The Avro VZ-9 Experimental Aircraft Lessons Learned

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THE AVRO VZ-9 EXPERIMENTAL AIRCRAFT - LESSONS LEARNED

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Abstract

This paper discusses the development, manufacture and ground and flight test of the AVROCAR (VZ-9AV) aircraft. It covers, in the test phases, several shortcomings in the overall design objectives, briefly discusses flight test results and concludes with "lessons learned" and recommendations.

I Background

In the mid 1950's considerable interest was evinced by the US Air Force and the US Army in exploring new and radical concepts to meet mission requirements which were quite different for the two services. The Air Force, concerned with airfield interdiction of forward placed bases in Europe, was examining methods for aircraft survivability. These included studies on aircraft revetments, aircraft access to existing roads for take-off, Short Take-Off and Landing (STOL), and finally, Vertical Take-Off and Landing (VTOL). The US Army, on the other hand, was concerned with survivability of its platforms in a battlefield environment. In the Army's case moderate speed and high maneuverability were the driving forces (along with cost comparisons to existing light fixed wing aircraft and helicopters.)

The discovery in 1953 by British scientists that a circular jet curtain would produce a powerful ground cushion led AVRO Aircraft engineers to consider this phenomena, but not purely as a ground effect machine, but rather as the undercarriage for a vertical Ground Effect Take-off and Landing (GETOL) aircraft. The first effort in 1956 by AVRO Aircraft, under contract to the US Air Force, was design and feasibility studies of incorporating the ground effect with a radial flow propulsion system and jet control for a supersonic fighter aircraft. (WEAPON SYSTEM 606A) Figure 1.

In 1958, after a series of presentations by AVRO Aircraft to the US Air Force and US Army, the joint Army-Air Force AVROCAR program was approved and contracted to Avro Aircraft by the US Air Force. The intent of this program was to utilize prior WS 606A

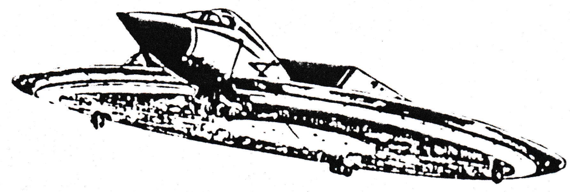

Figure 1. Weapon Systems 606A

studies and model tests to fabricate for the Air Force a proof-of-concept model and for the US Army a prototype of a "flying jeep" (Figure 2).

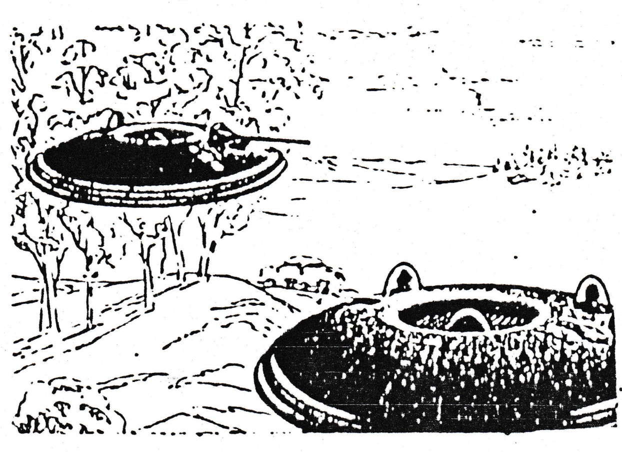

Figure 2. AVROCAR

The AVROCAR was proposed to be a new type GETOL aircraft suitable for operating at low speeds in the ground effect and also capable of speeds in excess of 250 knots at altitudes up to 10,000 feet.

II Description of Aircraft

Figure 3 is a three-view general arrangement of the vehicle. It is a flying wing design of circular platform approximately 18 feet in diameter. In cross section the wing is a cambered ellipse with a thickness to chord ratio of approximately 20 percent.

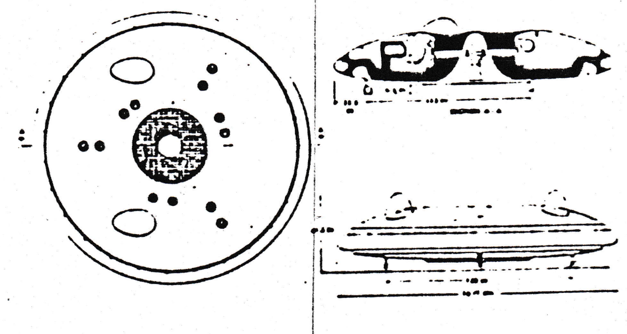

Figure 3. Three-view of AVROCAR

The wing is symmetrical about the vertical centerline, resulting in a radial structure. The bottom of the vehicle stands approximately 6.5 inches off the ground, has an overall height of 4.8 feet and was to take-off vertically at a weight of 5,650 pounds which included a payload of 2,000 pounds and fuel for over a 100 mile range.

Three Continental J69-T9 turbojets (927 pounds S.L. static thrust, 27 inch overall diameter, 364 pounds weight) are symmetrically disposed horizontally around the centerline of the aircraft with their exhaust directed inboard (Figure 4). The exhaust is collected in a

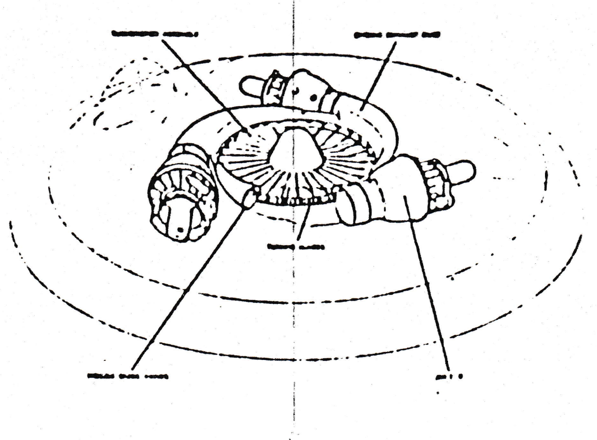

Figure 4. AVROCAR Exhaust System

tusk-like chamber and directed through nozzle guide vanes to impinge upon turbine blades attached at the outer edge of the turborotor assembly (Figure 5).

The turborotor (Figure 6) draws in air through a central circular opening and forces it radially outward through diffuser ducts in the main structure (Figure 7). Some of the air forced out by the turborotor is directed back to turbojet inlets, but the majority of the flow is expelled from an annular nozzle at the wing periphery.

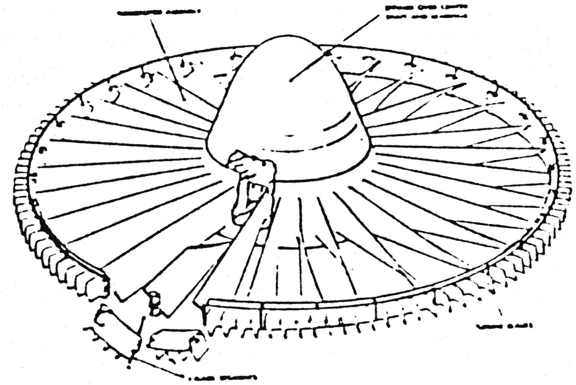

Figure 5. Tip-Driven Turborotor

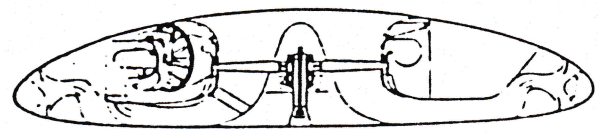

Figure 6. AVROCAR Ducting System

A smaller part of this main flow escapes from an inner annulus to stabilize the ground cushion. The control system was complex. This will be described later in this paper.

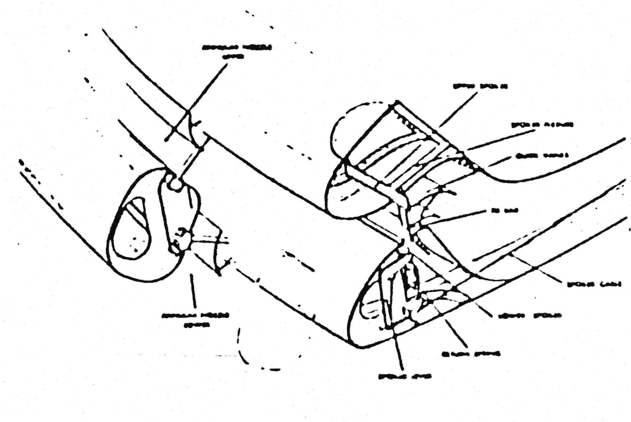

Figure 7. Reactive Control

The peripheral jets are directed downwards for take off and this annular jet in the presence of ground provides an appreciable thrust augmentation. This is known as the ground cushion effect and the approximate flow pattern close to the ground is illustrated in Figure 8.

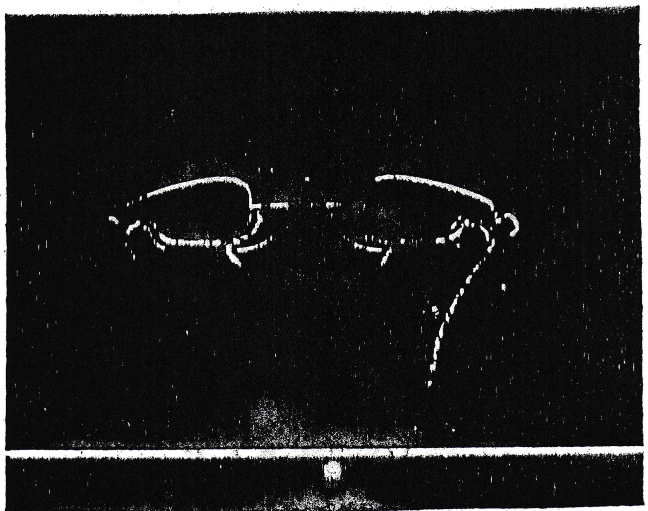

Figure 8. Ground Effect Flow Pattern

The vehicle could hover and move within the ground cushion. Transition to forward flight was to be accomplished by gradually deflecting some of the jet flow from the peripheral nozzles to the rear. The vehicle was to accelerate forward, and climb upwards. The jet sheet at the rear of the wing induces a large lift coefficient which, together with the low wing loading, enabled the wing to support the aircraft at a speed of 45 miles per hour. For landing, descent was to be made at constant power until the presence of the ground effect was sensed. Power was then reduced to settle the aircraft onto the ground.

III Program Factors

The initial outlook for the AVROCAR program was quite favorable. The contractors, AVRO Aircraft Limited and Orenda Engines Limited, both of Toronto, Canada, were major companies with extensive experience in aircraft and propulsion system design. Both companies were heavily involved in manufacturing the RCAF CF105, a supersonic fighter interceptor, and a major program buy for the Canadian Government. As a consequence, major facilities existed for design, fabrication and test and an excellent design team with engineering back-up from the CF105 team was on hand. In addition, considerable testing of the radial propulsion system had been accomplished under the ongoing AF contract which had directed a conceptual design study and small scale model tests of the supersonic fighter aircraft design. AVROCAR funding appeared adequate and the schedule appeared reasonable. From the government side, the technical support available from the AF Propulsion Laboratory and the Flight Dynamics Laboratory was outstanding. This available technical support was undoubtably disportionately large for a relatively small program. This support was probably due to the novelty of the concept which certainly intrigued many Wright-Patterson AFB engineers. In addition, NASA (AMES) and Edwards AFB provided timely and outstanding support. A brief comment. In these present days of increased bureaucracy where extensive documentation to include Program Introduction Documentation (PID) and agency Memorandums of Agreement (MOA) are a requirement, it was extremely refreshing to visit the AMES facility, discuss testing requirements in their 40 foot wind tunnel with NASA scientists and "seal the deal" with a handshake. This was also true at Edwards AFB where the only correspondence needed was a TDY fund citation for the Edwards test pilot. Only one ominous cloud hung over the AVROCAR program from its onset. The US and Canadian governments were discussing Canadian cost sharing and acquisition of the proposed USAF F-108 supersonic fighter aircraft. During the middle of the AVROCAR program the Canadian Government and the US Air Force reached agreement on the F-108 project and the AVRO ARROW CF-105 program was canceled and the few existing aircraft were scrapped. It is ironical that the Air Force F-108 program also was later canceled. Cancellation of the CF-105 program certainly did not contribute directly to the eventual AVROCAR outcome, but it did dampen the enthusiasm and support of the AVROCAR program, particularly in its later stages.

IV Avrocar Tests

Fabrication of the AVROCAR was completed in May 1959 (Figure 9) and the vehicle was installed in the static rig (Figure 10). The objective of the ground test was to develop the aircraft to the stage where it could be demonstrated that initial hovering would be reasonably safe. Three sub-objectives were as follows:

a. Performance: Measure the performance of the aircraft in ground effect and establish the maximum lift available

b. Control: Establish the control characteristics and develop the control system to provide satisfactory handling characteristics for the initial hovering trials.

c. Structure: Verify the structural integrity and mechanical operation of the aircraft.

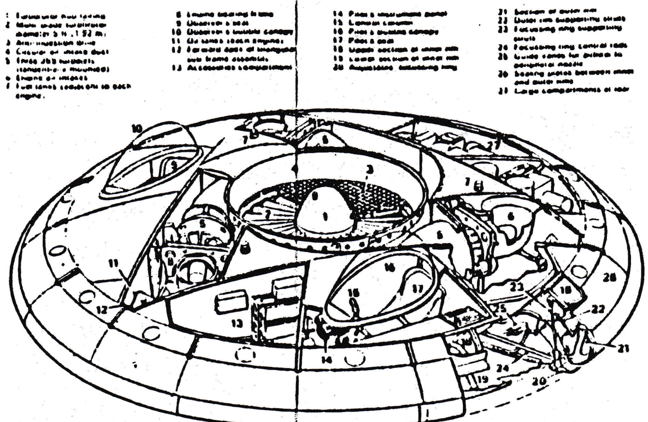

Figure 9. AVROCAR Cut-Away

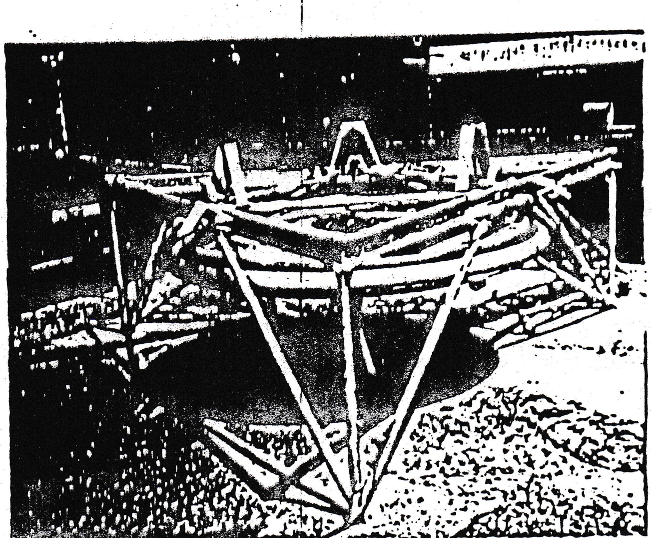

Figure 10. Static Rig

During the period of 9 June through 21 October 1959, 44 separate tests were conducted. From the onset the AVROCAR was beset with high jet intake temperatures caused by ingestion of excessive exhaust gases. Many design changes were accomplished over the four month period and some improvements were obtained, but at the conclusion of the static tests it was only possible to run the J-69 engines at 95 percent RPM. To improve this performance it was apparent that major analysis and redesign were necessary. Notwithstanding, the decision was made to initiate ground effect hovering flights. Simultaneously, evaluation of the AVROCAR turborotor was accomplished by Orenda Engines Limited.

The AVROCAR Turborotor was a single stage axial-flow fan driven by a turbine fixed to the tips of the fan rotor blades. This single stage turbine was driven by the exhaust from three J-69 engines. The design point for the AVROCAR fan was:

Air flow weight	550 lb./sec
Total pressure ratio	1.1
Speed	2780 rpm

The final configuration test provided the following test results:

Air flow weight	340 lb./sec
Total pressure ratio	1.1
Speed	2570 rpm

The reasons for the unsatisfactory performance were as follows:

a. Inlet conditions forced the compressor to operate far from the design point towards stall.

b. There was a heavy boundary layer at the compressor inlet, together with apparent stalling of the fan blade tips which resulted in a flow deficiency of about six percent at any operating point.

c. The turbine produced less than design power, consequently design speed of the fan was not achieved using full power of the jet engines exhaust. Note: These tests were performed on an Orenda test rig where full power of three J-89 engines could be simulated.

d. During these tests it became readily apparent that there were excessive losses in the downstream ducting system. During the test periods many changes were made in an attempt to improve the deficiencies, but large losses still remained at the conclusion of the static rig tests.

V Summary of Aircraft Performance (Vertical Lift):

a. Unacceptable inlet temperatures prevented J-69 100 percent rpm (95 percent maximum).

b. Turborotor performance problems limited the turbo fan blades to 2570 rpm.

c. Excessive downstream duct losses were never fully resolved.

d. The final static rig maximum lift (out of ground effect) obtained was 3,150 pounds. This compared to a design goal of over 5,000 pounds of lift out of ground effect.

VI Controls:

This fully reactive control system was complex. Flight control was derived from the turborotor air being fed in diffuser ducts, formed by the primary structure and expelled from annular nozzles at the wing periphery and in the undersurface of the vehicle. The direction in which the air was deflected was controlled by positioning spoiler rings located in the throats of the peripheral nozzle. Raising or lowering the spoilers directed the air up, down, or horizontally. Therefore, the spoilers could control and maneuver the aircraft by bending the jet of air differentially over opposing sectors of the periphery. The spoilers were designed to rapidly respond to pilot control which allowed, in turn, rapid response of the jet flow. To assist pilot control, the turborotor itself was allowed to "float" a small amount by not being rigidly fixed to the aircraft structure. This allowed the turborotor to act as a gyroscope, pitching or rolling in reaction to outside control forces, thus "damping" outside pitch or roll motions. The relative motion of the gyroscope was stepped up by a mechanical linkage into the central control post. The central control post was directly linked to the spoilers through a number of mechanical cables. This allowed rapid change of spoiler position as the turborotor reacted to outside motions. Pilot control was also directed to the control post by pneumatic bellows. The pilot could override the gyroscope control reaction by such changes. This gyroscopic effect performed the same function as the fixed stabilizer of a conventional aircraft. This reactive control system resulted in creating two undesireable characteristics. In hover, the center of gravity is near the center of the disc or wing. As forward motion is acquired, this center lift moves forward in the disc resulting in a statically unstable aircraft. Secondly, nose-up pitching movement in counteracted by deflecting the propulsive power downward at the rear of the aircraft disc. Loss of propulsive power would mean that the aircraft could not "glide."

To establish control performance the AVROCAR was tested in a tethered mode, (Figure 11), hovered within the ground effect (free flight) (Figure 12) and a full scale model was tested in the NASA AMES 40 foot wind tunnel. During the period of Spetember thru November 1959, 27 tests were accomplished in the

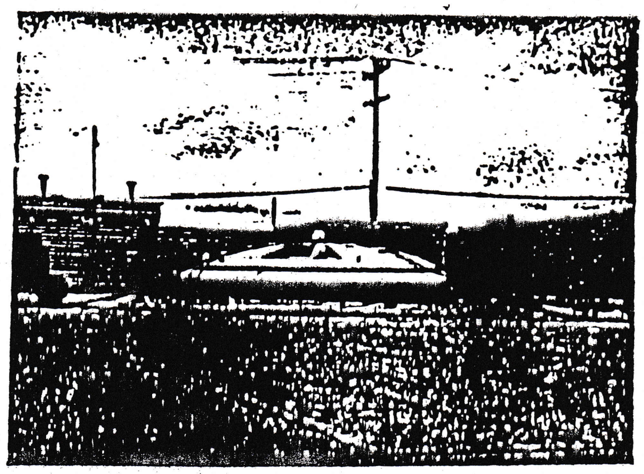

Figure 11. Tethered Rig

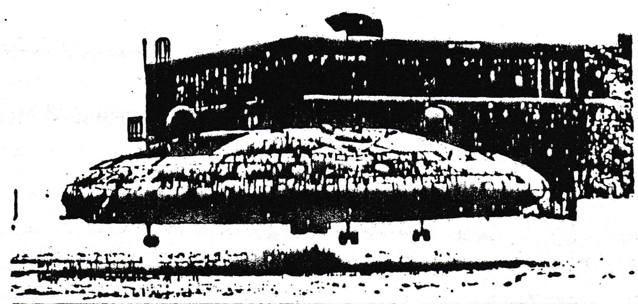

Figure 12. Hovering Test

tethered and free flight modes. This period of time is best characterized as frenzied as many changes to the control system were tried as test results were gathered. The end result was not favorable. Aircraft stability was fair to marginal within the ground effect, but as a height of five to six feet was obtained, violent oscillations occured and power had to be immediately decreased. It was not possible to control the AVROCAR at this critical height where it was apparent that the air cushion itself became unstable (Figure 13). Attempts to alter this instability were not successful. Major changes to the control system were tested, but the end result was the the AVROCAR just could not be controlled above three to four feet in height. During tests at AMES it was demonstrated that the controls were not capable of deflecting the jet sufficiently under forward flight conditions to provide the necessary thrust component or control movements.

VII Summary

To further plague the situation the AVROCAR program entered into an overrun situation primarily

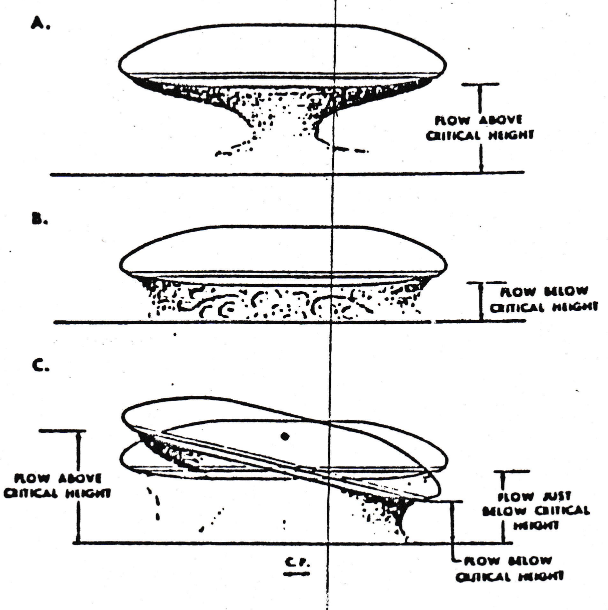

Figure 13. Critical Ground Effect Pattern

caused by extensive changes to the AVROCAR and a lengthened test program. After the last hovering test on 5 December 1959, all work ceased on the AVROCAR program. Subsequent "get well" programs were proposed by Avro Aircraft, but were considered and rejected by the Air Force and in June 1960, the program was terminated.

VIII Lessons Learned

This program was the first serious attempt to exploit the ground cushion effect to create Ground Effect Take-Off. The first and foremost lesson learned was that the design concept was far too complex and consisted of several unproven or never tested concepts. The turborotor design was novel. The circular platform with reactive (mechanical) controls was highly complex. The phenomena of the ground cushion as critical height was obtained proved highly unstable and changeable with attitude adjustments. Utilization of the fan rotor as a gyroscope proved undependable and interjected severe control oscillations. One problem chased another. Inlet temperature caused by the configuration reduced engine RPM capability. The turborotor operated with less than design power and its own inefficiency resulted in major loss of aircraft lift.. The radial ducts and their convoluted shapes further reduced lift and airflow for the reactive flight controls. And finally every change to any part of the overall system affected other parts with negative effects. The result was chasing problems caused by design change from one part of the aircraft to another. It is strongly recommended that any program involving a new or novel concept be kept as simple as possible. Much more attention to the "novel concept" should include extensive exploratory work (analysis and wind tunnel tests) prior to aircraft fabrication. Finally, and most important, with the exception of that portion of the design which is novel (in the case of the AVROCAR it is use of the ground effect) use proven and demonstrated propulsion and control systems. This suggestion does raise another question which can be widely debated. Is it better to design a new platform incorporating the new concept or modify an existing proven aircaft? This author has no further comments on this question. It is interesting to note that the AVRO "concept" was tried again at Bell Aircraft on a Dehavilland Buffalo, and a degree of success was obtained. To this date, however, GETOL has been pigeonholed. Unless some overriding mission requirement dictates another attempt at utilizing the ground cushion in lieu of landing gear, GETOL will remain an interesting concept not fully exploited.

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