# CANADIAN EXPERIENCE WITH AIR CUSHION VEHICLE SKIRTS

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## ABSTRACT

*Canadian developments in air cushion skirts are discussed, with emphasis on the authors' experience. Early field trial and laboratory tests of two European designs, a multicell and a loop-segment system, are reviewed; both are shown to have deficiencies. A simplified version of the loop-segment skirt, developed for use on large platform cushions, is described. Although this skirt is attractively simple both to build and to maintain, and although it has been used successfully on a small high-speed craft, it is shown to have significant dynamical limitations. A hybrid cellular-segmented skirt is proposed to circumvent these limitations, and results obtained from model tests of components of such a skirt are presented, together with some field test data obtained from a recreational vehicle. It is suggested that hybrid configurations may be the appropriate development path for most skirt systems; this includes those using a bag to obtain the responsiveness necessary for adequate comfort at high speed.*

## RÉSUMÉ

*L'auteur discute des développements au Canada des jupes pneumatiques dans l'optique de son expérience. Il passe en revue les premiers essais pratiques et tests en laboratoire de deux concepts européens, un système multicellulaire et un système de « boucles segmentées »; Les deux présentent des lacunes. L'auteur décrit une version simplifiée de la jupe à boucles segmentées, mise au point pour son utilisation sur de grands coussins de plate-forme. Bien que la construction et l'entretien de cette jupe soit pratique, et bien qu'elle ait été utilisée avec succès sur un petit véhicule à croisière rapide, elle présente des limites de dynamique importantes. Une jupe hybride cellulaire-segmentée pour contourner ces limites et les résultats obtenus à la suite d'un essai sur maquette des composantes d'une telle jupe sont présentés, ainsi que quelques données d'un test pratique effectué sur un véhicule de plaisance. Il est proposé que des configurations hybrides puissent être la façon de mettre au point la plupart des systèmes à jupe, y compris ceux qui sont munis d'un sac pour obtenir la réactivité nécessaire pour un minimum de confort à grande vitesse.*

## NOMENCLATURE

### Roman

| | |
|---|---|
| A | area, $A_b$ is area of vehicle base |
| $C_A$ | feed orifice area coefficient = $A_f/A_b$ |
| $C_M$ | pitch or roll moment coefficient = $M/WL_r$ |
| $C_m$ | discharge coefficient at skirt hemline |
| $C_{PC}$ | cushion power coefficient = $Q_e(\rho_a/2WA_b)^{1/2}$ |
| $C_{QC}$ | cushion flow coefficient = $p_dQ_e(\rho_aA_b/2W^3)^{1/2}$ |
| $C_{SC}$ | fan slope coefficient = $\{Q(dp_d/dQ)/p_d\}_e$ |
| $C_{SW}$ | skirt material weight coefficient = $\sigma_sA_b/W$ |
| HSC | hard structure contact during roll or pitch motion |
| h | hovergap |
| $k_f$, $k_s$, $k_u$ | dimensionless coefficients which are constant for a particular skirt geometry |
| $L_r$ | a reference length, equal to base width for roll, and base length for pitch |
| M | cushion restoring moment |
| p | pressure |
| Q | cushion air flow rate |
| U | forward speed of vehicle |
| V | velocity |
| W | gross weight of model or vehicle |

### Greek

| | |
|---|---|
| $\alpha$ | roll angle |
| $\theta$ | pitch angle |
| $\rho$ | density |
| $\Phi$ | finger or segment angle defined in Figure 1 |
| $\sigma$ | surface specific weight of skirt material |

### Subscripts

| | |
|---|---|
| a | air |
| b | base |
| c | cushion or central cavity |
| d | delivery pressure at fan exit |
| e | equilibrium, or zero $\alpha$ and $\theta$ |
| f | feed orifice |
| w | water |

## INTRODUCTION

In the mid-1960s it was widely believed that Canada's extreme climate and special transportation problems presented challenging opportunities for the air cushion vehicle (ACV). A National Research Council (NRC) study had concluded that there were particular requirements for certain types of ACV that had not then

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been developed.[1] Characteristically Canadian applications were thought to include: amphibious ferries providing year-round service in regions where ice formation or floating debris prevented effective use of other types of ferry; amphibious lightering for Arctic communities; off-road vehicles, possibly with limited amphibious capability, to service development sites and remote communities; and utility craft for search, rescue, survey and patrol operations under adverse weather conditions.

The air cushion principle seemed ideal for many of these applications. For example, it can be difficult and expensive to move heavy loads required for engineering projects in sparsely populated regions having limited road access. Furthermore, even moderately loaded tracked or wheeled vehicles can cause damage to terrain such as muskeg which may take years to recover. Air cushions, many believed, would greatly reduce the damage. And an ACVs ability to operate with seeming impunity over ice, snow and floating obstacles in water suggested that it could be an ideal general transportation vehicle on the innumerable lakes and rivers that constitute Canada's inland waters.

The discovery in 1971[2] that ACVs could be particularly effective as icebreakers provided additional impetus for their development. In certain ice conditions they were found to be much more efficient than conventional icebreakers, thus offering the possibility of extending the shipping season on the Great Lakes and at some Arctic ports. But they were also shown to be effective in a role no other vehicle could attempt. Communities located near rivers are often subject to flooding during the spring thaw as a direct result of winter ice-jams. An aerodynamically-propelled ACV can enter these locations and clear the ice long before the spring thaw, thus eliminating the problem.

All modern ACVs use various types of flexible seal or skirt to enable them to increase wave or obstacle clearance ability while keeping lift power at economically feasible levels. Consequently, as one might expect, the NRC study identified the development of skirt systems to suit the Canadian conditions as being of great importance.[1] It observed that low temperatures, abrasion associated with movement over ice and rocks, and snagging on obstacles all posed special problems for both choice of skirt material and methods of construction. Curiously, however, it concluded that skirt geometry changes were not needed to meet the Canadian requirements.

At that time the skirt most commonly used on large vehicles was the *bag-finger* system depicted in Figure 1. This skirt has three main elements: a bag ABO attached to the vehicle periphery and inflated to a pressure $p_b$ slightly above that in the cushion, $p_c$, fingers or segments BB'CD attached to the bottom of the bag, and inflatable stability keels dividing the cushion into three or four interior compartments. Cushion air is pumped first into the bag and thence through orifices N into the cushion at the top of the fingers. The bag, by changing its shape in response to changes in both $p_b$ and $p_c$ induced by vehicle motion, can filter out long wavelength disturbances; thus at high speed it can contribute significantly to ride comfort. The fingers, or segments, keep the effective hovergap to a minimum in the presence of short wavelength disturbances; also their geometry is such that, in the event of damage to one, its neighbours expand to re-establish the cushion seal. At the vehicle stern, to prevent water scooping, the fingers are usually replaced by modified elements such as cones. The compartmentation provides for static stability in pitch and roll. In early designs the outer profile of the fingers BB'C was straight; more recent designs include the knee at B' to increase the cushion footprint area. Most designs also include a device to suppress a dynamic instability involving oscillation of the bag and known as *skirt bounce*; this is usually an elastomer-fabric web connecting a part of the bag such as B to the vehicle base.

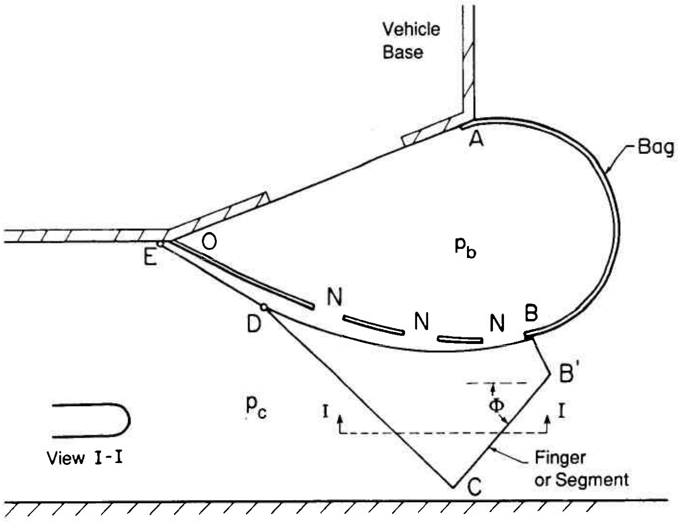

**Figure 1**
**Basic elements of bag-finger skirt**

Now this skirt was developed for high-speed marine vehicles usually experiencing only limited operation over land or obstacles in shallow water. It has proven highly successful in this role; however, as noted above, many Canadian applications were expected to involve a significantly different operating environment. Contrary to the conclusions of the NRC report, we believed that this required the evolution of different geometries, in order to sustain the cushion effectively, and to reduce the cost of both manufacture and maintenance. For example, at low speeds the bag might not be needed; and interior stability keels can only be serviced by lifting the vehicle.

Perhaps the major Canadian ACV industrial activity in the last 30 years has been the development of Bell Aerospace Textron's Voyageur amphibious cargo transporter, and its U.S. military derivative, the LACV 30. However, this 41-tonne vehicle used the bag-finger skirt essentially unmodified. Hence we review Canadian projects which involved skirt development and the experience gained as a result. We believe that the conclusions drawn here also provide direction for the future evolution of the bag-finger skirt.

## INITIAL EVALUATIONS

### A First Step

The second author's involvement in skirt development began in 1963, when Canadair Ltd. of Montreal was exploring the possibility of developing ACVs. At the time the project was started the quantity of air required to sustain a cushion over various surfaces was not accurately known, so that cushion flow rates $Q_c$ were much higher than considered necessary today. This in turn implied that intake momentum flux was one of the major sources of drag, so that a basic aim of the project was to find ways of reducing $Q_c$. The skirt system that was eventually developed achieved this in two ways. The first was to collect and recirculate lift air before it left the cushion periphery, and the second was to make the skirt surface-following in order to minimize hovergap variation as the craft passed over obstacles.

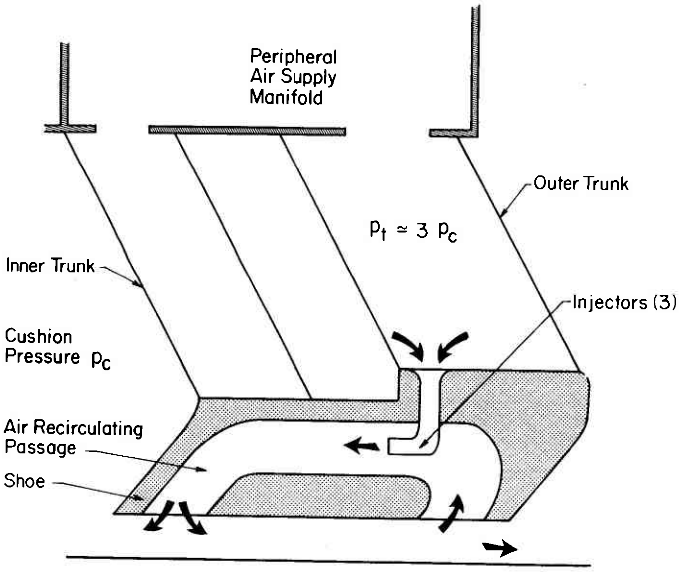

**Figure 2**
**Unit of skirt used on Canadair test vehicle in 1963**

The concept finally chosen is depicted in Figure 2; it comprised a large number of identical units attached to the periphery of the vehicle. Each unit consisted of a shoe containing injector nozzles and return ducting, which was attached to two elastomer-fabric cylinders called trunks, which in turn were attached to the vehicle base. Air at a pressure of about $3p_c$ was fed to the injectors through the outer trunk. This high pressure inflated the trunks and prevented them from being forced outwards by the cushion pressure. Recirculation was achieved by using the injector nozzle to both pump air into the cushion interior through the inner port shown in Figure 2, and to create suction at the outer port. The shoe itself was made from a relatively rigid elastomer, in order to retain the required shapes of the air passages. To achieve the surface-following capability, the geometry of the trunk-shoe combination was chosen so that, when the pressure in the gap between the shoe and ground increased, the system was forced out and upwards to a new equilibrium.[3]

Tests using two-dimensional models demonstrated the feasibility of the concept, and a man-carrying demonstration vehicle built and trials conducted. These showed that static stability in pitch and roll could be achieved without using interior compartmentation. Also, since each skirt unit was attached to its own removable frame, it could be serviced without lifting the vehicle. However, the project was cancelled in 1967 owing to operational problems, such as the accumulation of ice and snow in the recirculating ducts, and to other factors.

### Field Trials of Two European Skirts

The first attempts to develop applications of the type envisaged in the NRC report[1] used two European skirt systems. The second author's company (JKA) decided, as a first step, to develop towed air cushion rafts and similar devices to move heavy loads. It was expected that this would be less technologically demanding than the high-speed amphibious passenger-carrying ferry, and thus would lead to early economic viability.

The first project was the development of a 2.5-tonne payload raft for use by the forestry industry. A variation of a multicell system developed in France was selected for this project. The basic concept is attractively simple; as shown in Figure 3 it consists of several slightly-tapered, inverted truncated cones, with the number of cells determined by payload and stability requirements. Stability also requires that the pressure in the cells drop as the flow through the cell increases; this can be obtained either by suitable use of the lift fan pressure-flow characteristic, or by regulating orifices between feed duct and cell as depicted in Figure 3.

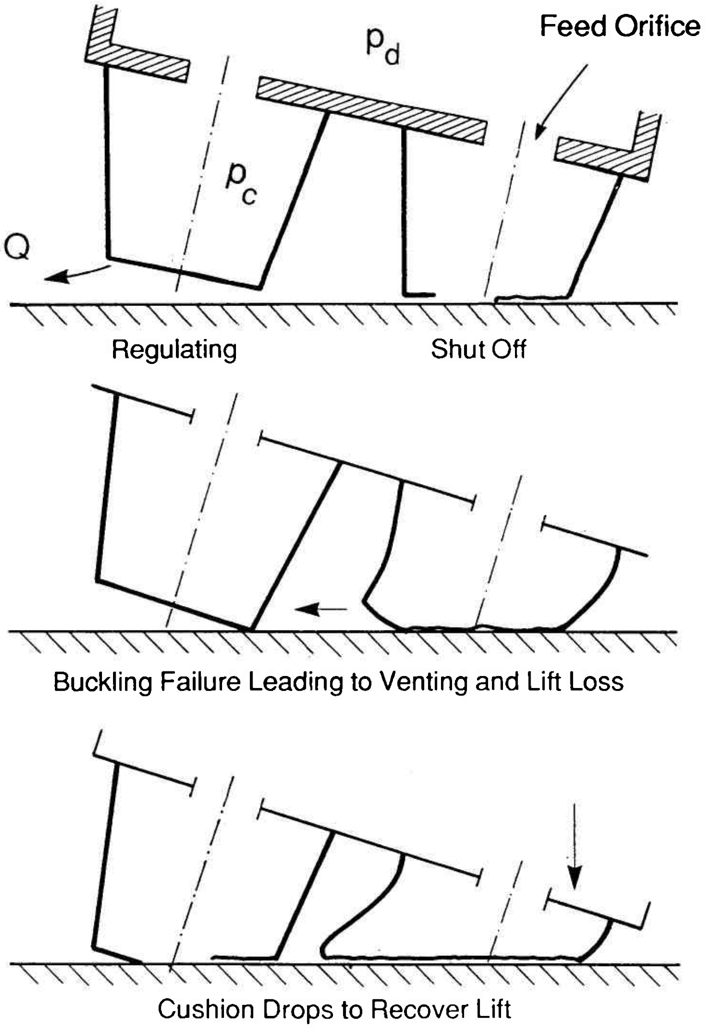

**Figure 3**
**Multicell concept; also illustrating the buckling failure mechanism**

Although it was used successfully in this form on the Bertin BC7 Terraplane, it requires high installed power because the footprint area is low and the hovergap flow area is high. Vehicles such as the present forestry raft included the outer skirt depicted in Figure 4. The cushion air was fed from two lift fans by a system of ducts both to each cell and to the outer skirt volume. In addition to its perceived ability to sustain a cushion over rough ground more effectively than its competitors, this configuration was thought to have a special advantage for the present application: dampers in the cushion air ducts could be used to adjust the craft trim and thus permit a wide range of payload positions.

Trials were performed at the Federal Forestry Research Establishment at Petawawa, Ontario, where the craft was towed through a typical forest cut-over area. This vehicle, which had a hard structure clearance of 0.56 m., could negotiate such obstacles as tree stumps having heights up to 0.46 m without damaging the skirt. Furthermore, it would sustain the cushion when travelling over the

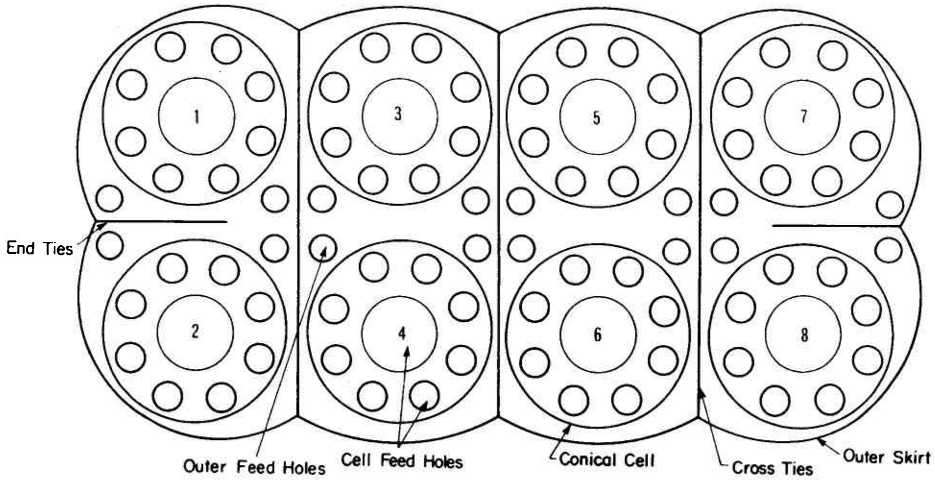

**Figure 4**
**Schematic of base of multicell skirt at hard structure level showing cross-sectional geometry of the outer skirt. Multiple feed orifices were used for each cell because a single central orifice generated an internal vortical flow which prevented deployment of the cell**

highly porous slash remaining after tree-cutting. However, it used a relatively high $p_c$, and the associated dust generation created severe operating difficulties.

A second project investigated the feasibility of using towed rafts for transportation to construction sites in swampy areas. An important motivation for this work was that operations at such sites with conventional vehicles are often limited to the winter months. It was envisaged that air cushion transporters would permit year-round operations while causing less damage to the terrain.[4] Two 15-tonne payload craft were constructed, one by JKA using the multicell system described above, and one by Terracross Ltd. using a loop-segment skirt. In dynamical terms this skirt is basically a bag-finger skirt in which $p_b = p_c$, so that the inner bag OB in Figure 1 is not required. However, there are other significant differences. Interior compartmentation is not used; it relies instead on contact with the surface so that vehicle pitch and roll displacements force local collapse of the segments. This in turn causes lateral movement of the centroid of the cushion footprint relative to the vehicle base. For high-speed vehicles this centre-of-pressure shift approach to generating restoring moments is augmented by mechanisms which allow the operator to move the segment inner attachment point E laterally as required during manoeuvres. Based on ideas developed by Britain's Hovercraft Development Ltd. (HDL), in an attempt to minimize skirt wear, it also used skirt material which is significantly lighter than the bag-finger equivalent.

The trials, undertaken at Ragueneau, Quebec, showed that a properly integrated design of traction unit and air cushion trailer could operate at average speeds of at least three times that of conventional vehicles, thus allowing a major increase in transportation productivity.[4] Also, as anticipated, they did inflict much less damage on the terrain.

However, skirts were the main cause of mechanical failures. The route included debris remaining after tree-cutting, so that damaging due to snagging was a major problem. The multicell's highly stressed outer skirt was especially prone to damage. The straps used to attach the inner portions of the loop-segment skirt to the vehicle base were subject to frequent snagging and, on occasion, the segments scooped up mud. Terrain porosity could also cause this skirt to lose its cushion seal with skirt damage being caused when the vehicle dropped to the ground. It also exhibited behavior attributable to its reliance on surface contact to obtain stability. A representative drag coefficient for this skirt was given as 0.025; for the multicell skirt it was 0.013. Also motion over certain kinds of damp terrain could cause a *tuck-under* instability; the front part of the skirt could be dragged under the vehicle, causing loss of cushion seal and complete loss of cushion lift. For both skirts, some repairs required winching the vehicle on its base to ground firm enough to allow jacking, thus incurring additional skirt damage. These and other difficulties clearly demonstrated that this type of application required the development of improved designs.

### Laboratory Investigations

In the early 1970s a series of theoretical and experimental investigations of the dynamical properties of various skirt systems was initiated at the first author's Institute (UTIAS). The first project involved a detailed investigation of the roll stiffness properties of the two skirts used in the Ragueneau trials.[5,6] One of the aims was to develop a rational basis for comparing the suspension properties of different skirt geometries. However, during experiments undertaken to obtain the data required for these comparisons, a number of deficiencies in the skirt systems were identified.

The data were obtained from two models. In the first, skirts were attached to a 2.44 m × 1.22 m planform air supply box, which was mounted over a smooth flat table. The box motion was constrained by a harness system which could be set up to allow any desired combination of heave, pitch and roll. Air was supplied through flexible ducts by a centrifugal fan equipped with a variable speed drive. By adjusting the fan speed during a test, any desired effective fan characteristic could be obtained. The second model was a 4.2 m × 2.0 m aerodynamically propelled vehicle having a mass of 900 kg. It was to be flown on the 43.6 m diameter UTIAS circular test track, and was also designed specifically to allow testing of different skirt configurations. For tests on both models, two skirt materials were used. Both were elastomer-coated fabrics; one, designated 'blue', had a surface density $\sigma = 0.237\ \mathrm{kg/m^2}$ and for the other, designated 'white', $\sigma = 0.609\ \mathrm{kg/m^2}$. For both multicell models, air was fed by the fan to a single plenum box, which in turn fed each of the cells by separate regulating orifices in the manner depicted in Figure 2.

At the time these experiments were undertaken there was no established practise for comparing cushion systems or for scaling model tests. One useful index of performance is the air flow power required to sustain the cushion. This automatically includes penalties for systems that use fluid losses to attain stability or that use a geometry which increases $p_c$ or $Q_e$ relative to its competitors.

This power must, of course, be determined at a value of $Q_e$ that is representative of the design; so that $Q_e$ must be scaled appropriately for the tests.

According to the principles of dimensional analysis, to scale $Q_e$ for model tests, one must select an appropriate reference speed $V_r$ and area $A_r$ and define the flow coefficient $C_Q = Q_e/(V_r A_r)$; $C_Q$ must be the same for the full-scale system and its model. Mantle[7] suggested setting $V_r = U$ and $A_r = L^2$ where U and L are, respectively, the forward speed and overall vehicle length. Since the UTIAS tests were undertaken at zero U, an alternative had to be chosen. In this respect note that $Q_e$ depends on $p_c$, the cushion geometry, the roughness of the surface over which the vehicle travels, as well as on U. Now, for a given skirt geometry, $p_c$ is determined largely by the hovering condition; that is, if the vehicle weight is W and base area is $A_b$, then $p_c = W/(k_f A_b)$ where $k_f$ is the ratio of cushion footprint area to $A_b$. Also the air escape process from the cushion is known to be orifice-like, in which case

$$Q_e = C_m L_s h_e (2\rho_c/\rho_a)^{1/2} \tag{1}$$

where $L_s$ is the peripheral length of the cushion footprint, $h_e$ is a mean hovergap, $C_m$ is a discharge coefficient, and where $\rho_a$ is the atmospheric air density. These considerations led us to choose the flow coefficient

$$C_{QC} = Q_e(\rho_a/(2WA_b))^{1/2} \tag{2}$$

and, with $p_d$ the pressure at the lift fan exit, the power coefficient

$$C_{PC} = p_d Q_e (\rho_a A_b/2W^3)^{1/2} \tag{3}$$

By using Equation (1) it can be readily shown that $C_{QC}$ is equivalent to a non-dimensional hovergap $h_e/L$; that is

$$\frac{h_e}{L} = k_s C_{QC} \tag{4}$$

where $k_s$ is a dimensionless coefficient which depends on the geometry of the cushion but not its size. Typically for a circular planform cushion having diameter L, $k_s = 1/(4\ C_m)$. For full-scale vehicles, $0.001 \leq C_{QC} \leq 0.01$ approximately, with the lower values being used on low-speed platform cushions and the higher values on high-speed marine vehicles.[8] The coefficient $C_{PC}$ is the non-dimensionalized air flow power $p_d Q_e$ at the point the air is delivered to the cushion system. According to the usual scaling arguments, if the model test conditions are such that $C_{QC}$ is the same as that for the full scale vehicle, then $C_{PC}$ will also be the same, and it can be used to compute the power required to sustain the full scale cushion.

Finally note that, in the present approach, scaling forward speed effects requires $C_U = U(\rho_a A_b/2W)^{1/2}$ to be the same for both model and full-scale vehicle. Manipulation of the above expression shows that $C_U = k_u C_{QC}/C_{QU}$, where as for $k_s$, $k_u$ depends on geometry but not on size. Hence the present approach is consistent with that suggested by Mantle.[7]

Figure 5 gives measurements of roll moment coefficient $C_M = M/WL_r$ as a function of roll angle a for a multicell skirt having the geometry in Figures 3 and 4. These were obtained from the 2.44 m × 1.22 m model when operating at high $C_{QC}$. Included in this graph is a prediction and two sets of measurements. The theory is simple in concept; it uses standard orifice flow formulae based on Bernoulli's law and assumes discharge coefficients for the flows from box to cell, cell to outer skirt volume, and to atmosphere. However, the flow areas from the cells and from the outer skirt depend on the model heave height and roll angle in a complex way, so that these must be determined by digital computation.[5] The theory indicated that roll stiffness for this type of cushion should be sensitive to both the properties of the pressure-flow relationship of the fan or air supply system and the area of the feed orifices depicted in Figure 3. Accordingly we introduced a fan slope coefficient $C_{SC} = \{Q(dp_d/dQ)/p_d\}_e$, and an orifice area coefficient $C_A = A_f/A_b$, and these were monitored in making comparisons. In the experiments a known moment was applied to the vehicle and the roll angle measured. However, as shown in Figure 5, in some cases the effective moment was determined from the measured footprint pressure distribution.

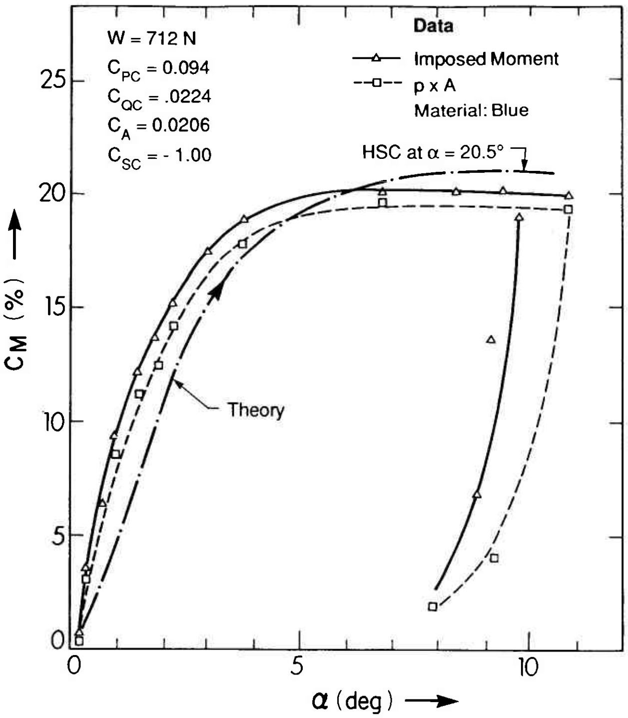

**Figure 5**
**Roll moment characteristic of original multicell skirt at high lift power showing hysteresis caused by cell buckling. For these tests, the 'blue' skirt material was used giving $C_{SW}$ = 0.0097**

The most striking feature of these results is a very large hysteresis in the roll moment as computed from both the movement of test weights carried by the model and the measured footprint pressure distribution. Whereas the theory predicted that α could increase to 20.5° before the rolled-down side of the model would contact the ground (HSC), a sudden and almost complete loss of moment occurred at about α = 9°. The cushion could not be restored to α = 0° until almost all the applied moment had been removed. This behavior was traced to a buckling failure of the conical cells that provided the pitch and roll stiffness of this cushion. As shown in Figure 3, if, at high $C_{QC}$, the hemline of the cells on the downgoing side contact the ground, the flow through them becomes shut off and the internal pressure equals $p_d$. Also the high value of $C_{QC}$ causes the pressure in the volume enclosed by the outer cushion to drop, so that the cell is subject to an asymmetric internal pressure loading, and thus can buckle, leading to venting and loss of cell lift force.

A simple theory which assumes that the skirt material is a membrane and is loaded only by the air pressure, and that failure occurs as soon as either of the principal membrane stresses becomes negative, predicts that this occurs when the roll angle is equal to the cell taper angle.[6] However, the experiments showed that the phenomenon is more complicated than this; it depends on both cell height and the details of surface contact.[6,8] Observation of a single cell showed that buckling was preceded by a complex wrinkling process and that, in most instances, venting failure would not occur until several minutes had lapsed.[6] Thus stress-relaxation phenomena associated with the viscoelastic properties of the skirt material were implicated. The protracted nature of this process suggests that if vehicle motion momentarily forced the cells into an unstable region, venting failure might not occur; however, many other operating conditions could easily cause complete failure.

During these tests we also discovered that, even when buckling failure did not occur, the $C_M - \alpha$ curves displayed considerable hysteresis; Figure 6 gives examples of this behavior. It was eventually concluded that this hysteresis could involve two mechanisms; the first being sliding friction between skirt and ground, and the second, viscoelastic phenomena in the skirt material triggered by surface contact. The presence of sliding friction was detected by simply placing between the cushion and table surface a board which in turn was resting on a large number of tubes having their axes aligned parallel to the model roll axis. When the model rolled, the board would move laterally with the portions of the skirt in contact with it. Figure 6 shows an example of behavior attributed to skirt material properties.[6] When the multicell skirt was tested on the much larger circular track model, both cell buckling and hysteresis was observed, thus confirming that our observations were not an artifact of the first test model.[5,6]

The UTIAS loop and segment model was also found to be subject to considerable hysteresis. Figure 7 gives data obtained using the moving board technique to identify the effects of sliding friction. In this case sliding friction clearly played a major role, affecting both hysteresis and the maximum rolling moment generated. The data also illustrate behavior encountered with both skirts: creeping, ultimately attributed to viscoelastic effects in the skirt material. In this instance, when the moment increment leading to HSC was applied, 10 minutes elapsed before it occurred. In general it was found that, while both skirt models could be subjected to considerable hysteresis in pitch and roll, the segmented skirt appeared to be much more susceptible to the effects of sliding friction; this observation seems consistent with the behavior observed at Ragueneau.[4]

## SEGMENTED SKIRT DEVELOPMENTS

### Vehicle Applications

One of the earliest applications of the loop-and-segment skirt in Canada occurred in 1971, when a 24.2 m × 17.4 m, 250-tonne towed platform cushion was designed and built to transport heavy equipment in the Arctic. It was during trials of this vehicle, at Yellowknife, NWT, that the significance of an ACV's icebreaking capability was first recognized. It was subsequently modified and used in trials by the Canadian Coast Guard at Tuktoyaktuk, NWT, in 1972–73, and at Thunder Bay, Ontario, in 1976,[2] and the success of these trials led to the developments described below.

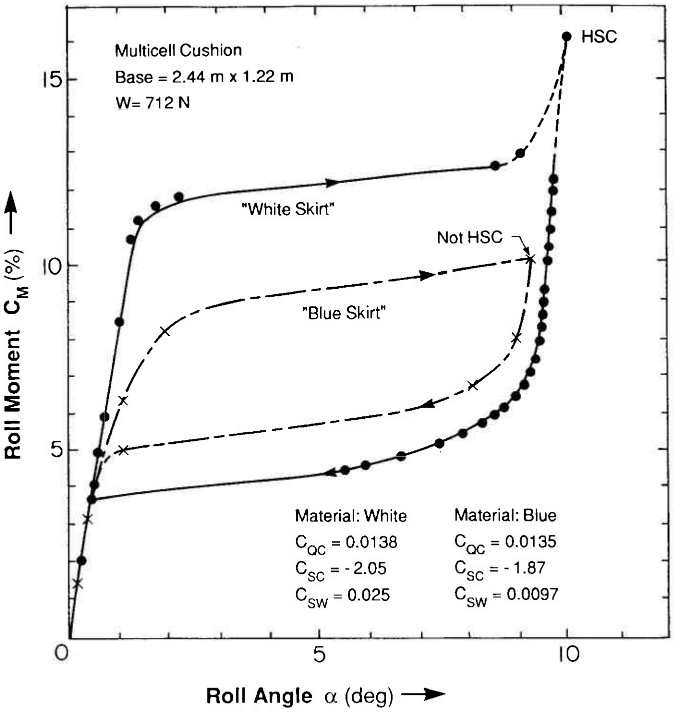

Figure 6
**Roll moment characteristic of multicell skirt showing hysteresis in the absence of cell buckling. Here $C_{PC}$ = 0.0268**

In 1976, Hoverlift Systems Limited of Calgary (HSC), used a segmented skirt on a 10.66 × m x 5.49 m, 12.5-tonne, cable-operated river ferry.[9] This is a variant of the loop-segment skirt; for low speed applications the long-wave filtering function of the loop is not required, so that it is eliminated.[10] To offset the reduction of the footprint area associated with elimination of the loop, the segment geometry included the knee depicted in Figure 1. The ferry was used at a crossing of the Peace River at La Crete, Alberta

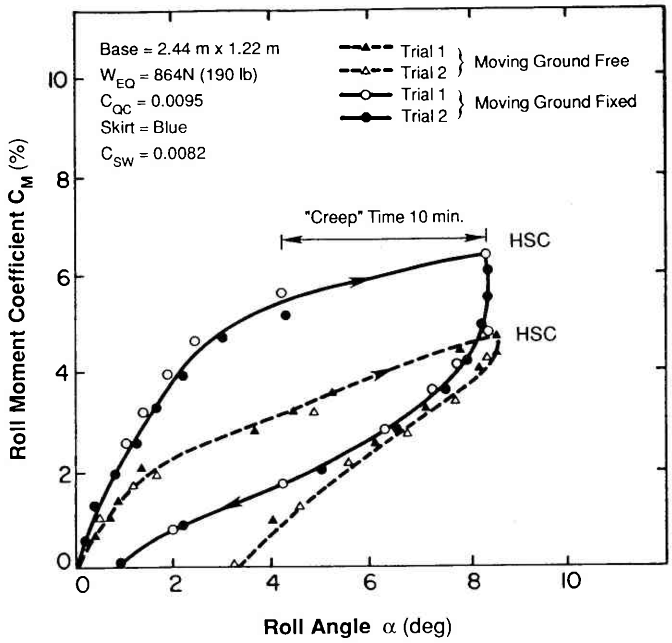

Figure 7
**Roll stiffness characteristics of cushion dynamics model equipped with a single plenum chamber loop and segment skirt including the effect of skirt-ground friction**

in the winter of 1977. A number of operational problems were encountered, two of which are noted here. First, following an accepted practise, in order to prevent scooping of water or ice while under motion, the segments at both ends of the ferry were enclosed, thus forming flattened cones. During freezing conditions it was found that large ice balls could build up in the interior of the cones, and the accumulated weight could seriously impede operation. The second problem was that in cold weather the segments would often not inflate properly, thus preventing establishment of the cushion seal. It has been noted that one of the functions of the loop in the original loop-segment skirt was to act as a duct to supply air to the top of the segments in order to ensure their proper inflation, especially over water.[10] In this vehicle, the air was simply pumped into the central cushion cavity.

In 1977 HSC designed and built a 24.7 m × 24.7 m, 270-tonne platform cushion (ACIB) specifically for ice-breaking. This cushion, which had a hard structure clearance of 2.0 m, proved capable of breaking ice up to 0.95 m thick, and 0.60 m ice continuously at 6 kn.[11] This may be compared with an average speed of 2 knots for a conventional 6000-tonne ship breaking 1.00 m thick ice. By using a television camera, the interior of the cushion was observed during motion over ice and water. Scooping of ice lumps or water did not seem to present a problem. It was, however, found that significant damage to two adjacent segments would seriously impair cushion action so that, unless segments could be replaced from the craft deck, failure of any segment would require an immediate return to base.

Because of its attractive simplicity, the second author used it on a 11.2 m × 5.74 m, 6.7-tonne aerodynamically propelled vehicle, the Air Trek 140. This vehicle, shown in Figure 8, which used air-cooled diesel engines and carried a 1.36-tonne payload, at speeds up to 17 m/sec over water, and 20 m/sec over ice. The segments were connected to the vehicle base in such a manner as to allow one person to change a segment while standing on the craft deck, either when the craft is sitting on the ground or floating in water. To eliminate the scooping problem noted above, the rear segments were not enclosed; instead a flap consisting of a single sheet of skirt material to cover the segment interior was used.

## Laboratory Studies

As part of a program to investigate the dynamics of the segmented system as used on the ACIB, models were built at UTIAS for both the test table and the circular track.[12,13] Figure 9 gives typical pitch stiffness data for a segmented skirt obtained from the UTIAS 2.44 m × 1.22 m test model. Two skirt materials were used in these tests. The first, a urethane-coated nylon fabric with $\sigma = 0.075$ kg/m$^2$ — 'red') gave negligible hysteresis, while the second, polyethylene film, with $\sigma = 0.12$ kg/m$^2$ ('polyethylene') generated large hysteresis.[12,13] We discovered that this skirt system was subject to a very strong pitch-heave instability when the red segments were installed, but which could not be excited when the polyethylene segments were installed. Similar experiments on the UTIAS circular track test vehicle showed the same static and dynamic behaviour, thus — as for the multicell skirt — confirming that these phenomena are not artifacts of the test procedures. We inferred that the hysteresis in the pitch moment was suppressing the instability.

We initially thought that, beyond a certain critical $\alpha$ or $\theta$, the knee in the segment could cause a sudden loss of stiffness.[13] A simple theory for the stiffnesses of this skirt, which was in excellent agreement with the pitch stiffness data for the nylon-urethane material shown in Figure 9, predicted that the cushion would become statically unstable, with $dC_M/d\theta$ becoming negative at about $\theta = 4°$.[12] However, observations showed that the segment buckled at its upper edge at $\theta = 3.5°$, so that $dC_M/d\theta$ remained positive up to HSC.

The major role apparently played by the static hysteresis in the dynamics of the segmented skirt for both test table and circular track models led us to explore possible mechanisms and to assess its potential full-scale significance. It is clearly not associated with large-scale venting of the type depicted in Figure 3. As illustrated in Figure 7, previous tests on multicell and loop-segment skirts had implicated sliding friction and viscoelastic effects. However, the moving board technique showed that sliding friction played only a minor role in generating the segmented skirt hysteresis. One possible viscoelastic mechanism is as follows. When, during vehicle

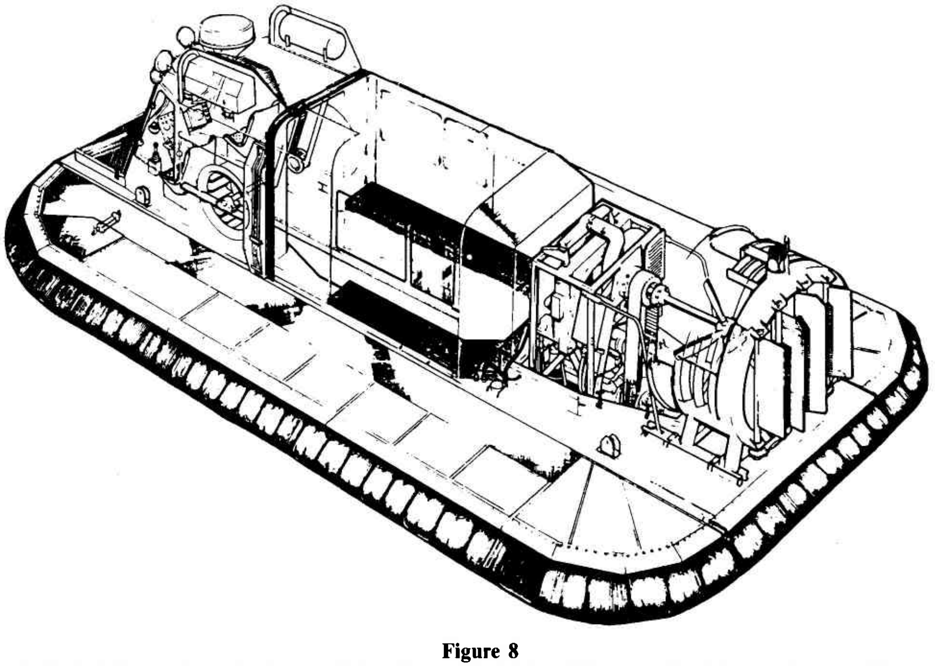

**Figure 8**
**Air-Trek 140 aerodynamicall-propelled utility ACV. This vehicle uses diesel-hydraulic propulsion and the side-bodies can be folded to allow transportation on a flat-bed trailer**

attitude motion, certain segments are forced into contact with a rigid or unyielding surface they must collapse or deflate locally. As these segments subsequently move away, reinflation is retarded by stress relaxation or creep phenomena, so that the associated contact forces are reduced below those exerted during deflation. Dynamic uniaxial tension tests on samples of the two skirt materials used to obtain the data in Figure 9 showed that stress relaxation could extend over several minutes and longer, enough time for this to act in static tests.[14] Also data such as those in Figure 6 suggest that, for a given skirt material composition, the hysteresis is approximately proportional to material thickness, or weight. Tests on single conical cells having the same material composition but a range of thicknesses mounted over a ground-board which executed heave oscillations for frequencies in the range 0.03 Hz to 11.1 Hz confirmed the existence of contact forces essentially independent of frequency and proportional to material thickness.[15]

This suggested that an appropriate parameter to scale these forces for a given skirt material composition is a skirt weight coefficient $C_{SW} = \sigma A_b/W$. For the 270-tonne ACIB, $C_{SW}$ was estimated to be 0.0056,[13] whereas for the polyethylene segments used to obtain the data in Figure 9, $C_{SW} = 0.0067$. Consequently we sought evidence for the existence of hysteresis in the segment contact forces on the ACIB. This was obtained as follows.[13] With the platform hovering over a flat surface, cushion pressure was monitored as lift fan speed and $Q_e$ was first increased through the full operating range, and then decreased. The results are shown in Figure 10; cushion pressure was clearly higher during the increasing $Q_e$ portion of the cycle, in which the segments are moving away from the ground, thus indicating that the segments were carrying less of the platform's weight. During the portion of the cycle in which the segments are being forced towards the ground the data in Figure 10 suggests that they supported up to 4% of the vehicle weight. Forces of this magnitude can contribute significantly to damping.[16,17]

Two key issues are the significance of this mechanism for other skirt geometries and during operation over water. The UTIAS tests clearly indicate that it can occur on other geometries; furthermore measurements of roll stiffness on a full scale vehicle reported in a British operating manual[18] display large hysteresis which it attributes to skirt material properties. The presence of the associated hysteretic contact forces over water would depend on the extent of skirt deflection by the water surface during attitude motion, and this in turn should depend stgrongly on the forward speed of the vehicle. During experiments at UTIAS relating to heave stability over water,[13] observations of segments mounted on a small water tank indicated that they would essentially undeflect at zero forward speed. However as speed builds up, owing to the water inertia, significant deflections should occur; indeed, when planing speeds have been attained, the dynamic pressure of the water impinging on the segments can be an order of magnitude larger than $p_c$, so that the water surface should be unyielding. Hence the hysteretic contact forces should approach rigid surface values. Comments made in the above British operating manual are consistent with this view. It notes that the bag-finger skirt undergoes a significant loss of roll stiffness in moving from ground to water but that this loss is recovered as speed builds up.[18]

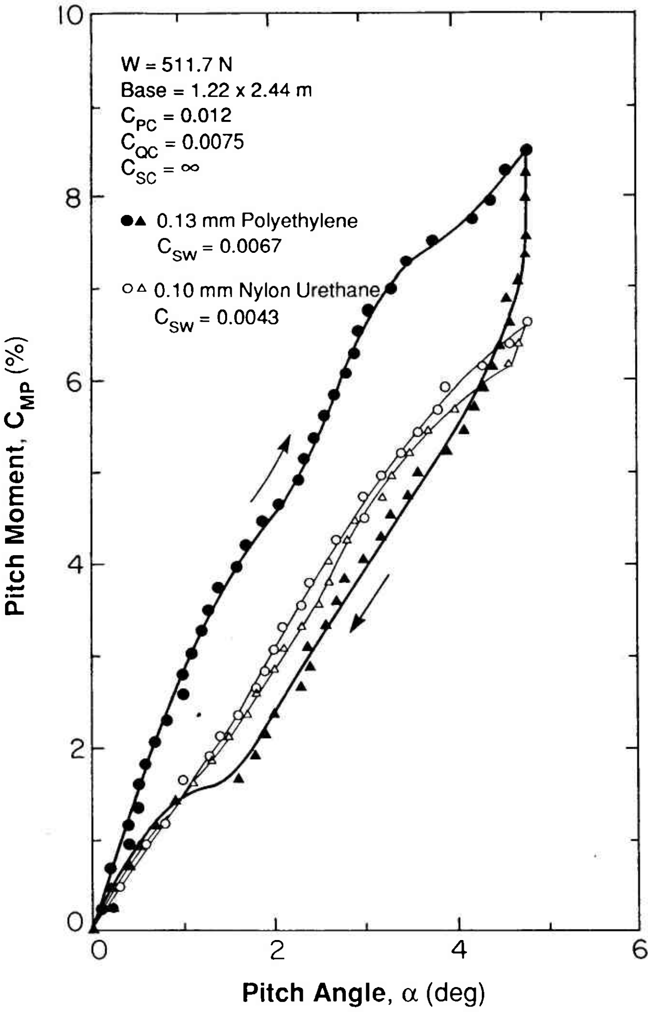

**Figure 9**
**Measurements of pitch stiffness for an uncompartmented segmented skirt obtained on a 2.44 × 1.22 mm model**

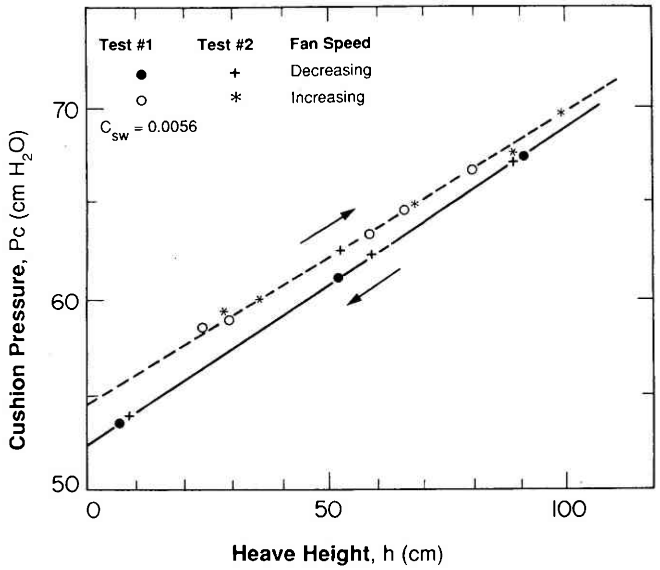

**Figure 10**
**Measurements of $p_c$ used to infer the existence of hysteresis in segment-surface contact forces on the ACIB. The increase in $p_c$ associated with the increase in heave height is caused by the reduction in footprint area**

## THE DEVELOPMENT OF CELLULAR SKIRTS

### Discussion

As applied to the Air-Trek 140, the segmented skirt avoided the maintenance and repair difficulties of other systems; interior stability skirts were not used, and individual segments could be changed from the craft deck, even when floating in water. However, it has several limitations, especially in relation to its use on high-speed vehicles operating in a predominantly marine environment. The first is that, since pitch and roll stiffness is determined almost entirely by the segment angle $\Phi$, and since in practise $\Phi$ cannot be less than about 35°, the basic cushion stiffness cannot be increased significantly. Furthermore a detailed analytical and experimental investigation has confirmed that this skirt is inherently unstable with, apparently, only the hysteretic damping suppressing it.[16,17] Thirdly it appears that, even though it uses only one cushion volume, one cannot simply locate the lift fans conveniently near the engines and then pump the air directly into the cushion. Provision must be made to ensure rapid replenishment of the cushion air at the front of the vehicle in the case of wave-pumping, and possibly to ensure inflation of the segments in all circumstances.[10] For the Air Trek 140, hydraulic power transmission was used to permit location of the lift fans well forward, as shown in Figure 8.

In relation to these limitations, it is noted above that the loop-segment concept allows incorporation of a lateral shift mechanism to augment stability. Furthermore the loop provides a duct to offset the effects of wave-pumping and, by inducing tension at the top of the segments, affects additional protection against tuck-under instabilities when operating over water.[10] However, we ruled out the use of lateral shift to augment stability and control because of its mechanical complication and because it poses maintenance and operational problems which may be especially severe in a cold climate. Also both the Rageneau trials and the UTIAS tests imply that, in overland operation, the loop makes the skirt sensitive to sliding friction.

One approach to improvement seemed to us to be the development of multicell systems. However, the system as tested at Ragueneau clearly had major deficiencies. The outer skirt in Figure 4 had to be eliminated, but the basic conical cells on their own required too much lift air power, and were inaccessible for maintenance. Furthermore the laboratory tests showed that they can be subject to an unacceptable buckling instability. In addition, its overland pitch and roll stiffness has an undesirable feature: for small angles it is very stiff and then as the angle increases it becomes very soft, with the transition being quite abrupt unless high $Q_e$ is used; this is in sharp contrast to its stiffness characteristic when in the displacement mode over water, where the stiffness is much lower and essentially linear.[6] Clearly the designer needs much more control over the basic attitude stiffness characteristics of the vehicle.

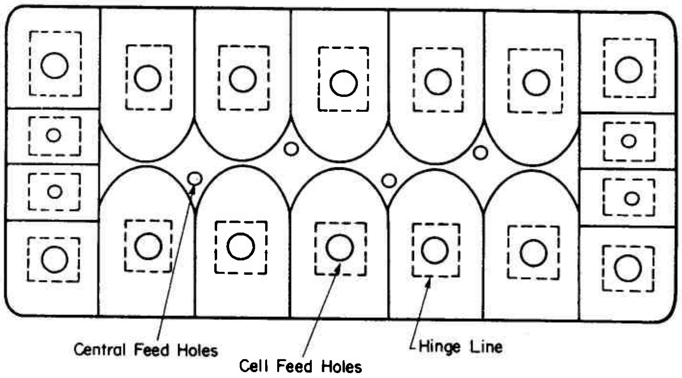

**Figure 11**
**Geometry at vehicle base of an early pericell concept known as Flexicell. This system was intended for use on vehicles with a high centre of gravity**

All of these considerations, it seemed to us, suggested the development of a configuration with the cells located at the perimeter of the cushion, to provide the basic cushion seal, the compartmentation for static and dynamic stability, to maximize the restoring moments that they generate, and to facilitate maintenance. Within the ACV industry this configuration is known as a pericell skirt.

### Developments

We now review briefly some of the developments that led to the evolution of the current designs. The second author's initial attempts to improve upon the multicell system were an outgrowth of his experience at Canadair. Thus the first designs simply eliminated the shoe in Figure 2, with cushion air being supplied by a low-pressure fan, and the closed trunks being inflated by a second low-volume flow compressor. After some development of the geometry of the bottom of the trunks, it was found that both a good seal and adequate stability could be attained. However, the experiences with towed rafts noted above strongly suggested that the trunks would, in routine operation, rapidly become punctured. Furthermore the force required to move the trunk over an obstacle was found to be excessive. Testing with open-ended trunks showed that, if their cross section was kept large in relation to their height, and if they were slightly tapered, then the pressure required to keep them inflated was only about 1.3 $p_c$. It was also found that positive provision had to be made to keep the pressure in the central cavity below that in the cells, otherwise the cells would not deploy properly. In some early designs a central blow-off valve was used, but more recently we have used a number of segments in a portion of the periphery.

Figure 11 shows the base geometry for one of the early pericell concepts developed specifically for the forestry industry; this design incorporated two additional novel features. The first was in the mounting of the cells; each was attached to a plate which could be removed from the vehicle without raising it. The second feature was an anti-snagging arrangement. The cells were attached to their mounting plates along the dotted lines shown in Figure 11. When a cell passed over a large obstacle such as a tree stump, its top could peel away from the mounting plate, thus allowing the cell to deform freely. This greatly reduced damage caused by snagging. Figure 12, which is a comparison of the roll stiffness of this configuration with that of the original multicells as obtained from UTIAS models, shows that for the same test conditions it generates over twice the restoring moment capacity.

However, testing of this skirt revealed other problems requiring modification of the cell geometry. If damage to the cell interior caused the cell pressure to approach $p_c$, then it would tend to buckle outwards. The solution adopted was to modify the geometry so that it acted as if it were a segment when this occurred. Figure 13 shows the geometry adopted for this purpose; it includes a knee as in Figure 1. Also, since removal of the material below the line OD converts the cell into a segment, the angle ODC is kept greater than 90°.

### Current Designs

Although operational experience with the Air-Trek 140 when equipped with a segmented skirt has been favourable, nevertheless it was felt that a cellular system could provide further improvements. Consequently in 1982 the second author undertook a model test programme in order to guide selection of a suitable configuration. The specific objectives were to increase pitch and roll stiffness to make the craft more tolerant of positioning of the payload, and also to eliminate the need for a ballast trim system, thus increasing payload and profitability.[19] The configuration finally chosen was a hybrid, using cells on the front and sides, and segments at the rear. Cushion air distribution was approximately 50% to the centre, 15% to each side, and 10% to front and rear. The basic cell configuration was that shown in Figure 13.

Figures 14, 15 and 16 give typical model test results. Figure 14 gives measured roll stiffness for W = 427 N with the model hovering over a rigid surface for three fan speeds. The 2000 and 2200 rpm data show, for $\alpha$ increasing, the two-slope stiffness characteristic of the earlier multicell designs, with very large hysteresis occurring when a decreases. The 2500 rpm data show only a single slope, with greatly reduced hysteresis. However, when W is increased to 569 N, data obtained at 2500 rpm revert to the characteristic two-slope behaviour, thus confirming that this and the hysteresis are generated by surface contact.

Figure 15 gives roll stiffness data obtained with the model hovering over water at W = 427 N and for the three fan speeds. Stiffness is reduced somewhat but, perhaps surprisingly, the 2000 rpm data shows evidence of hysteresis. Owing to the limitations of the towing tank used for these tests, stiffness data could not be obtained when the model was being towed forward. Finally, Figure 16 shows the effect of cropping the cells as shown in Figure 13 along the line EG in order to reduce the 'two-slope' stiffness characteristic. This also reduces the hysteresis, while the basic stiffness is about twice that obtained by using segments alone.

### Applications

These ideas have been applied to a two-seat recreational ACV; this vehicle, when using an uncompartmented-segmented skirt, was subject to a serious plough-in problem. To provide additional pitch stiffness, the 17 front segments were replaced by cells, with the results shown in Figure 17. Operational trials have shown that the plough-in problem has been eliminated even for speeds as high as 30 knots over water and 60 knots over ice. More recently they have been applied to a 450 kg payload utility vehicle.

## CONCLUSIONS

Although the widespread use of ACVs in the variety of roles envisaged in the NRC report[1] has not occurred, there are, nevertheless, numerous instances in which their effectiveness has been demonstrated. In Canada the Coast Guard uses them for ice-breaking and navigational aids servicing in the St. Lawrence Region, and for search and rescue in coastal British Columbia. Furthermore, there is a modest but well-defined and growing market for vehicles of the size of the Air-Trek 140 and smaller.

For this class of vehicle, while the uncompartmented segmented skirt is attractively simple both to construct and to maintain, for many applications it does not provide adequate stiffness and damping in pitch and roll. In contrast, a hybrid cellular-segmented skirt gives the designer much greater freedom to tailor

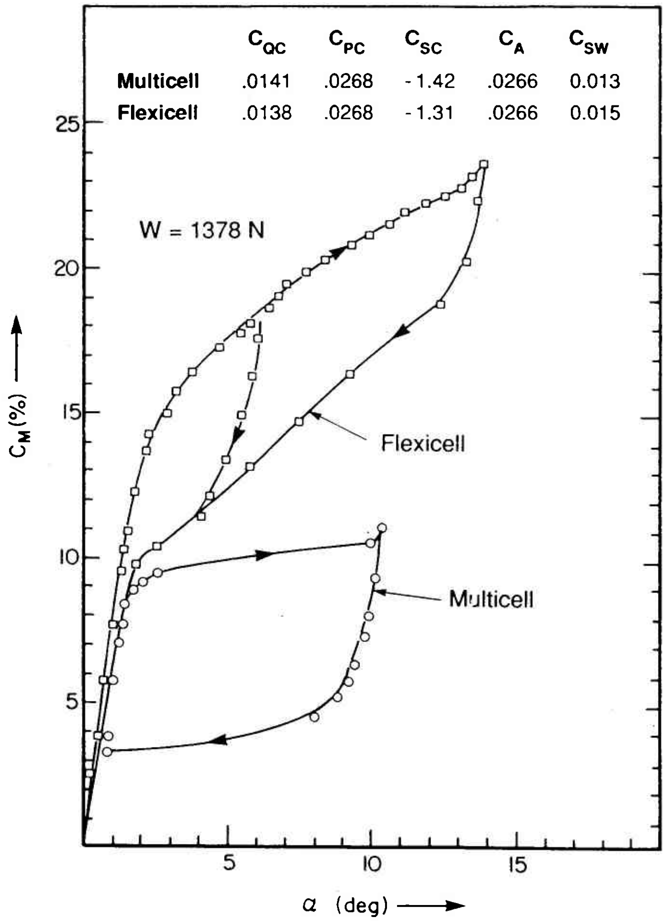

**Figure 12**
**Comparison of roll stiffness of the Flexicell skirt with that of the multicell**

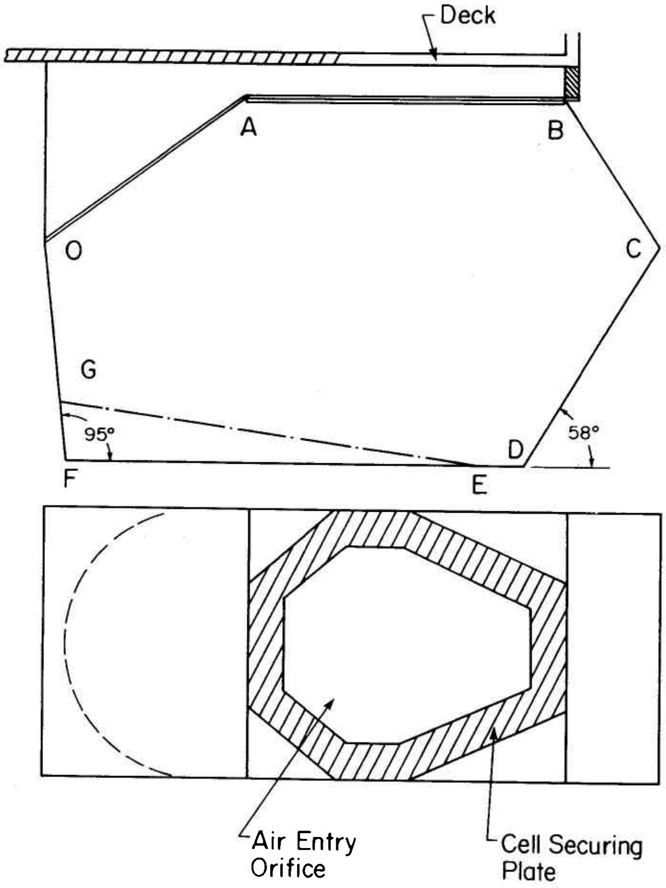

**Figure 13**
**Current cell geometry as used on the hybrid skirt system**

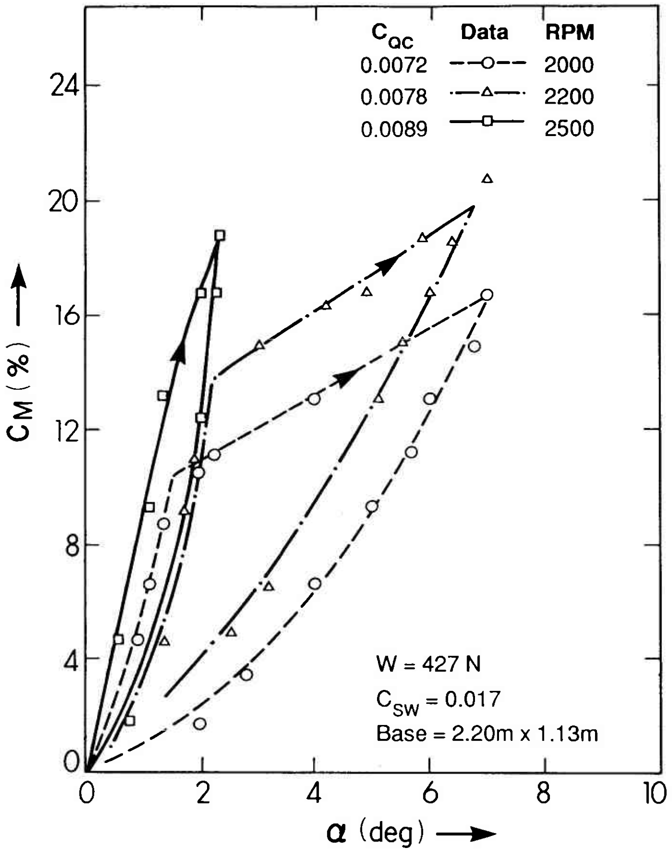

Figure 14
Effect of fan speed on rolling moment of the hybrid skirt model

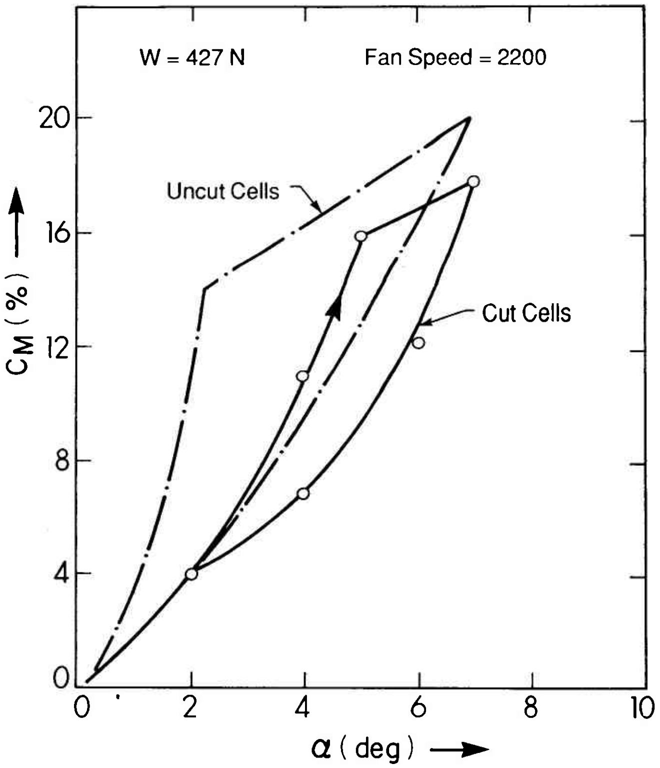

Figure 16
Effect of roll stiffness of cutting cells along the line EG in Figure 12

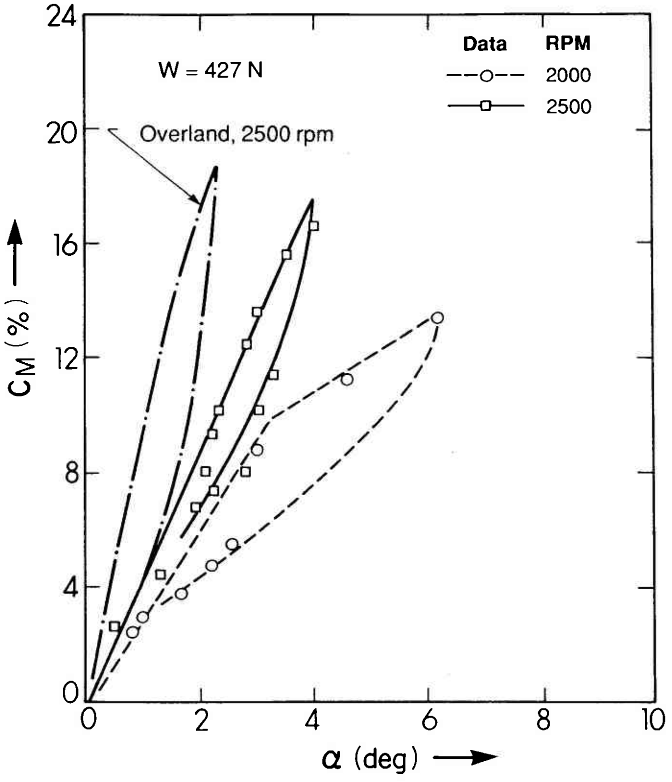

Figure 15
Comparison of overland and overwater stiffness of the hybrid skirt model

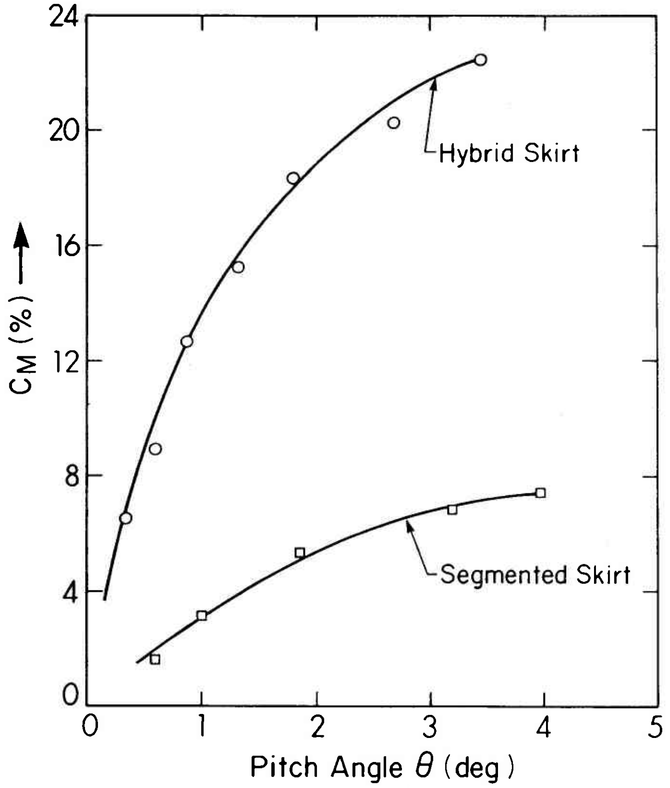

Figure 17
Comparison of pitch stiffness of two-seater recreational ACV when fitted with segments and with 17 front segments replaced by cells. Since data were taken only for roll angle increasing, hysteresis was not observed

the cushion dynamical properties to the requirements of a particular application, while still meeting the basic requirement of accessibility for maintenance. The major disadvantage is the need to provide ducting to feed some of the cushion air to the cells, but the advantages conferred in such areas as greatly reduced susceptibility to tuck-under are worth the complication. We also believe that the ideas are also applicable to cushion systems on larger vehicles which use a bag to increase cushion depth or to improve ride comfort.

Finally it appears that more work is required to understand the role in cushion dynamics of the viscoelastic skirt material phenomena repeatedly observed here, both at model and full scale.

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## REFERENCES

1 **German, W. H., et al —** *Air Cushion Vehicles: Their Potential for Canada,* **National Research Council of Canada, Ottawa, Canada, NRCC 10820, December 1969.**

2 **Hope, A. A., Udell, J., Tapiero, M., et al —** *Air Cushion Icebreaking Bow Development Program, 1975–78,* **Transport Canada, Transportation Development Centre, Montreal, Canada, Report No. TP 1924, July 1980.**

3 **Newman, B. G., and Jones, D. —** *Theoretical Analysis of an Internally Braced, Two Dimensional Air Strut which is Partially Buckled,* **Aeronautical Quarterly, Vol. 19, February 1975, pp. 71–79.**

4 **Eggleton, P. L., and Laframboise, J. E. —** *Field Evaluation of Towed Air Cushion Rafts,* **Transport Canada, Transportation Development Centre, Montreal, Canada, Report TDA-500-166, January 1974.**

5 **Sullivan, P. A., Hinchey, M. J., and Delaney, R. G.** *An Investigation of the Roll Stiffness Characteristics of Three Flexible Skirted Cushion Systems,* **University of Toronto Institute for Aerospace Studies, Toronto, Canada, Report No. 213, March 1977.**

6 **Sullivan, P. A., Hinchey, M. J., Murra, I., and Parravano, G. J. —** *Research on the Stability of Air Cushion Systems,* **University of Toronto Institute for Aerospace Studies, Toronto, Canada, Report No. 238, November 1979.**

7 **Mantle, P. —** *Air Cushion Craft Development,* **David W. Taylor Naval Ship Research and Development Center, U.S. Navy, Bethesda, Maryland, U.S.A., Report DTNSRDC 80/012, January 1980.**

8 **Fowler, H. S. —** *On the Lift-Air Requirement of Air Cushion Vehicles and Its Relation to the Terrain and Operational Mode,* **National Research Council of Canada, Ottawa, Division of Mechanical Engineering Report ME-246, NRC 17492, May 1979.**

9 **Parkes, G. —** *The Design, Building and Early Operation of the LaCrete Hoverferry,* **Proceedings of 11th Canadian Symposium on Air Cushion Technology, Vancouver, Canada, September 1977, pp. 97-100.**

10 **Dyke, R. W., Halifax Engineering, Panama City Beach, Florida, U.S.A., private communication.**

11 **Laframboise, J. E., Transportation Development Centre, Transport Canada, Montreal, Canada, private communication.**

12 **Sullivan, P. A., Hinchey, M. J., Hartmann, P. V., Dupuis, A., Green, G. M., and Graham, T. A. —** *Research into Air Cushion Stability,* **Transportation Development Centre, Transport Canada, Montreal, Canada, Report TP 3109E, January 1982.**

13 **Sullivan, P. A., Hinchey, M. J., Graham, T. A., Byrne, J. E., Dupuis, A. D., Milligan, N., and Walsh, C. —** *Investigations of the Dynamics of Large Air Cushions,* **Transportation Development Centre, Transport Canada, Montreal, Canada, Report TP 7560E, April 1986.**

14 **Graham, T. A., Sullivan, P. A., and Hinchey, M. —** *Skirt Material Effects on Air Cushion Dynamic Heave Stability,* **Journal of Aircraft, Vol. 22, No. 2, February 1985, pp. 105-108.**

15 **Milligan, N. H. —** *An Investigation of Air Cushion Vehicle Skirt Hysteresis,* **University of Toronto, Toronto, Canada, Department of Aerospace Science and Engineering, M.A.Sc. Thesis, 1987.**

16 **Graham, T. A., and Sullivan, P. A. —** *Pitch-Heave Dynamics of a Segmented Skirt Cushion,* **Proc. 1989 Intersociety Advanced Marine Vehicle Conference, Arlington, Va, U.S.A., June 5-7, 1989, pp. 334-347.**

17 **Graham, T. A. —** *Pitch-Heave Dynamics Models for an Air Cushion Vehicle,* **University of Toronto, Institute for Aerospace Studies, Toronto, Canada, Report No. 343, February 1992.**

18 **Graham, T.A. —** *Stability and Control of Hovercraft, Notes for Commanders,* **Ship and Marine Technology Requirements Board, Department of Industry, London, England, 1980.**

19 **Jones, D. —** *Hybrid-Cellular Air Cushion Skirt Evaluation,* **Transportation Development Centre, Transport Canada, Montreal, Canada, Report TP 5934E, October 1984.**