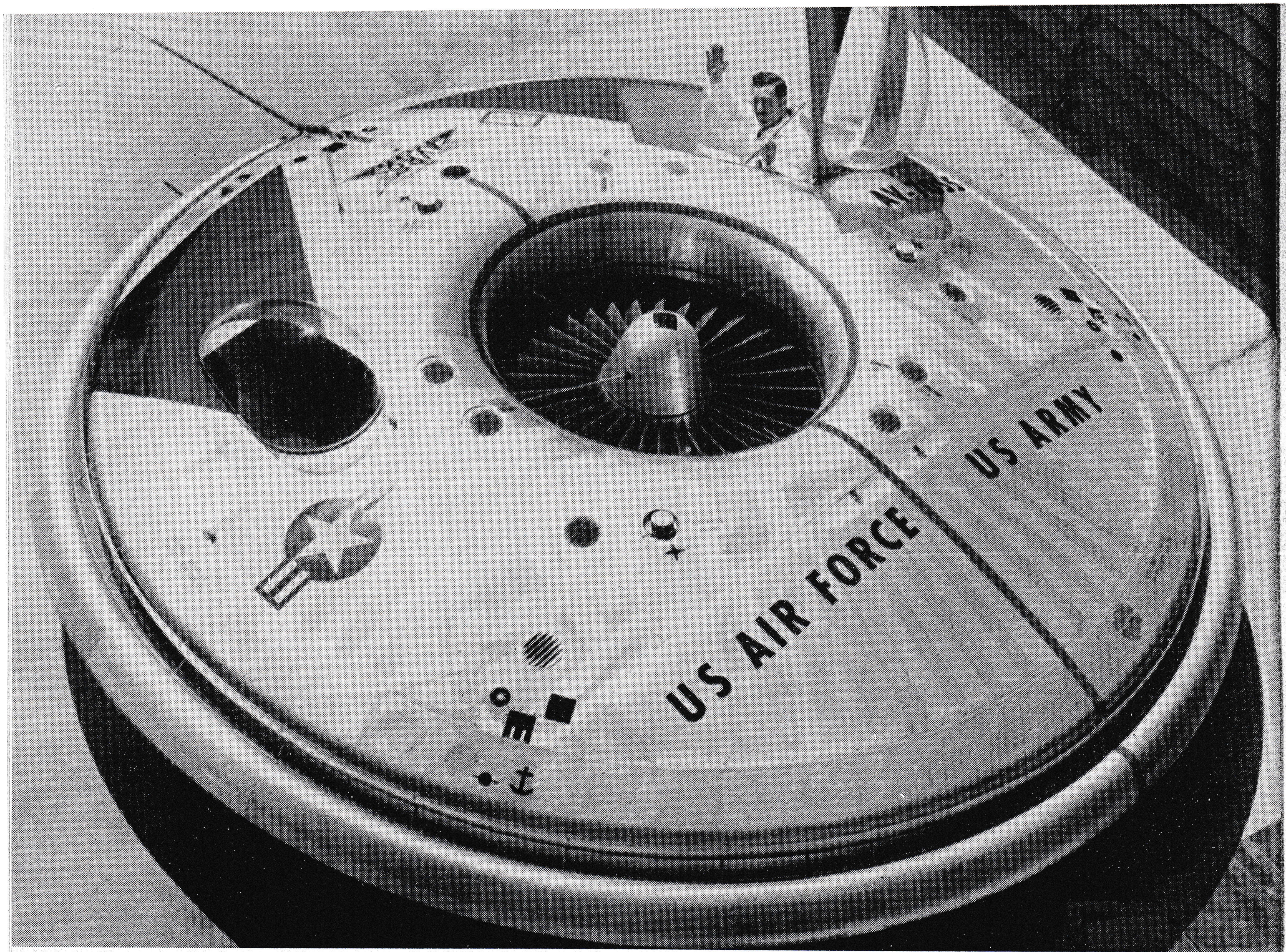


JOINT SPONSORSHIP of the U.S. Army and U.S. Air Force signifies the high hopes held for the Avrocar project. But so far, control and power loss problems have made the design team's goal of vertical ascent into free air elusive, if not unattainable.

RL. 894-1961

Proving Out a Flying Saucer

According to Avro engineers, the Avrocar demonstrated its ability to fly aerodynamically in recent full-scale wind tunnel tests in the U. S.

The vehicle's ability to hover in ground effect has been demonstrated during recent trials conducted by Avro at Malton International Airport.

Details of the program leading to the production of Avro's "flying saucer", or Avrocar as it is now known, have been guarded closely for several years. But full details of the aircraft's design and development were revealed last month at the annual convention of the Canadian Aeronautical Institute. Through the co-operation of the author, Avro designer J. C. M. Frost, and the Canadian Aeronautical Institute, Canadian Aviation presents the following condensation of the W. Rupert Turnbull lecture, entitled "The Canadian contribution to the ground cushion story".

By J. C. M. Frost

Chief Design Engineer,
VTOL, Avro Aircraft Ltd.

It is unfortunate that Avro had its sights set on developing a supersonic vertical take-off aircraft when the company's engineers stumbled upon the ground cushion in 1953—two years before Cockerell discovered it in the U.K. Had this not been the case we might have paid more attention to its possible uses as an amphibious surface vehicle, rather than as the undercarriage for an aircraft.

Though we realized its potential as a substitute for the wheel or the caterpillar track, and that it would operate over water, we missed its potential as a method of improving the potential of a water-borne craft, as developed by Cockerell in the Hovercraft.

We had been trying to find a subtle alternative to using brute jet thrust to raise an aircraft vertically, and the possibility of raising a supersonic aircraft 15 feet into the air using thrust only two-thirds of its weight was attractive enough to us as aircraft engineers to make us shelve other end uses for the time being. We had graduated from the tail-sitter and were studying a circular version of a flat-riser with a peripheral jet, when first we discovered that we had ground augmentation.

We explored this to its more obvious extremes by models. The first had the jet issuing from a peripheral slot and being deflected downwards in a circular curtain by a Coanda effect on the curved lower lip of the nozzle, so producing a positive ground cushion with a relatively thick jet curtain. The jet in the second model issued from its centre, producing a negative ground cushion, or sucking on to the ground.

May Hold Key Patent

At this time our studies were being funded by the Canadian government. It is thanks to such people as Dr. O. M. Solandt and Dr. J. J. Green of the Canadian Defence Research Board, and to the directors of A. V. Roe Canada Ltd., who allowed us to engage in what must have seemed like optimistic crystal-gazing, that this country holds what may one day prove to be the key patent in the principle of the ground cushion concept.

Having discovered this method of augmenting lift, what type of aircraft would benefit most from its application? There were a number of factors. Early tests indicated that the circle was the optimum shape for a peripheral jet and that if this were stretched gradually into an ellipse, the ground cushion 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 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, but for an aircraft which would cruise supersonically, there was little disadvantage in low aspect ratio.

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 take-off, and directed rearwards to provide thrust in forward flight. The jet sheet so formed issuing from the trailing edge, giving the wing the benefits of a jet flap.

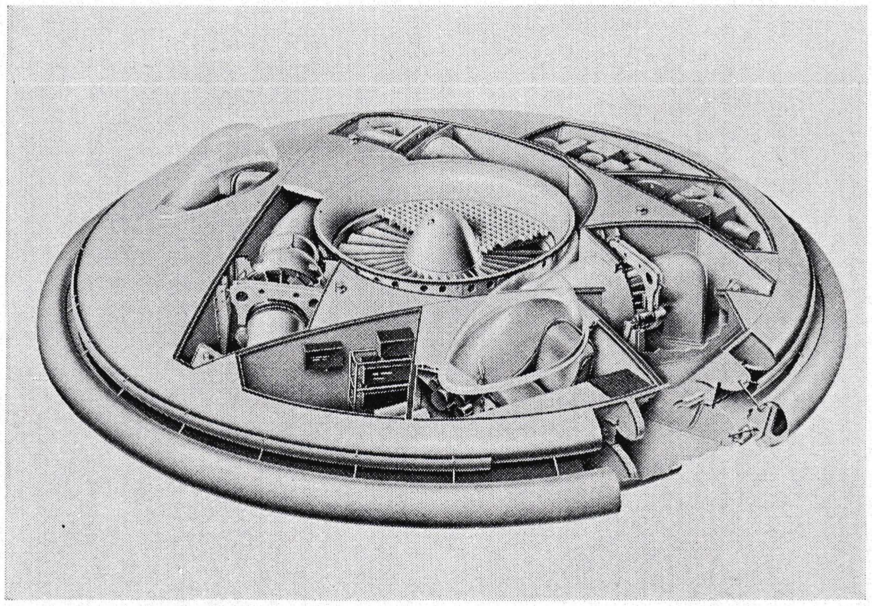
Consequently a number of supersonic models using wings of circular planform ranging in thickness from two to eight percent were studied. At this juncture the U.S.A.F. Air Research and Development Command became interested in our activities and this resulted in our being awarded a study contract involving subsonic and supersonic wind tunnel testing, static testing of the ground cushion, and configuration studies. We designed a suitable jig on which to start the ground cushion studies, and a great many tests were carried out on this in the years between 1955 and 1958.

This time proved most frustrating. An attractive idea, which on the face of it could form a substitute for wheels and suspension, and seemed so simple, developed into an extremely difficult aerodynamic problem. Unwittingly, we were trying to solve the hardest part of the problem first by attempting to realize augmentations to raise the vehicle 1.5 times its diameter.

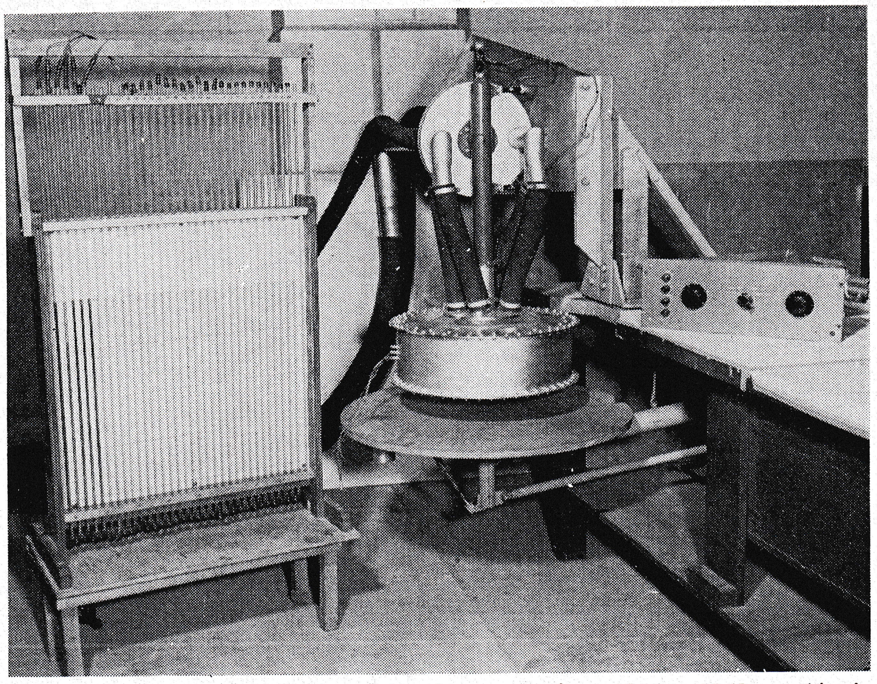
Sights Were Set High

Cockerell, in his design of a water-borne vehicle could initially be satisfied with a height over diameter ratio which did not exceed .06. We, on the other hand, started with our vehicle on its wheels at this height and sought to achieve much greater augmentation.

We also hoped to find a way of substituting the cushion of air under



DISPOSITION of the Avrocar's engines, fuel tanks and crew, is illustrated in this sectional drawing. Later, the engine intakes were turned to breathe from the top.



AVRO ENGINEERS spent a frustrating three years, from 1955 to 1958, on this rig trying to develop their valuable ground cushion effect discovery into a usable force.

the wing for the basic aerodynamic lift of the wing itself without destroying the cushion effect during transition, and at the same time overcoming problems of instability. We learned that the annular jet cushion, although quite stable close to the ground, becomes progressively more unstable as height is increased; 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.

We also found that 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 percent of the momentum thrust of the nozzle by the separation which is present on the undersurface of the body.

Problems Can Be Solved

These problems rapidly became apparent within the first year of testing —and we have been trying to get around them ever since. Though we are not entirely satisfied with all the solutions found, we feel that the more basic problems can be solved.

Since Avro started testing, many other bodies on both sides of the Atlantic have carried out similar research, and the basic fundamentals of the annular jet are now well understood. But interest has been largely focussed on problems associated with the lower values of height over diameter ratio, in the vicinity of .15 downwards. Problems to be tackled in the higher ratios, particularly those of stability and economy, have been approached by very few besides Avro.

Most successful of the many devices we used to obtain stability in pitch and roll was the introduction of a central jet, or inner annular jet ring. We found that an inner jet equal to a quarter the momentum of the outer peripheral jet would completely stabilize the system statically and dynamically from close to the ground until the whole arrangement becomes neutrally stable. Presence of the central jet also extended the height of the ground cushion effect.

In addition to tests made on the ground cushion rig, three wind tunnel models, one subsonic and two supersonic, were also built. The subsonic model, five feet in diameter, was tested at the Wright Air Development Centre, Dayton, and the others were tested at the U.S. Naval research tunnel at the MIT. A total of 900 hours of subsonic tunnel testing and 250 hours, supersonic, were completed, and an extensive background on the behaviour of the circular planform wing in forward flight was obtained. Some results obtained from the models are still classified.

The U.S. Army became interested in the project in 1956, and Avro was given a contract to build two machines as research vehicles. This was the first financial support received for the production of actual hardware.

It was this vehicle that became known as the Avrocar. It was to be 18 ft. in diameter, having a circular wing with a 20 percent eliptical section and two percent camber. The gross weight was estimated at 5,650 lb., with a useful load of 2,000 lb. Power was supplied by three Continental J-69-T-9 turbojet engines (basically the Turbomeca Marbore II, developed to meet American requirements, and having a maximum rating of 920 lb. static thrust).

Performance estimates for the Avrocar were a maximum speed at sea level of 225 knots; rate of climb at sea level of 4,500 ft/min; ceiling (limited by no oxygen for crew) 10,000 ft; range at sea level with 1,670 lb. payload, 145 nautical miles; range at 10,000 ft, 180 nautical miles.

The U.S. Army requirement that the vehicle should be able to take-off vertically and hover out of influence of the ground was not the best concept for a ground cushion vehicle, and necessitated installing considerably more power than otherwise would have been necessary. It would have been more economical to have it take-off into aerodynamic flight only from the ground cushion.

Helicopter Comparisons

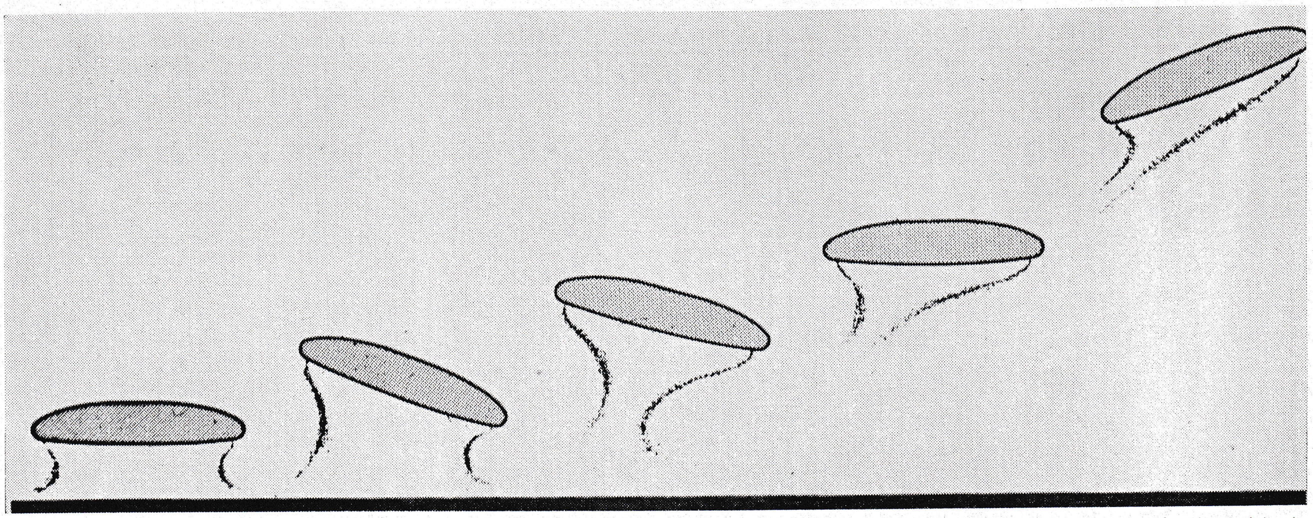
Wind tunnel tests had indicated that hovering in ground effect, the vehicle would be comparable to the helicopter—its obvious competition—and that in forward flight the lift-drag ratio of the Avrocar would give it an advantage. It was hoped that forward flights speeds of 240 knots might be developed.

Hovering out of ground effect, however, the Avrocar would be vastly inferior on the basis of lift per horsepower, due to the very high disc loading of the fan. This did not seem too great a disadvantage since we did not see the necessity for flying long in this condition.

The Avrocar was equipped with a five 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 the three J-69-T-9 engines.

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

The fan, designed and built by Orenda Engines Limited, had hollow sheet metal fan and turbine blades, and a simple central bearing arrangement using only two taper roller bearings. In 300 hours of test running not one mechanical failure occurred which could be contributed to the fan or turbine.



TRANSITION PHASE of the Avrocar from hovering to forward aerodynamic flight is shown here diagrammatically, with the curtain of air first being transformed into a column upon which vehicle rises, and then being deflected rearwards for flight.

The fan was designed to handle 550 lb. of air per second at a pressure ratio of 1.07 to 1. The three exhausts from the J69 engines each occupied 120 degrees of the turbine inlet area, and each engine had its own jet pipe fashioned in the shape of a tusk 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 passed from the bottom of the fan below the cockpits, engine bays, and cargo compartments, to the peripheral nozzle around the circumference of the vehicle. The mixed temperature of the air in this duct was calculated to be 100 degrees C under design conditions.

Early problems included the discovery on the Orenda rig that the mass flow passed by the fan was only 400 lb. per second, resulting in loss of about one-third of the thrust, and the exhaust temperatures increased from the estimated 100 degrees C to 160. This deficiency was caused by mixing the hot high energy exhaust from the turbine with the cold lower energy flow from the fan on the first bend of the duct system.

Cure for this serious defect was fairly obvious—to carry the hot flow further around the bend—but the Avrocar was almost built when it was discovered, and the remedy would have meant making a major structural modification. It was decided to carry on and fly the machine at a reduced thrust level in the ground cushion, then modify the duct to pick up the missing thrust later. The loss of mass flow meant that the vehicle would not be able to hover out of ground effect.

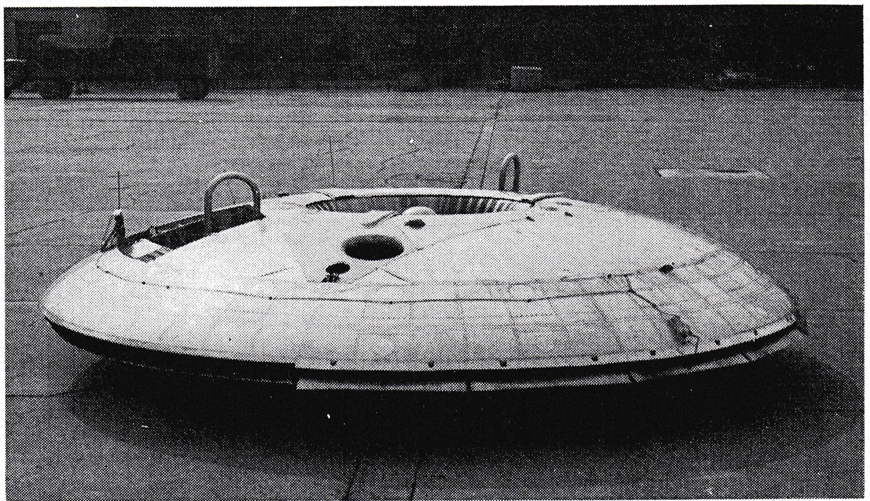
Another trouble was associated with the intakes for the engines, originally placed so as to be fed from the duct so that the engines would be rammed to the extent of the pressure ratio on the main rotor (1.07 to 1). To avoid consuming any of the hot exhaust from the tip turbine, an arrangement of radial ribs 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. The engines overheated and so the intake ducts had to be turned upwards to allow them to breathe directly from the upper surface of the wing. Losing the ram effect was calculated to lose 5 percent of the total thrust.

Jet Sheet Propulsion

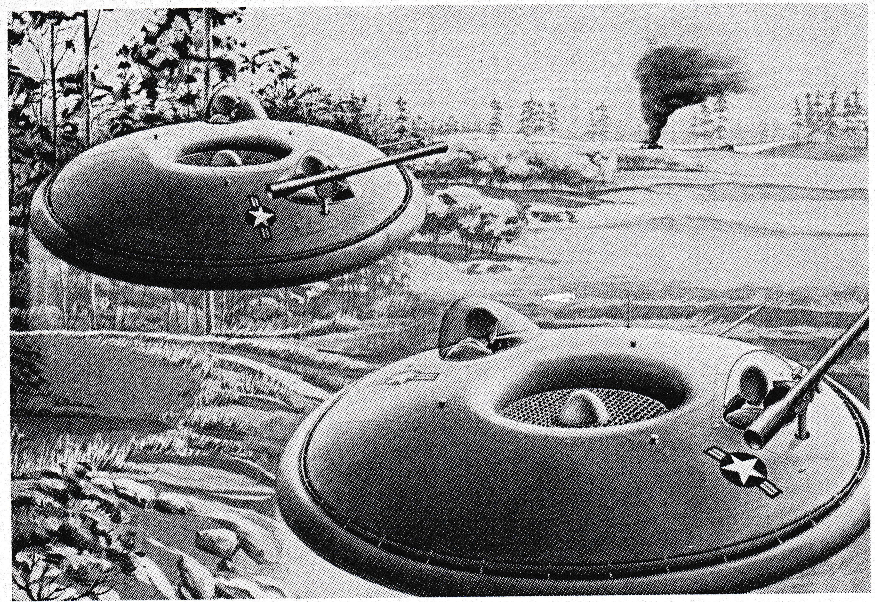
The ducts carrying the gases from the fan and the tip turbine terminated with a sudden contraction to the final nozzle at the rim of the vehicle. The gases were exhausted to atmosphere through the nozzle either perpendicularly downward in the form of a circular curtain, or in a generally backward direction in the form of a jet sheet.

One of the problems to be tackled was the separation mentioned earlier, which considerably reduced the lift of the annular jet out of ground effect. This was overcome by deflecting the airflow inwards towards the centre progressively as the vehicle rose. It was found that when the jet was deflected through about 60 degrees from the vertical, the inner edge of the airflow attached itself to the lower edge of the vehicle, the whole jet meeting in the centre and being deflected vertically downwards in an escaping column of air.

Model tests showed that the lift achieved with this system was between 85 and 95 percent of the momentum existing at the peripheral nozzle. This loss we could tolerate



MODIFIED DISC. When the first tests in April, 1960, indicated that movement of the focussing ring alone would not provide enough thrust for transition, Avro engineers added a further outlet for the jet at the sides and rear. This picture shows the increased diameter of the Avrocar that resulted from these modifications.



U.S. ARMY'S EXPECTATIONS of the Avrocar project were indicated by artist's conception of the vehicles bobbing up from cover to deliver deadly blast at enemy.

since we had allowed 15 to 20 percent of extra thrust in the Avrocar for such eventualities.

The critical height of the Avrocar was the cause of considerable dynamic instability. As the jet flow becomes unattached the vehicle is disturbed causing one side to fall, while the other side rises. On the falling side the jet jumps out unfocussed; the rising side stays above the critical height and remains focussed. This flow change moves the centre of pressure towards the low side, tending to tilt the vehicle back to the level position.

Unfortunately this flow change is associated with a considerable hysteresis. The jet becomes detached at some angle of deflection, but does not attach itself again until the vehicle has tipped well past the angle at which it became detached, causing an overshoot, and a divergent motoring action. The situation was eventually cured on the Avrocar by increasing the strength of the central jet and increasing the sensitivity of the stabilizing system.

It was found, contrary to what is, I think, the accepted belief, that with a vehicle with a focussed jet like the Avrocar, the lift does not fall off with forward speed, but increases.

The Avrocar being circular, and the engines being evenly disposed along with the fuel and to some extent the two operators, the centre of gravity is close to the centre of the plan area. The aerodynamic centre was found to be 28 percent of the root chord. The wing, therefore, had a negative static margin, which means that it is both statically and dynamically unstable in aerodynamic flight, and must be artificially stabilized. This was achieved by mechanical rather than by electronic means, in the following manner:

The turborotor was allowed a small degree of freedom 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, which in turn directs the peripheral jet to produce corrective pitching or rolling moments from jet reactions at the rim of the vehicle.

Lacked Control Power

A number of other difficulties had to be overcome. Control power was considerably less than planned for initially, and the angular amplifications of the precessional oscillations characteristic of the gyroscope were objectionable.

The mechanical control of the jet was originally achieved by spoilers 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 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.

During testing on a 1/20th scale model it was found that by moving the control ring fully to the rear, the total jet was deflected 45 degrees, realizing 70 percent of the momentum thrust in the forward direction.

To obtain the full performance we had estimated it would be necessary to find a method of deflecting the jet all the way backwards and recover 90 to 95 percent of the gross thrust. But we were 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.

Hovering tests within the ground cushion were carried out at Malton, and after considerable control development, proved satisfactory. The vehicle travelled at speeds of up to 35 mph.

The first attempt at proving inflight capability with the machine in the 40 x 80 ft. wind tunnel at Ames in April, 1960, was not satisfactory. It was apparent that the focussing control did not deflect the jet as far aft as had been indicated in the model tests. This meant there was insufficient thrust available for transition, or to trim out the powerful nose-up moment produced by the intake. We were given a further contract to modify the control system to rectify this.

Since the focussing ring had proved an effective hovering control, we left this alone, providing a further outlet for the jet at the rear and sides of the vehicle. This was controlled by a transition door, which would direct the air past the focussing ring for hovering, or allow it to escape 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.

Small-scale wind tunnel tests indicated this arrangement produced beneficial effects which brought the aerodynamic centre back with respect to the centre chord of the wing, and increased the lift curve slope from 1.8 to 3, as though the aspect ratio had been artificially increased.

Further full-scale tests at Ames, with the modified vehicle were completed in April, this year. The results —which have not been fully reduced —making allowance for the reduced thrust level still present in the vehicle, appear to be satisfactory, and to establish that both transition 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.