Avro Arrow Design

THE development of the Avro Arrow all-weather fighter was due to be described last night at the Royal Aeronautical Society's Fourteenth British Commonwealth Lecture by Mr. J. C. Floyd, A.M.C.T., P.Eng., F.R.Ae.S., F.C.A.I., M.I.A.S., vice-president, engineering, of Avro Aircraft, Ltd. His lecture was entitled, "The Canadian Approach to All-Weather Interceptor Development."

Mr. Floyd ranged widely over all aspects of Arrow development; the account below, based on his lecture, covers the design background to the Arrow and describes its test-flying to date.

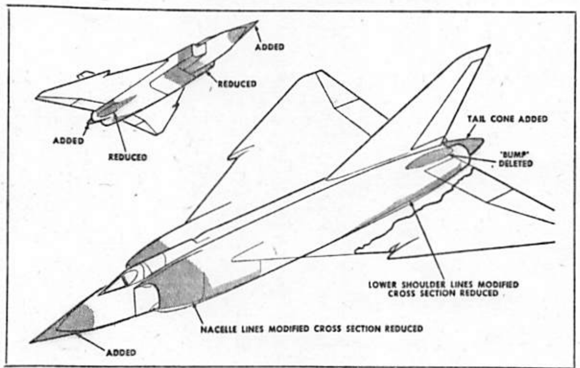
In the autumn of 1952 the R.C.A.F. decided that it would have to replace the CF-100 within a specified time by a supersonic all-weather fighter. The decision to design and develop in Canada was taken entirely because of the peculiar Canadian defence requirements, the non-availability of a suitable weapon elsewhere and the ability to meet Canadian requirements which had already been established by the Canadian aircraft industry. Preliminary design on this aircraft, which was given the project number CF-105, was completed by the summer of 1954. It had two Rolls-Royce RB-106 engines with afterburners and a two-man integrated fire-control system; the armament was a mixture of air-to-air missiles and 2.75-in. air-to-air rockets.

But early in 1954 the RB-106 engine project was abandoned by Rolls-Royce. Orenda were at that time designing a large supersonic engine as a private venture which was well matched to CF-105 requirements but would not be available for the first few aircraft. The Curtiss-Wright J67 appeared to be the most suitable engine for the earlier version and the initial aircraft were therefore designed around it. However, in 1955 it became obvious that the U.S.A.F. was going to abandon the development of the J67, and the Pratt & Whitney J75 was substituted.

Aerodynamically the CF-105 was a considerable advance over contemporary aircraft, and there were few reports or tests available on which to base a firm production design. Stability and control problems were probably the most difficult to assess and an extensive wind-tunnel programme was instituted.

But as the design of the aircraft had to proceed at the same time its basic layout was frozen on the basis of stability and control characteristics largely predicted from theory. By mid-1954 production drawings were going out for manufacture.

A tailless delta was chosen as giving the best compromise between structural and aeroelastic efficiency combined with a thin wing and the large internal fuel capacity needed. A tail was omitted because of the problems involved in putting it on top of a thin fin above the effect of wing downwash or putting it so low, again out of the downwash, that large landing angles would be impossible. In addition, at that time tailed deltas had bad stalling characteristics; the large increase in downwash at the stall made the tail strongly destabilizing.



The shaded areas and modified lines indicate the changes made to the original design of the CF-105 following area-rule studies.

Configuration

The R.C.A.F. had established a requirement for a two-seat twin-engined aircraft. Preference for a crew of two was partly based on the complexity of the newer fire-control systems, and the fact that, while the chosen system was intended to be entirely automatic during the mid-course and terminal phases of the attack, it was the intention to press home an attack on the basis of a manual mode if the automatic mode should fail.

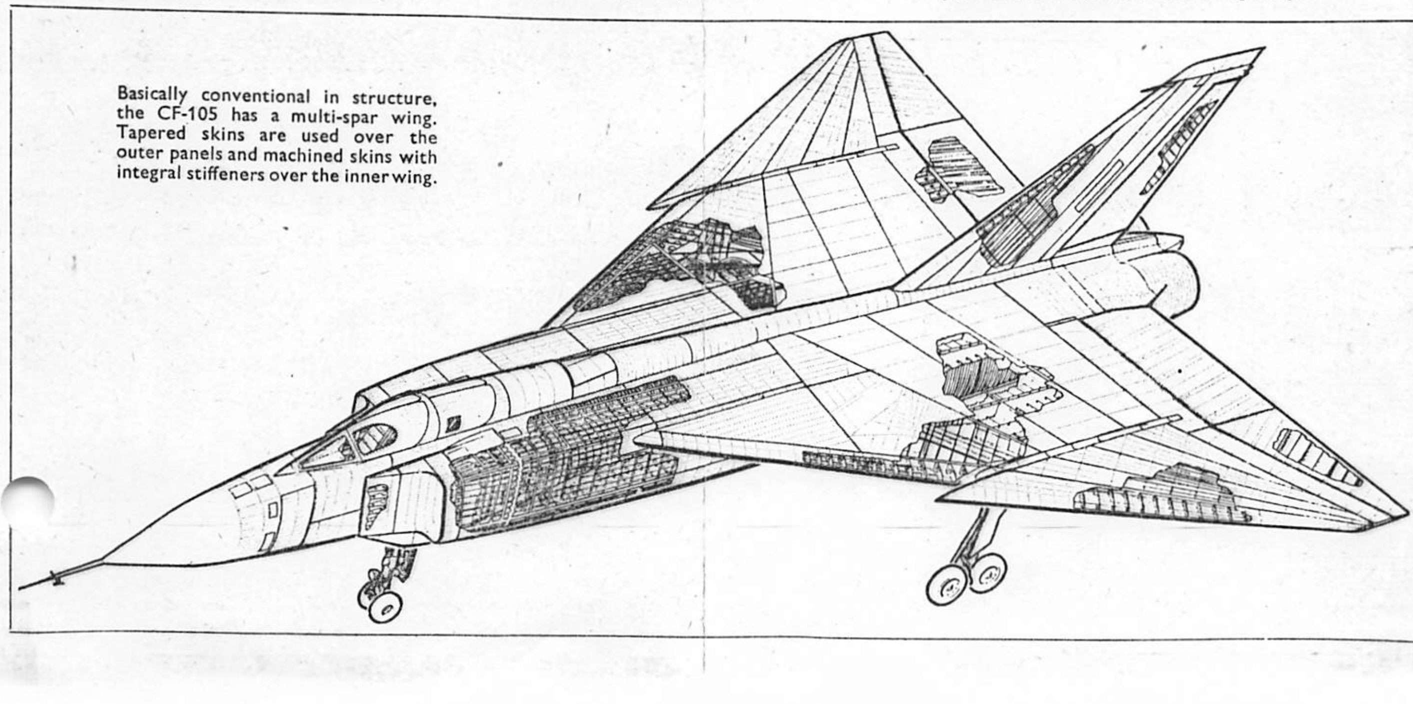
The choice of two engines was based on a combination of circumstances, the advantages being obvious in reduced attrition, especially during training. One of the most important powerplant factors, however, was that with the very large weapon package required as payload, and the large amount of fuel carried for the range requirements, the size of the aircraft was obviously going to be such that there was no single engine large enough to power it.

Aerodynamic design was planned so that aerodynamic speed limits would not be less than the structural ones. The aluminium-alloy structure was good for speeds above Mach 2 and aerodynamic limits were set no lower.

Wing Thickness

To achieve this the thinnest possible t/c ratio was chosen. This was initially 3% over the whole span, but aileron reversal demanded a thicker and stiffer section; finally 3.5% was used at the wing root and 3.8% at the tip. Choice of the delta wing meant that a thin wing section was possible without a large weight penalty. An added advantage of the tailless delta was that the extensive experience of the Avro company at Manchester with delta research aircraft was available for the design.

Aeroelastics played a large part in the design; all types of aeroelastic and flutter problems were examined from first principles



Basically conventional in structure, the CF-105 has a multi-spar wing. Tapered skins are used over the outer panels and machined skins with integral stiffeners over the inner wing.

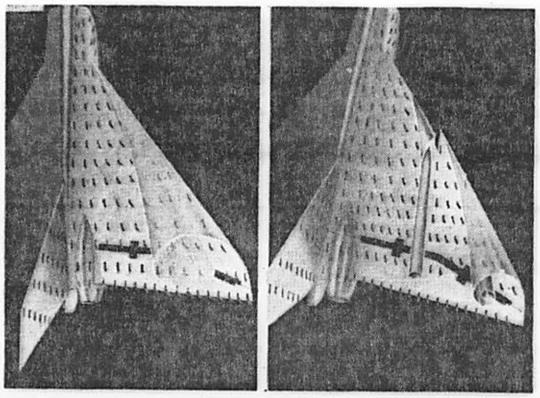
and much work was done with digital computers.

Because of the short elevator arm of the tailless delta, trim drag was a problem. High elevator angles required for trim at high altitude increased the elevator drag considerably. Negative wing camber was introduced to minimize this; this camber, in effect, builds-in elevator angle without excessive control-surface drag. The CF-105 camber of ½% negative was chosen to give a good compromise between the positive angles to trim at low altitude and the negative angles required at high altitude.

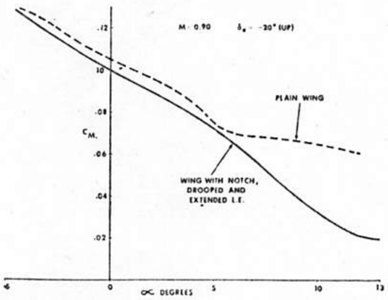
greater flexibility it provided. Engine and armament changes could be made without affecting the basic wing structure, which is carried through the fuselage without a break. This simplifies the wing-to-fin attachment, as it is unnecessary to carry the fin structure down through the engines. The fin has a 4% t/c ratio.

Area Rule

Much theoretical work was done in applying Area Rule to the CF-105 and as a result changes were made at the early design stage to take advantage of it. Eleven 1/30-scale plastic models of the CF-105 were made and



These vortex patterns clearly show the differences in airflow between a plain wing and the one with a notch and extended leading edge which was adopted to avoid pitch-up.



Effect of wing modification is seen in these pitching-moment curves.

A clean wing was chosen originally, but early in the design the wing was modified to have leading-edge droop, a semi-span notch and an outer-wing chord extension. These changes were introduced after tunnel tests had shown a non-linearity in the pitching-moment curve at moderate angles of attack. This pitch-up effect might have caused tightening in the turn.

This condition is, apparently, caused by vortices which start at the tip and move to the apex of the swept wing. Low-pressure air is collected from the fuselage and causes a breakaway outboard of the area covered by the vortex, which is mainly at the trailing edge. The effective aerodynamic centre moves forward, causing the pitch-up.

Tests were made with a notch alone; in effect, this acts as a boundary-layer fence, but produces the same effect over the whole speed range, rather than over the limited speed range for which a fence is effective. But with a notch alone the test results could not always be repeated; the addition of a leading-edge extension greatly improved results. Tests were made with eight different notches and three leading-edge extensions. Notch depth appeared to be the most critical parameter; in practice a very deep notch could not be used because of structural problems.

During design of the wing close attention was paid to the work done on cutting the induced drag of the Convair F-102 by drooping its leading edge (conical camber), and the work done by Avro in Manchester on drooping the Vulcan leading edge to increase the buffet boundary by preventing leading-edge breakaway at high angles of attack.

This work influenced the choice of a 10% chord increase in the outboard leading edge of the CF-105 because this extension would allow the effective wing droop to be increased. Wing droop was installed on the CF-105 wind-tunnel model—8° inboard and 4° outboard. This raised the buffet boundary considerably. At the normal subsonic cruise Mach number the lift coefficient at the outset of buffet went up from 0.26 with the extension alone to 0.41 with the extension plus droop. Supersonic drag did not appear to be increased appreciably.

Avro (Manchester) work on alleviating shock-induced rear separation by vortex generators showed that for a t/c of under 5% this was unlikely to be a problem and thus vortex generators were not used on the CF-105.

No appreciable aerodynamic effect of significance attaches to the 4° anhedral of the CF-105 wing. This was chosen purely to reduce the length of the undercarriage. A high-wing layout was adopted because of the

cuts were taken on them to represent various Mach numbers. The cuts were checked on a planimeter, the results fed into a digital computer and plots made around the aircraft at 0°, 45°, 90°, 135° and 180°. Most of the results were obtained around Mach 1.5 and as a result of this investigation the aircraft's radar nose was sharpened, the intake lips thinned down, the cross-sectional area of the fuselage below the canopy reduced and an extension fairing added at the rear to smooth out the Area-rule curve.

Engine and Intake

The first five CF-105s have Pratt & Whitney J75 engines; the sixth aircraft is the first Mk. 2 with Orenda Iroquois engines. The Iroquois is a two-spool axial-flow gas turbine with a pressure ratio of 8 to 1 at sea-level static conditions. Compressor air is bled for driving air-turbine fuel pumps and for aircraft services.

This engine has an afterburner which is an integral part of the basic engine. Its operation is fully automatic; the engine has a modulated final nozzle which produces the desired thrust-to-temperature relationship at the selected power lever setting.

Intake gills adjacent to the compressor inlet open at M=0.5 and allow air to by-pass around the engine for cooling purposes and to alleviate spillage at high Mach numbers. In this way it is possible to achieve near-optimum performance with the CF-105's fixed-geometry intake in the subsonic, transonic and supersonic speed ranges. If air that could not be swallowed at high Mach numbers by the engine were allowed to spill from the intake lips there would be a high drag penalty, bad pressure recovery in the intake, and possibly destabilizing effects from the spillage air.

The intake has a boundary-layer bleed which diverts two-thirds of the boundary-layer air over the top and bottom of the wing; the other third is taken into the heat exchangers of the air-conditioning system. The 12° intake ramp creates an oblique shockwave at supersonic speeds to allow optimum pressure recovery in the intake. Combined with the normal standing shock this prevents turbulent conditions in the intake over most of the Mach range. Boundary-layer air is sucked through perforations on the face of the ramp; this prevents fluctuating flow or "intake buzz" in the intake.

An integrated electronic system was to have been the brain and nerve centre of the Arrow weapon system. It was a very sophisticated system to provide automatic flight control, airborne radar, telecommunications and navigation, and special instrumentation

The complete weapon pack can be hoisted into position under the Arrow in a matter of minutes.

and pilot displays. It could operate in either fully, automatic, semi-automatic or manual environment. As reported in THE AEROPLANE last week, development of this system has now been cancelled and the Arrow is to be modified to use a system installed in U.S. all-weather interceptors.

The missile weapons of the CF-105 are carried in a large armament bay. A variety of different missiles can be carried in a removable pack which fits into the armament bay.

The basic flying-control system of the CF-105 is fully powered and duplicated. Surfaces are operated by dual jacks supplied by independent hydraulic systems.

Obtaining adequate natural aerodynamic stability for an aircraft with the speed and altitude range of the CF-105 was very difficult, especially because of its low aspect ratio. Directional stability was a particular problem. Longitudinal dynamic stability of the CF-105 was satisfactory at low altitude. Above 40,000 ft. the natural damping required augmentation to make the aircraft an effective weapon-launching platform.

It was decided to obtain the required stability on all axes artificially. As failure of the artificial stability system could be a problem over some areas of the flight envelope, it was decided that the system must have the same or better reliability than a standard power-operated control system.

The first engine-running in the aircraft took place on December 4, 1957, taxi trials were started on Christmas Eve, 1957, and the first flight was made on March 25, 1958.

Stage One of the flight-test programme on the first aircraft covered the period from first flight until April 23, 1958, during which time nine flights were made. The first two flights were for pilot familiarization. The aircraft flew supersonic on the third flight, and on the seventh flight reached a speed well over 1,000 m.p.h. at 50,000 ft. in a climb while still accelerating.

Practically all of the flights have been made at a weight considerably in excess of the mission weight estimated for the Mk. 2 operational aircraft, as the installed weight of the J75 engines is higher than that of the Orenda Iroquois, and ballast is also required in the nose to balance this extra weight. Average take-off weight has been around 57,000 lb., and landing weights have been around 54,000 lb.

The following comments were extracted from the pilots' reports:—

The nosewheel can be lifted off by very gentle movement of stick at just over 120 knots.

Unstick speed is about 170 knots A.S.I., with an aircraft attitude of about 11°.

Acceleration is rapid, with negligible correction required and no tendency to swing.

Typical touch-down speed is a little over 165 knots. (The normal landing procedure is to stream the drag 'chute on touch-down when the nosewheel has settled.)

There was no indication of stalling at the maximum angle of attack at 15°.

Stability steadily improved with speed.

Change of trim was negligible except in the transonic region, where small changes of trim were required.

No attention was required by the pilot to prevent over-controlling.

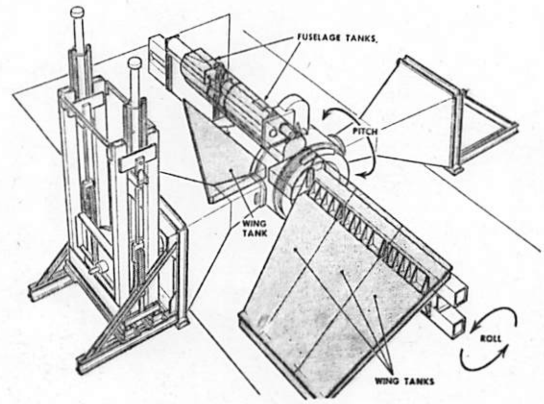
In turns, stick force was moderate to light, but always positive, with no tendency to pitch up or tighten.

In sideslip, the aircraft was a little touchy without the damper, but excellent with damper switched on.

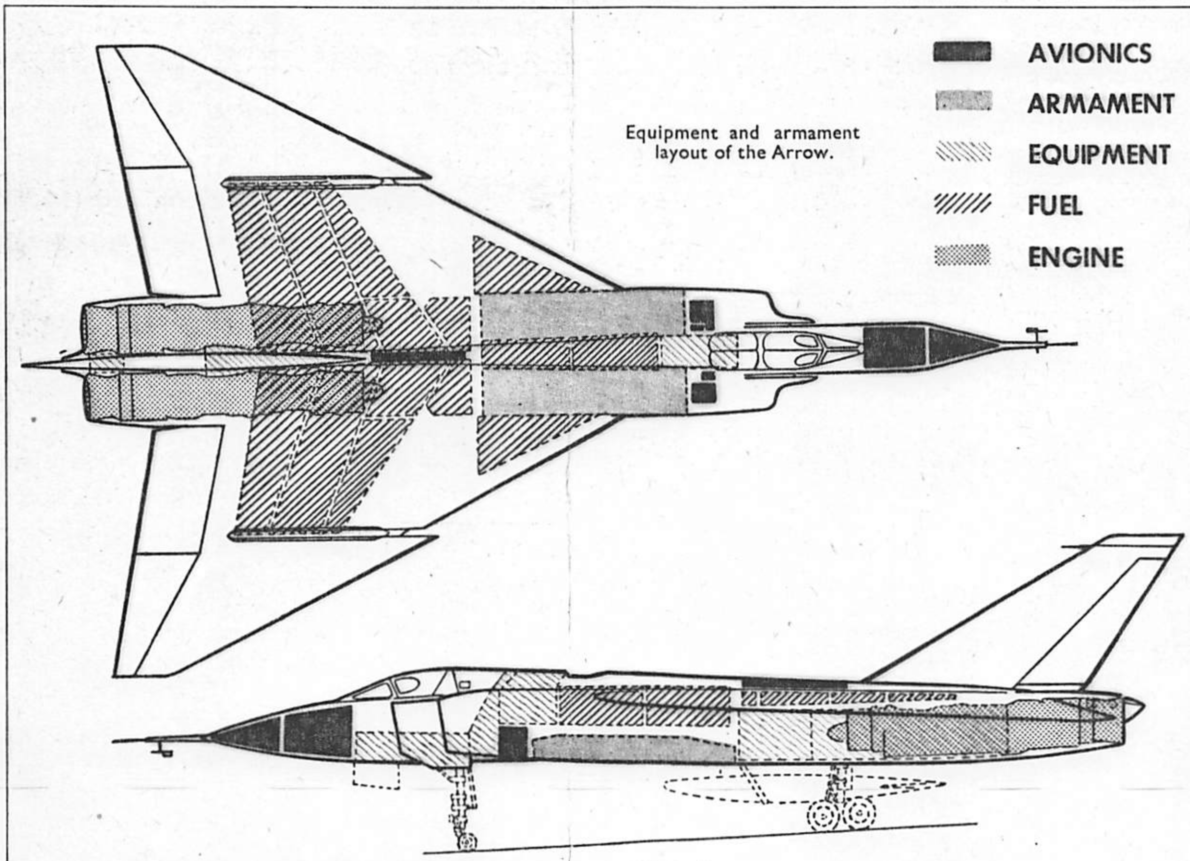
To quote the pilots: "In general, the handling characteristics and performance of the aircraft agreed well with estimates."

After Stage One flying the first aircraft was given a thorough inspection, and was flying again on June 7 on Stage Two testing. On the 11th flight, on June 11, the port undercarriage leg twisted on landing and put the aircraft out of commission for several months.

Aircraft 2 and 3 have now taken over the bulk of the current test programme and, in proving the flight envelope, have flown at speeds considerably in excess of those achieved on the first aircraft.



A sketch showing the general layout of the fuel system test rig used in development of the Arrow.



Equipment and armament layout of the Arrow.