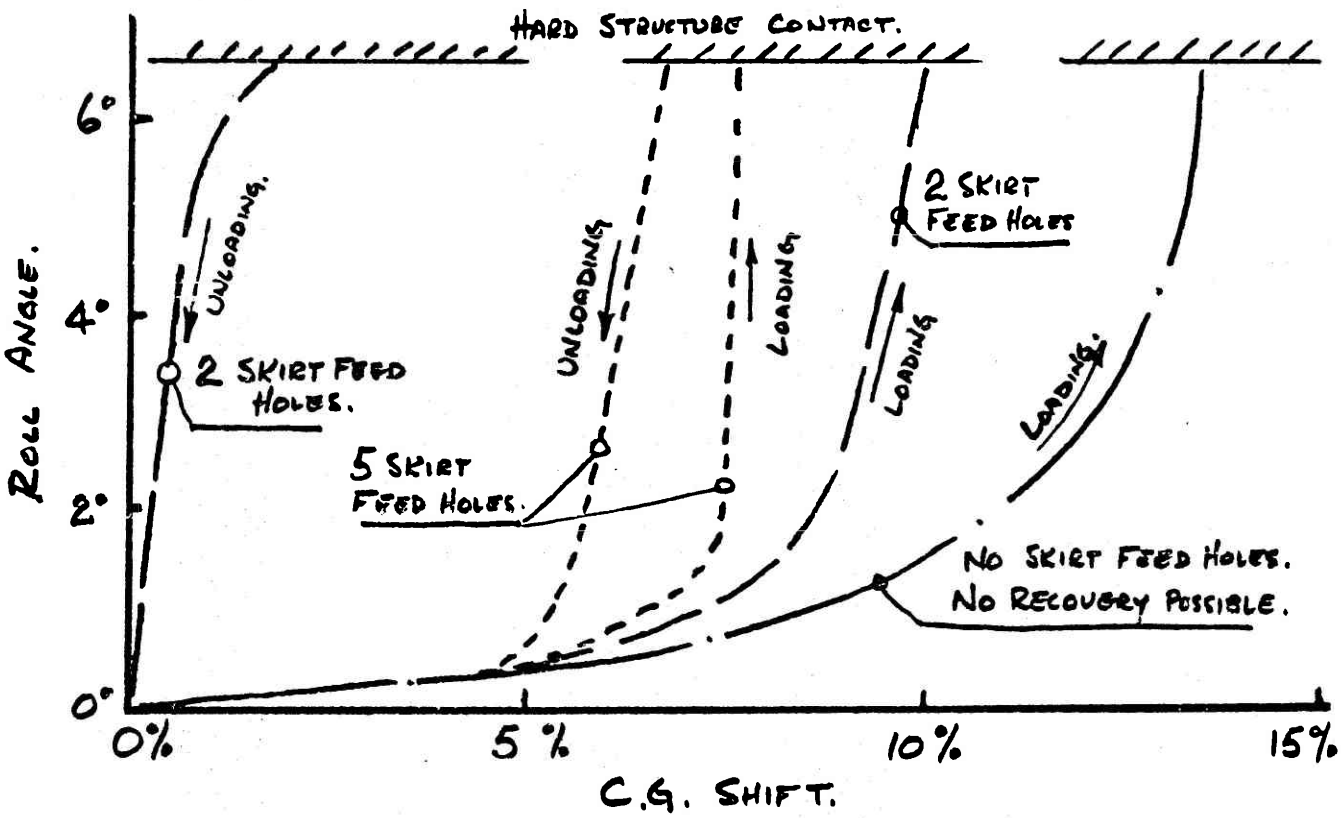


FIG. 9.

The effect of separate feed holes to the cushion area, instead of feeding the cushion entirely through additional hovergap Δh under the jupes, was also well demonstrated by experiments on Grishkin 2, whose peripheral skirt and jupes were made identical lengths (i.e. $\Delta h = 0$) for this experiment.

Fig. 10 shows that increased skirt feed decreases initial roll stability (as does increased Δh, in Fig. 3), but also reduces the hysteresis between collapse and recovery. Each of 8 jupes had 4 feed holes 2.5 cms diameter, while the skirt area was fed by zero, 2, or 5 holes 2.5 cms diameter, as indicated on the curves. With zero skirt feed, the vehicle would not recover from the fully rolled position.



EFFECT OF SKIRT FEED HOLES ON ROLL STABILITY.

FIG. 10.

(c) ROLL-STABILITY FROM THE SPLIT-FEED SYSTEM

If the lift air supply to the skirt system is split, so that the port cells receive air from one fan, while the starboard cells are fed from a separate fan, then great roll stability can result. This system, which was installed in HEX-1 for the Multicell skirt experiments, is shown below in Fig. 11.

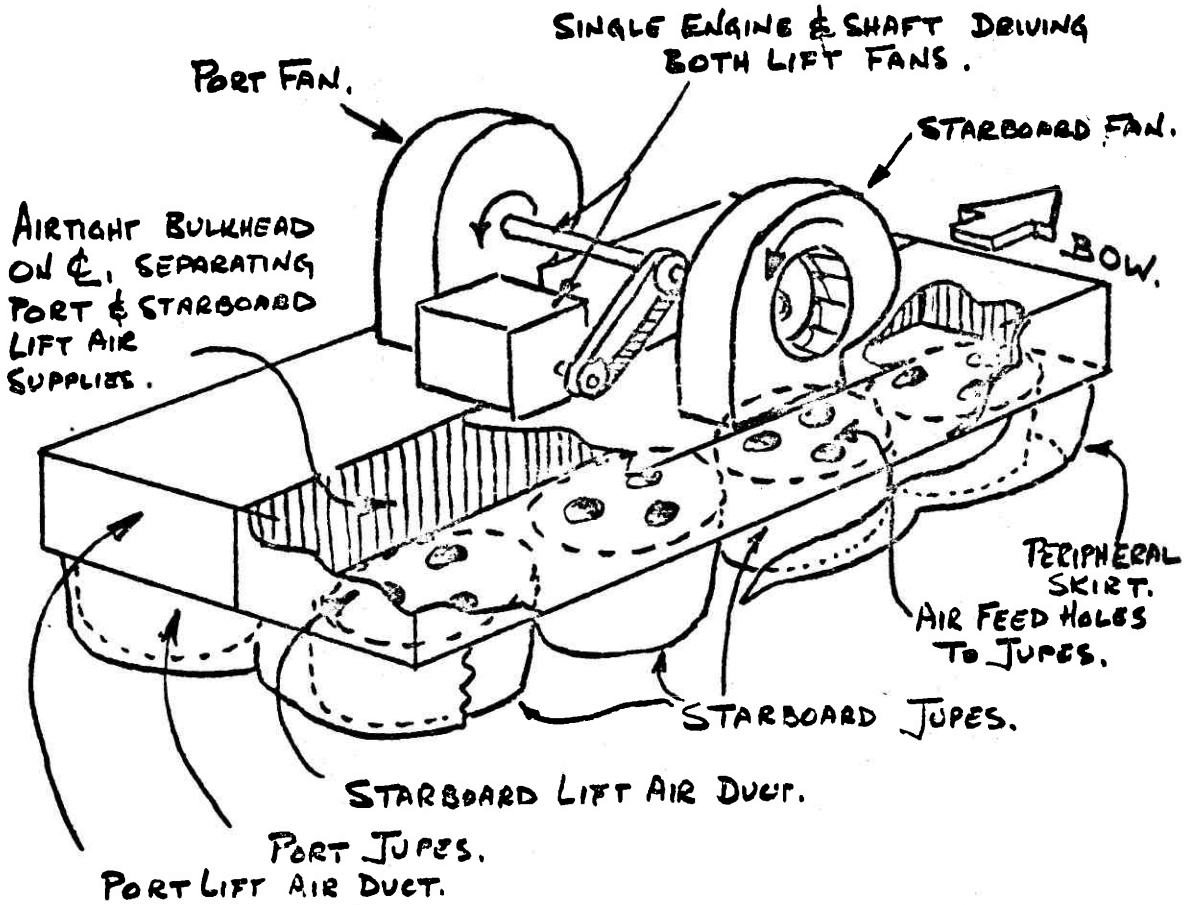
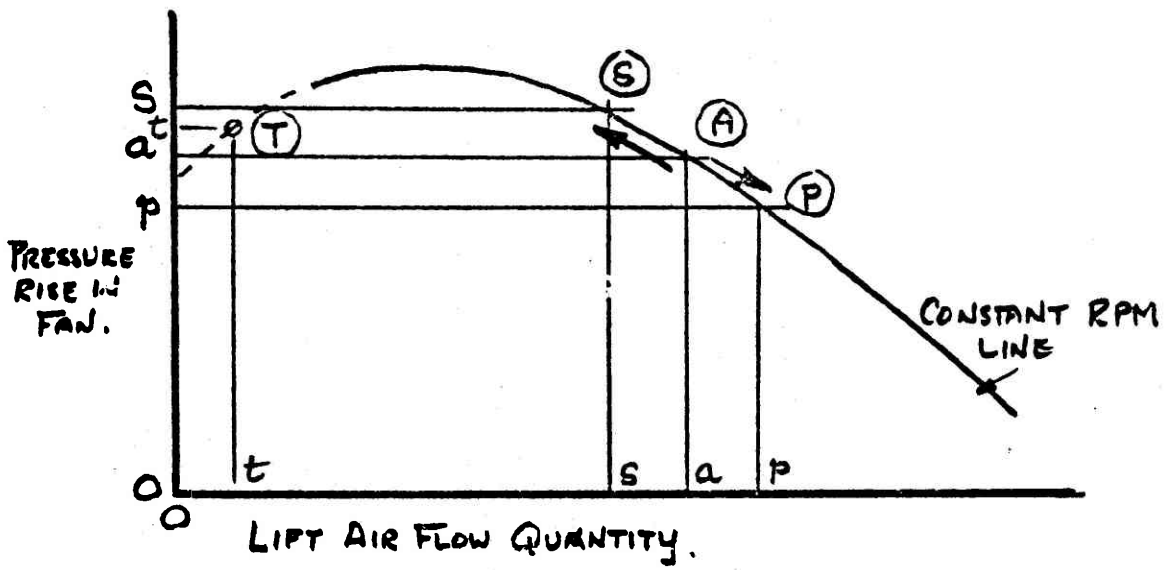


DIAGRAM OF LIFT-AIR SYSTEM OF HEX-1.

FIG. 11.

The mechanism of this stability is explained by reference to the typical lift blower characteristic shown in Fig. 12.



TYPICAL FAN CURVE, SHOWING ROLL STABILITY MECHANISM.

FIG 12.

In the normal level hover position, the operating point of both fans is (A), giving a flow and pressure of "a". If the vehicle rolls starboard side down, the hovergap is reduced to starboard with resulting reduced flow from the starboard blower, moving its operating point to (S), with an increased delivery pressure "s". The port hovergap conversely increases, with increased flow and reduced pressure "p" on the port skirts.

The pressure differential between skirts on the two sides of the craft is therefore increased above what would be given by differential leakage if the two air supplies had remained at the same operating point.

If the roll is severe enough to almost completely seal the down-side cells, this could perhaps force the starboard blower operating point to (T), on the unstable "back" of the blower curve. This would render recovery almost impossible, and may be a major cause of the roll-recovery hysteresis previously described.

This mechanism clearly affects only roll stability. Pitch stability will not be affected unless the air supply is from four sources, two forward and two aft.

If the two blowers are driven by separate engines, normal control of the roll can be achieved by differential power input to the two sides, running the two blowers at different speeds. However, in the HEX-1 installation, as shown, both blowers were on the same shaft. Assuming that both blowers have identical characteristics, and have similar ducting to the skirts, the system will function as described above, and this assumption has been made in the design of a number of vehicles. However, blower impellers built to normal commercial standards do not all have identical performance curves, and this has led to stability troubles in various vehicles. This problem is almost entirely restricted to the Multicell skirt, since the division of lift air supply between areas of the cushion is not nearly so complete in any other type of skirt system.

The problem was experienced acutely in HEX-1, and is discussed in detail in Ref. 3. It is shown there that minor mechanical damage to the impeller blading of one fan was equivalent to a 1.3% CG shift, which produced a 0.7° roll, made it very difficult to get the vehicle up into level hover, and led to collapse onto the starboard side when lift power was reduced. Slight straightening of the blower vane trailing edges eliminated the effect. The "damage" was in fact so small that considerable inspection effort had to be made before it was detected.

It is therefore considered that this system of roll-stability in the Multicell skirt is so sensitive that careful consideration should be given before relying on it in a vehicle design.

Similar roll-instability or bias can result from unequal pressure losses in the ducting on the two sides (or ends) of a vehicle. This may sometimes be the result of using identical fans and scrolls on the two sides, instead of a right- and left-handed pair. Considerable ingenuity may be needed to avoid this, owing to the impossibility of obtaining right- and left-hand engine rotation.

(D) HEAVE STABILITY

Any skirt system can suffer from vertical oscillation, heave instability, or "bounce". The Multicell system, particularly the forms without a peripheral skirt, is no exception. It seems likely that in the absence of perturbations due to forward motion, the aerodynamic lift system can be disturbed by such small causes as fan delivery pulsation due to blade-passing frequency. If the air duct and skirt cavity system goes into resonance, the whole vehicle may start bouncing with a frequency from 0.1 up to 10 Hz, and amplitudes from zero to 25 cms. The energy available has been found sufficient to bounce a 37,000 kg vehicle with a fingered skirt, or to toss 1000 kg blocks of concrete off an air cushion pallet on a Multicell skirt, among many other examples.

Essentially, the mechanism of "bounce" appears to be as follows. When the vehicle is momentarily depressed by some disturbance, the air in the skirt system is compressed to higher then equilibrium pressure, and a net lift force raises the vehicle. This excess lift force falls to zero as the vehicle passes its equilibrium height, and then turns negative but the vehicle continues to rise due to its inertia. The hovergap now opens more than usual, and unless excessive air feed is available the air pressure in the skirt falls,

so that lift is less than vehicle weight. When the vehicle's upward inertia is expended, it therefore falls. This closes the hovergap, seals the skirt to the ground, permits pressure to be raised above normal, and the cycle repeats.

It will be realised that the sensitivity of this process is related closely to the available rate of air supply (controlled by blower characteristic, duct and cell feed holes) and to the "valve characteristic" of the skirt/ground hovergap.

It may reasonably be suggested that the Multicell skirt has a very abrupt "valve characteristic". That is to say that as the hovergap 'h' alters, the exit area alters linearly, to the sudden absolute cut off point.

By way of contrast, a fingered skirt would be expected to have a much less abrupt cut off, as the full-hovergap is eclipsed, leaving triangular gaps between fingers which are finally eclipsed at a much more gradual rate.

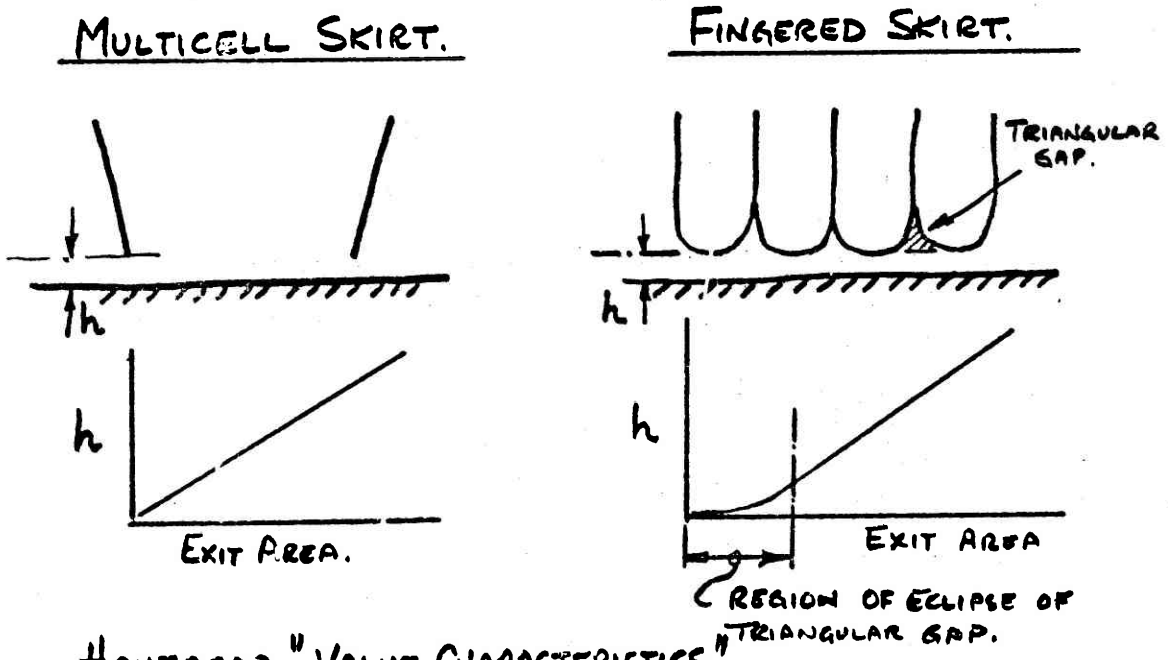


FIG. 13.

It might also be suggested that the more complex system of Multicell skirt plus peripheral skirt will have a less well defined resonance, and therefore be less liable to bounce, owing to the presence of two skirt/ground orifices in series.

In an analysis in Ref. 4, Hill showed that the condition for heave stability was that the height of the air space within cushion/skirts was less than a term whose relevant variables were (a) hovergap, (b) 1/pressure differential between cushion/skirt pressure and atmosphere, and (c) an expression for the steepness of the blower characteristic curve at the operating point. Experiments on the Grishkin models showed that the first two factors (a) and (b) are valid. Variation of (c), the blower characteristic, is difficult to simulate experimentally, but the present writer would accept this factor without difficulty. Indeed, a very parallel question was discussed at the end of the roll stability section above.

Section 5 on Skirt Element Stability suggests that flow phenomena within the cell should be considered, in addition to Hill's criteria.

The implications of this analysis are entirely undesirable. They are that, to reduce the likelihood of heave instability:

1. The height of the hardhull underside above ground should be minimised. This reduces the vehicle's obstacle clearance height.

2. The hovergap should be large, which increases lift air flow and lift horsepower.

3. The cushion pressure (and hence vehicle lift per unit footprint area) should be minimised.

4. The blower characteristic should be as steep as possible. This improves roll stability (see previous

section) but reduces the operating range of the vehicle between max. and min. payload, and the range of porosity of ground over which it can travel.

In view of these implications which are contrary to just about all other design requirements, it is hardly surprising that many ACVs have suffered from bounce. In many cases it has been avoided only by the high impedance in the air ducts from blower to skirt, or by the fact that too small an air supply has avoided getting the craft to full hover with a positive hovergap at which condition Hill's analysis applies. This fact explains the common method of getting a craft to stop bouncing by throttling back the lift engine. The equilibrium hovergap is thus reduced to zero, and the damping of the crumpled skirt and eclipse of the hovergap over much of the bounce cycle together stop the process. Hill's analysis (Ref. 4) should be consulted for a fuller discussion.

Another potent method of damping the bounce of a high-pressure skirt system was found to be the addition of a Helmholtz resonator to the lift air feed duct. In one case, a 45 gallon drum with a 3" pipe neck was connected to the air feed duct, and the bounce immediately stopped.

Bounce has also been staved off by partially filling the cell cavity with a flexible bag inflated to well above cell pressure. This in effect reduces the height of the hardhull underside above ground, but with a new "hardhull" which yields to some extent on contact with obstacles.

The bounce problem is so acute when the cushion pressure is raised above 10/20 kilopascals (2.5 psig or so) that it is one of the major difficulties in the development of high pressure air cushion lift systems, which has even led to consideration of the use of an incompressible fluid in the lift system, as in the "Waterskate".

(E) ROLL STABILITY OVER WATER

The roll stability of a Multicell skirt system hovering over water is markedly different to that hovering over land. It closely corresponds to the stability of an array of diving-bells.

One must first look at the normal hovering mode of an ACV over water, and realise that this discussion is limited to the stationary, or at least the low speed case. The over water behaviour at high (above-hump) speed is completely different, and is not discussed here.

An ACV hovering over water, at low or zero speed, is in effect a normal displacement craft, whose "hull" is bounded on the sides by the skirt, and on the bottom by the under surface of an air bubble. The depth of this bottom "surface" below free water surface is equal to the air pressure in the cushion-bubble expressed in cms. of water.

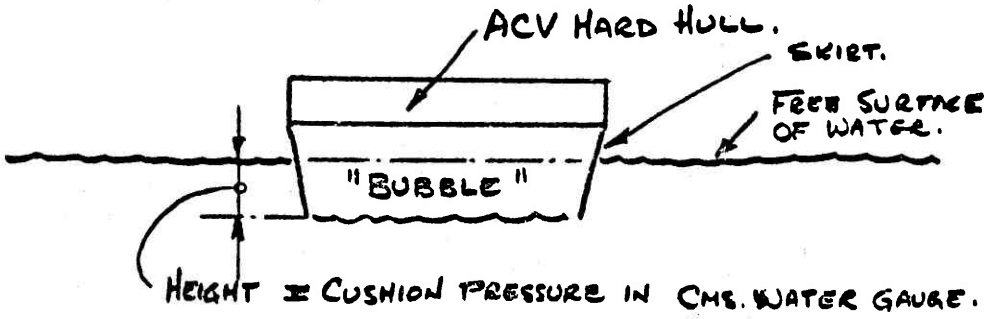


FIG. 14.

The craft will therefore find equilibrium at a depth of immersion equal to the pressure required to hover the total weight of the craft. If any higher pressure is applied to the cushion air, the bottom of the bubble will extend below the skirt, and air will escape under it and bubble up to the surface.

If the pressure is held constant with the vehicle's centre

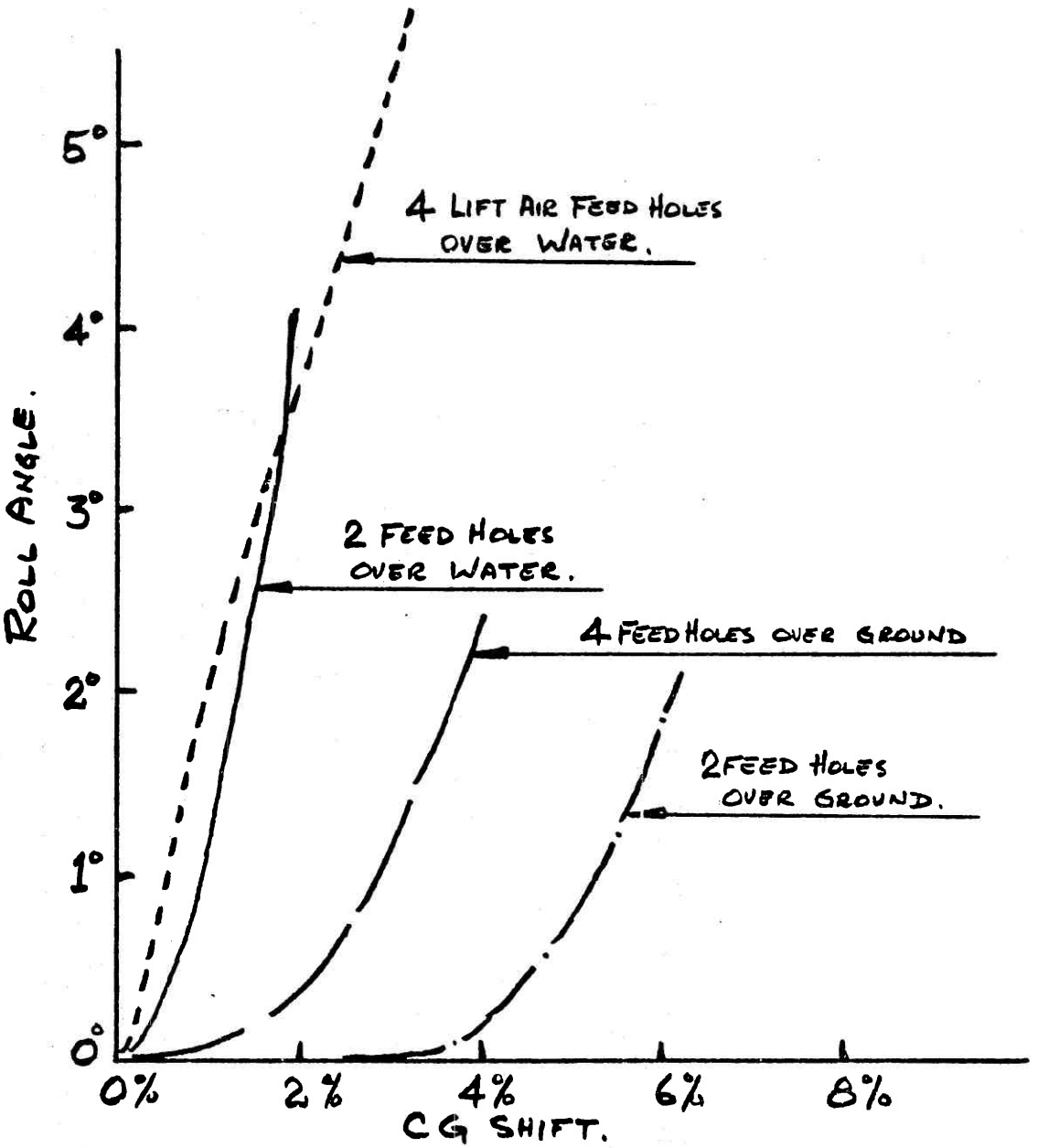
held at constant height, and the vehicle is rolled, the skirt on one side will descend below the bottom of the cushion bubble. On the other side of the vehicle, the skirt will rise, and air will therefore bubble out under it and escape to the surface. In the case of a single uncompartmented cell, this would not provide stability through any restoring force. However, if there are two separate cells, one on the up-rolled side and one on the down-side, and their airfeeds are separate and not excessively large, then the down-side cell will continue at constant pressure to exert lift on its side of the craft, while the cell on the up-side will blow off air, lose pressure, and exert less lift, thus tending to restore the craft to level hover. Furthermore, the greater the roll, the greater the pressure differential, and hence the restoring force.

Experimental results relevant to this note again spring from tests on the Grishkin model series, and are shown in Fig. 15. For comparison, these results of roll tests of the Grishkin 2 model, having 8 Multicell skirts plus a peripheral skirt, are plotted together with the roll stability curves for the same model over a concrete floor (shown already in Fig. 9), and show the stability with the two and with four lift airfeed holes per cell. It is clear that the model is much less stiff in roll over water, and that the response is practically linear, instead of having the very critical "knee" characteristic of the Multicell skirt over land. It is also noted that there is no hysteresis between the load and unload curves.

It is noted that the Grishkin models were all scale versions of full-size vehicle skirt systems, and the test results showed very close agreement between model and full size vehicle in all cases, at least as far as roll stability was concerned.

As a final comment to this section on stationary hovering stability, Fig. 16 compares the stationary roll stability

of a simple bag skirt, a 50% HDL loop and segment skirt, and a Multicell plus peripheral skirt system over land. All these curves are taken from tests on the "Grishkin" family of comparable models, (see notes on Fig. 16 graphs).



COMPARISON OF ROLL STABILITY OF MULTICELL SKIRT WITH PERIPHERAL SKIRT, WITH VARIOUS LIFT AIR FEED HOLES, OVER LAND & OVER WATER. FIG 15.

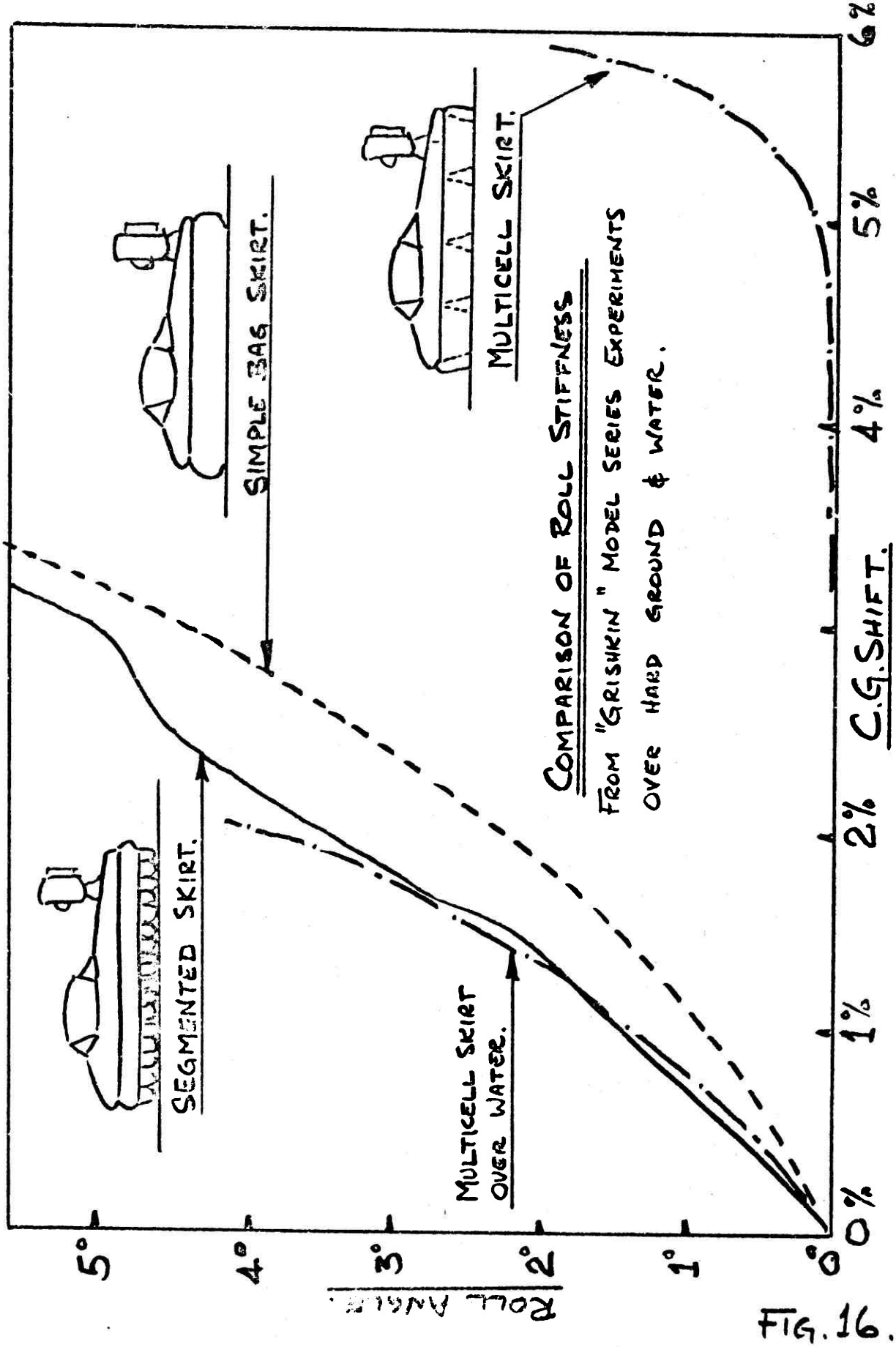

COMPARISON OF ROLL STIFFNESS
FROM "GRISHKIN" MODEL SERIES EXPERIMENTS
OVER HARD GROUND & WATER.
SIMPLE BAG SKIRT.
MULTICELL SKIRT.
SEGMENTED SKIRT.
MULTICELL SKIRT OVER WATER.
ROLL ANGLE
0°
1°
2°
3°
4°
5°
0%
1%
2%
4%
5%
6%
C.G. SHIFT.

FIG. 16.

FIG. 16.

4. VEHICLE STABILITY (IN MOTION)

In the previous section the stability of the vehicle while hovering stationary was discussed, and it was shown that the typical Multicell skirt, usually with a peripheral skirt, is very "stiff" in roll, up to a critical value of rolling moment, after which it collapses, due to collapse of the individual cells as Euler columns. It recovers with difficulty after the removal of the rolling moment, sometimes with a severe hysteresis. In some cases, it will not recover.

When the vehicle is in motion, it appears that the same picture emerges, but with much lower values of rolling moment causing collapse. Experiments in this regime are far more difficult than in the stationary case, and the discussion which follows is based much more on "engineer's reasoning" and "pilot's assessment" than on precise measurement and elegant experiment.

The first difficulty in experimenting with roll stability of the vehicle in motion over land is common to all types of skirt. When the vehicle assumes a rolled attitude, the skirt on the down-side has a greater frictional drag than that on the up-side. The vehicle therefore tends to turn towards the down-side, and can only be held on a straight course by an oblique tow force, or by strong rudder action, both of which are likely to apply secondary rolling moments, positive or negative, and confuse the issue.

The second difficulty in the present case is inherent in the stiff roll characteristic of the Multicell skirt. As was noted in the previous section, these skirts show little response to an applied rolling moment up to a critical value, beyond which point almost immediate collapse ensues. The experiment therefore resolves itself into finding this critical moment, below which there is little measurable roll, and above which the skirt collapses. As will be discussed in a later section on skirt element stability, this collapse point is a question of skirt element stability, rather than of vehicle stability, and is determined to a large extent by transverse forces at the skirt base. These transverse forces are complex, being generated partly by steady-state micro-

friction, and partly by discrete obstacles, and it is these latter which are liable to collapse skirt and vehicle in a very unpredictable manner, rendering vehicle-stability experiments in motion a most imprecise exercise.

Speaking of the stability overland of the whole vehicle in roll and pitch, which are very similar, although specific experimental data are lacking for the reasons stated above, experience in model tests on Grishkin 2, in piloting the C-105 and HEX-1 vehicles, and observation of other Multicell vehicles, allows the following comments to be made:

1. Within its critical roll/pitch boundaries the vehicle is far stiffer than with other forms of skirt.

2. Once the critical value is exceeded, the skirt system collapses suddenly, dropping the vehicle violently onto its hard hull in whatever direction its inertia was driving it. When the dust has cleared, stationary stability may permit the vehicle to regain even keel, or it may be necessary to drop to the ground to level it, subsequently rising to hover level, again.

3. High lift-fan RPM "stiffens" the skirt, and extends the critical point. Any reduction of lift RPM "softens" the cells, and permits earlier collapse. With other forms of skirt it is normal practice to reduce lift RPM and "drag the skirt" when improved directional control is needed for tight manoeuvers. This cannot be done with the Multicell system. Anything less than full-hover makes a vicious collapse almost inevitable.

4. Even at full lift RPM, movement over a high-drag surface tends to tuck-under the leading edge of the front cells, bringing more skirt material into frictional contact with the ground and forcing the vehicle "down on its knees" in a manner exactly similar to the well-known over water "plough-in". This is very noticeable over dry grass, which possesses a very high coefficient of friction. Wet grass has far less effect, due to the lubricant effect of the water film on the hairy leaves.

Experience over water has been very limited, but the following comments can be made, based on tests on the HJ-15 (below hump speed only) and the C-105 (below and above hump speed).

1. In the low speed (displacement) mode, the vehicle retains the linear "diving bell array" stability shown in Fig. 15. It is probably necessary to exercise caution that hydraulic side-forces on the leading cell walls due to motion do not rise high enough to collapse the cells. This could lead to a rapid overturn, and would occur when the depth pressure plus the dynamic pressure due to the motion through the water equalled the internal pressure in the cell.

2. In the high speed (planing) mode, the vehicle is extremely stable in pitch and roll, at least in smooth water. At 15/20 meters/sec. the C-105 could be put into a 90° skid with no perceptable roll, and was quite stable.

However, the impact from a ridge of water at high speed is very severe, and is liable to collapse the leading edge of the Multicell skirt system, with disastrous results. Hitting a 50 cm. high wake at about 15 meters/sec with the C-105 caused just such a collapse, and an instant plough-in. A well-shaped underhull prevented any overturning tendency, but the high drag of the collapsing cells produced an extremely rapid deceleration.

5. SKIRT ELEMENT STABILITY

From the preceding discussion, it became clear that vehicle stability depends crucially on the stability of the cells or jupes forming the skirt assembly, and that the stability of these cells is quite a complex matter, owing to the complexity of the force systems imposed on them.

We will consider the single cell and the forces acting on it, firstly when stationary, and then in motion. The air flow in and

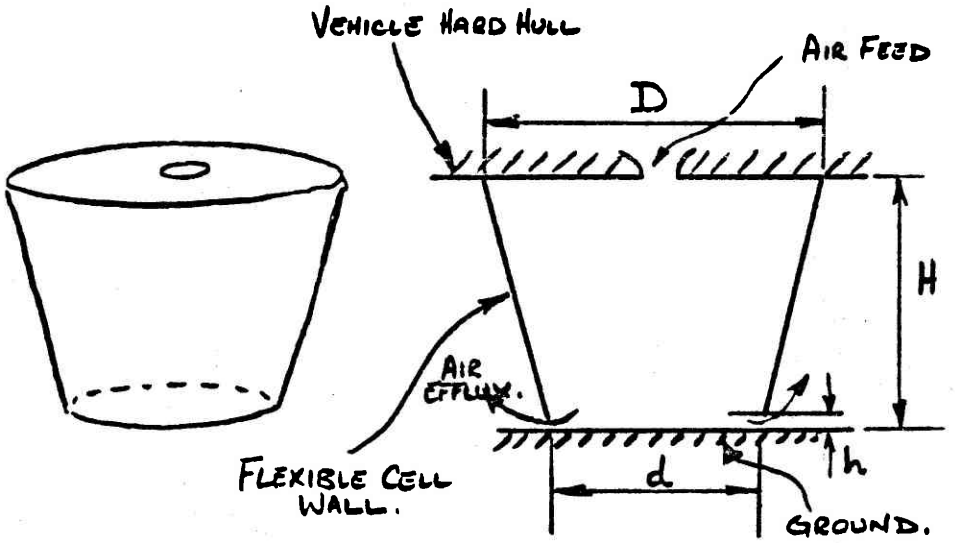


FIG. 17.

out of the cell is assumed to be small, so that dynamic effects of flow within the cell may be neglected, and the cell considered

simply as a trucated cone membrane attached to the vehicle hull, forming an unattached seal with the ground, and developed by the air pressure (Ps) within being greater than the atmospheric air pressure (Pa) without.

The cell wall is therefore exposed to two forces, a horizontal hoop tension and a vertical tension due to the differential pressure (Ps - Pa) acting vertically downwards on the annulus projected by the conical walls between D and d. Between these two forces, the cell wall is inflated into a structural column, without relying on any inherent stiffness of the material. This form of wall therefore results in a column of contained air, at cell pressure Ps, of base area covered by the footprint of diameter d, available to support its share of the weight of the vehicle.

Providing the loading is truly axial down the centre of the trucated cone, this is a very stable arrangement, and is in fact the column treated in classical structural theory by Euler's method.

We will now consider the cell's characteristics. As a member of an array, if it is truly circular, it cannot be packed closer than in a square grid whose square sides are equal to D. This limits the number of cells possible under the vehicle. If the top attachment is anything but a circle, as in certain developments of the Multicell skirt, the cell section will in any case rapidly tend to transform to circular at stations removed from the attachment plane.

The footprint area, which determines the lift per cell, is that of the circle of diameter d, and for maximum lift this should be as large as possible. But cell structural stability is obtained, as was pointed out above, by the cell pressure acting on the annulus projected by D-d, and as d increases this annulus decreases and stability therefore suffers.

From Euler's classic theory, it follows that as the Aspect Ratio of the column (H/mean diam.) increases, so the column becomes more likely to collapse by buckling. Since the height H is fixed by the required ground clearance of the vehicle's hull, the diameter D is made as large as possible. However, if we are to stabilise the vehicle in roll by having two rows of cells side by side, the attachment diameter D cannot be more than half the vehicle width.

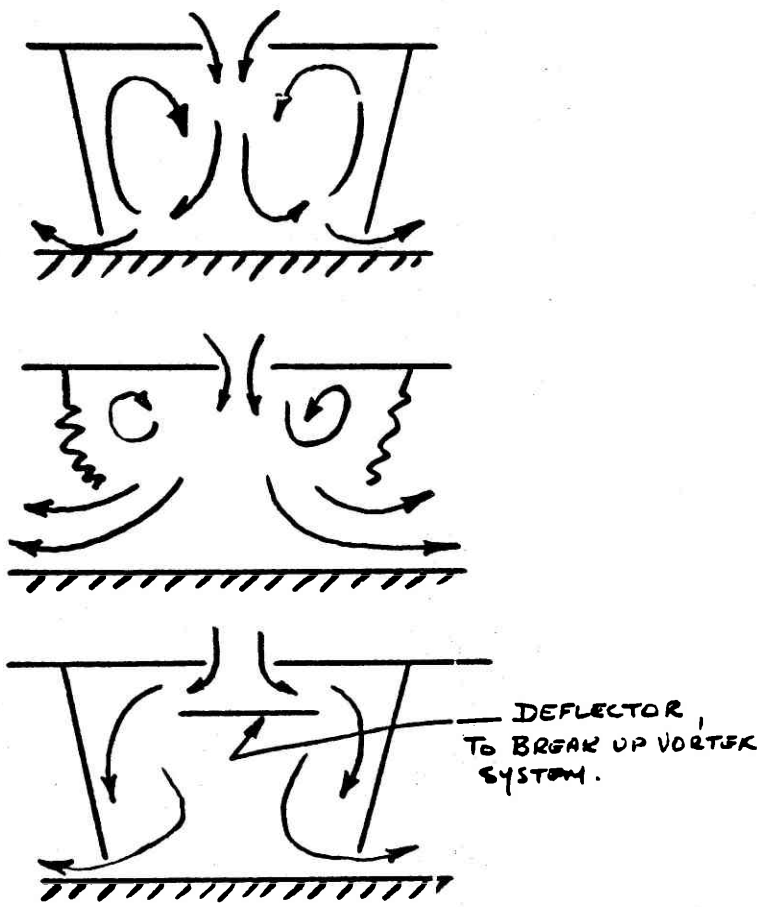
Following from these considerations, from data given in Ref. 2 and from experiments in the CASPAR program, some quantitative meaning can put to the theoretical discussion above. These figures are mainly derived from ACVs of orthodox planform, where total length equals twice the total width, but they appear to apply in a fairly general manner.

The attachment diameter D is a little less than half the vehicle width, and it has been found that the skirt height H should not exceed .45D. Tests have shown that a skirt can deflect over an obstacle up to about .75 its height H, so that a Multicell vehicle can clear obstacles of height up to about .075 its total length.

In order to obtain structural stiffness of the inflated cells, in the .25 to .75 atmosphere (gauge) cell pressure range, it is often suggested that a total included cone angle of the cell of 8° is satisfactory. This may be so over very low-friction surfaces (marine or wet foreshore environment) but the CASPAR program results suggest strongly that at least a 10° cone angle is desirable over most terrain, to maintain a well developed cell while in motion. This naturally reduces the available footprint area and lift for a given vehicle plan area, but is essential to keep the cells developed.

Ref. 2 states that the hovergap h is typically 1% to 2% of D, which in conjunction with a 0.7 coefficient of discharge for this type of efflux gap will determine the lift air flow of the vehicle. However, this question has received much attention in the CASPAR program, and will be discussed at length in a later section of this report.

Another factor which has a strong influence on the stability of the inflated cell is the arrangement of the airfeed holes. It has been found that if the air is fed in through a single hole near the centre of the attachment circle, it tends to form a vortex in the cell (Fig. 18) with disastrous results, often lifting the whole cell up to the vehicle frame. This was frequently encountered in the Grishkin 2 experiments, with undesirable feed hole arrangements. The use of transparent plastic skirt material allowed it to be seen very clearly.



EFFECT OF FEED HOLE ON SKIRT DEVELOPMENT STABILITY - FIG. 18.

Various methods of breaking up the vortex have been proposed, including using a number of small feed holes scattered over the attachment area, the use of a porous inlet bag to break up the jet, or a deflector. Provided the deflector is not such as to be damaged when the vehicle sits down or traverses a large obstacle, it is probably the best solution. It is certainly effective.

Sullivan at UTIAS also showed that the vortex formation is probably more severe at very small values of H/D, but these are outside the normal range used in vehicles.

Finally, the stationary stability of the cell is subject to a time-dependent effect, which has not yet been satisfactorily explained. While operating HEX-1 in early 1974, over smooth terrain, it was observed that after a period of stable hovering an unexpected collapse could occur. On a number of occasions the vehicle was set at a hovering condition, and a long series of observations was attempted. After perhaps 10 minutes, while lift engine RPM, airflow, and all other observed functions remained constant, the vehicle would within 30/60 seconds settle and collapse on one side.

Later Sullivan reported the same phenomenon with single cells on an external lift-air supply, and showed a remarkable series of photographs taken at one-minute intervals. After over 5 minutes of stable operation a crease appeared in the cell, spread, and collapse occurred.

At the time of writing an adequate explanation has not been proposed.

When the vehicle and its Multicell system are set in motion over the ground, additional forces are imposed on the skirt. These are primarily transverse forces opposing the motion, and comprise continuous microfriction of the ground at the bottom edge of the

cell, continuous fluid forces (of air or water) up the front face of the cell, intermittent forces due to collision with obstacles by the front face of the cell, and intermittent snagging forces of jagged obstacles catching in the rear wall of the cell.

Looking at the single cell again, it is clear that such a transverse force, particularly at the lower edge of the cell, will tend to cause the very buckling failure described in the Euler theory.

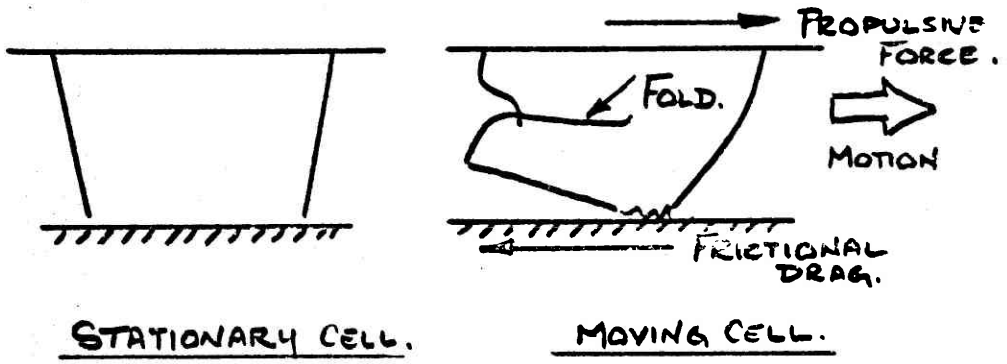


FIG.19.

At first sight it might be expected that these forces would act equally on all cells, causing general collapse of the vehicle, and when the vehicle starts from rest over rough ground this is often the case. However, when the vehicle in motion encounters an obstacle, or notably rougher ground, they act first on the leading cells, causing a pitch, which rapidly increases as the leading cells become more heavily engaged by reason of the pitch, and therefore generate more transverse force, in a vicious circle.

If the vehicle is in a skidding turn when the rough ground or obstacle is encountered, the "leading" cells will be on one side or on the front outer corner, and a plough-in or roll, often of very drastic nature, results from the collapse of the leading cells.

From the foregoing, it would seem reasonable to suggest two tentative conclusions. Firstly, the cell-stability while in motion, and hence the vehicle stability, has a considerably lower limit than that measured in the static case, since the additional transverse forces on the cells tend to buckle them and lead to collapse of the cells earlier than under pure vertical-axis loading. This tendency will increase as the terrain becomes rougher, or has a higher coefficient of friction.

Secondly, one might suspect that the Multicell skirt system described might have a somewhat more vicious characteristic, from the pilot's point of view, than other skirt types. The great roll-stability of the Multicell within its working range leads the pilot to take greater liberties, since the roll is negligible and gives no warning up to quite high values of applied rolling moment. However when the critical point is reached, and rough surface or an unnoticed obstacle may make this unexpectedly early, then complete cell-collapse occurs, with no half measures.

A number of the points described above are well illustrated by experience in the very brief development of a small air cushion raft (ACR-1) for some work in the CASPAR program. A raft about 2.5 meters long x 1.3 m wide was required, with no great lifting capacity but with great roll and pitch stability, for towing experiments behind a floatation-tyred vehicle. To get maximum stability at some sacrifice of lift, in a very easily built vehicle, a simple Multicell skirt was used, consisting of 8 cells in two rows of four, without any peripheral skirt.

The cells were based exactly on existing data (from the C-105 vehicle) and were 0.65 m. D, 0.30 m. H, and had an included cone angle of 8°. Each cell had one feed hole .075 m. diameter at the centre of its roof, with a deflector loop hung under it.

At the first attempt, the raft hovered satisfactorily, but as soon as it was towed forward over grass about .075 m. high, the cells all dragged back and collapsed, dropping the raft on its skids. In an attempt to increase the cell pressure, the feed holes were

opened out, with very slight reduction of the cell-buckling tendency.

A second attempt to reduce the pressure loss in the feed system in order to increase cell pressure was by removing the feed air deflectors. This immediately caused the air vortex within the cells, and lifted most of the raft's skirts, collapsing the vehicle.

The deflectors were replaced, and the effect of reducing the cell aspect ratio, by reducing the height H by 20% was tried. Again, a small improvement was noted, it was possible to tow the raft a little faster before collapse ensued (up to perhaps 1 meter/sec over the .03 m. grass).

Finally, the cells were removed and replaced with a set of the same 0.65 m. D, 0.24 m. H, but with an included cone angle of 11°. The results were very satisfactory, and the raft could be towed on straight or figure '8' course over the same grass at over 5 m./s. without any sign of cell collapse. Movies showed good cell stability even when the raft was towed at this speed over a hump in the ground which threw the towing vehicle and its driver into the air. The raft hardly bounced. It cells compressed slightly on meeting the obstacle, redeveloped, left the ground slightly as they left the hump, but remained developed as they returned to the ground and went on.

This set of tests gives some feeling for the relative effects of cell aspect ratio, air feed and cell pressure, deflector effect, and cone angle on cell stability.

6. DRAG (OVERLAND OPERATION)

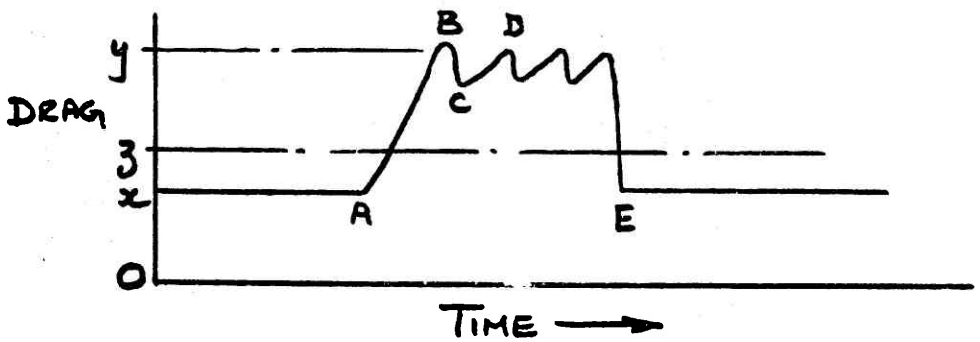
The attitude to drag has evolved considerably as the CASPAR program has progressed. Measurements have shown that at low speed and with adequate lift air supply, skirt/terrain interaction drag is usually small compared with other components of drag on the vehicle in overland operation (notably the slope drag). The main emphasis has thus shifted to determining the "adequate" lift air flow required to reduce the skirt/terrain drag to this small value, and at the same time to reduce skirt wear to an acceptably low value. This latter aspect is particularly important in connection with the use of air cushion load relief with on-road vehicles. The NRC experiments on the ACAT-1 air cushion relieved on-road trailer brought this out with extreme force. While in some applications, high rates of wear over a short required life may be acceptable, in general it appears more valid to take the position that any measurable wear rate is too high, and indicates a wrong approach to the problem.

A second consideration which has shaped the course of the CASPAR program is the intended application of the type of skirt system on test. It was made clear that the Multicell skirt system was being developed for use over "snaggy" terrain, including cut-over lumbering areas, rather than relatively smooth but weak ground, such as swampy foreshore or polder. The measurement of "drag", and the understanding of the physical meaning of these measurements, over "snaggy" ground is extremely difficult, and is still a developing subject.

Essentially, there are two points at issue, when the drag is to be measured over terrain which includes discrete obstacles, such as tree stumps or rocks.

Firstly, assuming that we have a constant-speed propulsion system whose force can be instantly adjusted as required to overcome fluctuating drag, how is the graph of force against time, distance, or terrain features to be interpreted? Fig. 20 shows an idealised drag history as a vehicle passes over a discrete obstacle. From the "normal" drag (x newtons) at point A, the passage

of one cell over the obstacle raises the drag force to y Newtons. As the cell wall disengages the drag falls, but at C the next wall engages, and the drag rises to a peak again. After the last



DRAG HISTORY OF MULTICELL ACV PASSING OVER AN OBSTACLE.

FIG. 20.

cell has negotiated the obstacle, the drag falls to the "normal" value again at E.

How then is the "drag" to be stated? Clearly the propulsion system or tow hitch must be able to overcome the 'y' value peaks, although craft inertia will smooth out many of these peaks. However, the normal operating drag of the craft will be represented by the 'x' value, which will determine the economics of fuel consumption. Or should some "mean" value 'z' be stated as the drag?

So much for the difficulties of interpreting "true" records. However, most "drag measurements" are simply not true records, and therein lies the second problem.

To begin with, the "constant speed propulsion system" assumed

above is rather mythical. A more realistic description of practical systems is "constant-force", with the speed fluctuating wildly, and vehicle inertia storing and releasing energy to smooth out the worst peaks.

Next, the characteristic of the propulsion system and linkage have to be accounted for. An airscrew propulsion system acts as a roughly constant force device, in series with an extremely soft spring coupling.

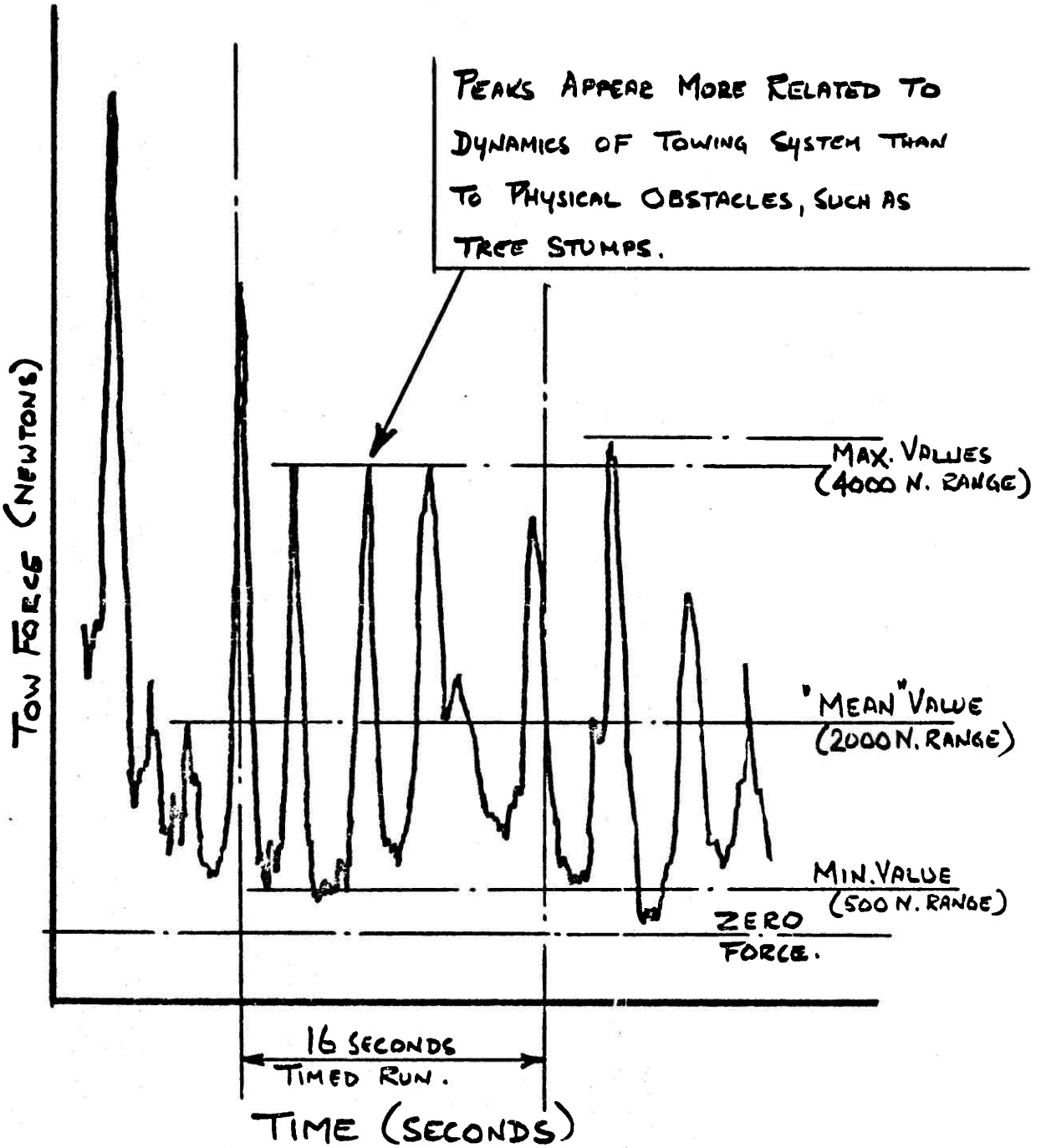
Towing the craft on a long tow-cable from another vehicle or a winch gives a rather similar result, but with a much stiffer spring whose oscillation period is very visible in the record.

Towing the craft on a rigid link from another vehicle removes the "smoothing" influence of the spring linkage. However, if the towing vehicle is clambering over the rough test track, its motion is probably jerky, shocks from each vehicle react on the other and the record will show the shock loads of the rigid coupling in a way which masks the "real" drag loads by a factor of two or even much more.

The difficulty of interpreting the "true" data is therefore compounded by the difficulty of producing a propulsion system which will give true data in the first place, and then not obscure it with spurious forces and hash.

Fig. 21 shows a straingauge recording from a gauge in the tow-line attachment to HEX-1, as it was towed at about 1 m./s. over a soft forest track with tree stumps, using 80 meters of steel tow cable from a stationary winch.

Various approaches to this problem are at present under discussion and experiment.



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

FIG. 21.

Such results as are available and acceptable confirm the general view of overland skirt drag, that the drag rapidly decreases as lift-air supply increases, until at the point where "full hover" (with a positive hovergap) is established the skirt drag reaches a minimum at which it remains constant despite further air flow increase.

It can also be seen that the drag is considerably affected by the nature of the terrain, and it appears that porosity has a greater effect than coefficient of friction, in that porosity absorbs much of the lift air flow, leading to a virtual reduction of lift air flow and thus dropping the vehicle into the high-drag regime at less than full hover. Since in this regime the drag is due apparently mainly to the work done in deforming terrain and skirt where they interfere, the contribution of "friction" in the true sense of the word is overshadowed.

With respect to low speed operation over water, and over semi-fluids such as heavy snow or light mud, there appears to be little difference between the drag-behaviour of Multicell and segmented skirts. Despite the difference in entry angle between the almost-vertical front face of the Multicell skirt and the roughly 45° face of segmented skirts, both appear to behave like a bluff-nosed displacement hull in water. A heavy bow-wave is raised and the drag due to building this wave and then attempting to climb it is high. Very similar "waves" are produced both in water and in the semi-fluids. Wet snow in particular forms a "roller" or wave which pushes along in front of the skirt, and absorbs considerable energy. When driven over about 3 cms of snow over hard flat ground, the Multicell C-105 raised an 8-10 cm "bow wave" and left ridges like this a craft-width apart, behind it. When HEX-1 was towed over 15-20 cms of heavy wet snow, its Multicell skirt pushed up a 30-45 cm diameter roller of snow, and rolled this along in front of it like a snowball. Very similar occurrences are reported by the operators of segmented skirt vehicles.

The meaningful measurement of drag must therefore include simultaneous measurement of lift-air flow, which in the CASPAR

program has been achieved by calibrating the inlet bellmouth of the lift fans against an acceptable standard (see Ref. 1) and subsequently measuring bellmouth throat static pressure during test runs. Curves may then be plotted relating drag to lift air flow, or in non-dimensional terms Tow Coefficient to Lift Air Coefficient, over a specified terrain and at a specified speed.

At the low speeds so far tested, aerodynamic drag and lift air momentum drag have been neglected, and slope drag has been corrected out of the presented results, so that these do in fact represent the skirt/terrain interaction drag alone. The Tow Coefficient is defined, with the above qualifications, as:

$$\text{Tow Coefficient} \equiv \frac{\text{Total Towing (or drag) Force}}{\text{Total Vehicle Weight (force)}} \times 100\%$$

The Lift Air Coefficient is defined as:

$$\text{LAC} \equiv \frac{\text{Lift Air Volume Flow} \times \sqrt{\text{Cushion Pressure}}}{\text{Total Vehicle Weight (force)}} \times \sqrt{\frac{\text{Air Density}}{2}} \times f$$

Where f is a function relating any particular vehicle plan shape to an arbitrary standard of a 2:1 rectangle, for which f = 1.

The whole subject of ACV drag is dealt with in some detail in Ref. 5.

There does not seem to be too great a difference between the drag of Multicell and segment skirts, although the comparison is greatly confused by the differing operational methods used, with the two types of vehicle. Because of stability considerations, the Multicell vehicle is always operated at about maximum availalbe lift air flow, and hence at minimum attainable drag. However, the segmented skirt vehicle is often operated with a lower lift air flow, and hence is thought to have a higher drag. The small amount of truly comparable data available suggests that the Multicell system probably has a somewhat higher drag than the seg-

mented type, while the simple bag skirts has a considerably higher drag than either, at least until the "full-hover" regime is attained.

A further analysis of skirt drag data has been proposed by Decker in an unpublished report to the Associate Committee. Further experiments are planned in the hope of validating this analysis. If this is achieved, the data from HEX-1 and other sources can be subjected to this system, and the picture greatly clarified.

In the meantime, Fig. 22 summarizes the whole of the systematic drag data available at the time of writing, and is presented without further comment.

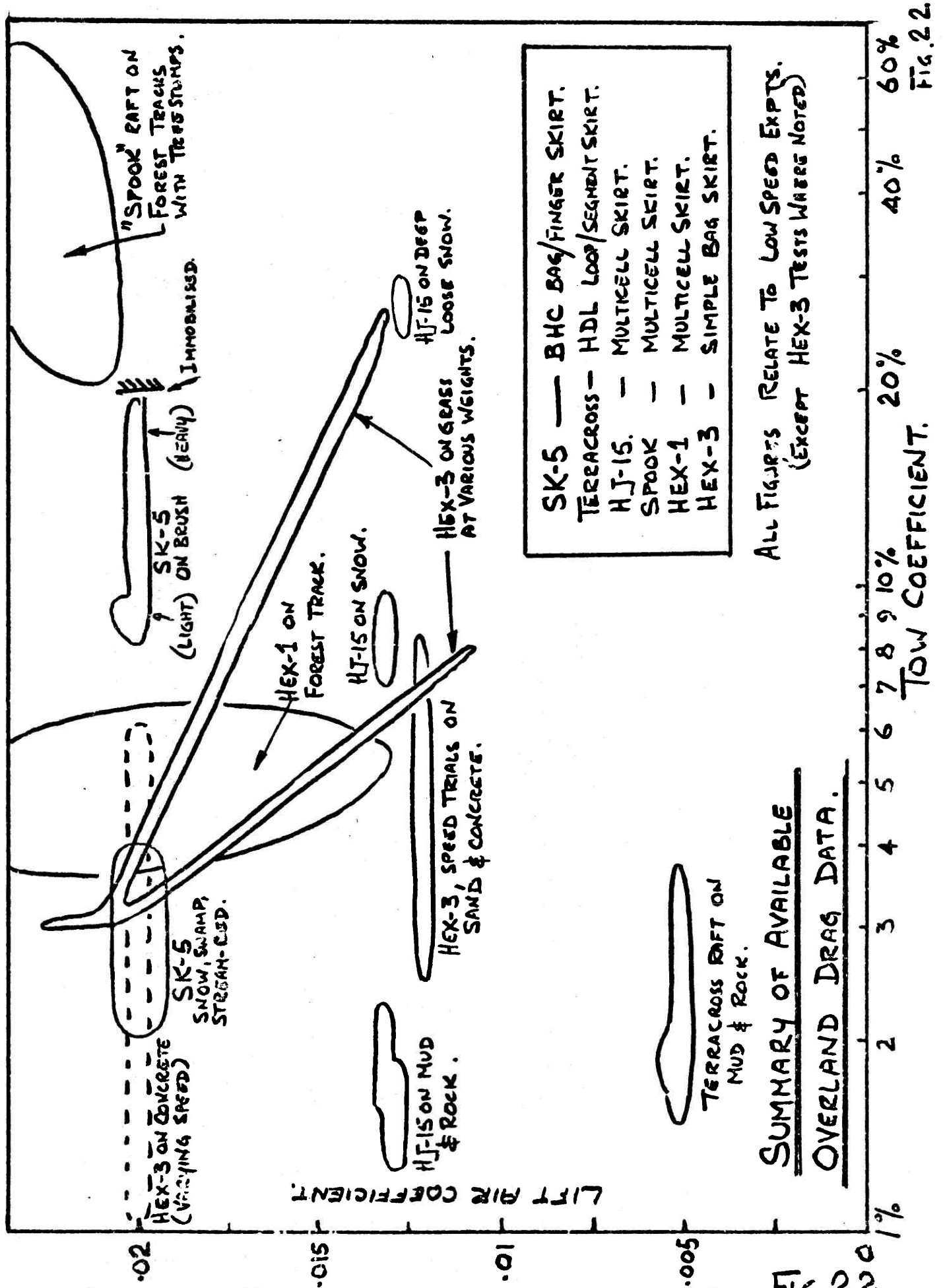

SUMMARY OF AVAILABLE
OVERLAND DRAG DATA.
ALL FIGURES RELATE TO LOW SPEED EXPTS. (EXCEPT HEX-3 TESTS WHERE NOTED)
SK-5 — BHC BAG/FINGER SKIRT.
TERRACROSS — HDL LOOP/SEGMENT SKIRT.
HJ-15. — MULTICELL SKIRT.
SPOOK — MULTICELL SKIRT.
HEX-1 — MULTICELL SKIRT.
HEX-3 — SIMPLE BAG SKIRT.
"SPOOK" RAFT ON FOREST TRACKS WITH TREE STUMPS.
IMMOBILISED.
SK-5 (LIGHT) ON BRUSH (HEAVY)
HJ-15 ON DEEP LOOSE SNOW.
HEX-3 ON GRASS AT VARIOUS WEIGHTS.
HEX-1 ON FOREST TRACK.
HJ-15 ON SNOW.
HEX-3, SPEED TRIALS ON SAND & CONCRETE.
SK-5 SNOW, SWAMP, STREAM-CSD.
HEX-3 ON CONCRETE (VARYING SPEED)
HJ-15 ON MUD & ROCK.
TERRACROSS RAFT ON MUD & ROCK.
LIFT AIR COEFFICIENT
.02
.015
.01
.005
0
1%
2
3
4
5
6
7
8
9
10%
20%
40%
60%
TOW COEFFICIENT.

FIG. 22.

7. OBSTACLE PERFORMANCE

Once again, in order to make sense of this apparently simple subject, the discussion has to start with some careful definition of the problem. It must also be understood that a driver's skill and experience in approaching obstacles at the best speed and angle will get a vehicle over obstacles which another driver considers impassable.

There are two general classes of obstacles, positive and negative, lumps and potholes. Both abound in off-road terrain.

If a positive obstacle is wide, and has a sloping approach face, it becomes a steep hill, and enough brute-force thrust will push the ACV up it, provided that the front skirt face does not collapse. In the case of the Multicell skirt, the stability of the cells against buckling and collapse was discussed in detail in section 5 above. The performance of vehicles with this type of skirt over such obstacles is good, and seems little different from any other skirt type. A very slow and cautious approach is likely to leave the vehicle gasping for thrust, without inertia to assist it. A very slowly applied frontal pressure may also collapse the front cells most easily.

With a faster approach the cells will derive added stiffness, since the air in them will have less time to escape either under the hem or back through the feed holes. This transient stiffness and the added approach inertia is likely to help float the craft over the obstacle. Too fast an approach however will impose high transient stresses in the inflated skirt structure, especially if it is made of heavy stiff fabric, and may rip it from its attachments.

The pilot has therefore to adapt his balance of courage and caution very shrewdly to the approach to each obstacle. A diagonal approach to the obstacle often helps. Hitting first on one corner lessens the shock, and avoids loss of lift over the whole front end while the craft is rising over the obstacle.

When the obstacle becomes less than the width of the craft and very steep fronted, for example a tree stump, then a new difficulty occurs. This is the "snagging" problem.

By its basic nature as an inflated seal to retain the cushion air, any type of skirt is designed to retain within it whatever is put inside its periphery. This applies as much to tree stumps as it does to cushion air. And while the cushion air can change shape and flow out in a thin jet under the hovergap without damaging the skirt, a tree stump cannot. Further, since all skirts have a base smaller than their upper dimensions for stability of vehicle and of skirt structure, they have a strong tendency to collect any obstacle and slide it evermore firmly into their clutches, rather than sliding easily off it.

The Multicell has fewer "bags" than the segmented/fingered skirt, with its great number of small cones, and the cells are often tougher than the smaller segments. The cells however have a form more prone to snagging than the cones, and less easily replaceable than segments when they do become snagged and ripped. When the Multicell skirt snags, it will very often slip off the obstacle. Sometimes however it does not, and brings the craft to a halt if it is moving slowly, or either rips out the tree stump or tears the skirt if the vehicle's inertia is too much for tree stump or fabric.

A rig-test program on this subject is described in detail in ref. 6.

In the tests on HEX-1 over the forestry track, it was repeatedly towed over tree stumps 30 cms high and 30 cms diameter, firmly rooted stems of 5 cms diameter, and rocks up to 40 cms square by 100 cms long. While the largest rock and at least one tree stump were uprooted in some 20 hours of operations, at about 1 m./sec., the skirt only received one tear, about 20 cms long in its 2.75 mm. thick rubber/nylon fabric/rubber material, which had already survived some 80 hours of operation at the Forestry Research Station at Petawawa without noticeable wear or damage.

A forestry research AC raft wearing a more sophisticated Multicell designed by Jones, with the anti-snagging design mentioned below, was towed over the same forest track for some 20 hours without suffering any skirt damage.

In section 5, it was pointed out that a large included cone angle in the cells made for greater structural stability. Unfortunately it also makes for greater snagging effectiveness, and lessens the chances of the skirt slipping off the snag.

It is this fact which has led to some very effective development by Jones of "anti-snagging" skirts for use in the Canadian forestry or muskeg environment. Development to shapes more complex than the pure cone have given increased stability to the cell, while sophisticated attachment of cell to hull has given the cell much improved ability to release snags without reducing its effectiveness as an air seal.

The negative obstacle, the hole or trench, shows the Multicell at a distinct advantage over the segmented skirt. Again the process is very speed-sensitive.

If the hole is of small extent relative to the craft, and the craft moves slowly across it, then the Multicell craft will lose lift from only one of many cells at a time. The feed holes to the cells being small, this does not drain the lift air supply, and the craft proceeds with little difficulty. A segmented or bag skirt with no subdivisions, or a fingered skirt with stability keels, would have no such advantages, and would be likely to lose lift and get stranded.

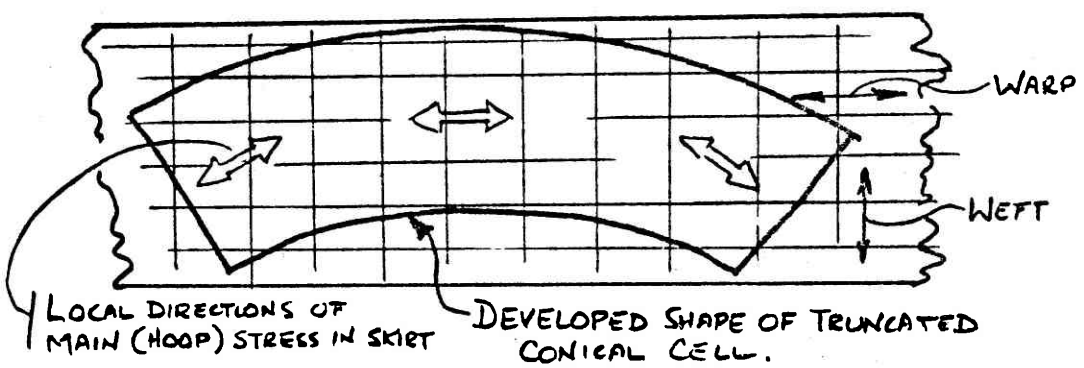
As the ditches become wider, a higher speed approach becomes necessary to get the vehicle across before too much air is lost from the lift system.

There is of course a limit, and seat harness to protect pilot and windshield from each other is a good protection against the effects of overoptimism.

8. STRUCTURAL CONSIDERATIONS

The single cell unit from which the Multicell skirt assembly is built up is geometrically simple, but its fabrication does pose two problems; it has to be made from a rectangular sheet of woven material, and this flat sheet has to have its edges joined to make the truncated conical cell.

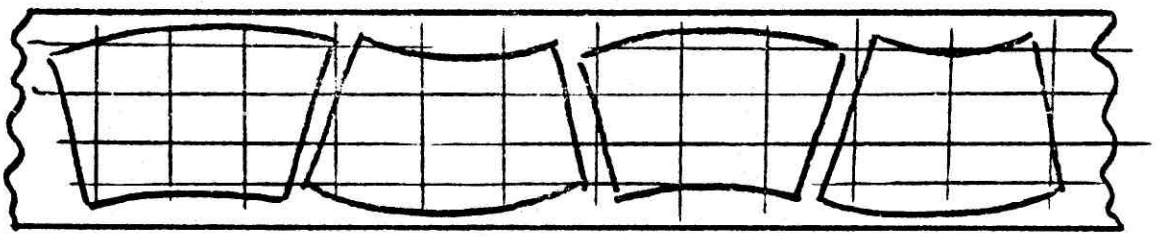
The rectangular sheet of conventional coated woven material has its two sets of threads, warp and weft, at right angles, and hence has different tensile strengths in different directions. Maximum strength is developed along the warp, the strength in the weft direction is less, and diagonally the strength is least. When such a material is exposed to air pressure it will therefore tend to stretch non-uniformly, with different strength and elongations in different directions relative to the rectangular grid of the weave. When a conic development is laid out on a woven sheet, the warp direction will not be properly aligned with the cone in all places. Fig. 23 makes this clear.



LAYOUT OF CELL ON WOVEN MATERIAL. FIG. 23.

This arrangement is clearly not satisfactory, and is liable to cause the inflated skirt to distort in an unsymmetrical manner, perhaps hastening the onset of buckling and collapse of the inflated column.

It is possible to reduce this tendency greatly by cutting the skirt in several pieces, and joining these, as in Fig. 24.



REVISED CUTTING PLAN OF ONE CELL.

FIG. 24.

This will greatly reduce the misalignment of stress and threads, but at the expense of more joints.

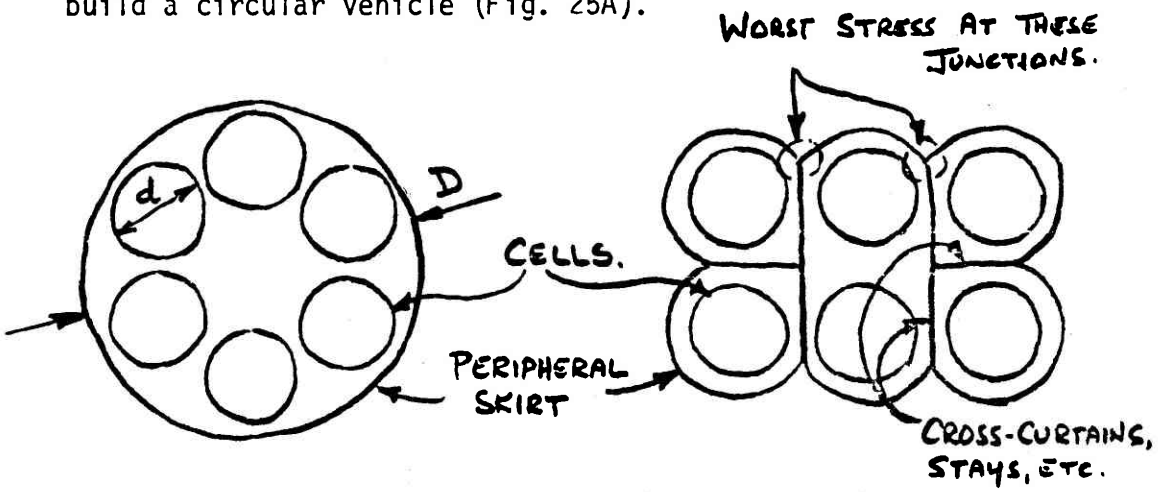
The joint, apart from its cost and possibility of failure, is undesirable because it introduces a discontinuity into the material (a strip of double thickness and stiffness) and failure is likely to occur at the edges of this strip.

A possible solution lies in the use of newer woven fabrics now becoming available, in which the weave is on three axes at 120°, instead of two at 90°, and a much closer approach to uniform properties in all directions is possible.

Other than this particular problem, it does not appear that the Multicell skirt has any different material requirements from any other skirt type. It may be remarked in general that for over-land use, which has been the main concern of the CASPAR program, snagging and abrasion resistance are likely to be much more important than in marine practise (refs 7 and 8).

The layout of the individual cells to form a complete skirt system involves a major structural problem which seems likely to determine future development of the Multicell skirt. This concerns the peripheral skirt, a fine concept which has revealed itself to be a structural disaster.

As was explained earlier, to increase the total lift and reduce the air flow of a group of isolated cells, they are often enclosed within a single peripheral skirt. Like the single cells, this outer skirt will assume a circular planform unless restrained in some way. The simplest layout is therefore to build a circular vehicle (Fig. 25A).



A. CIRCULAR PLANFORM VEHICLE.

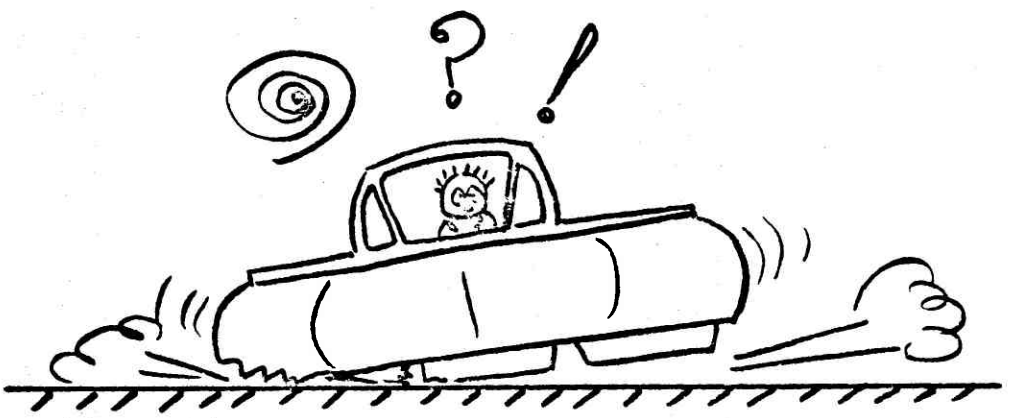
B. RECTANGULAR PLANFORM VEHICLE.

MULTICELL LAYOUTS WITH PERIPHERAL SKIRTS.

FIG. 25.

However, experience with the circular planform of the C-105 soon revealed its shortcomings as a vehicle. Docking requirements are unusual, and the directional stability of a vehicle whose length equals its beam is less than admirable. But the chief disadvantage lies in the skirt stressing. The hoop stress in a cylinder of unit length is proportional to its diameter. Since the ratio of peripheral skirt diameter 'D' to cell diameter 'd' was 4:1 in the

C-105, a typical example, the skirt hoop stresses would have been in this ratio. To make matters worse, the stress is also proportional to the pressure difference across the cylinder wall. Since only about 10% of the pressure drop from supply to atmosphere is normally reckoned to take place across the cell wall, with the remaining 90% across the peripheral skirt wall, the stress ratio will be further multiplied by a ratio of 9:1. The final ratio of hoop stress between peripheral skirt and inner cells is therefore 36:1. Since it is clearly not possible to use material of corresponding thickness, the results are highly undesirable. Although the C-105 peripheral skirt never actually failed, disaster was only averted by frequent inspection and maintenance. Further, the skirts were designed to have equal heights when inflated to the designed conical shape. However, the stress inequality ballooned the outer skirt, lifting its lower edge, and presented a distressing display of underwear, with resulting poor stability and lift (Fig. 26).



OVERSTRESSING OF PERIPHERAL SKIRT.

FIG. 26.

Photographs of the near-circular SEDAM N-102 reveal heavy hoop-reinforcing of the peripheral skirt, suggesting attempts to deal with the same problem.

The rectangular layout, (Fig. 25B) while easier to navigate and dock, is no instant answer to skirt-stress problems. In order to retain the peripheral skirt and prevent it bulging towards its

natural circular form, it is held in by cross-curtains or stays. These can also be used to control pressure distribution within the cushion area, with more or less success. However, they have three disadvantages. Being flat, they are rather unstable and can flap; being transverse they tangle with obstacles, which is serious in a vehicle built specifically for logging operations; and worst of all, they are a stress man's despair. At the point where cross-curtain and peripheral skirt meet, (Fig. 25B) there is the highest stress concentration in the whole assembly, there is a joint between three pieces of fabric, which forms a stiff spine with its inherent stress raising potentialities, and there is continual flexing from the several transient force inputs to the area.

In HEX-1 and the early HJ-15 builds, which are the only vehicles with this configuration directly observed during the CASPAR program, these joints have been the site of more skirt failures than any other one point. This is particularly noticeable as the thickness of skirt material is increased, in larger and heavier overland vehicles.

The alternative Multicell arrangement which abandons the vulnerable peripheral skirt is to group a row of tightly spaced cells round the periphery of the craft, much like a row of segments or fingers, and use these to seal in the cushion pressure under the main footprint of the vehicle, at the same time possessing a much greater roll or pitch stiffness than the segment or finger arrangement. This approach was foreshadowed in the early British "Convoluted Skirt", was tried briefly by Aerojet of USA, in their "Pericell", and has been developed to a high degree by Jones in Canada as the "Unicell" and "Flexicell".

These systems can be made to have another great advantage. The orthodox Multicell array is difficult to get at for repair or maintenance. Since the cells are spread over the whole underside of the vehicle, it must be lifted bodily to work on them, or replace them. This is not easy in the field. However, cells placed only round the periphery are much easier to get at, and can even be mounted individually in "slide-out" frames.

It seems likely that arrangements such as these will be the direction for future developments of the Multicell skirt.

9. SPECIFIC CONCLUSIONS (ARRANGED UNDER CHAPTER HEADINGS)

Chapters 1 (Introduction) and Chapter 2 (Description) are straightforward, and do not require discussion in this section.

3. VEHICLE STABILITY (STATIC)

A. Overland

Roll and pitch stability are discussed, and the simple description of the small-displacement roll is extended to cover successive phases up to final collapse and recovery, including a large and important hysteresis effect. The mechanisms involved are discussed in detail and a quantitative example is given.

The effect of the cell air feed hole acting as an impedance in the supply system is shown, and quantitative examples are given of the magnitude of this effect.

The effect of the shape of the blower characteristic on the stability of a vehicle having a two-blower lift system is shown, with an example. It is seen to be extremely sensitive, to the extent of demanding selection and tuning of the pair of blowers.

Heave stability is considered, and appears likely to be more fragile in the Multicell system than in a segmented or fingered skirt, owing to the less abrupt "valve cut-off characteristic" of the scalloped edges of the fingers compared with the edges of a Multicell array which all lie in one horizontal plane. An analytical treatment is quoted, showing the factors in skirt geometry which lead to heave instability, and two methods of reducing the instability are discussed.

B. Over Water

Roll stability in stationary hover over water is quite different to that overland, and is explained by treating the vehicle as an array of diving bells, whose vertical stability determines the roll characteristics of the vehicle.

4. VEHICLE STABILITY (IN MOTION)

The stability in motion is more limited than when the vehicle is stationary, owing to friction forces on the skirt hem tending to collapse the cells.

The vehicle is still very stiff in roll and pitch, but sudden collapse occurs without warning, and at lower values of rolling (or pitching) moment than when stationary.

High lift air pressure is essential to maintain a well developed skirt, and the vehicle can therefore not be operated at partial lift air flow, as is often done on other forms of skirt.

Over water some care is still needed, even below hump speed, not to generate enough side-force on the skirt-hem to collapse the leading cells. Above hump speed the vehicle is exceptionally stable, although again hitting a wave can cause collapse of the leading cells, with a violent plough-in following immediately.

5. SKIRT ELEMENT STABILITY

The forces on a stationary cell are considered, and it is shown that the cell when inflated is in principle a structural column. The geometrical proportions necessary for stability are defined quantitatively.

The instability due to improper air feed hole arrangements is discussed, and the remedy described.

An unexplained time-dependent cell-collapse is described.

Forward motion introduces additional forces tending to collapse the cell, leading ultimately to plough-in, over both water and land. It appears that this may lead to a more vicious collapse, with less warning, in the Multicell system, than in the segmented or fingered skirts.

Finally a series of experiments is described, which suggests the predominant influence of cell cone-angle on cell stability.

6. DRAG

The difficulties of measuring and interpreting drag over rough land are discussed. Drag over smooth terrain at low speed is found to be small relative to hill-climbing drag, provided that enough lift air flow is available to put the vehicle into full hover, without skirt dragging. Since the Multicell system needs good cell inflation for stability, it often appears to have lower drag than a corresponding segmented skirt vehicle, but this is probably because the segmented skirt system is operated at lower lift air flow.

The vital importance of lift air flow measurement in defining drag is emphasized, and the available drag/lift air flow data are summarized.

7. OBSTACLES

In general, the ability of any A.C.V. to traverse obstacles

greatly dependent on the skill of the driver in choosing the best approach direction and speed.

Obstacles are divided into 3 types, bumps or hillocks, snags, and holes or ditches.

Traversing a bump is essentially a short hill-climbing exercise, and provided excess speed does not collapse or rip the skirt, and insufficient speed does not allow loss of lift air amidships as the bows rise over the obstacle, no difficulties are seen.

Snags (e.g. tree stumps) tend to engage firmly in a conical cell, which often finally slides off them, but sometimes "pockets" the snag and rips. New forms of cell (the Flexicell, etc.) have special attachments to the vehicle which allow them to deform and slip easily off snags.

The third obstacle, the hole, is a hazard to an ACV since it provides a large temporary leak to drain away large amounts of lift air. The Multicell is less vulnerable to this loss than other systems since it is divided into many separately fed elements. If one is momentarily drained of air, the total flow is not greatly depleted, and the loss of lift is minimized by the compartmented nature of the cushion.

Again, approach at optimum speed is important.

8. STRUCTURE

The truncated cone cell is geometrically simple, but its

manufacture poses problems, due to the weave of the material, and to the added stiffness of all joints. New materials may reduce these problems.

The peripheral skirt, used in most practical Multicell assemblies, suffers badly fron high hoop stresses and from the stress concentrations at the junction points necessary in any but circular vehicle planforms.

These drawbacks are serious, but are avoided by developments in the Pericell, Unicell, and Flexicell directions. These arrangements, consisting of a peripheral row of cells, can have the cells mounted so that they can easily be replaced in the field, which is not readily possible with the original Multicell systems, in which the whole underside of the vehicle was covered by cells.

10. GENERAL CONCLUSIONS

The design, construction, and performance of the Multicell skirt system, both in its elements and as a complete system on a vehicle, have been discussed. In a general sense this skirt shares the main characteristics of all skirt systems in ACVs, but it has certain very individual characteristics which are quite unlike those of other systems.

While at first sight it is an extremely simple system, in fact its design is extremely subtle. Its performance is potentially excellent, but it contains some serious traps for the unwary designer or pilot.

The system is not yet fully understood, but the discussion and data in this report should enable a designer or pilot to use it with reasonable confidence, and to continue to add to the understanding of it by their experience.

The simple Multicell system as originally designed is unlikely to see further serious use, but developed versions, such as the Unicell, Flexicell, etc. appear to hold great promise.

11. REFERENCES

1. Fowler, H.S. "The CASPAR A.C.V. Research Project Report No. 1: Programme and Basic Data" N.R.C. Associate Committee on Air Cushion Technology, Technical Report 3/74 (March 1974)

2. Bertin, J. "French A.C.V. Developments" CASI Journal Jan. 1968, pp. 1-12

3. Fowler, H.S. "The CASPAR A.C.V. Research Project Report No. 2: The Sensitivity of a Two-Fan, Single-Engine, Multicell A.C.V. to Individual Fan Performance" NRC ACACT Tech. Report 6/74 (Sept. 1974)

4. Hill, R. Wingate "A Track-Laying A.C.V." Journal of Terramechanics, 1975, Vol. 12 No. 3/4, p. 201-216

5. Fowler, H.S. "The CASPAR A.C.V. Research Project Report No. 3: On the Drag of A.C.V.s Overland" NRC ACACT Tech. Report 1/75 (Feb. 1975)

6. Murchison, H.G., Silversides, C.R. & Tsay, T-B., "Studies Related to the Possible Application of A.C.V. Technology in Logging" Dept. of the Environment, Forest Management Institute, Information Report FMR-X-52 (May 1973)

7. Trillo, R.L. "Marine Hovercraft Technology" Leonard Hill Books Ltd. London (1971)

8. Gardner, E.R., & Morris, J. "Coated Fabrics for A.C.V.s Used for Moving Loads" Symposium on Air Cushion Handling, Paper No. 8 BHRA Fluid Engineering, Cranfield, Bedford, England (Oct. 1974)