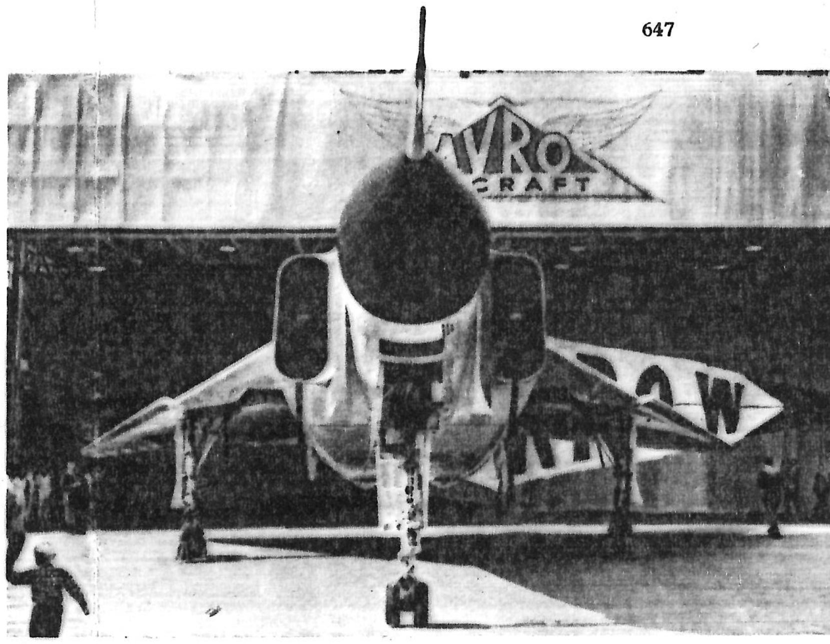
ARROW

A World-leading Intercepter by Avro Aircraft

By THE TECHNICAL EDITOR



EARLIER this month Avro Aircraft, Ltd., one of the chief member-companies of the Hawker Siddeley Group, conducted a significant ceremony at their factory at Malton, near Toronto. At ten minutes past three on the afternoon of October 4 the Hon. George R. Pearkes, V.C., Canadian Minister of National Defence, pulled a cord which opened wide the large curtain seen in the background to the picture on the right. Through the opening came a lowly tractor; and behind it appeared the biggest, most powerful, most expensive and potentially the fastest fighter that the world has yet seen—the CF-105 Arrow.

We in Britain have nothing like it. Two years ago we curtailed the development of a machine which would have begun to approach it—the so-called "thin-wing Javelin"—and have since relied implicitly on a superb electronic defence environment and relatively small weapons such as the English Electric P.1B and Thunderbird and the Bristol Bloodhound. Even the U.S.A. has nothing like the Arrow; yet in that country the development of manned intercepters is by no means dead. North American Aviation hold a development contract from the U.S. Air Force in respect of Weapon System 202A, which enjoys a development priority equalled by only one other U.S.A.F. aeroplane. The vehicle for this weapon system will be the F-108, a chemical-fuel aircraft intended to reach at least Mach 5 (a scarcely credible figure).

In the face of such sophisticated defence systems as those of the U.S.A. and the NATO countries it may seem surprising that Canada should pour out literally hundreds of millions of dollars upon the development of an indigenous intercepter for the R.C.A.F. On a recent visit to the Dominion the writer found no shortage of Canadians who are only too eager to point out ways in which this money could be better spent—and not all of them had a commercial axe to grind. Yet when one really studies the Arrow programme it makes sound sense and gradually materializes as something which may well prove to be a very wise investment. Not only is it the only weapon which can meet the future defence requirements of the R.C.A.F. but it is also the only aeroplane of any type in the British Commonwealth which can fly at more than twice the speed of sound; moreover, it can hold its maximum speed indefinitely. Such aeroplanes are going to be of inestimable value, and one this year is worth several next year.

Considered solely as a weapon system, the chief *raison d'être* of the Arrow is to be found in the enormous extent of the area which it is designed to defend. Including her numerous water areas Canada covers no less than 3,737,923 square miles, and is thus much larger than Europe or the U.S.A. During the past five years the electronic defence systems of North America have improved out of all recognition, and there exists today a formidable barrier of long-range radars and fighter bases all controlled from a unified H.Q. in the State of Colorado, U.S.A. Yet this "infrastructure" is of no value unless the means exist to intercept and destroy any raiding bomber which might be encountered. Nothing at present available can do this, unless one is prepared to finance the cost of not merely dozens but hundreds of bases for such devices as Bloodhound, Bomarc and Nike Hercules. It is a job which calls for a big, long-range, piloted aeroplane, with a flashing performance and all the tools of the intercepter's trade.

It is fitting that the mighty task of producing such a weapon should fall to Avro Aircraft, since that youthful company was responsible for Canada's first home-defence intercepter (it was also the first all-Canadian aeroplane and the Dominion's first jet aeroplane). The prototype of this machine, the CF-100, flew in January 1950. Under the impetus of Avro's dynamic president, Crawford Gordon Jr., appointed in October 1951, large scale production of the CF-100 started. Only now is this tapering off, with more than 600 of the big machines delivered to the R.C.A.F. and a substantial number still on order both for that service and for the Royal Belgian Air Force. There are some who would denigrate it; yet the success of this all-Canadian aircraft represents a tremendous achievement which has done much to instil into Canadians a long-overdue appreciation of their ability to design and build advanced aircraft fully comparable with those of America, Britain or any other country. This self-confidence must be regarded as a pre-requisite to the successful development of the CF-100's successor.

Avro began to evaluate project studies for such a successor in 1951. It was in September of that year that the company worked three possible studies into a brochure which, to start the ball rolling, was then submitted to the R.C.A.F. in Ottawa. One of the three projects faintly resembled the Gloster Javelin, with two Sapphire 4 engines. This was used by the Canadian air staff as the basis for an Operational Requirement for an all-weather intercepter capable of carrying missiles internally and—this was the real challenge—of catching supersonic bombers at high altitude.

This O.R. specification was received by Avro in March 1952. To find the optimum configuration to meet it, the company set to work on further designs. All of these employed delta wings (and, unlike the Javelin, no horizontal tail). Only by adopting the delta shape could wing depth be made sufficient to accommodate the undercarriage and the requisite quantity of fuel; and at the same time it provided ample area for high-altitude manœuvrability and permitted a fairly light and easily made structure. Finally, the Avro team chose two geometrically similar wings, and planned around them two projects, under the company numbers C104/1 and C104/2 (the C103 was a swept version of the CF-100).

Although both the C104 studies were intended to carry similar armament and to seat a pilot and navigator in tandem—Canada did not subscribe to the doctrine of the single-seat "automatic" intercepter, of the type then sponsored by the U.S.A.F.—they differed markedly in size and, to an even greater degree, in weight. The 104/1 was a design for a single-engined machine in the class of the F-106B, powered by either the Avro T.R.9 (a project which later was developed into the Orenda Iroquois), the Bristol Olympus 3 (a high-rated project intermediate between the Olympus 100 and 200 series) or the Wright J67 (an American development of the Olympus 100 series). It was to have an armament of both guided (Velvet Glove) and spin-stabilized missiles fired automatically by an advanced electronic system. The 104/2 was considerably larger—much bigger even than the Javelin—and was to have had two of whichever of the above three powerplants was selected.

Both configurations of the C104 were evaluated by the National Aeronautical Establishment in Ottawa, whose resulting recommendations were submitted in October 1952. While agreeing with Avro that the C104/2 would have higher performance and reliability than would its single-engined competitor, and was preferable on a number of other counts, the N.A.E. felt that the design as submitted could be refined to reduce weight and increase all-round performance. This was made particularly necessary owing to a number of changes in the R.C.A.F. requirement, the most demanding of which was an increase in the specified operational altitude. Accordingly Avro developed an improved configuration under the company designation C105. Compared with the C104/2 the new proposal was more compact and lighter, and promised to meet all the revised requirements admirably. It was submitted to the R.C.A.F. in June 1953.

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By September the first tunnel-model had begun to yield readings, and since that time several thousand tunnel hours have been logged on C105 configurations at all speeds up to more than Mach 2 (just how much more we may not say). The total number of tunnel models constructed was 17, ranging in scale from 1/80 to 1/6, and these were tested chiefly at the N.A.E., at the Langley Aeronautical Laboratory of the N.A.C.A. and at the Cornell Aeronautical Laboratory. Nevertheless, even the excellent facilities thus made available could not fully explore the whole flight envelope of the C105 without introducing complications and possible inaccuracies. To fill in the gaps Avro established a programme of free-flight model testing, using ballistic air-dropped models and large-scale models with solid-propellant boost motors. Nine of the latter were fired at the range of the Canadian Armament Research and Development Establishment at Port Petrie, Ontario, and two more were tested at the N.A.C.A. Pilotless Aircraft Research Station at Wallops Island, Virginia, the work occupying from December 1954 to January of this year.

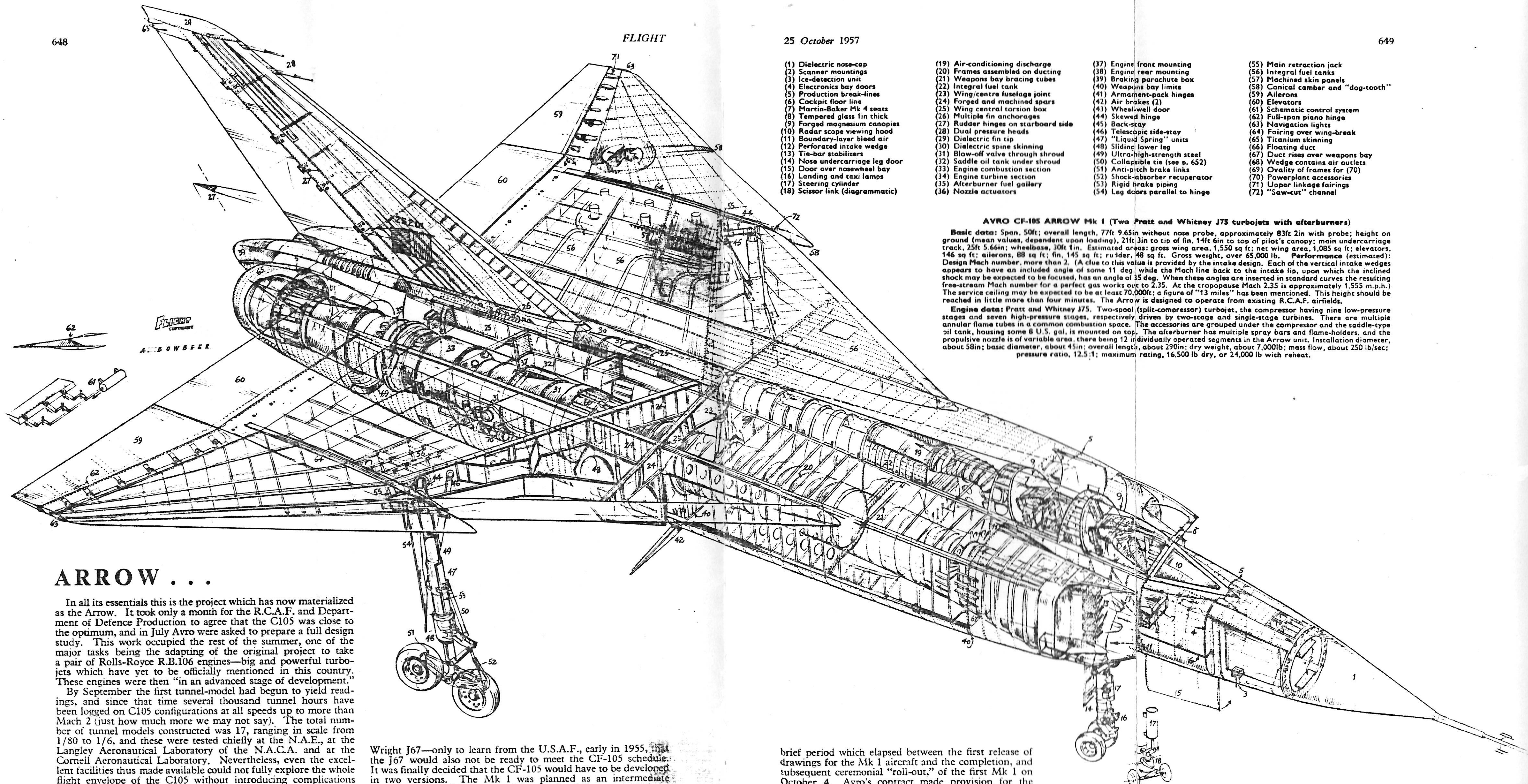
During 1954, when the preliminary design was complete, the R.C.A.F. adopted the CF-105 designation, and the whole project moved into the detail stage. Configuration was fixed in a form which has only altered in minor details since, and the complete CF-105 weapon system was planned, with Avro acting as the prime contractor for all of it (thus breaking new ground in Canada). But progress was soon retarded by the prospect of unavailability of the R.B.106 engine, and Avro turned back to the Wright J67—only to learn from the U.S.A.F., early in 1955, that the J67 would also not be ready to meet the CF-105 schedule. It was finally decided that the CF-105 would have to be developed in two versions. The Mk 1 was planned as an intermediate development machine, powered by a pair of Pratt and Whitney J75s. The Mk 2 was foreseen as the definitive operational machine, with two of the more powerful Orenda PS.13 engines (since named Iroquois).

During 1955 an engineering mock-up was built, and almost at once it was changed to accommodate the Pratt and Whitney engines. This mock-up was evaluated by the R.C.A.F. in February 1956 and on the same occasion a mock-up of the armament pack then envisaged was assessed. By 1956 the mock-up was again being worked upon, first in order to fit it for the Iroquois engine and later in order to convert it completely to the configuration of the Mk 2 aircraft. This had to be done relatively early in order to permit all necessary modifications to be incorporated in the Mk 2 engineering-release.

Illustrated in a diagram on page 650 is the remarkably rapid progress of the CF-105, and it particularly emphasizes the brief period which elapsed between the first release of drawings for the Mk 1 aircraft and the completion, and subsequent ceremonial "roll-out," of the first Mk 1 on October 4. Avro's contract made provision for the manufacture of a small batch of Mk 1s, and these are at present in various stages of construction. Production tooling has been used from the outset and should production be ordered it will undoubtedly build up in Cook-Craigie fashion. The tooling methods adopted by Avro can be described in some detail, and are of exceptional interest; but it is appropriate first to outline the general characteristics of the CF-105 itself (the aircraft was named Arrow early this year).

Probably the most fundamental foundation upon which a designer plans a new aeroplane is the type of wing which is chosen. As already noted, Avro's preliminary design office, under Jim Chamberlain (now chief of technical design) adhered throughout to the delta. The Arrow wing is, however, in no way related to that of the other Hawker Siddeley Group deltas, the Javelin and Vulcan. The British deltas are subsonic aircraft, and the Arrow is the first supersonic design actually to be completed by the Group, the Gloster "thin-wing Javelin," Avro (Manchester) 720 intercepter, Avro 730 bomber and Avro 731 research aircraft projects all having been cancelled while in the development stage.

In the initial stages of the design Avro aimed at the very ambitious thickness/chord ratio of 3 per cent, a ratio lower than that of any Western aeroplane yet to take the air. It soon became clear, however, that the percentage would have to be allowed to rise, even if only slightly, if the main undercarriage



(1) Dielectric nose-cap
(2) Scanner mountings
(3) Ice-detection unit
(4) Electronics bay doors
(5) Production break-lines
(6) Cockpit floor line
(7) Martin-Baker Mk 4 seats
(8) Tempered glass 1in thick
(9) Forged magnesium canopies
(10) Radar scope viewing hood
(11) Boundary-layer bleed air
(12) Perforated intake wedge
(13) Tie-bar stabilizers
(14) Nose undercarriage leg door
(15) Door over nosewheel bay
(16) Landing and taxi lamps
(17) Steering cylinder
(18) Scissor link (diagrammatic)
(19) Air-conditioning discharge
(20) Frames assembled on ducting
(21) Weapons bay bracing tubes
(22) Integral fuel tank
(23) Wing/centre fuselage joint
(24) Forged and machined spars
(25) Wing central torsion box
(26) Multiple fin anchorages
(27) Rudder hinges on starboard side
(28) Dual pressure heads
(29) Dielectric fin tip
(30) Dielectric spine skinning
(31) Blow-off valve through shroud
(32) Saddle oil tank under shroud
(33) Engine combustion section
(34) Engine turbine section
(35) Afterburner fuel gallery
(36) Nozzle actuators
(37) Engine front mounting
(38) Engine rear mounting
(39) Braking parachute box
(40) Weapons bay limits
(41) Armament-pack hinges
(42) Air brakes (2)
(43) Wheel-well door
(44) Skewed hinge
(45) Back-stay
(46) Telescopic side-stay
(47) "Liquid Spring" units
(48) Sliding lower leg
(49) Ultra-high-strength steel
(50) Collapsible tie (see p. 652)
(51) Anti-pitch brake links
(52) Shock-absorber recuperator
(53) Rigid brake piping
(54) Leg doors parallel to hinge
(55) Main retraction jack
(56) Integral fuel tanks
(57) Machined skin panels
(58) Conical camber and "dog-tooth"
(59) Ailerons
(60) Elevators
(61) Schematic control system
(62) Full-span piano hinge
(63) Navigation lights
(64) Fairing over wing-break
(65) Titanium skinning
(66) Floating duct
(67) Duct rises over weapons bay
(68) Wedge contains air outlets
(69) Ovality of frames for (70)
(70) Powerplant accessories
(71) Upper linkage fairings
(72) "Saw-cut" channel

AVRO CF-105 ARROW Mk 1 (Two Pratt and Whitney J75 turbojets with afterburners)

Basic data: Span, 50ft; overall length, 77ft 9.65in without nose probe, approximately 83ft 2in with probe; height on ground (mean values, dependent upon loading), 21ft 3in to tip of fin, 14ft 6in to top of pilot's canopy; main undercarriage track, 25ft 5.66in; wheelbase, 30ft 1in. Estimated areas: gross wing area, 1,550 sq ft; net wing area, 1,085 sq ft; elevators, 146 sq ft; ailerons, 88 sq ft; fin, 145 sq ft; rudder, 48 sq ft. Gross weight, over 65,000 lb. **Performance** (estimated): Design Mach number, more than 2. (A clue to this value is provided by the intake design. Each of the vertical intake wedges appears to have an included angle of some 11 deg, while the Mach line back to the intake lip, upon which the inclined shock may be expected to be focused, has an angle of 35 deg. When these angles are inserted in standard curves the resulting free-stream Mach number for a perfect gas works out to 2.35. At the tropopause Mach 2.35 is approximately 1,555 m.p.h.) The service ceiling may be expected to be at least 70,000ft; a figure of "13 miles" has been mentioned. This height should be reached in little more than four minutes. The Arrow is designed to operate from existing R.C.A.F. airfields.

Engine data: Pratt and Whitney J75. Two-spool (split-compressor) turbojet, the compressor having nine low-pressure stages and seven high-pressure stages, respectively driven by two-stage and single-stage turbines. There are multiple annular flame tubes in a common combustion space. The accessories are grouped under the compressor and the saddle-type oil tank, housing some 8 U.S. gal, is mounted on top. The afterburner has multiple spray bars and flame-holders, and the propulsive nozzle is of variable area, there being 12 individually operated segments in the Arrow unit. Installation diameter, about 58in; basic diameter, about 45in; overall length, about 290in; dry weight, about 7,000lb; mass flow, about 250 lb/sec; pressure ratio, 12.5:1; maximum rating, 16,500 lb dry, or 24,000 lb with reheat.

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units were to be stowed inside. Another figure fixed early in the design was the leading-edge sweep angle of 61 deg. Instead of drag-producing fences, Avro decided to maintain chord-wise flow by using "saw-cuts" of the type fitted to the P.1.

Tunnel testing showed that the original wing could not achieve optimum performance under conditions of high angle of attack, and progressive modifications were introduced as a result of later aerodynamic data. The chief alterations made were the incorporation of conical camber and a dog-tooth leading edge. Conical camber, briefly described in an analysis of the F-102 aircraft in our issue of April 19 last, consists of a progressive drooping of the leading edge from the root outwards, so that the tips meet the incident air at a marked negative angle of attack. It has the effect of reducing induced drag and is especially beneficial at high altitude (it is a feature of the Vulcan B.2). The dog-tooth provides a marked "kink" in the leading edge plan-form which creates a vortex to improve flow over the outer wings, particularly at high angles of attack, without incurring the penalties of "turbulators." The revised wing has an increased sweep-angle of 63 deg 30 min on the outer panels.

These sweep angles are enough to provide tremendous axial dimensions across the wing, and the root chord is more than 440in (for comparison, the corresponding dimension on the Brabazon was 372in). This is ample to provide a moment-arm for elevators mounted at the trailing edge, and a horizontal tail has therefore been dispensed with. Fully powered control surfaces are mounted on the wing in four sections from tip to tip, the inboard pair being elevators and the outboard controls being ailerons. Just over half way from the aircraft centre-line to the wing tip is a major structural joint between the inner wing and the outer wing; the inboard section is used as an integral tank and also accommodates the complete main undercarriage units. As a small diagram on p. 651 indicates, the wing is further sub-divided along spanwise joints, and the control surfaces are separated from the wing proper by the control boxes.

Turning to the fuselage, this can be described rather rudely as a rectangular box, roughly the same width as the hull of a DC-7 or Stratocruiser, with a narrower, needle-like nose projecting from the front. From front to rear this structure measures nearly 80ft and houses, in order, a radar fire-control, a pressurized cockpit for pilot and navigator, a fuel tank surrounded by air ducts on either side and a weapons bay underneath, and a pair of exceedingly large and weighty aero engines, complete with afterburners. At the rear, the body depth is decreased so that it can fit directly beneath the wing, and the big, swept vertical tail (the area of which was increased during Arrow tunnel-testing) is joined along the rear, upper centre-line to complete the basic airframe.

It is appropriate now to describe in some detail the tooling methods which Avro Aircraft have adopted for the Arrow, since these are of outstanding interest and break new ground in several respects. As previously noted, the shape of the aircraft was determined by extensive tunnel testing, as a result of which it was possible to determine the basic lines of the airframe with a very high degree of accuracy. These lines were then used to control the construction of full-scale master models. These masters served two purposes: first, they proved the lines by the act of splining in the templates and, second, by filling in each model three-dimensionally to the correct skin-profile, they provided an accurate pattern for the manufacture of production tooling.

Initially, all sheet-metal drawing is done on thin glass-cloth using an ordinary pen, this material having flexibility, durability and excellent dimensional stability. Master control templates, or M.C.T.s, are prepared by exposing photo-sensitized 0.051in dural sheet for $2\frac{1}{2}$ min against the glass-cloth drawing (for identification purposes, M.C.T.s for the Arrow Mk 2 are tinted pink). Templates too large to be reproduced from a single drawing (the limit is 16ft × 4ft 6in) are built up from sections which are spliced together with butt-joints. Symmetrical patterns are formed by printing from both sides of a half-drawing terminated at the axis of symmetry.

Two M.C.T.s are produced, one of which is retained in an *ad hoc* library and the other is built into the master model of the part concerned. The master models are each built up on a surface-table, upon which is mounted a vertical steel column with a true square section to provide four faces from which to work. On these faces the M.C.T.s are positioned by an optical transit method and finally clamped, dowelled and riveted. When all templates have been proven, tie-rods are pushed through holes about an inch in from the edge of each template and the entire master is then wrapped in brass or bronze mesh, upon which is laid Kish Epoxy 203 or 407, a low-cost plastic with an asbestos filler which is built up to within about one-eighth of an inch of the finished surface. The final contour is achieved by applying a finish-coat of 418T splining resin, which is trowelled precisely to the template contour. This plastic is bought by Avro for about 95 cents per pound, but considerable quantities are required for each master model. When the plastic has been applied and smoothed, the contour between the M.C.T.s is determined by working over the face of the model between each adjacent pair of templates with a carefully profiled flexible wooden strip coated with red crayon on the face adjacent to the model. All high-spots stand out in red, and the facing is then scraped by hand to produce the required finish. The model is completed by the addition of station, trim, tangency and butt-joint lines.

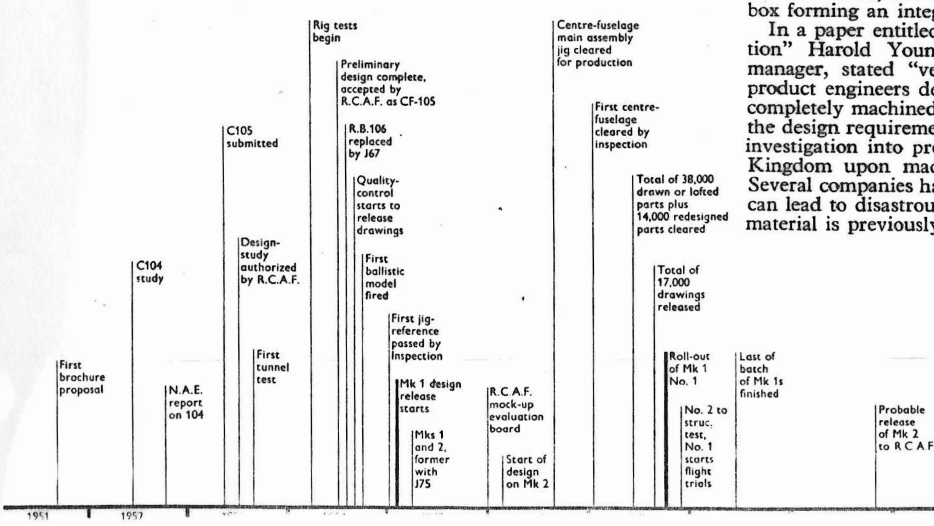
After splining the master templates, corrections may be made to the original glass-cloth drawing. Stretch-press or drop-hammer tooling can be made direct from the master, after which the first aircraft parts are brought back to the master for checking. The drop-hammer tools are generally of Kirksite, with about $\frac{3}{8}$in of cast Epoxy superimposed. Glass-cloth drill and router jigs are located directly on the master model, and rubber baskets, drill jigs and stretch moulds may also be reproduced direct from the master, a foam core being used to lighten the tools for the largest parts. Skin panels with particularly difficult contours can be reproduced by tracing from the master on to a sheet of vinyl and then developing on to the flat.

Throughout the tooling programme, preparations for production have followed immediately upon engineering-release of each detail part. Following a practice which seems to be essential if advanced aircraft are to be developed in a reasonable time, there is no prototype and the first machine built is being immediately backed up by several other Arrow Mk 1s, after which the Arrow Mk 2 follows with a very slight delay. Complete interchangeability has been achieved from scratch.

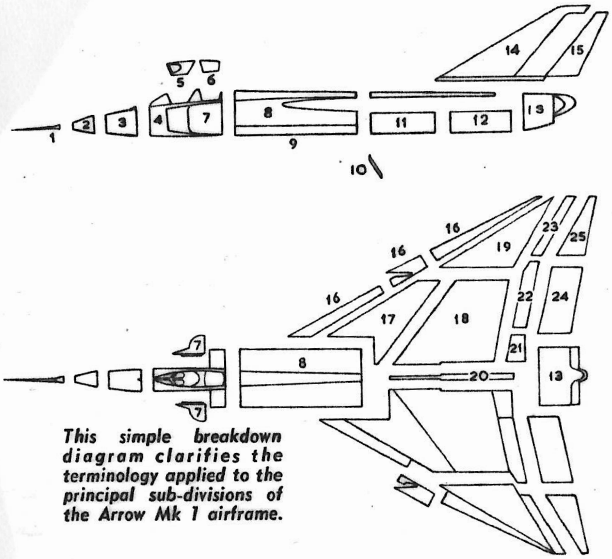
Before describing the jigging and the assembly methods followed during the erection sequence, it is appropriate to describe the airframe of the Arrow insofar as security permits. This description has been deliberately reduced in scope to meet a request by security officials in Ottawa.

Port and starboard halves of the wing-group are manufactured separately, and are joined by massive forged transverse members and bolt-rows close to the axis of symmetry. The inner wing forms the basis for the whole aircraft and comprises a leading-edge portion, a front portion, a main torque box, a trailing-edge portion (which acts as a housing for the powered controls) and the elevators. All the main sections are built in vertical jigs. The main central portion of the inner wing could be described as the backbone of the structure, and it is immensely strongly made with heavy machined skins and multiple forged spars and chord-wise members, the whole assembly being built up into a sealed box forming an integral tank.

In a paper entitled "Machining Approach to Aircraft Production" Harold Young, the company's production engineering manager, stated "very early in the design-scheme stages our product engineers determined that integrally stiffened skins and completely machined structural members were necessary to meet the design requirements." His department conducted a thorough investigation into previous experience in the U.S.A. and United Kingdom upon machining from rolled plate and solid billets. Several companies have learned to their cost that such operations can lead to disastrous distortion of major work-pieces unless the material is previously stress-relieved in a stretch-press (for which

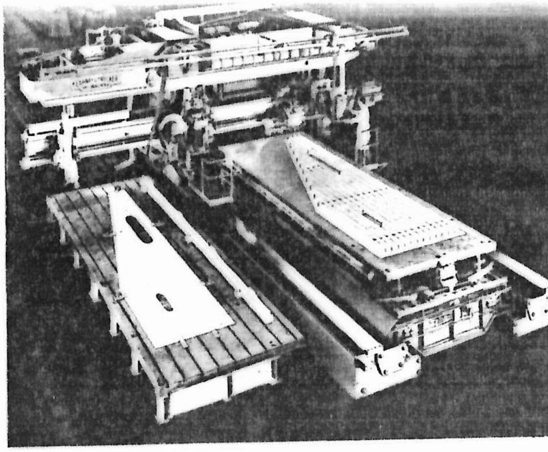


The diagram on the left outlines some of the important milestones in the Arrow development-cycle. Avro claim that the man-hours per pound ratio for the first Mk 1 is only about 80 per cent of the mean N. American value for comparable projects; in any case, the two thickened vertical lines are commendably close.



(1) Probe
(2) Radome
(3) Radar fire-control
(4) Front fuselage
(5) Pilot's canopy
(6) Navigator's canopy
(7) Air intakes
(8) Centre fuselage
(9) Armament pack
(10) Air brakes (2)
(11) Duct bay
(12) Engine bay
(13) Rear fuselage
(14) Fin
(15) Rudder
(16) Leading edge of inner wing, outer wing and transport joint
(17) Front inner wing
(18) Main torque box
(19) Main outer wing
(20) Wing centre box
(21) Inner trailing edge, inner wing
(22) Outer trailing edge, inner wing
(23) Trailing edge, outer wing
(24) Elevator
(25) Aileron

This simple breakdown diagram clarifies the terminology applied to the principal sub-divisions of the Arrow Mk 1 airframe.



Described in column 1 below, this Kearney and Trecker skin mill is one of the largest machine tools ever to be bought by an aircraft company. The work table is 28ft by 9ft, and a further indication of scale is provided by the operator.

purpose a stretch of some 2 per cent is required). In the basic design of the Arrow the maximum size of commercially available stress-relieved plate was limited to a cross-sectional area of 140 sq in (maximum plate thickness 3in), a value dictated by the limiting pull of 6,000,000 lb of the largest existing stretch-press. Plate thickness and cross-section may very shortly be doubled.

Avro do not inspect all the heavy plate coming in for Arrow production, but conduct spot-checks with ultrasonic reflectoscopes to determine the inclusion content. All stretcher-stress-relieved plate is received fully heat-treated and is machined in that condition. Such material is employed for approximately 85 per cent of the heavy machined portions of the Arrow airframe, the remainder being hand forgings.

The photograph above shows the 200-ton Kearney and Trecker skin mill which went into operation at Malton thirteen months ago. This is the biggest mill ever made by this famous company. It was constructed to Avro specifications and, although it cost Kearney and Trecker over $1m, Avro were charged only $350,000 and the Milwaukee company are now recovering on further sales at a price of $600,000. As used by Avro at present, the work-table is 28ft × 9ft, although extra sections can be added. In order to minimize floor-space, the table is stationary and the cutters are mounted on an overhead gantry. Basic gantry speed is 30in/min, but on a straight-through cut with rise-and-fall tracer control a feed of 100in/min is possible, while for conventional milling the speed may rise to 160in/min, and 240in/min is adopted for rapid traversing without cutting. The mighty work-pieces are retained by a universal vacuum chuck built into the table which is pivoted on a vertical axis to allow milling of tapering webs. Machining is conducted on a direct copying basis from a template, mounted on an adjacent table, across which moves a stylus with an 8-oz contact pressure; the stylus readings are transmitted to an electronic centre which releases the desired pattern to the 70-ton cutter head. The latter comprises horizontal and vertical heads, one rated at 50 h.p. at 1,800 r.p.m. and the other at 100 h.p. at 3,600 r.p.m.; both heads can tilt up to 5 deg.

To watch this mill at work is quite an experience. A typical slab of high-strength light alloy for an Arrow wing skin goes on to the work-table weighing some 3,300 lb. Using a 10in diameter cutter at 3,600 r.p.m., and employing rise-and-fall tracing for thickness-variation, it is possible to maintain a feed of 100in/min on a cut 1½in deep and 2½in wide, with a resulting metal-removal rate of 375 cu in/min. During test-runs 9ft/min was held on a cut 2¾in × 1¾in. The coolant system provides a flood-flow of over 62 Imp. gal/min in order to maintain correct tool temperatures; while, to keep the machine from burying itself in chips, the swarf roars on to a conveyor belt which feeds mobile scrap-bins. Finally the machined skin comes off the bed with a weight of 290 lb.

It is intended to supplement the giant mill by a smaller (20ft × 6ft) vertical profile miller. Unlike the skin mill the new machine will be of the planer type, with a moving table and a tracer system for rise-and-fall milling and hydraulic copying in the plane of the table. Yet another machine which Avro will install will be a development of the conventional type of router used for routing and end-milling. This machine will also accommodate skins measuring 20ft × 6ft but will be confined to finishing portions of pockets and peripheries which are perpendicular to the plane of the table. A further pair of machines which have been built for Avro are designed primarily for profile-milling integrally stiffened ribs, spars and formers. Both machines have automatic tilting heads, and to simplify template manufacture the axis of tilt has been arranged below the cutter head and can be adjusted to coincide with the mould-line of the work-piece.

Earlier it was stated that 15 per cent of the heavy machined Arrow parts are cut from hand forgings. Die forgings are not used, for a variety of reasons. As an illustration of the problems involved it is possible to cite the case of a typical wing spar, which is shown in the cut-away drawing as the only truly transverse spar. This part has a ruling web-thickness of 0.1in, and for weight-control purposes the tolerance specified is ±0.005in. As far as the writer knows, no company has yet succeeded in achieving production with die-forged parts thinner than about three-sixteenths of an inch (0.1875in), and this spar would require machining on all web surfaces. Moreover, in the quantities in which the Arrow is likely to be built, hand forging is preferred on economic grounds. Assuming a production run of 50 sets of parts, die forgings would each cost $2,980 (comprising $360 for the forging, $240 for the machining and $2,380 for the die-cost per part). Hand forging eliminates the latter factor entirely; the basic forging costs $1,279 and machining $546, making a total of $1,825—a saving of $1,155 per part.

Most of the early experience with hand forgings was achieved with 75S and 14S high-strength light alloy. With these alloys distortion during machining was prevalent, and it became customary to rough-machine down to about 0.125in or 0.25in above finished size and then heat-treat before finish-machining. Most of the Arrow parts are now being produced in the relatively new 79S alloy, which is received in the T8E13 condition and requires no heat-treatment after machining. Tests have also shown that heavier cuts may be taken with 79S while preserving the distortion-free properties. At present, however, the new alloy is restricted to hand forgings with two parallel sides not more than 6in apart and with a maximum cross-section of 72 sq in.

Another new tool which Avro have purchased for the Arrow programme is a rubber press of exceedingly advanced design which is probably the largest such tool in the world. Designed to Avro requirements by Siempelkamp, of Krefeld, Germany, the new press can exert a total force of 15,000 tons on a pad measuring 120in × 60in × 12in. Unusual features of its design are that the main frame is constructed from metal laminations arranged in groups of six, each lamination weighing 10 tons, and that the 19in working stroke is applied from below, the loading table being forced upwards into the pad.

In the manufacture of the wing the multiple machined spars and chordwise members are assembled in exceedingly accurate jigs mounted in the vertical plane. Very little of the jigging is tubular, nearly all of it being assembled from standard sections, frequently two channel-sections being mounted face-to-face to form a box with flat sides. Casting and machining is widely used throughout the jig construction and all portions are standardized in form. The larger jigs are sub-divided into portions provided with numerous accurately located pick-ups which can be set up on a surface table, the size of the portion being so chosen as to permit numerous people to work all around it. Each jig portion is completely finished to the required degree of accuracy before being brought to the final production floor, where the parts are simply assembled with practically no optical positioning or filling with low-temperature expanding alloy. The various jig portions are held together by splice plates.

Full details of the wing construction may not yet be published, but it is obvious that a considerable amount of high-strength steel is employed for all the more highly stressed portions, and in particular for all the main structural joints and root members along the spar ends. Many of the less highly stressed areas are stabilized with bonded metal honeycomb, the bonding medium being Narmco 4021 which can resist temperatures appropriate to flight at Mach numbers greater than 2. Bonding is also employed for numerous structural joints, especially those involv-

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ing the attachment of extrusions to sheet members. One field in which Avro broke much completely new ground is the bonding of magnesium alloys, which are extensively used in the Arrow airframe. Rigid control has to be applied at all stages of the bonding processes, owing to the very fine dimensional tolerances and the arduous thermal conditions under which every bond will operate in service.

Turning to the fuselage, the structure is again sub-divided into major sub-assemblies. Several feet of the extreme nose—made by Brunswick—is formed from non-structural dielectric material (and in production aircraft will clearly serve as a radome). Continuing to the rear, the next section is obviously to be occupied by the exceedingly comprehensive search and tactical radar and fire-control system. This bay must be air-conditioned to dissipate the considerable quantity of heat generated by the equipment which it houses, and photographs show that it is enclosed by four substantial access doors which open along longitudinal piano hinges. The radar nose terminates at the front pressure-bulkhead of the cockpit. The latter is an integral part of the front fuselage, which also incorporates the intakes and the nose undercarriage.

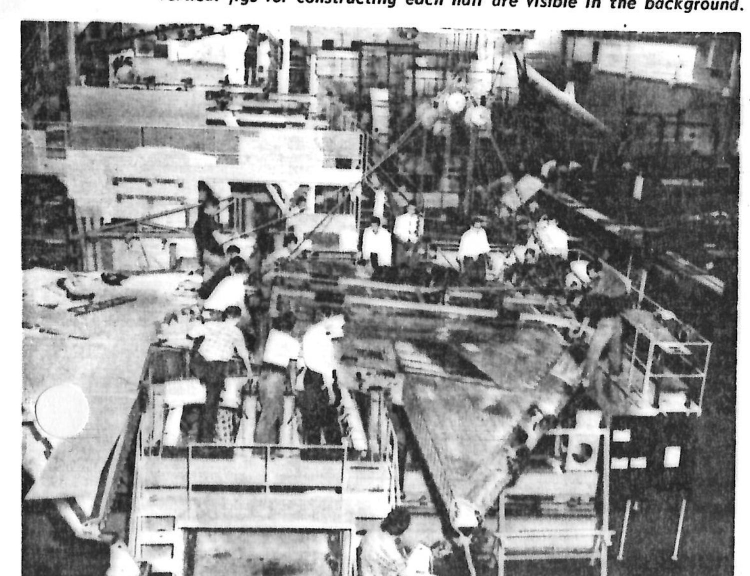
Each of the laterally mounted intakes has a fixed geometry and is devoid of a centre-body, although the edges of the intake are exceedingly sharp. These intakes were developed with the help of the Lewis Flight Propulsion Laboratory of the N.A.C.A. and, although probably reaching peak efficiency at one supersonic Mach number, the arrangement undoubtedly has high efficiency over a very wide range of flight conditions. The inner wall of the intake is a flat vertical surface which lies some inches clear from the mould-line of the fuselage proper, the boundary layer being diverted through the resulting gap. The sharp edge of the shock-forming wedge which separates the boundary layer from the engine air has a novel interior structure consisting of small hemispheres attached to the inner and outer walls and joined to each other by rods in a manner reminiscent of molecular models.

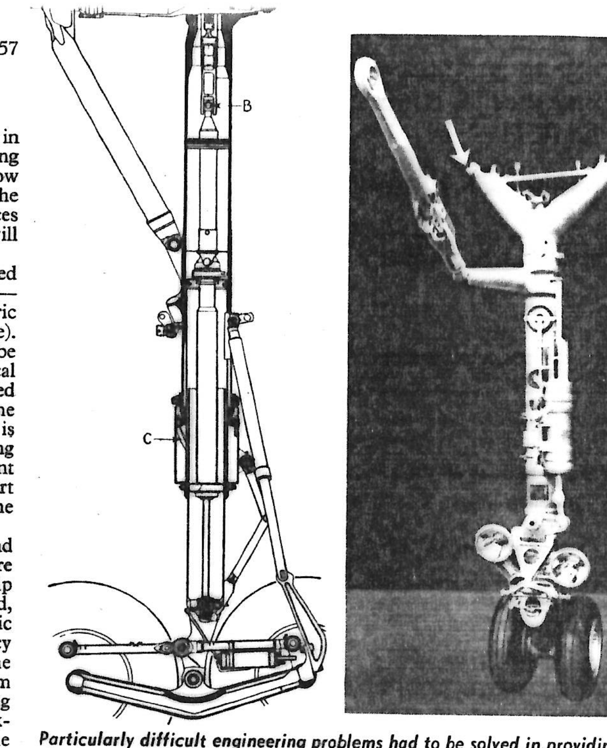
Pilot and navigator sit in tandem Martin-Baker Mk 4 seats in a comfortable cockpit provided with an acutely raked, razor-edged windscreen and separate partially glazed canopies. The latter are of unique design in that each consists of port and starboard halves, which are hinged along their lower edges to the cockpit boundary longerons. When a canopy is shut, its two halves are locked by multiple bolts along the upper centre-line; the unit can be power-opened in clam-shell fashion for normal entry and exit of the crew. Manufacture of the canopies presented immense problems, and the material is a magnesium alloy not previously used in N. America.

Pilot vision, frequently unsatisfactory in aircraft of this nature, was perfected with the aid of a special cockpit rig. A dummy cockpit was mounted at the correct height and angle on a truck which became a familiar sight at Malton Airport. Avro's experimental test pilots, led by Don Rogers, spent hundreds of hours in consultation with the design staff responsible for cockpit layout and instrumentation, and the result—as those who have examined the mock-up can testify—is outstanding. The U.S.A.F. Director of Flight Safety, the renowned Gen. Joseph Caldara, is on record as describing the Arrow cockpit unequivocally as the best layout he had seen.

One of the complicating factors in the design of the centre fuselage is that much of the underside is broken into by a missile

Joining the port and starboard inner wings in their horizontal jig. The vertical jigs for constructing each half are visible in the background.





Particularly difficult engineering problems had to be solved in providing the Arrow with an undercarriage. The main gear (left) by Dowty carries tandem wheels. As it retracts, eccentric A on the skewed axis pulls up linkage B, shortening the unit by 8½in; as the lower leg comes in it is turned by cam C to lie flat in the wing. The nose gear (right), by Jarry, is of equally ingenious design. The arrow points to the retraction jack pivot on the starboard branch of the "Y." When down the unit is locked and braced by the folding strut acting on the projecting arm. The photograph clearly shows the steering system.

bay (larger than the bomb-bay of a B-29) which houses a truly immense armament pack. No details of the weapons carried may be published,* but the space available is quite remarkable, not the least impressive dimension being the width of some 10ft. The armament pack occupies the lower part of the centre fuselage and the missiles must clearly be lowered beneath the aircraft before launching. Inspection shows that the pack itself is arranged to hinge downwards about a transverse axis at its rear end immediately before the missiles are fired. It will also be noted that a detachable pack makes the Arrow inherently versatile.

Along each side of the centre fuselage pass the engine ducts, each of roughly oval section and curving across the weapons bay. Major portions of the ducts are allowed to float axially, being restrained at one end only and locked at the other end in sliding joints. The wisdom of this unusual feature becomes apparent when it is appreciated that the Arrow may take off in air at 50 deg below zero Fahrenheit and accelerate until the kinetic heating and ram compression make the intake air well over 300 deg F hotter. The remainder of the centre fuselage—the space between the ducts above the armament pack—provides accommodation for fuel and for air-conditioning.

The next section of fuselage is known as the duct bay and, as its name implies, houses continuations of the floating ducts and joins the centre fuselage to the engine bay. Beneath the duct bay are mounted the two speed-brakes, which are very strong and unperforated surfaces hinged at their forward ends and actuated by Jarry hydraulic jacks. The engine bay itself then follows and, like the duct bay, it comprises a wide, flat-topped assembly roughly half the depth of the centre fuselage and attached to the underside of the wing by multiple bolts down each side.

These portions of the body are completely slab-sided and meet the wing at a perfect 90-deg joint with no fillet of any kind. The Avro designers were aware of the N.A.C.A. area rule (*Flight*, September 30, 1955) from an early stage in the design, and the Arrow has naturally been planned to conform to the rule insofar as it is applicable to a machine of high supersonic performance.

Between the engines the under-surface of the fuselage rises, to reduce the overall cross-section and improve maintenance accessibility. The lower rear part of each powerplant bay can be removed to provide access to the engine afterburners and hot parts (the word "hot" is only relative in the case of the Arrow) and to allow the complete powerplants to be "pulled" and replaced.

* *Several Canadian companies are collaborating in the development of Sparrow 2, a fully active radar-homing air-to-air weapon originally evolved by Douglas from the Sperry-Raytheon Sparrow family.*

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At the extreme rear of the body is the short rear-fuselage assembly which fairs-in the propelling nozzles. In the centre is a fairing which forms the tail of the fuselage proper, and houses the braking parachute. Readily detachable to the rear as a single unit, the rear fuselage incorporates a considerable amount of titanium alloy and stainless steel, and stainless-steel blanket-shrouds are also provided around both engines.

Like the wing, the fin is of exceedingly strong multi-spar construction, and it is designed to bear immense air-loads. Each of the swept fin spars terminates at its lower end in a fork-fitting in high-strength steel, the geometry of the joint being shown by the large drawing. The joint is finally covered by a small fairing which forms a continuation of the dorsal spine. The rudder is attached at several points along a hinged axis swept at 46 deg.

As already noted, the main wing structure is separated from the control surfaces by what are described either as the control boxes or the trailing-edge members. These are immensely strong assemblies, which, by an incredible display of ingenuity, have been persuaded to accommodate all the operating jacks and control circuits for the elevators and ailerons. Avro were responsible for the design of the powered controls, and they have employed a single large jack, made by Jarry Hydraulics, for each surface.

The control surfaces themselves are attached by piano hinges extending across the entire span of each portion (a fact which emphasizes the immense strength of the wing since any appreciable bending would render such hinges inoperable). Each control surface is gapless and unbalanced, and no tabs are to be seen. Moreover, the trailing edges are slightly blunted, particularly on the ailerons, to reduce drag and flow-breakaway.

It will be appreciated that a fighter of this type, weighing more than 30 long tons and—like all deltas—with its nose high, requires an undercarriage of no mean proportions. The design of the gear was, however, complicated by the presence of the armament pack in the fuselage, which made it imperative that the entire main units should be capable of stowage inside the exceedingly thin wing. The firm which finally obtained the contract for the main gear was Dowty Equipment of Canada, and a recent paper by G. F. W. McCaffrey, their chief engineer, has highlighted some of the immense problems which his firm met and overcame. One of the greatest of these problems was the development of manufacturing processes in steel with an ultimate tensile strength of 260,000 to 280,000 lb/sq in.

Each main leg measures some 104in from the upper hinge-axis to the bogie pivot. In order to permit the entire unit to lie within the wing the leg is hung from a skewed axis and the complete gear is shortened, twisted and trimmed during the retraction cycle. Twin wheels are used on each leg and, unlike the CF-100, these are arranged in tandem in order to restrict the complete unit to the very limited depth available inside the wing. The centre of the bogie beam is pivoted to a tubular member which is restrained against vertical movement by a Dowty Liquid Spring shock-strut.

Upon landing, the rear wheel makes initial contact with the ground and rotation of the bogie beam is then resisted by tension in the collapsible tie member. Accordingly, the Liquid Spring closes, and the vertical velocity of the front wheel is held to the rate of descent of the aircraft, rather than twice this value. During retraction, the torque-carrying members of the gear are disengaged, thus allowing the whole bottom part of the undercarriage to rotate through some 40 deg under the action of a cam while linkage from the pivot cross-shaft pulls up the lower part of the leg through a distance of some 8½in. Horizontal loads are resisted by a telescopic side-stay which also contains an internal lock to hold the unit in the down position. The back-stay is not telescopic, and it is worth noting that it was the forward (anti-drag) loading on the leg which designed the structure in bending. Wheels and brakes on the Arrow Mk 1 are by Goodyear. Rigid pipe, employing swivel joints and trombone slides, is used for all braking piping, and twin brake-links prevent pitching.

One could write a book on the work which Dowty had to do to turn this undercarriage into a production job. The basic material for the main outer leg, the sliding member, the bogie beam and the back-stay are all forged in the company's Dowcan 110 ultra-high-strength steel (which approximates to S.A.E. 4340). The largest forging, the main outer leg, initially weighs about 1,000 lb; machining reduces this value to 167 lb in the finished state. The bogie beam, although smaller, is particularly tricky in view of the fact that it has a complex shape with material in three mutually perpendicular directions. U.H.T. steel bar is also used for the operating sleeve, the cross-shaft, the side-stay and several smaller details. Carbide tools are widely used for machining in the heat-treated state, and both cadmium and chromium plating is employed (both processes requiring tremendous research programmes). It is worth noting, incidentally, that the U.S.A.F. Wright Air Development Center prohibit cadmium plating on parts heat-treated above 200,000 lb/sq in. Yet another relevant factor is the incidence of static fatigue in U.H.T. steel parts, although Dowty believe that by the time the aircraft has been built and prepared for its first flight static fatigue would either have already occurred or no longer be a problem.

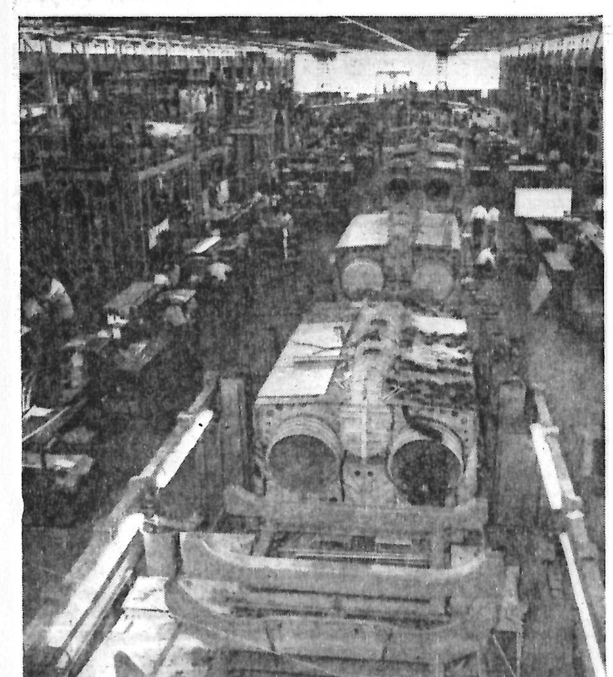
During the design of the Arrow gear an absolutely rational stress analysis on derived loads had to be investigated, owing to the dynamic interaction of the flexible undercarriage and flexible wing. It involved seven or eight times as many calculations as were necessary when the company designed the undercarriage of the CF-100. Extensive drop-testing was necessary to prove both the behaviour of the main gear and the performance of the Liquid Spring shock absorbers for both the main and nose units.

Principal contractor for the nose gear is Jarry Hydraulics. Like Dowty's main legs, the nose gear is manufactured in U.H.T. steel, the members being machined from heavy forgings. At the upper end of the leg a Y-junction and diagonal arms lead to the widely spread hinge axes, the assembly being joined by four submerged-arc welds. Levered suspension is used to compress the Dowty Liquid Spring, and wheels and tyres are by Dunlop.

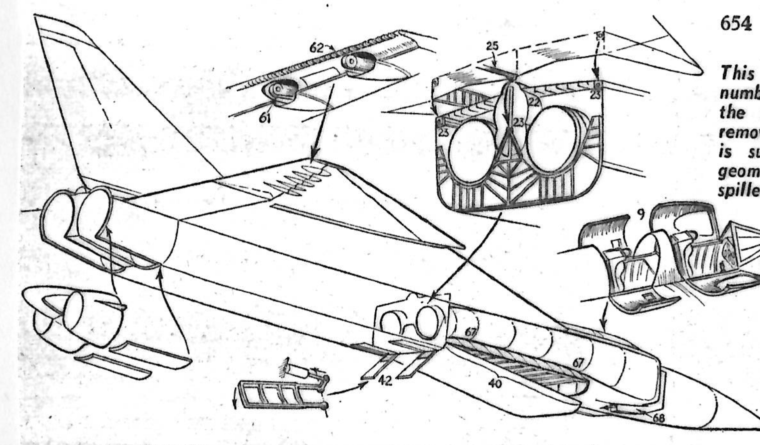
Particularly worthy of note is Jarry's patent steering geometry, which employs a vertical jack and bell-crank to which is hinged the upper half of the main scissors-linkage, which in turn moves the lower half of the scissors via a ball joint. Except for the piston, the steering system is of light alloy and it operates at the full pressure of the hydraulic system. The complete assembly retracts forwards. The nose unit has undergone cyclic retraction tests, using electric heaters and dry-ice packs to simulate specified extremes of temperature. Very successful drop testing—with a complete absence of shimmy—has been carried out against Jarry's 12ft-diameter drum, which can be spun up to a simulated speed of 200 m.p.h., well above the Arrow touch-down speed.

Jarry have also conducted extensive research into high-temperature hydraulic systems. In special applications they are producing units in which the ends of actuator rods remain at 880 deg F, ambient temperature being 550 deg F and fluid temperature being 450 deg F. Sealing materials and shapes have been developed largely at their own expense, and they are well advanced in systems capable of operation from −65 deg F up to the temperature limits of the Arrow. All indications seem to suggest that the Arrow Mk 1 should be capable of reaching its performance boundaries while still using MIL-5606 fluid.

Virtually all the systems of the Arrow are subject to security restrictions, and no quantitative data may be given. It is, however, possible to comment on the air-conditioning system, for which the contractor is AiResearch. Included in this circuit is the largest stainless-steel heat exchanger yet developed for airborne use (the choice of material being dictated by the arduous bleed-air conditions). Development of this heat exchanger has spurred a complete family of related units, all of which utilize plate and fin construction assembled by a new vacuum-brazing technique to give homogeneous bonds devoid of impurities. Downstream of the heat exchanger is an AiResearch cooling turbine which feeds the cockpit; other items developed by AiResearch include five oil coolers, two actuators and an electronic temperature control. Avro, however, make all the air-



A recent view of Bay I at Malton, showing (front to rear): the final "marry-up" jig; a row of Mk 1 centre fuselages; a complete Mk 1; and the metal mock-up, by the exit door.



This sketch is complementary to the drawing on pages 648-9 and the numbering follows the key to that drawing. Points worth noting are the detachable rear fuselage and under-surface for powerplant removal, aileron hinge and linkage, the manner in which the fuselage is supported by the wing, air-brake operation, armament-pack geometry (problematical), discharge from the intake wedges of air spilled through the wedge perforations, and canopy arrangement.

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conditioning ducting, and this considerable undertaking has been eased by the employment of plastic tooling for these components. Avro describe the "output" of the refrigeration system as "sufficient to generate 23 tons of ice a day."

As already noted, virtually the entire wing forms an integral tank for the conventional kerosine-type fuel. The heavy boundary members around the periphery of the fuel space in the wing are provided with a continuous groove of basically circular-segment section which runs along all the faces which form butt-joints with the skin. The tank bays are then rendered fuel-tight by the injection of sealant into these grooves. It has been determined that, for an effective seal to result, the gap between the adjacent surfaces of all tank-joints must not exceed 0.003in before the sealer is applied. Notwithstanding the employment of the matched contour template system, such tolerances are virtually impossible to hold, and final matching on assembly can be achieved only by local metal removal or build-up. The former method is preferred, and it is accomplished by machining all spanwise members to their correct size and leaving a wedge of material on the chordwise ribs where the latter are joined. The amount of metal left on the chordwise members rises to as much as 0.02 to 0.03in and falls away to zero some 5 or 6in from the join. The bleeding is performed with a portable sander.

It would be logical to conclude that Avro have had to undertake extensive research into the technology of fuel systems for supersonic flight. In particular the depth of the Arrow wing is very small compared with its area, and, in spite of the fact that the skins are relatively thick, the fuel temperature is likely to stabilize fairly rapidly at something like 200 deg F when the aircraft is operating at full power. Photographs do not give evidence of a probe for flight refuelling. The fuel-contents system is by Minneapolis-Honeywell and is fully transistorized. The maximum fuel-flow exceeds one-quarter-ton per minute.

As already noted, Avro are making a batch of Arrow Mk 1 aircraft, all of which are in existence at least as major details. All will have two Pratt and Whitney J75 turbojets with afterburners. The second airframe to be built is being very fully instrumented and will be employed on structural testing. The aircraft recently "rolled out" was the first off the line, and the rest of the Mk 1s should fly within the next few months.

In view of the singularly massive nature of the Arrow airframe it is desirable to describe the principal sequences in the erection of the aircraft from its major sections. The work really begins with the assembly of the inner wing, the central torque-box being built up from fore and aft, port and starboard quarters. The aft sections, forming complete integral tanks, have heavy machined skins. To the latter are then attached separate leading edges.

The inner wing is then used as a platform upon which the rest of the aircraft is assembled. First to be put in is the centre fuselage, which is rolled up at trolley height (appreciably lower than the position it will occupy when the aircraft is finished). The next part to be brought up is the complete inner wing itself, which weighs some four tons. When fully bolted-up, the inner wing is offered-up to four jig pick-up locating points which ride in vertical slots in matching portions at the tips of the wing box. Each pair of mounting pick-ups is joined by a fore-and-aft beam which is raised by hydraulic jacks and takes the whole weight of the wing. The next step is to raise the centre fuselage and locate it correctly under the wing. When the "marrying-up" has been accomplished the structure is largely completed by the addition of the duct bay, the front fuselage, the fin, the control boxes and control surfaces, the engine bay and the main undercarriage.

Oil is then drained from the four rams upon which the wing tips are resting, and the aircraft is lowered on to its main undercarriage. A special jack is provided to carry the nose of the aircraft; this jack is mounted on longitudinal rails and pulls down the nose-gear pivot sufficiently close to the ground for the rear end of the fuselage to be raised away from the jigging. The aircraft is then moved out forwards until completely clear of the jig, when it is tilted and the stalky nose undercarriage attached to its machined-steel pivots.

A deep pit has been dug in the floor of Bay 1 at Avro's factory at Malton in order to allow the Arrow to undergo systems-testing, including nose-undercarriage retraction, with the aircraft in level-flight attitude. Engine ground running is being carried out with the assistance of a row of large silencers which, although used principally by the lower-powered CF-100s, are also suitable for the big J75s of the Mk 1 Arrow. Water cooling is provided in the sound suppressors for use during afterburning runs.

In the final-assembly state the Arrows make a striking and bold picture, resplendent in a green protective skin of strontium chromate and festooned with cables, test leads, bright yellow trestling and a hive of men who do their best to prove that Canadians enjoy bright colours. As already noted, almost the entire skin is light alloy, although it must obviously operate close to its thermal limit at some 275 deg F. Parts of the nose are made in spot-welded stainless steel, and most of the structure along the spine is of titanium, since it is heated by the discharge from the air-conditioning system. The total weight of titanium in the finished aircraft is approximately 600 lb—a substantial figure, yet less than one per cent of the gross weight.

The first Arrow is at present undergoing an intensive pre-flight test programme and is expected to fly at Malton near the end of the year. For the very good reason that there is probably nowhere else in Canada where the Arrow could be based during a flight-test programme it is probable that all the early flying will be done at Malton—in spite of the fact that it is a busy civil airport close to built-up areas and to the city of Toronto itself. Extensive telemetering is to be used during the flight development, and all signals received from the aircraft will be processed in a large vehicle—painted in the company colours of blue and gold and representing an investment of $350,000—which produces magnetic tape for the company's numerous electronic computers, chief of which is a big I.B.M. 704 installation. This vehicle is at present based on the airfield at Malton but would probably accompany the Arrow wherever it might go.

It is likely to be several months before Avro complete the first Mk 2 Arrow. This all-Canadian aircraft will differ in several respects from the Arrow Mk 1, particularly in that the Iroquois engines—lighter and more powerful than the J75s—will be installed as true supersonic powerplants with ejector-type nozzles inducing a very high airflow over the engines themselves (*Flight*, September 6, p. 413).

Future operational Arrows will be equipped with an exceedingly advanced electronic weapon system, named Astra I. This embraces search, automatic flight, fire control, navigation and communication; it is being developed by the Radio Corporation of America and the Minneapolis-Honeywell Regulator Company, and subcontracts on behalf of Astra have been awarded to R. C. A. Victor in Montreal, Honeywell Controls in Toronto and Computing Devices of Canada at Ottawa. Many other contracts have been placed for ground-support items which complete the Arrow weapon-system. Very little of the existing R.C.A.F. hangar and apron equipment can be made applicable to the Arrow, and a joint Avro/R.C.A.F. maintenance engineering group has had to design over 200 different pieces of Arrow ground equipment. The starter truck, for example, contains a gas-turbine powerplant, and the ground-conditioning truck can maintain the Arrow's weapons and electronics at a consistent 55 deg F.

Development of the Arrow is probably the largest "aeroplane" task at present being tackled anywhere outside the U.S.A. and possibly the U.S.S.R. Nearly a year ago it was estimated that the research and development costs had reached $200m, and the pace of the work is being maintained at the high level which is essential if the project is to achieve success. Even at the height of the production learning-curve it is expected that each Arrow will cost more than $2m.

It is inappropriate to comment at this time on the Arrow's future prospects. It is designed to be an operationally flexible and versatile aircraft—it could certainly do duty as a photo-reconnaissance or ground-attack machine—and Avro are taking steps to increase its performance appreciably during the next few years. So much effort and sound engineering has gone into the programme that it deserves final success, and if the next year is passed without cancellation, then such success should be assured.