THE CANADIAN CONTRIBUTION TO THE GROUND CUSHION STORY†

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ORIGIN OF THE GROUND CUSHION

It often happens that new ideas are thought of and worked upon in different parts of the world at the same time without one group having any knowledge of the other's activities. In many cases this is due to a general rise in the level of the state of the art, so that there are numbers of groups working who are all on the verge of taking the next step within the same period.

In the case of the ground cushion, this was not so, since it was technically possible for the Wright Brothers to have built a ground cushion vehicle at the same time they flew the first airplane.

It is therefore surprising to find at least three groups working on ground cushion concepts between the years 1953 and 1956, apparently without knowledge of each other. Avro discovered the ground cushion in 1953 while studying the flat rising vertical takeoff airplane. Cockerell came on it in England in 1955 while making efforts to reduce the drag on ship hulls, and Carl Weiland of Switzerland in about 1956.

In actual fact, Toivo Kaario of Finland built and tested the ram wing, a first cousin to the ground cushion, as early as 1935, and in 1949 he built one with a fan in it which must have been the first example of a ground cushion machine supplied by a plenum chamber, as distinct from the annular jet used by Avro and Cockerell.

It is unfortunate that our sights were set on developing a supersonic vertical takeoff aircraft when Avro stumbled on the ground cushion, otherwise we might have paid more attention to its possible uses as an amphibious surface vehicle, rather than the undercarriage for an aircraft. We did realize its potential as a substitute for the wheel and the caterpillar track; we also realized that it would operate over water; but we missed its potential as a method of improving the performance of water-borne craft (which Cockerell was so quick to promote with the Hovercraft).

At first sight the problems of overland operation looked formidable. To operate over roads would require the ability to drive accurately and not get blown off course; in turning a corner there must be no sideslip; and to cross unprepared terrain a ground clearance of at least 4 ft would be necessary. All these problems we decided to tackle later. For the time being we were aircraft engineers and the possibility of raising a supersonic aircraft vertically 15 ft into the air, with its thrust only two-thirds of its weight, was attractive enough.

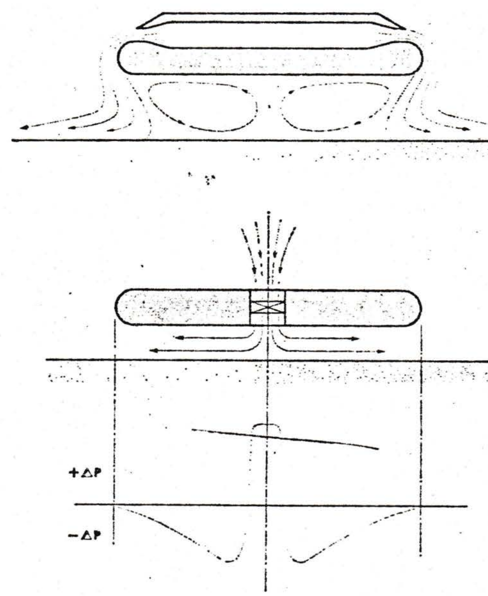

Figure 1
Ground effects

We had been trying for quite a while to find an arrangement using aerodynamic subtlety, rather than the jet thrust brute force method that others were experimenting with. Dr. Griffiths of Rolls-Royce was proposing the flying bedstead, but it had not flown. We had just graduated from the tail-sitter type and were in the process of studying a circular version of a flat riser with a peripheral jet when we first discovered we had a ground augmentation.

We immediately explored this to its two more obvious extremes, as shown in Figure 1, the upper diagram representing a section through the type of model we were using, with the jet issuing from a peripheral slot and being deflected downwards in a circular curtain by Coanda effect on the curved lower lip of the nozzle, so producing a positive ground cushion with a relatively thick jet curtain. The lower

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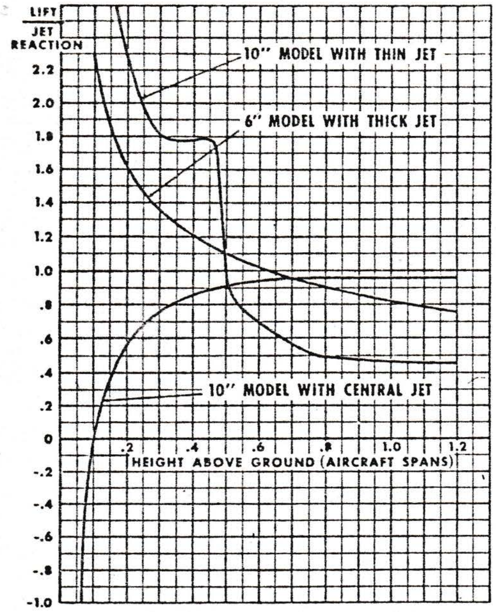

Figure 2
Comparison of ground effect curves

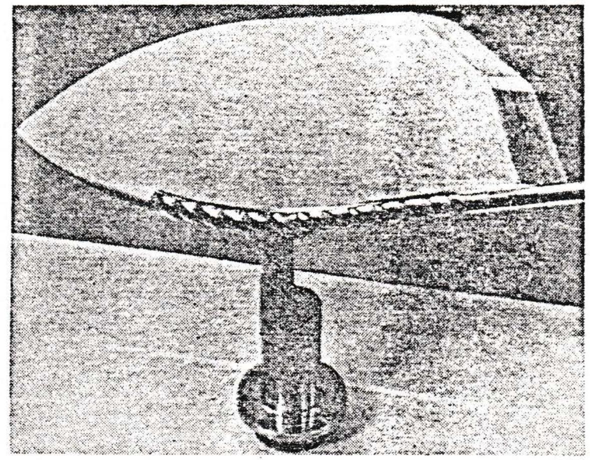

Figure 3
Jet flap model — tested in Woodford tunnel

diagram represents a circular body, with the jet issuing from its center, producing a negative ground cushion, or sucking, on to the ground.

Figure 2 shows two curves for the positive ground effect: one with a thick jet producing a fairly smooth curve, and the other a thin jet showing the characteristic step associated with a sudden change of flow pattern. The third lower curve shows the negative ground effect.

During this period our studies were being funded by the Canadian Government and it says a great deal for the farsightedness of such people as Dr. O. M. Solandt and Dr. J. J. Green of the Defence Research Board that we were allowed to continue with what, at that time, must have seemed like optimistic crystal gazing. It is thanks to these people and the directors of A. V. Roe Canada Limited that this country now holds what may one day prove to be the key patent in the whole principle of the ground cushion concept.

CHOICE OF AERONAUTICAL APPLICATIONS FOR THE GROUND CUSHION

Having discovered this method of augmenting lift it was necessary to consider what type of aircraft would benefit most from its application. There were, of course, a number of factors involved. Early tests indicated that the circle was the optimum shape for a peripheral jet and that if this were gradually stretched into an ellipse the ground cushion so produced became progressively less effective as the aspect ratio of the ellipse increased. For aspect ratios much in excess of 4, and for the size of wing we were prepared to contemplate (effectively 30 ft diameter), it was not possible to obtain a useful augmentation at a worthwhile height.

There would, therefore, be some aerodynamic penalty in applying the ground cushion to the wing of a subsonic airplane of this scale.

For an aircraft which would cruise supersonically, there was little disadvantage in low aspect ratio. So it was decided to apply the cushion to the wing of the supersonic aircraft, with the jet exhaust leaving vertically from the periphery of the wing for takeoff and able to be directed rearwards to provide thrust in forward flight. The jet sheet so formed issuing from the trailing edge gave the wing the benefits of a jet flap. At that time Davidson and Stratford of the National Gas Turbine Establishment had not published their work on the jet flap. We were, however, aware of some of the advantages associated with this arrangement because of tests we had carried out ourselves on a model wing using a jet flap which we tested in the Woodford tunnel of A. V. Roe Limited, Manchester, England, in June 1953 (see Figures 3 and 4). This took place during one of our trips to England which occurred from time to time to confer with associates of the technical group at A. V. Roe Limited, with the Royal Aircraft Establishment, and any other organiza-

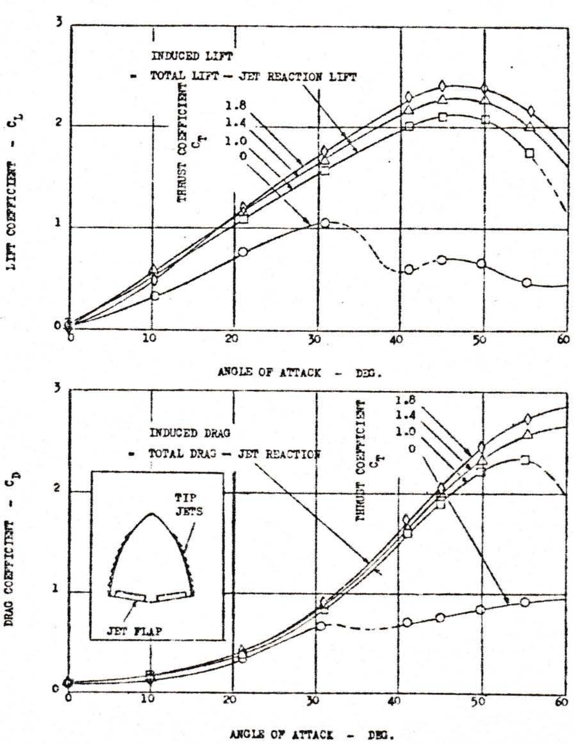

Figure 4
Aerodynamic characteristics with jet blowing: Woodford tunnel tests, March 1953

tion that was qualified to throw light on what we were trying to do. Many interesting and useful discussions took place and, as a group, we feel most indebted to those who took the trouble to listen to us.

Having reconciled ourselves to a low aspect ratio wing, it seemed a pity not to go all the way and use a circular planform. We argued that the circular wing would be the best compromise in which the poor subsonic lift/drag ratio — due to its low aspect ratio — would be largely offset by the fact that the circle provided an optimum duct system with minimum internal aerodynamic losses. The circle was the best shape for an annular ground cushion jet, and the optimum shape for structural simplicity and lightness. There were those who criticized us for this, on the basis that very little was known about the external aerodynamics of the circle, whereas a delta shape could be used on which a wealth of aerodynamic information existed.

We were sympathetic to this argument, but had been put off by a test carried out on a delta shape in which we found it difficult to obtain an even pressure distribution around the periphery of the nozzle. This could be further aggravated by the fact that the various diffusion passages generating from a central fan would all be different lengths, causing different pressure levels to exist throughout the system.

WELCOME ARRIVAL OF AMERICAN INTEREST

Still under the support of the Canadian Government, a number of supersonic aircraft, using wings of circular planform ranging in thickness from 2% to [illegible] were then studied.

At this juncture Dr. Solandt was able to interest General D. C. Putt, then head of the United States Air Force Air Research & Development Command, in our activities. The USAF interest resulted in our being awarded a study contract involving subsonic and supersonic wind tunnel testing, static testing of the ground cushion and configuration studies.

EARLY TESTS ON THE ANNULAR JET

Now, for the first time, we had money available to design a proper rig on which to start studying the ground cushion. A picture of this first rig is shown in Figure 5. The model was mounted centrally on the lower end of a 2 inch diameter vertical downpipe which in turn was mounted on a 2 inch diameter horizontal pipe. The horizontal pipe was cut near the downpipe and a 12 inch diameter wooden disc was fixed flange-wise around the end nearest the downpipe. The other end was supported in a sheet metal bracket, which faced the wooden disc to form an air bearing. The disc, the downpipe and the model were supported by three ring dynamometers connected to the downpipe and to pins on the bracket. Compressed air was supplied to the model through the horizontal pipe and the downpipe. A portion of the air supply escaped radially between the air bearing surfaces with the result that the air bearing could support large forces and moments normal to the bearing surfaces, while offering negligible resistance to forces and moments parallel to these surfaces. The latter were supported by the dynamometers.

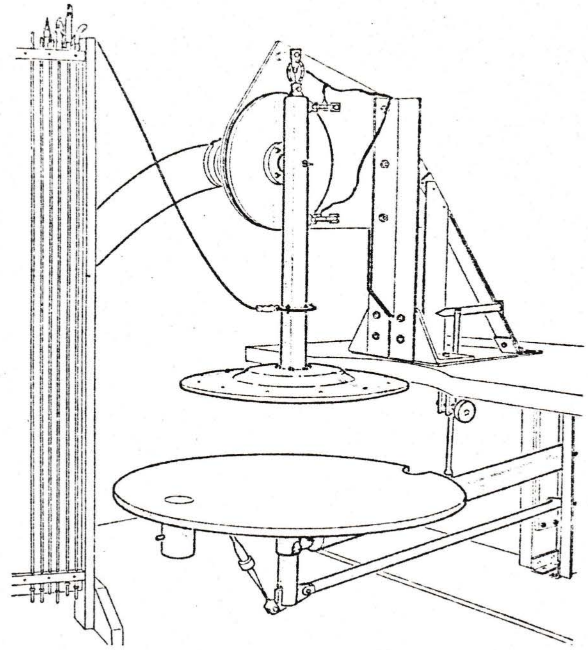

Figure 5
Ground effects model

A pitot head and a static tap were located at the lower end of the downpipe. The ground was represented by a circular flat plate below the model, which could be raised, lowered, and tilted. Pressures were measured with a multiple U-tube manometer, and forces measured by strain gauges mounted on the dynamometers connected through a selector switch to a single Baldwin SR 4 strain gauge meter.

A very great number of tests were carried out on this rig, and variations of it, over the three years between 1955 and 1958. During this period we altered every variable we could think of. Some of the more typical results obtained are shown in Figures 6, 7 and 8.

This was probably the most frustrating time of all, since this attractive idea, which on the face of it could form a substitute for both the wheel and its suspension and seemed such a simple system, turned out to be as difficult an aerodynamic problem as it is possible to find. We had nobody but ourselves to blame for the

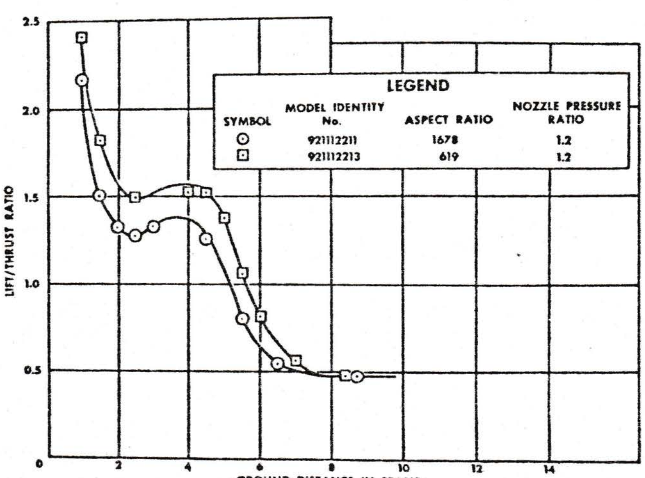

Figure 6
Effect of nozzle aspect ratio on lift/thrust ratio

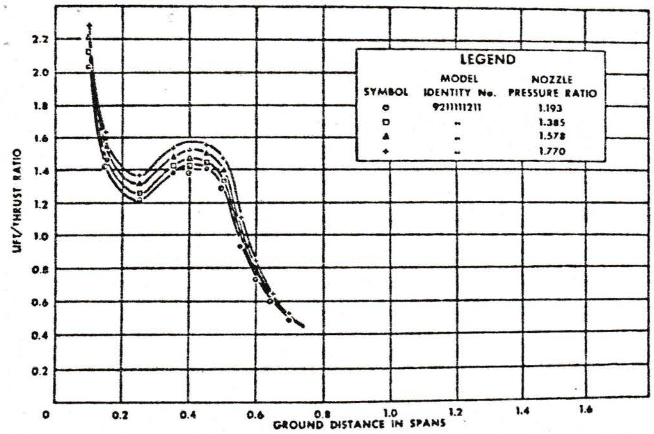

Figure 7
Effect of nozzle pressure ratio on lift/thrust ratio

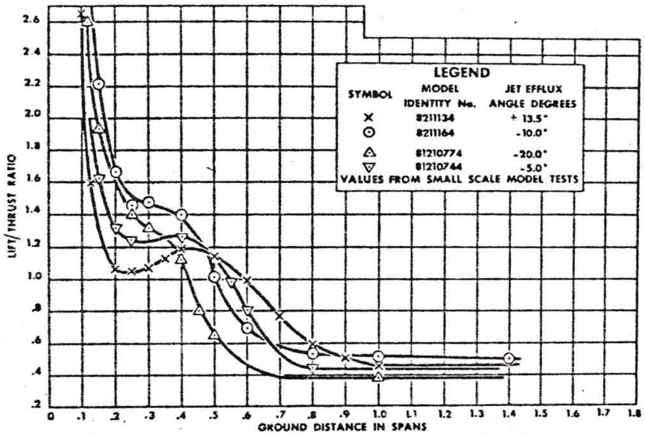

Figure 8
Effect of jet efflux angle on lift/thrust ratio

troubles we got into since, by virtue of the route we had chosen, we were unknowingly starting with the hardest end of the problem first. Cockerell, in his promotion of a water-borne vehicle, could initially be satisfied with a height/diameter ratio which did not exceed 0.06; we, on the other hand, started with our vehicle on its wheels at this height and were counting on realizing augmentations of 1.4 to 1.7, which we had measured at an h/d of 0.5. We were also hopeful of finding a way to substitute this cushion of air under the wing for the basic aerodynamic lift of the wing itself, without destroying the one before the other was in a position to take over, and also to satisfy the requirements of stability while this process was going on.

We very quickly learned that the annular jet cushion, although quite stable close to the ground, becomes progressively more and more unstable as the ground height is increased, and that before leaving the influence of the ground altogether, a height — which we named the critical height — is crossed where a sudden basic change in the flow pattern takes place. This change is associated with considerable hysteresis. The critical height at which this change takes place is altered by a number of variables:

(i) jet angle to the base,
(ii) vehicle angle to the ground,
(iii) forward speed of the vehicle,
(iv) undersurface contour, and
(v) jet aspect ratio.

Also, with a simple annular jet, once the influence of the ground is removed, the thrust in free air is reduced by as much as 50% of the momentum thrust of the nozzle by the separation which is present on the undersurface of the body.

All these problems rapidly became apparent within the first year of testing, and the situation was further complicated by the difficulty we experienced in determining exactly what the momentum thrust at the nozzle was, which continually led to testing inconsistency. The problem was that, although it was easy enough to measure the mass flow, it was hard to arrive at the total pressure at the nozzle — the other quantity required to compute the momentum thrust. This was due to the fact that the nozzle was rarely, if ever, exhausting to atmospheric pressure, and there was usually a pressure gradient across it. In an attempt to get around this problem, we resorted to making the model into a plenum chamber by ignoring the flow over the upper surface — which under static conditions did not amount to very much — and making the model violently out of scale in thickness, as is indicated in Figure 9. This helped considerably.

As mentioned, we found all these troubles within the first year, and have been trying ever since to get around them. Though we are not entirely satisfied with all the solutions we now have, we feel that the more basic problems can be solved.

Since we started testing, many other organizations on both sides of the Atlantic have carried out similar research, and the basic fundamentals of the annular jet are now well understood. Acceptable theories have also been evolved which explain and predict its general behaviour in a satisfactory manner. The first theoretical work to be published in this regard was that by Harvey R. Chaplin, of the David Taylor Model Basin, in his paper entitled, "Theory of the Annular Nozzle in Proximity to the Ground", July 1957.

Other work on annular jets has recently been carried out in Canada under Government sponsorship. At the Institute of Aerophysics, under the direction of Dr. G. K. Korbacher, studies were carried out by Mr. D. B. Garland on a model of an inwardly inclined annular jet, with the object of investigating the effects of changes in aspect ratio and pressure ratio on such an arrangement. Also, at the National Aeronautical

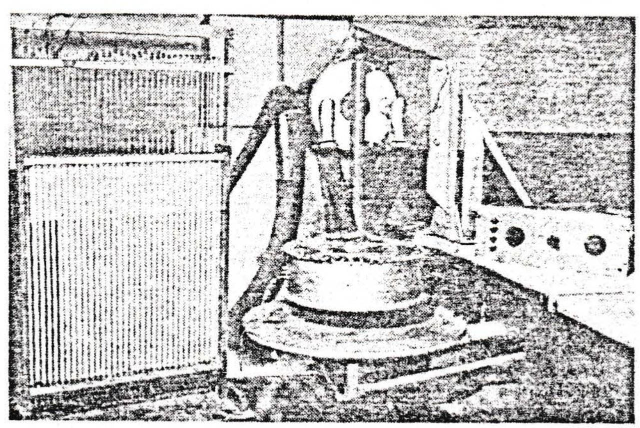

Figure 9
Ground cushion test rig using plenum chamber model

Establishment in Ottawa, a small scale triangular shaped ground effect vehicle has been built and is now being flight tested under the direction of Mr. A. D. Wood.

Interest to date, however, has been largely focussed on problems associated with the lower values of height/diameter ratio in the vicinity of 0.15 downwards; the problems to be tackled in the region above this height, particularly stability and economy, have still only been seriously approached by very few besides Avro.

The most serious problem encountered in the higher *h/d* values is the dynamic instability in pitch, roll and heave, which becomes worse as the value is increased. This is largely due to the very considerable reduction in damping which takes place as the value of *h/d* is increased.

We went to some trouble to measure the damping in heave, which we did with the model shown in Figure 10. This was a circular model, 10 inches in diameter, with a peripheral jet of compressed air which was supplied through a long flexible pipe. The model was suspended vertically from a long-travel, low-rate, steel spring. The model was then allowed to bounce up and down freely on the spring and the number of vertical oscillations to damp to half amplitude were counted. This was done for different ground heights and different jet arrangements etc. A typical curve showing the results is indicated in Figure 11.

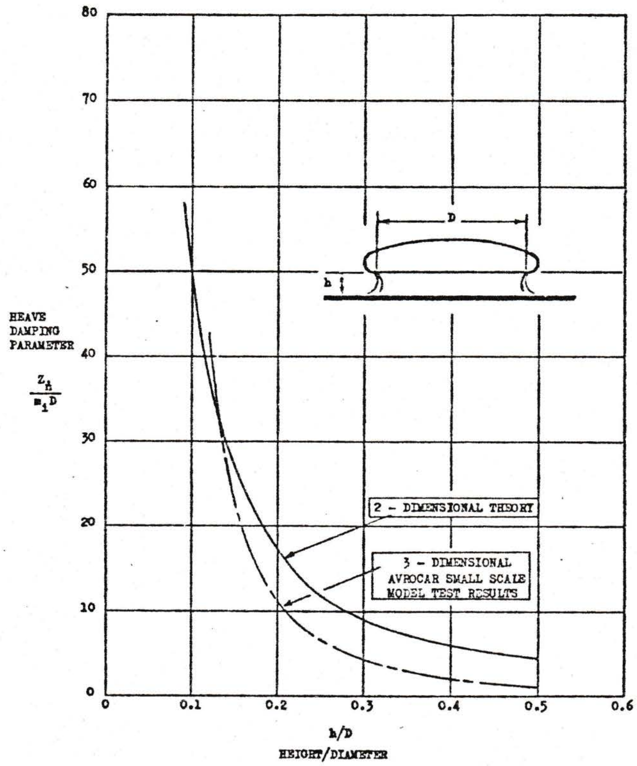

Figure 11
Heave damping

The greater part of our studies on the ground cushion in the latter years has been devoted to combating problems in this area of static and dynamic stability.

To obtain stability in pitch and roll, we tried various alternatives too numerous to mention. The most successful of all these was the introduction of a central jet, or inner annular jet ring (Figure 12). We found that an inner jet equal to ¼ of the momentum of the outer peripheral jet would be enough to completely stabilize the system statically and dynamically, from close to the ground until the whole arrangement becomes neutrally stable (ignoring sideslip effects which make it stable) when out of ground effect. The presence of the central jet also extended the height of the ground cushion (Figure 13). Combinations of central jet with undersurface contour also showed some promise with respect to reducing the strength of central jet required to produce stability. A three pad system was tried with considerable success. However, dividing the cushion area in order to have three pads appreciably reduces the height at which it is possible to have a given augmentation, so that this arrangement, though probably the most successful of all, was not very popular on that account.

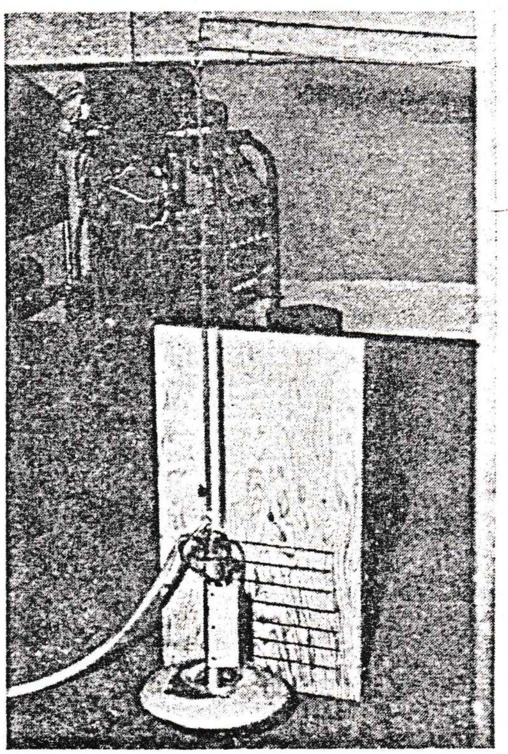

Figure 10
Model arranged for measuring ground cushion damping in heave

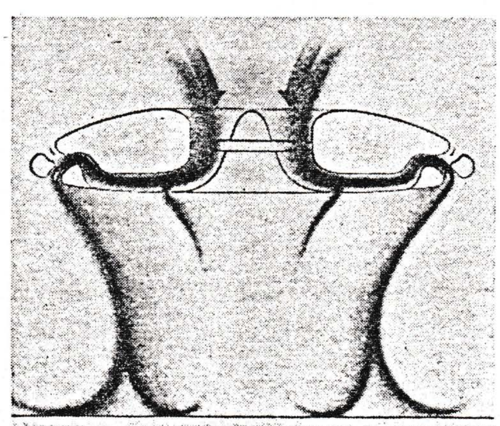

Figure 12
Flow distribution — hovering and ground cushion

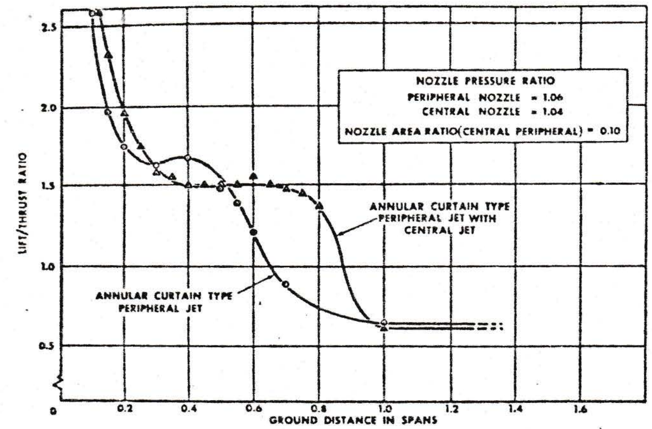

Figure 13
Effect of central jet on lift/thrust ratio

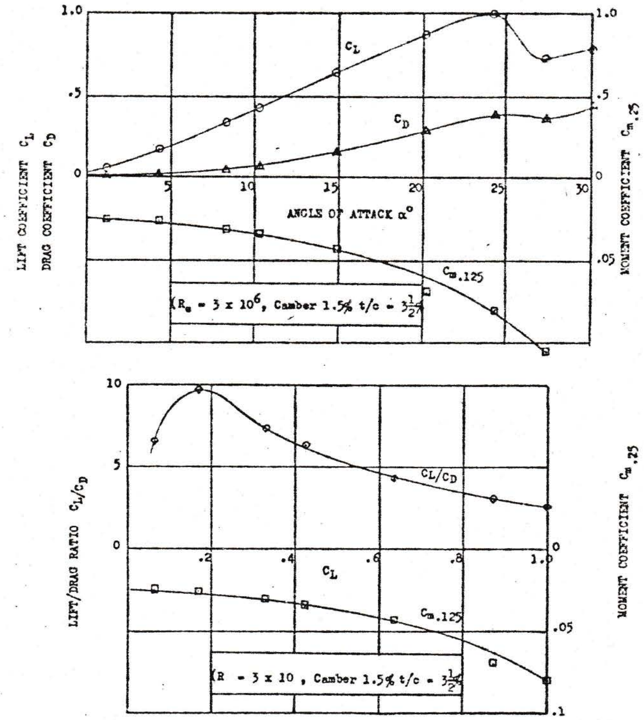

Figure 14
Measured subsonic characteristics for a thin cambered biconvex aerofoil of circular planform

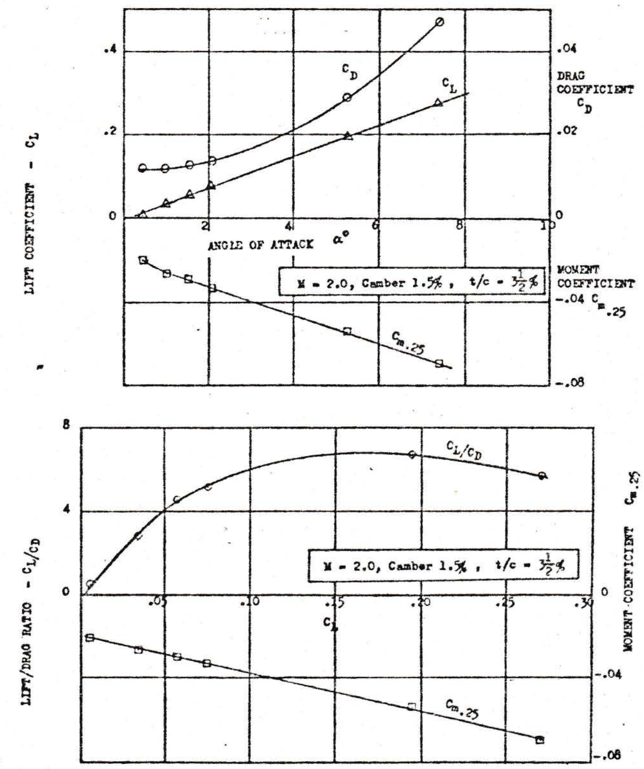

Figure 15
Measured supersonic characteristics for a thin, cambered biconvex aerofoil of circular planform

WIND TUNNEL TESTS ON THE CIRCULAR PLANFORM

Parallel with the work on the static ground cushion test rig, we built three different wind tunnel models, one subsonic and two supersonic.

The subsonic model was 5 ft in diameter and was tested half-plane and wall mounted in the 20 ft diameter tunnel at WADC, Dayton.

The other two were supersonic models and were tested in the Naval Research Tunnel at MIT. One was half-plane and wall mounted on a reflection plane, and the other, a full-plane model, was sting mounted.

The subsonic and supersonic half-plane models were equipped with peripheral jets supplied by compressed air, which was fed through a pipe in a special wall mounted balance on the reflection plane side. It was arranged that the peripheral jet could be deflected either downwards as a cylindrical jet curtain, or backwards past the trailing edge in the form of a jet sheet. The jet sheet could be deflected upwards or downwards about the trailing edge in the form of a jet flap, or elevator.

Typical results for lift, drag and pitching moments with a subsonic and a supersonic circular planform are shown in Figures 14 and 15. Further details on these models are still classified and cannot be discussed here. However, a total of 900 hrs of subsonic wind tunnel testing time and 250 hrs of supersonic tunnel testing time were logged, so that an extensive background on the behaviour of the circular planform wing in forward flight was obtained.

Up to this time the only work on circular planforms we could find was that by Charles Zimmerman, in a subsonic study on a circular planform Clark Y section wing. To the best of our knowledge nothing on the supersonic behaviour of circular wings existed.

REQUEST FOR PROPOSAL BY US ARMY

In 1956, while involved with the study program for the USAF, we received a visit from members of the US Army.

The Army were interested in vehicles which would provide them with more mobility. They concluded that flying was the only way to obtain completely unrestricted movement. However, they had to be able to fly close to the ground because the ground was their natural environment and offered protection and a chance of concealment.

A number of contracts had been awarded for vehicles which were expected to fulfil this function; these were mostly motivated by ducted fans, and became known as 'flying jeeps'.

The US Army had heard about our ground cushion activities and were optimistic that a vehicle using this principle would be more suitable. We studied the problem for a few weeks and made an

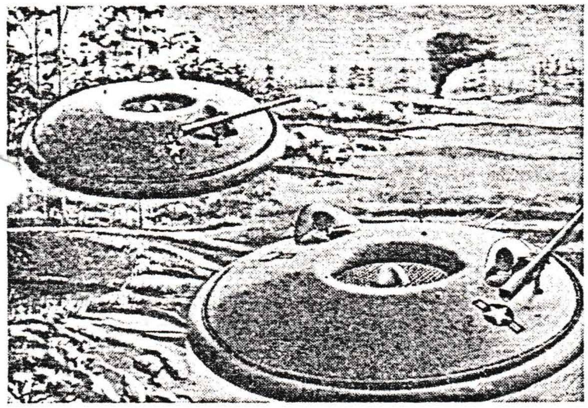

Figure 16
Avrocar

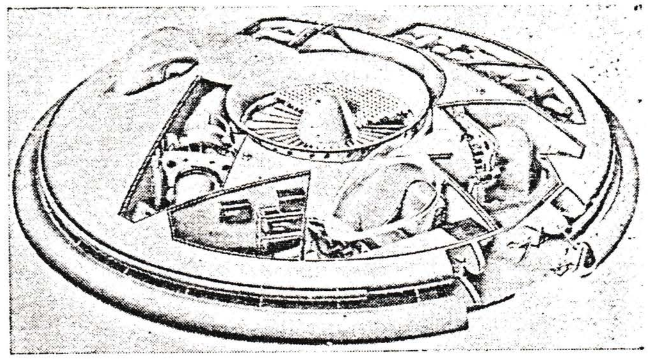

Figure 17
Structure cutaway

unsolicited proposal which we thought would fit. This was for a circular all-wing machine which could fly clear of the ground (using aerodynamic lift), as well as loiter close to the ground in the ground cushion. The proposal was well received, and some months later we obtained a contract to build two such machines as research vehicles. We had thus obtained our first financial support to build flying hardware. An artist's impression of two of these vehicles being used on an Army reconnaissance mission is shown in Figure 16.

DESCRIPTION OF THE AVROCAR

This vehicle became known as the Avrocar (see cutaway Figure 17). It was 18 ft in diameter, a circular wing with a 20% elliptical section and 2% camber, and its gross weight with 2,000 lb of useful load was estimated at 5,650 lb.

The power was supplied by three J69-T-9 turbojet engines, which we estimated would provide the following performance:

Speed and Climb		
Maximum speed at sea level	225 kts	
Rate of climb at sea level	4,500 ft/min	
Ceiling (limited by no oxygen for crew)	10,000 ft	
Range at sea level	145 nm	with 1,670 lb payload
Range at 10,000 ft	180 nm	

The leading dimensions and weights were as follows:

Diameter	18 ft
Gross wing area	253 sq ft
Aspect ratio	1.27
Thickness/chord ratio	20%
Maximum fuel capacity	177 US gals
Maximum gross weight for VTOL	5,650 lb
Empty weight	2,820 lb
Wing loading at max gross weight for VTOL	22.2 lb/sq ft

The US Army required that this vehicle should be able to take off vertically into free air and hover out of the influence of the ground. This was not the best concept for a ground cushion vehicle. It would have been more economical to have it take off into aerodynamic flight only from the ground cushion. The requirement to hover out of ground effect involved installing considerably more power than otherwise would have been necessary.

In proposing a subsonic circular wing we had some misgivings with respect to the low aspect ratio. It was, however, a compromise inasmuch as the vehicle was required to maneuver close to the ground among obstacles etc, and it was probable that equal periods of time would be spent hovering in the ground cushion and in aerodynamic flight. Also, the fact that it was designed to have vertical takeoff helped justify this compromise, since aspect ratio – the all important parameter when considering translational takeoff over a fixed height from the ground – would not be so noticeable by its absence.

The helicopter was the obvious competition, so it was necessary to see how the circular wing would compare with this. Hovering in the presence of ground augmentation, the Avrocar lift/hp would be comparable to the helicopter. Wind tunnel tests on circular planforms had indicated subsonic lift/drag ratios for thin wings as high as 11; we thought it reasonable to expect values of 7 on the Avrocar with its 20% thick section. This would give the Avrocar an advantage in forward flight since the lift/drag ratio of the helicopter is of the order of 4. We were hopeful, too, of developing up to speeds of 240 kts, well above the present range for helicopters.

Hovering out of ground effect, the vehicle would be vastly inferior on a basis of lift/hp, due to the very high disc loading on the Avrocar fan. However, we did not see the necessity for flying long in this condition.

The Avrocar was equipped with a 5 ft diameter fan situated in its center, exhausting via an internal duct system to a peripheral nozzle. The fan was driven by means of a tip turbine which used the exhaust from three J69-T-9 engines (see Figures 18 and 19). These engines, which we were using as gas generators – a function for which they were not designed – were not technically the most ideal for the purpose, the specific weight being high compared with other more sophisticated engines of that time; and a higher total pressure in the jet exhaust would have enabled us to obtain more work on the single stage fan turbine for the same mass flow and temperature. This is not a criticism of the engine, since there was a more modern version just becoming available which we could have had if we had wanted it. We chose the J69-T-9 because it was relatively easy to obtain, and was extremely rugged and dependable; at the time of writing,

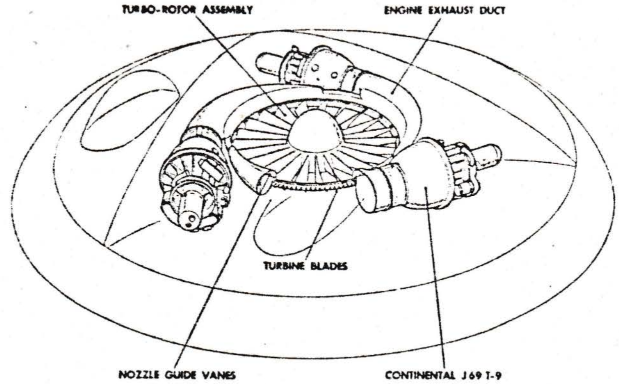

Figure 18
Engine installation

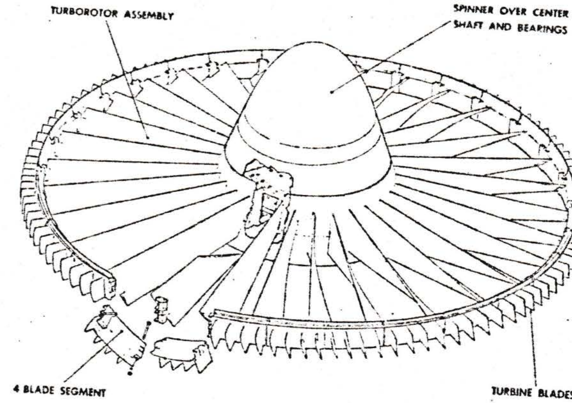

Figure 19
Turborotor assembly

we have not had one failure for which the engine could be blamed.

We took a risk in choosing the method of driving a fan with a tip turbine because of the large installed power we had to transmit. The three J69-T-9 engines, together, were designed to produce 3,000 shaft hp. The tip drive, if we could develop it, seemed to be lighter and simpler than becoming involved with gears, clutches, free wheel devices etc.

The fan with its tip turbine was designed and built for us by Orenda Engines Limited. It had hollow sheet metal fan and turbine blades, and a simple central bearing arrangement using only two taper roller bearings, a system we had developed earlier on a previous test rig. In 300 hrs of test running not one mechanical failure occurred which could be attributed to the fan or turbine.

Orenda Engines Limited also built an elaborate rig (Figure 20) to test the fan and develop it to preflight rating standard before installation in the Avrocar. On this rig we used one Orenda engine instead of the three J69's. This was to give more flexibility to the test and, since the Orenda engine developed greater power than the three J69 engines put together, it would provide an opportunity to test the fan under overspeed conditions. What mechanical trouble did occur was due to this rig, from which, on a few occasions, bits of metal etc would fall and find their way through the fan. At no time did this result in a catastrophic failure of the rotor. This was a remarkable achievement on the part of Orenda, and represents another Canadian 'First'.

General Electric have since designed and built an almost similar tip driven fan which is now operating successfully. They are advocating this for installation in the wings or fuselage of aircraft to provide a vertical takeoff capability.

The Avrocar fan was designed to handle 550 lb of air/sec at a pressure ratio of 1.07 to 1, and was driven by an impulse type turbine situated around its rim. The three exhausts from the J69 engines each occupied 120° of the turbine inlet area, and each engine had its own jet pipe fashioned in the shape of a tusk (Figure 18) and separate from its neighbour, so that should one engine fail the back pressure of the other two would not be fed back through the stopped engine. The hot exhaust from the turbine was mixed with the cold flow from the fan in a duct immediately below the fan.

This duct passes from the bottom of the fan below the cockpits, engine bays, and cargo compartments, to the peripheral nozzle around the circumference of the vehicle (Figure 21). The mixed temperature of the air in this duct was calculated to be 100°C under design conditions.

The first serious problem encountered on the Avrocar was the discovery, on the Orenda rig, that the mass flow being passed by the fan was only 400 lb/sec. This resulted in a loss of about 1/3 of the thrust and the exhaust temperatures increased from the estimated figure of 100°C to 160°C. The cause of this deficiency was due to the fact that we were mixing the hot high energy exhaust from the turbine with the cold lower energy flow from the fan on the first bend in the duct system, and the hot flow was separating from the wall of the duct and backing up the delivery from the fan. This was a serious situation since the Avrocar was practically built when the trouble was discovered, and though the cure was a fairly obvious one, namely, to carry the hot flow further around the bend, it was too late to carry it out on the Avrocar without a major structural modification.

It was decided therefore to carry on and fly the Avrocar at a reduced thrust level in the ground cushion, and modify the duct at a later date to pick up the missing thrust.

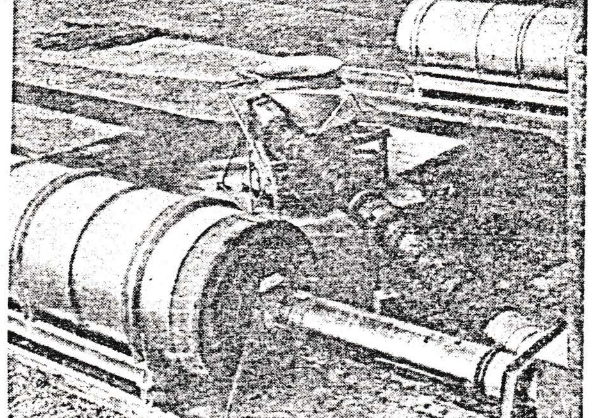

Figure 20
Orenda test rig for Avrocar fan

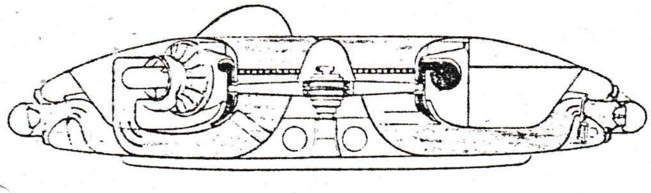

Figure 21
Cross-section general arrangement — Avrocar 1

This loss of mass flow meant that we would not be able to hover out of ground effect.

The second trouble encountered was associated with the intakes for the J69-T-9 jet engines, which were originally designed to be fed from the duct (Figure 21) so that the engines would be rammed to the extent of the pressure ratio on the main rotor (1.07 to 1). It was naturally important that these intakes should not consume any of the hot exhaust from the tip turbine of the main fan.

So that this would not happen, a structural ducting arrangement of radial ribs etc was devised at the local areas on which the intakes were breathing. The design of this was one of those clever arrangements and, as usually happens in such matters, it did not work.

On our first attempts to start the engines the intakes overheated and it was not possible to accelerate them past idling without exceeding their limiting jet pipe temperatures. This trouble was not altogether unexpected, and a fairly quick cure was already designed and partially manufactured.

What we had to do was turn the right angle ducts of the J69 intakes upwards, and allow the engines to breathe directly from the upper surface of the wing. In doing this we lost the benefit of ramming the engines with the main fan, which was calculated to lose 5% of the total thrust.

The ducts carrying the gases from the fan and turbine formed an integral part of the vehicle structure — a radial rib arrangement — in which the radial ribs with top and bottom skins formed at the same time a stiff structure for the vehicle and a natural diffuser passage for the gas. This passage started at the center under the fan and terminated with a sudden contraction to the final nozzle at the rim.

At the final nozzle the gases were exhausted to atmosphere either perpendicularly downwards in the form of a circular curtain, or in a generally backward direction in the form of a jet sheet. The direction of the jet was controlled by a mechanical stabilizer system, mentioned later.

GROUND CUSHION PROBLEMS ENCOUNTERED ON THE AVROCAR

The design requirements for the Avrocar were that it should be able to hover or loiter within ground effect and, when required, rise vertically and hover away from this influence. In order to do this a stable, or near stable, ground cushion in pitch and roll was essential.

The design of the Avrocar, therefore, included an outer peripheral jet, with the addition of a central jet which would be used during hovering, and which could be closed off in forward flight. Model tests indicated that a central jet with a strength of 20% of the momentum of the peripheral jet would be sufficient to reduce the unstable margin, so that at all heights above the ground the vehicle, in combination with its control system, would display the characteristics of stability or well damped neutral stability.

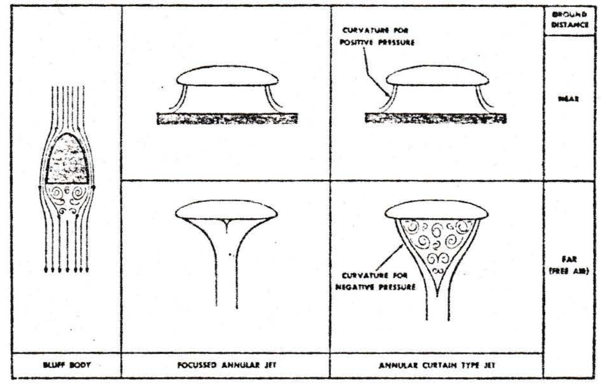

Figure 22
Bluff body analogy

The problem of rising out of ground effect was more difficult. As explained earlier, one of the troubles encountered with the annular jet ground cushion was that out of the influence of the ground the lift produced by the jet is only 50% to 60% of the jet momentum at the peripheral nozzle, and that this loss is due to the separation caused on the undersurface of the wing or body, making itself felt in the form of a negative pressure. Out of ground influence the peripheral jet curtain tends to coalesce into a solid jet at some distance below the base, forming a flow system which looks like a wine glass with the separation taking place within the bowl and the coalesced portion forming its stem (see Figure 22).

We had done tests to see whether this loss of lift in free air, due to this negative pressure on the base, could be recovered by interrupting the jet curtain so that the base area would be vented to atmosphere. The effect of doing this is shown in Figure 23, and it will be seen that as one method it was reasonably effective. However, it was also obvious that it would not do for the Avrocar. To interrupt sections of the peripheral jet would not only reduce the thrust by decreasing the nozzle outlet area but would at the same time push the fan nearer the surge line.

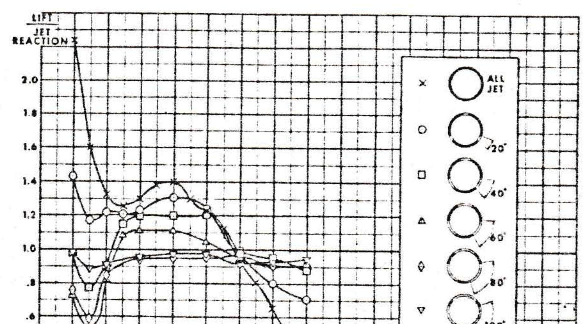

Figure 23
Effect of local jet blockage

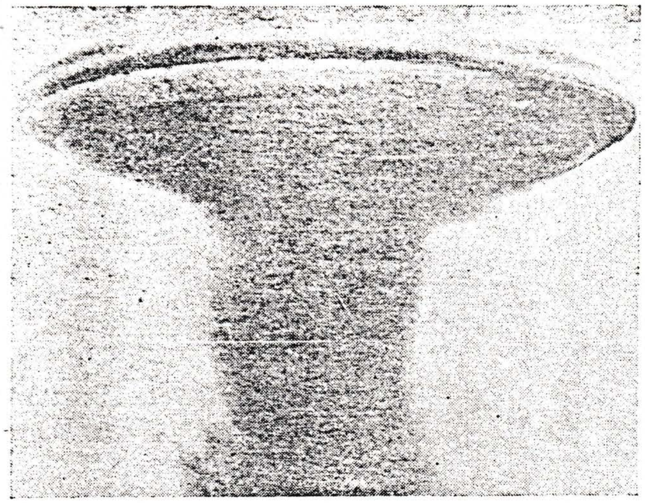

Figure 24

It had occurred to us that if the loss of lift in free air was caused by a separation, the best way to cure the trouble was not to have a separation, or to attach the flow to the undersurface (Figure 22).

This can be done, if the annular jet escaping downwards from the bottom of the vehicle is progressively deflected inwards towards the center. It will be found that when the jet has been deflected from the vertical through about 60° towards the center, the inner edge will attach itself to the lower surface of the body, the whole jet meeting in the center and being deflected vertically downwards in an escaping column — or tree trunk of air (Figure 24). The air outside will be drawn in around it forming an unseparated flow system. Model tests using this arrangement showed that the lift measured was between 85% and 95% of the momentum existing at the peripheral nozzle (see Figure 25). This was the sort of loss we could tolerate, and in estimating the free air hovering characteristics of the Avrocar we had allowed for 15% to 20% of extra thrust for such eventualities.

The characteristics of the focussed annular jet are slightly different in the ground cushion to those of the unfocussed jet. In the first place the ground cushion does not extend to such a high value of h/d, starting approximately at a value of 0.4 with the lift increasing gently up to an h/d of 0.3. From there on the cushion lift produced by the focussed jet increases more rapidly and reaches higher values than the unfocussed type; and when the vehicles reaches an h/d of about 0.2 there is a flow of configuration change and the jet suddenly becomes unattached from the lower surface, jumping out to form a conventional annular jet curtain with a cushion area of separated flow in its center. From the 0.4 value of h/d to the 0.2 value, the central tree trunk of air is progressively thickening (Figure 26). The 0.2 height at which the jet separates from the lower surface is the critical height for that degree of focussing. As mentioned earlier, all annular jets have a critical height and the value of this depends mainly on the angle at which the jet leaves the lower surface of the vehicle.

Figure 27 shows a family of generalized curves, indicating how the value of lift augmentation varies against h/d for a progressive change in the angle at

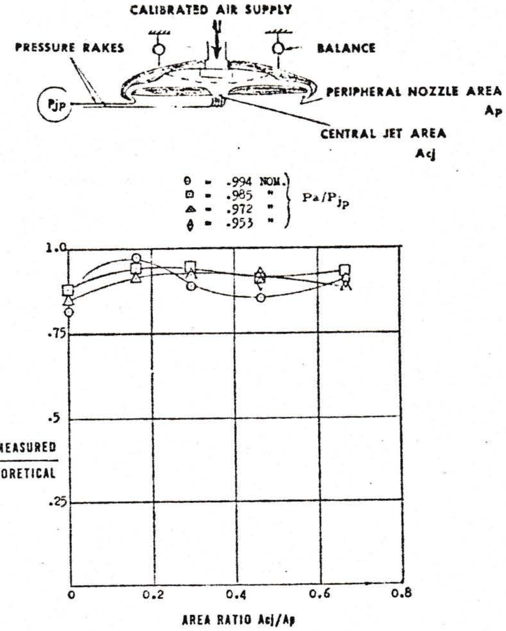

Figure 25
Effect of central jet on thrust efficiency of focussed jet

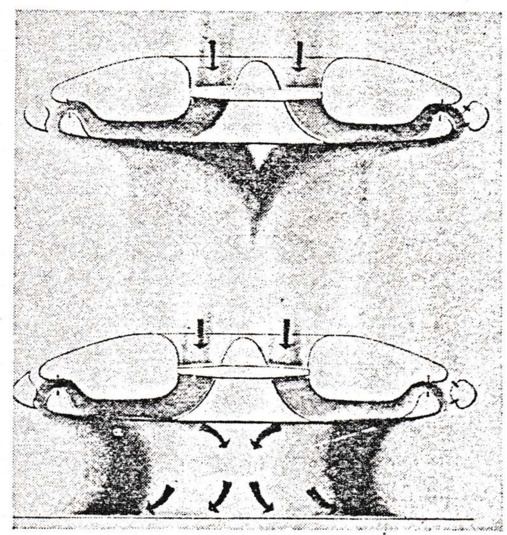

Figure 26
Air flow diagram — hovering

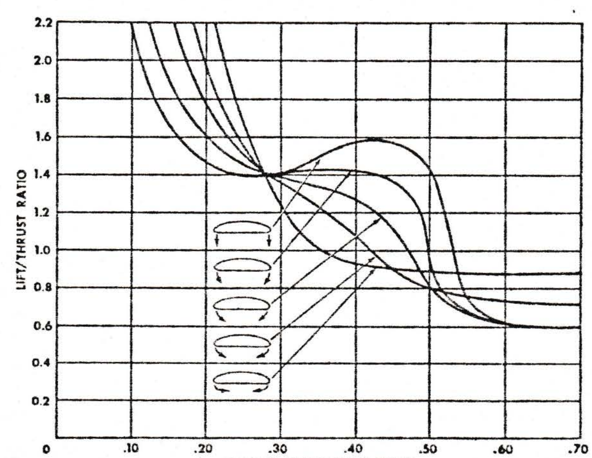

Figure 27
Idealized effect of jet efflux angle on lift/thrust ratio

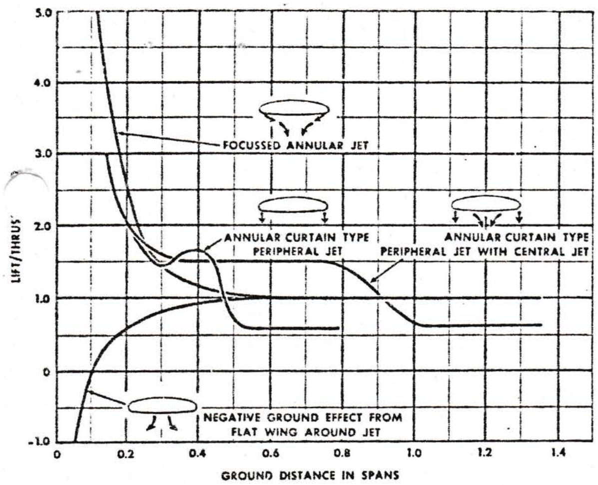

Figure 28
Ground cushion effects with annular curtain, central and focussed jets

which the jet leaves the lower surface of the vehicle. It will be noticed how the hump in the curve gradually disappears with progressive focussing; it is important to mention that this hump is associated more with the thinner peripheral jets. If relatively thick jet curtains are used the hump will be found to disappear as the jet is thickened.

Figure 28 is a summary curve showing the four basic forms, focussed, unfocussed, the plain central jet, and a combination of the last two.

The critical height on the Avrocar was the cause of considerable dynamic instability even though static stability was measured on the balance, and the explanation of this is as follows. Consider the vehicle to be just above the critical height with its jet focussed and attached to the lower surface, and that the vehicle is then disturbed causing one side to fall while the other side rises; on the falling side the jet jumps out becoming unfocussed, while the rising side stays above the critical height and remains focussed. This flow change on the low side will move the center of pressure towards that side, which is in the stable direction, tending to tilt the vehicle back again to the level position (Figure 29).

Unfortunately this flow change is associated with a considerable hysteresis; the jet becomes detached at some angle of deflection but does not attach again until the vehicle has tipped well past the angle at

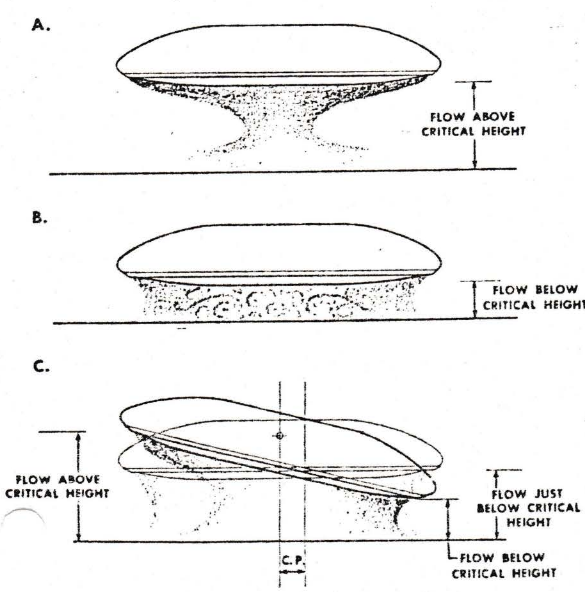

Figure 29
Jet flow regimes in area of critical height

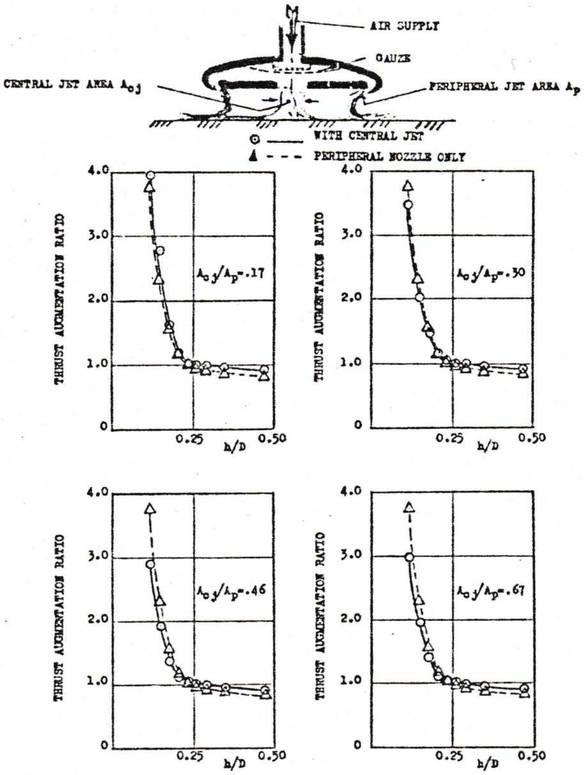

Figure 30
Effect of central jet on lift augmentation

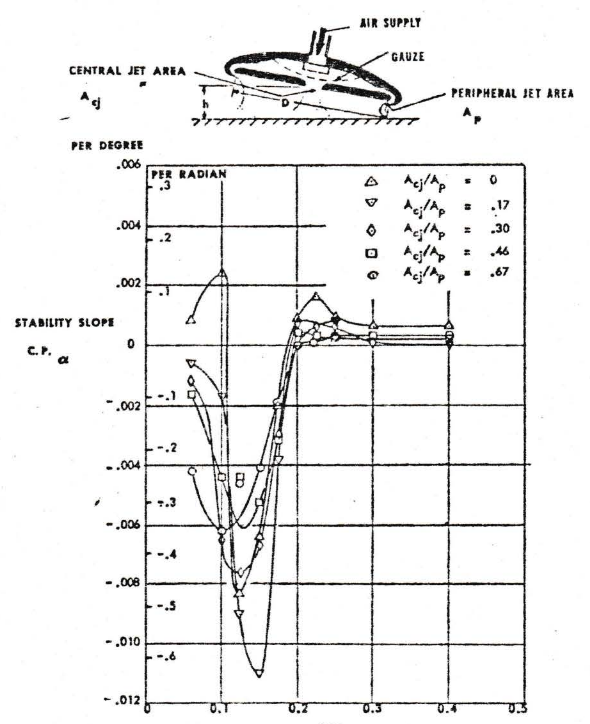

Figure 31
Variation of stability slope with height above ground and central jet strength

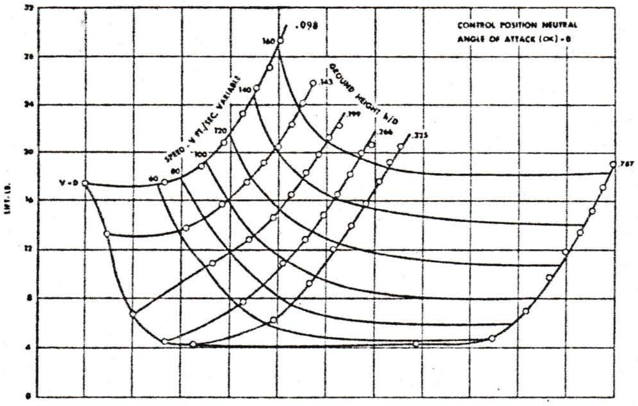

Figure 32
Lift vs forward speed and height above ground

which it became detached, so causing an overshoot in the other direction, making the opposite side become separated. This will cause a divergent motoring action.

On the Avrocar, the situation was eventually cured by increasing the strength of the central jet, and also increasing the sensitivity of the aircraft stabilizing system. Having decided to use a central jet of one form or another to stabilize the cushion, we were naturally interested to know the efficiency of this process and what loss of potential lift was being incurred by using it. We went to some trouble in this respect, employing a 1/20th scale model of the Avrocar with a central jet which could be varied in strength and size with respect to the peripheral jet. Some of the results of this investigation are shown in the curves of Figures 30 and 31. This investigation was carried out during a study contract on various facets of the

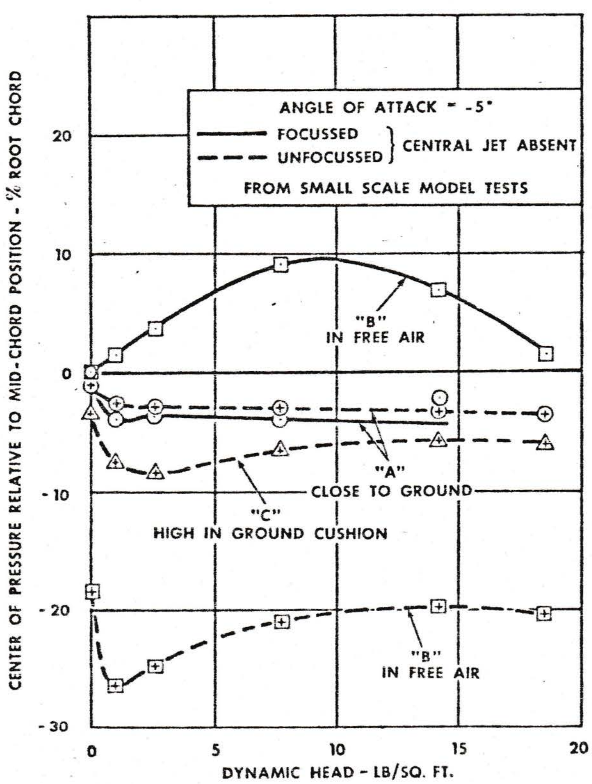

Figure 33
Effect of focussed annular jet on center of pressure location

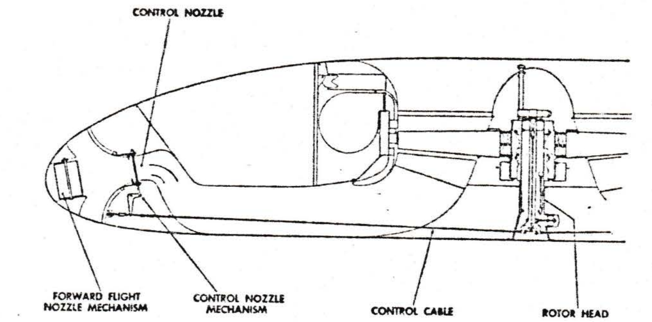

Figure 34
Control system schematic

Avrocar, funded during the last year by the Canadian Government. It will be seen that except for the very large sizes of central jet the penalty in ground cushion lift is not too serious.

Figures 32 and 33 show the effect of forward speed on lift and pitching moment for a vehicle with a focussed jet of the Avrocar type, and it will be noticed here that, contrary to what I think is the accepted belief, we show that the lift does not fall off but increases with forward speed.

THE AVROCAR STABILIZER

The Avrocar is circular in plan, the engines are evenly disposed, as is the fuel and, to some extent, the two operators; the center of gravity is therefore close to the center of the plan area. The aerodynamic center for a circular planform was found to be 28% of the root chord. The wing will, therefore, have a negative static margin, which follows that it is both statically and dynamically unstable in aerodynamic flight and must be stabilized by artificial means.

We have always mistrusted the use of electronics as a basic part of an essential control system, so to overcome this prejudice it was decided to solve the problem mechanically. This was done in the following manner.

The turborotor was allowed a small degree of freedom (½°) relative to the aircraft structure and a strong spring was arranged to restrict this movement. When the vehicle is pitched or rolled the fan, due to its gyroscopic couples, will absorb some of this freedom against the resistance of the spring. This small movement is then magnified about 20 times by a mechanical linkage depending on a system of flexures, similar to the arrangement used in a wind tunnel balance. The resulting motion is applied to the control system; this in turn directs the peripheral jet to produce corrective pitching or rolling moments from jet reactions at the rim of the vehicle (see Figure 34).

Figure 35 shows an isometric view of the central control post where this mechanical magnification takes place. At the bottom of the picture can be seen an aluminum casting which is part of the vehicle structure on which the main radial ribs terminate. A fixed internal shaft is socketed into this casting carrying a spherical bearing about half-way along its length. Mounted on this spherical bearing and surrounding the fixed central shaft is an outer shaft, which extends upwards past the top of the inner shaft. This outer shaft carries the two main bearings for the fan. Be-

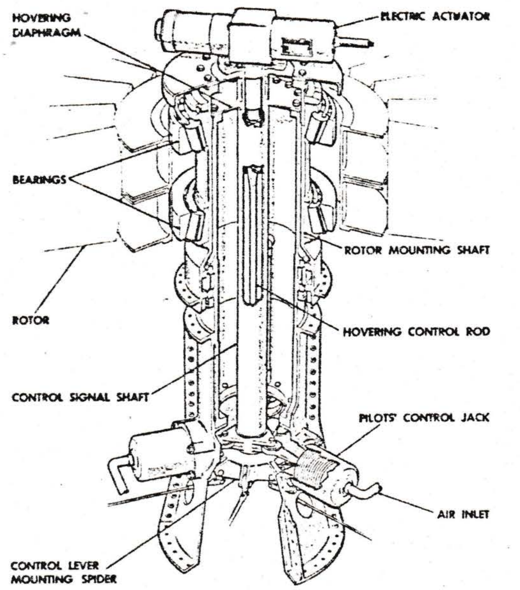

Figure 35
Turborotor shaft assembly

tween the top of these two shafts a gap of 0.04 inches has been allowed so that the top of the outer shaft will move relative to the top of the fixed center shaft about the spherical bearing. At the top of the outer shaft and the fixed center shaft are two diaphragm flexures, so that when the outer shaft moves relative to the center shaft — which it will do if the vehicle is disturbed in pitch or roll due to the gyroscopic couples from the rotor acting through the bearings — the two diaphragms will move laterally relative to each other a maximum of 0.04 inches.

The two diaphragms are joined together by a central control post so that when they move relative to each other the control post is tilted out of the perpendicular. The distance between the diaphragms is 1/20th of the distance from the lower diaphragm to the bottom of the control post. Therefore for a 0.04 inch relative movement of the two diaphragms, the bottom of the control post moves 0.8 inches in any direction, providing enough cable travel to operate the peripheral jet control mechanism and deflect the jet.

Originally the system was arranged so that the control moment would be applied in the same direction as the gyrocouple, at least for steady angular rates. The aircraft thus responded to disturbances as a large gyroscope, without requiring correspondingly large control moments to maneuver.

Analog and digital computer studies showed that the system worked in principle, reducing the effect of input disturbances, but that the resulting motion was poorly damped. The system was redesigned so that the control moment was applied at an angle of 20° to the gyrocouple in order to provide a component of the moment acting in opposition to the rate, i.e. damping. This system was satisfactory for small deviations from steady hovering or forward flight, with sufficient control power. The angle mentioned was denoted the 'rotor phasor angle'. Figure 36 shows three curves in which damping is plotted against the spring stiffness of the system. The curves represent boundaries between a stable and an unstable situation; everything

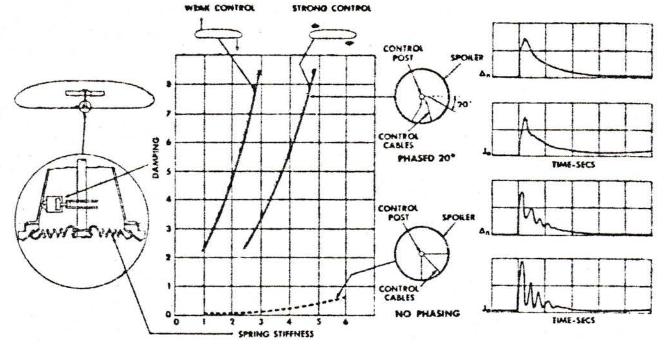

Figure 36
Gyro-stabilizer

to the right hand side of a curve is stable and to the left unstable. The two top curves represent two control systems of different strengths with 20° phasing, and the lower curve represents a system with no phasing. It will be seen how very little area exists to the right hand side of the lower curve. The plots on the right hand side of Figure 36 indicate the time the control system and the vertical accelerations on the vehicle take to damp out after an input disturbance. It will be seen that with 20° of phasing the damping is quite satisfactory; however, with no phasing at all it becomes very oscillatory.

Difficulties with this system were twofold. First, control power was considerably less than planned for initially, and the angular amplitudes of the precessional oscillations, characteristic of the gyroscope, were objectionable. Second, the directions of control input required for maneuver and for trim about any one axis were substantially different (approximately 90° in the original system and 70° in the damped system). Attempted maneuvers on a flight simulator which allowed large pitch angles and unlimited roll angles quickly showed the undesirability of such an arrangement. The system was then redesigned so that the control moment was applied at an angle of 95° to the gyrocouple. The component at 90° provided strong damping, while the remaining component was intended to cancel the gyrocouple, thus eliminating precessional oscillations (the 'cancelled gyro' system). Stick motions for maneuver and trim about any axis were then substantially the same. The actual angle required to cancel the gyrocouple depends on the overall system gain (control moment/aircraft rate), which varies with aircraft configuration and engine speed. 95° was selected as a suitable compromise.

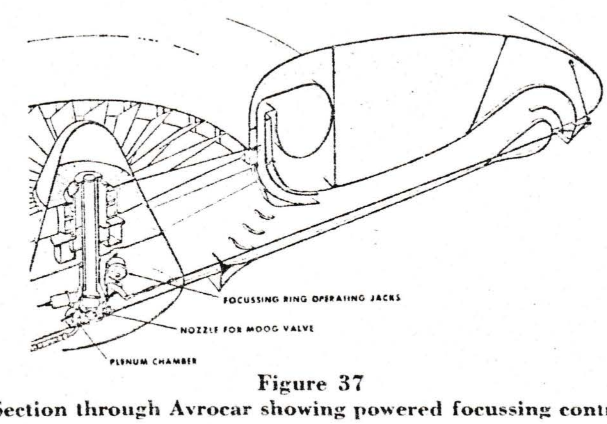

Figure 37
Section through Avrocar showing powered focussing control

CONTROL SYSTEM

The mechanical control of the jet was originally achieved by spoilers (Figure 34) forming a double ring around the periphery and projecting slightly from the sides of the radial duct. Outboard of the spoilers the duct was bifurcated with constant radius walls, to which the jet tended to adhere by the Coanda effect. Motion of the spoiler ring up or down resulted in corresponding deflection of the jet. The ring was connected to the rotor so that deflection of the rotor resulted in an angular deflection of the ring about the appropriate axis, producing the required control moment. The ring could also be raised or lowered, by means of an electric actuator, to provide control of the jet lift in hovering and low speed flight (the 'jet trimmer' control). After some development, including the elimination of the upper nozzle and the spoiler in six segments of the periphery, this system produced a good control characteristic with no loss of lift due to control.

In order to improve the hovering lift, the upper nozzle and the spoiler were eliminated completely and control was produced by a ring (Figure 37) at the outboard edge of the nozzle, which was connected to the rotor so that deflection of the rotor resulted in lateral deflection of the ring. This 'focussing ring' caused the jet to focus beneath the aircraft and to flow downward as a solid tree trunk of jet, as explained earlier.

This type of control was tested on a 1/20th scale model of the Avrocar and was found to possess two properties; as well as moving the center of lift it also altered the direction in which the jet vector left the vehicle (Figure 38).

On the model it was found possible, by moving the control ring its full amount rearwards, to deflect the total jet 45° and so realize 70% of the momentum thrust in the forward direction.

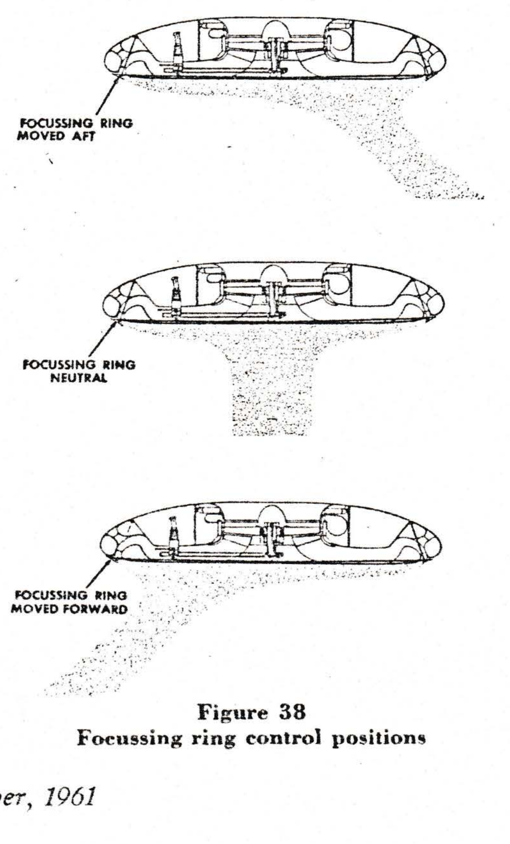

Figure 38
Focussing ring control positions

To obtain the full performance we had estimated, it would be necessary to find a method to deflect the jet all the way backwards and recover 90% to 95% of the gross thrust. We were, however, attracted by the simplicity of this focussing control. It seemed from our tests that enough thrust would already be available to make a transition from the ground cushion to aerodynamic flight and, since our contracts up to this period had all been fixed price, we were anxious to demonstrate this as early as possible without further redesign to the vehicle.

When the control ring is moved aft, a nose-down pitching moment is realized as well as a forward acceleration. This turned out to be a satisfactory state of affairs. Wind tunnel measurements indicated a strong nose-up pitching moment due to intake conditions with forward speed. As speed is increased so would be the nose-up pitching moment and to trim this the ring would be pulled further aft causing the center of jet reaction to move aft with a resulting nose-down moment; at the same time the jet is deflected rearwards, increasing the thrust. Provided this arrangement is sufficiently powerful, the 1/20th scale model indicated that thrust and pitching moments could be handled together and that transition would be possible (Figure 39).

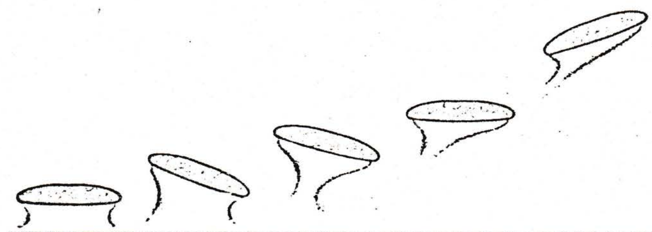

Figure 39
Transition flight path

A good deal of development produced a system with good control characteristics and improved lift, but with large aerodynamic forces on the ring due to the jet flow. Consequently, the rotor was connected to the ring through a pneumatic system involving Moog valves at the rotor shaft and bellows connected to the ring. This power control system (Figure 37) turned out to be very satisfactory.

It was arranged so that the pilot could apply control in pitch and roll through Moog valves on the control stick and bellows connected to the rotor control post. For maneuvering the system is ideally oriented in such a way that the pilot, in displacing the stick, applies the resultant of the following three moments to the rotor: a moment to supply the gyrocouple required for the desired angular rate, so that no unwanted control is applied by the rotor; a moment to deflect the controls sufficiently to supply the gyrocouple to the aircraft; and a moment to deflect the controls sufficiently to counteract natural damping. Since the first is generally the largest, all systems to date have incorporated a 90° change in direction (or 'pilot phasor angle') between the stick motion and the bellows force. For trim changes, however, the system

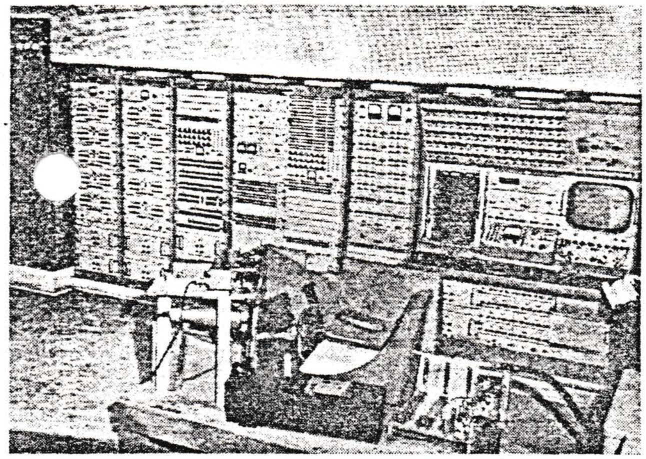

Figure 40
Avrocar flight simulator

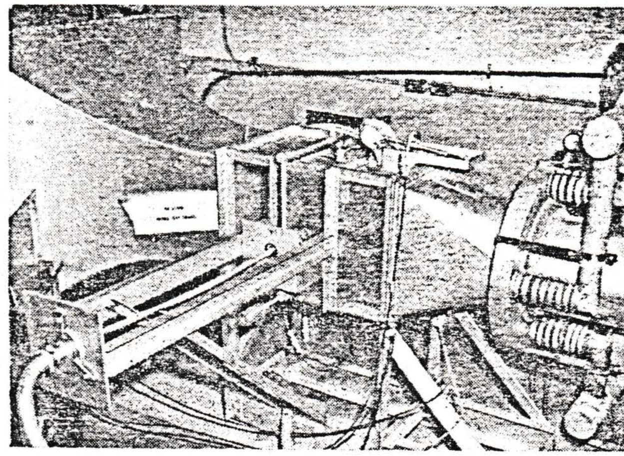

Figure 42
Avro 18 inch × 18 inch ejector wind tunnel

should be oriented so that statically the control moments applied would be in the normal sense, i.e. nose-up pitching moment for stick back etc.

Yaw control is applied by a twist grip on the stick driving Moog valves. The pressure is fed to jacks which operate vanes in the duct at the wing tips.

The Moog valve is a device which transforms small mechanical displacements into pressure signals. A nozzle supplied with compressed air (in this case, primary engine compressor bleed air) faces a plate which is connected to the moving elements. Upstream of the nozzle is an orifice, and between the orifice and the nozzle a tapping yields a pressure which is a function of the supply pressure and the gap between the no and the plate.

Previous studies of the spoiler control system using analog and digital computer techniques showed the characteristics of the system in hovering flight, and in forward flight at two speeds (100 and 265 kts). In view of the negative static margins, a simple flight simulator was rigged using a small control stick and an oscilloscope display of pitch, roll and sideslip angles (Figure 40). The analog was flown by several pilots

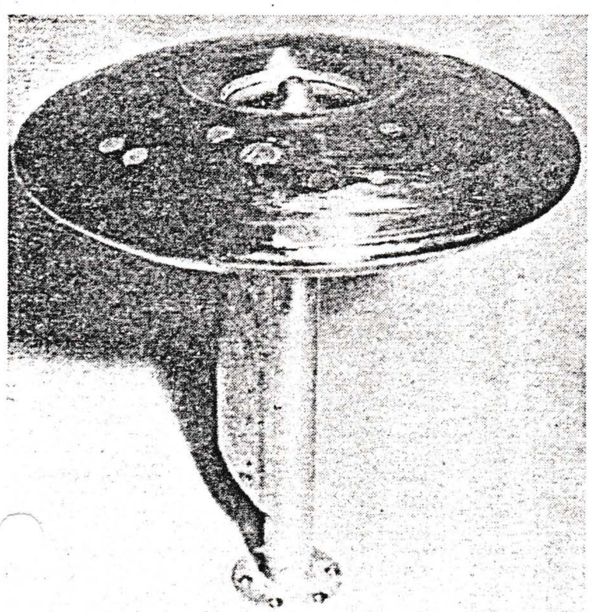

Figure 41
Avrocar 1/20th scale model

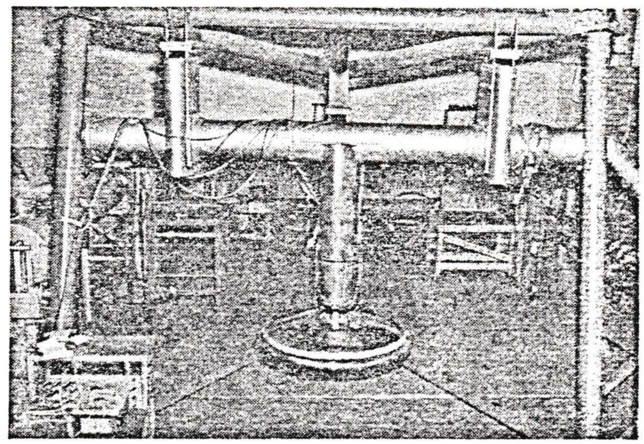

Figure 43
Avrocar 1/5th scale model

with various simulated aircraft and control system configurations in all three flight conditions. A height display and a height control were added for hovering, the latter being a lever simulating the throttle and a switch for the jet trimmer control.

The other test facilities and models used during the development of the Avrocar are shown in Figures 41, 42, 43, 44 and 45. These include the 1/20th scale model of the Avrocar (Figure 41) which was tested in the 18 inch × 18 inch ejector wind tunnel at Malton (Figure 42).

The 1/20th scale model was designed using an air ejector buried inside the wing. The primary air flow to this ejector was supplied at a pressure of 50 to 60 psi down the model mounting post. This was arranged to draw the secondary air flow in through the model intake, and exhaust both primary and secondary flows out through the peripheral nozzle. This model was used a great deal for ground cushion transition and in-flight testing; it suffered from the disadvantage that the intake mass flow was only about three-quarters of the exhaust flow which was quite a difficult situation to correct for. The other model used on the Avrocar was the 1/5th scale model (Figure 43). This was tested in the 20 ft wind tunnel at Dayton. In this model all the mass flow for the jet exhaust was supplied by the downpipe, across the tunnel balance. This resulted in the downpipe becoming very large compared with the model, which made drag measure-

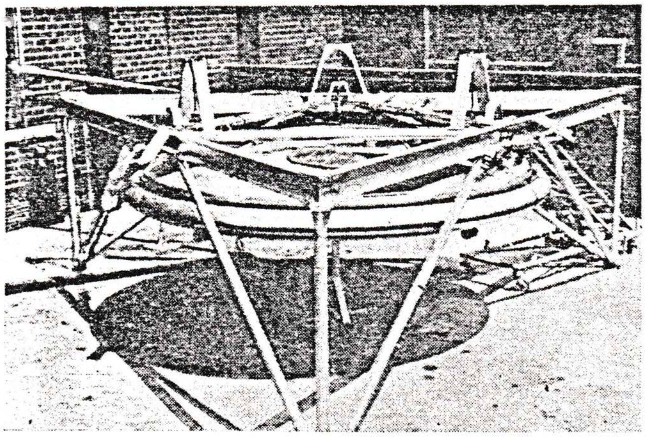

Figure 44
Avrocar test rig

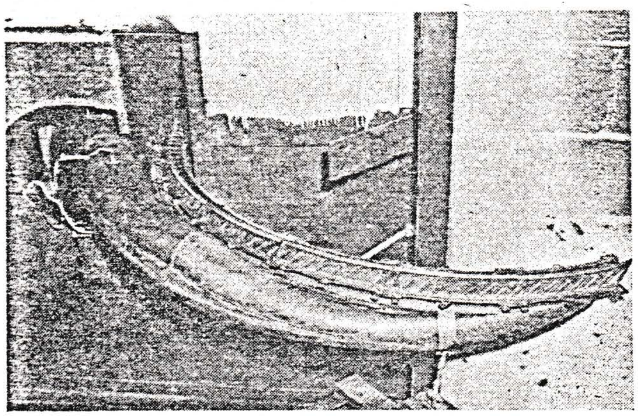

Figure 45
Test rig for Avrocar jet pipe showing fixed nozzle guide vanes

ments difficult to obtain with any degree of accuracy. It was not possible on this model to operate the intake and the jet together.

When the intake suction was applied, the model had to be turned upside down and suction applied to the downpipe; this was useful inasmuch as it provided an opportunity to separate the effects of intake suction from jet exhaust.

The static test rig shown in Figure 44 was built to test out the Avrocar full scale before flying it free. In this rig the vehicle was mounted on strain gauges at different heights above the ground so that lift, thrust and control forces could be measured statically. All controls were operated remotely from an observation room. About 60 hrs of testing was completed on the two vehicles in this rig.

Typical of other test rigs employed is the tusk, or jet pipe exhaust test, Figure 45, which was set up to measure the flow properties of this odd shaped exhaust pipe, using an actual J69-T-9 engine to blow through it.

AVROCAR HOVERING AND WIND TUNNEL TESTING

The contractual arrangement we had with the US Army instructed us to carry out hovering tests on the second Avrocar at Malton to prove feasibility in this area; and full scale tests on the first Avrocar in the 40 × 80 ft wind tunnel at NASA, Ames, to demonstrate, as far as is possible with a static system, the feasibility of aerodynamic flight and also that transition from the ground cushion to free flight is possible, with the trim and thrust forces available. If these three test areas were satisfactory a further contract would be negotiated to cover the second Avrocar during flight test at Malton. Due to the duct losses mentioned earlier, we did not have enough thrust to hover out of ground effect. The hovering tests were therefore limited to hovering within the ground cushion. These, after considerable control development, were carried out satisfactorily up to speeds of 35 mph.

The first attempt at proving in-flight capability with the Avrocar in the 40 × 80 ft wind tunnel at Ames was not satisfactory. On the full scale aircraft it became apparent that the focussing control did not deflect the jet as far aft as the model indicated it would. This resulted in insufficient thrust being available for transition and, as a further result, insufficient thrust to trim out the powerful nose-up moment produced by the intake.

We were therefore instructed to modify the Avrocar control system to put this right and were given a further contract to enable us to do so. The modification we proposed involved leaving the focussing ring alone, since it had proved to be a very effective hovering control, and providing a further outlet for the jet at the rear and sides of the Avrocar. This outlet would be controlled by a transition door which would direct the air past the focussing ring for hovering or, alternatively, allow it to escape generally rearwards past a control vane positioned at the outlet of this duct to deflect the jet to provide pitch or roll control during forward flight (Figures 46 and 47).

It was found as a result of small scale wind tunnel tests that blowing the jet exhaust rearwards from the back of the vehicle, and sideways and rearwards from

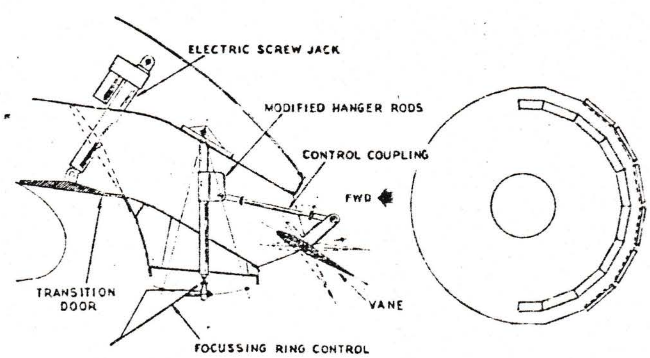

Figure 46
Modification to rear of Avrocar

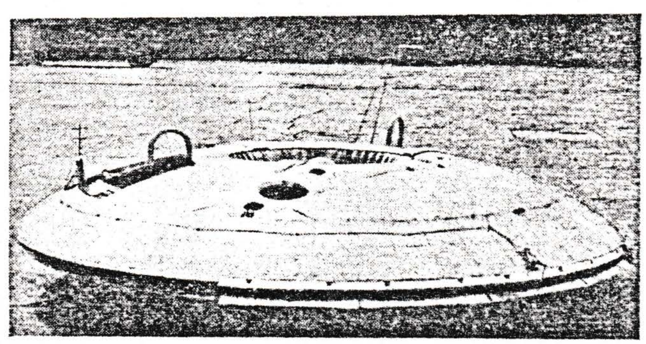

Figure 47
Avrocar showing modification to rear end

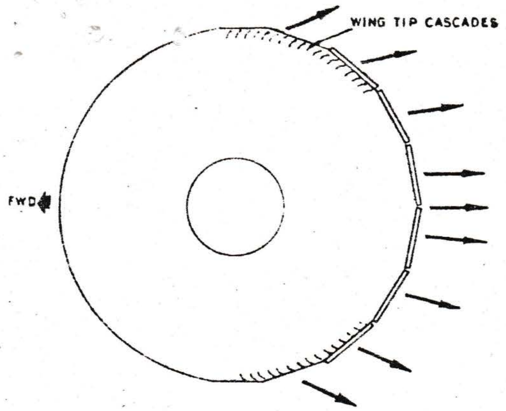

Figure 48
Jet flow in forward flight

the sides, resulted in the fan shaped deployment of the jet (see Figure 48), producing beneficial effects which brought the aerodynamic center back with respect to the center chord of the wing, and increased the lift curve slope from 1.8 to 3, as though the aspect ratio had been artificially increased.

The first unsuccessful tests were carried out at NASA, Ames, in April 1960. A further series, including the above modifications, have just been completed in April 1961. The results of these later tests, which have not been fully reduced, making due allowance for the reduced thrust level still present in the vehicle, appear to be satisfactory and establish that both transition with the Avrocar and aerodynamic flight are possible.

The next stage is to proceed with the flight testing of the vehicle, our objective for the last three years.

ACKNOWLEDGMENTS

The development of the annular jet in Canada has been a long process, extending over eight years of hopes and frustrations, with the outcome never really clear-cut.

Those who have had the optimism and tenacity to stay with it have, of necessity, been most stalwart and dedicated, and without their hard work and enthusiasm this development could never have taken place. Particular among these is T. D. Earl, who shared all our ups and downs and whose unceasing efforts and influence contributed largely to keeping us on course. We would like to express our appreciation to the Management of Avro for their encouragement, understanding and unfailing support.

And further, we would wish to express our thanks to all those who offered their support and enthusiasm from the sidelines; this has often contributed more to keeping us going than anything else.

McCURDY AWARD

The McCurdy Award will be presented at the Annual General Meeting, which will be held on the 14th and 15th June, 1962.

It is the premier award of the Institute and is presented annually

For outstanding achievement in the art, science and engineering relating to aeronautics.

The recipient shall be a person who, while a resident of Canada during recent years, has made a significant personal contribution in any field of endeavour, including, but not limited to, engineering, science, manufacturing, aircraft operations or management.

NOMINATIONS ARE INVITED

Each nomination should include

(a) The name and affiliation of the nominee,
(b) A citation of the particular achievement for which the nomination is being put forward,
(c) Confirmation that the nominee was a resident of Canada at the time of the achievement, and
(d) The name of the nominator.

The nominee need not be a member of the C.A.I.

Nominations should be in the hands of the Secretary not later than the 31st October, on which date they will be handed over to the Senior Awards Committee.