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Producing a Major Weapon System for the RAF

BRITISH AIRCRAFT CORPORATION

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TSR.2

Producing a Major Weapon System for the RAF

By MOLLY NEAL, BSc, DIC, AFRAeS

LAST month the first of 20 TSR.2 supersonic tactical strike and reconnaissance aircraft for the RAF left the works of British Aircraft Corporation at Weybridge, Surrey, and was taken to the A&AEE at Boscombe Down, Wilts, where it will make its first flight. The stringent specification laid down for this aircraft by the Air Staff, calling for exceptional versatility, performance and precision throughout the complete weapon system has posed technical problems on a scale entirely new to this country. New design techniques have been evolved; new industrial organizational concepts have come into existence; the high standards demanded of every component have raised the level of industrial skills in the many firms concerned; new materials have had to be developed to meet more severe environmental conditions; and advanced machine tools and manufacturing techniques have had to be adopted to handle "difficult" materials and achieve tighter tolerances than have hitherto been demanded.

Throughout Britain, the aircraft and engineering industries have since 1959 been involved in the supply of materials, components and equipment for TSR.2. Many small firms supply one particular component in which they have specialized skills, while large sub-contractors supply—for instance—powerplants, electronic equipment and powered flying controls. In all, well over 1,000 manufacturers are involved and, according to Mr Julian Amery, the Minister of Aviation, some 17,000 people during the development phase.

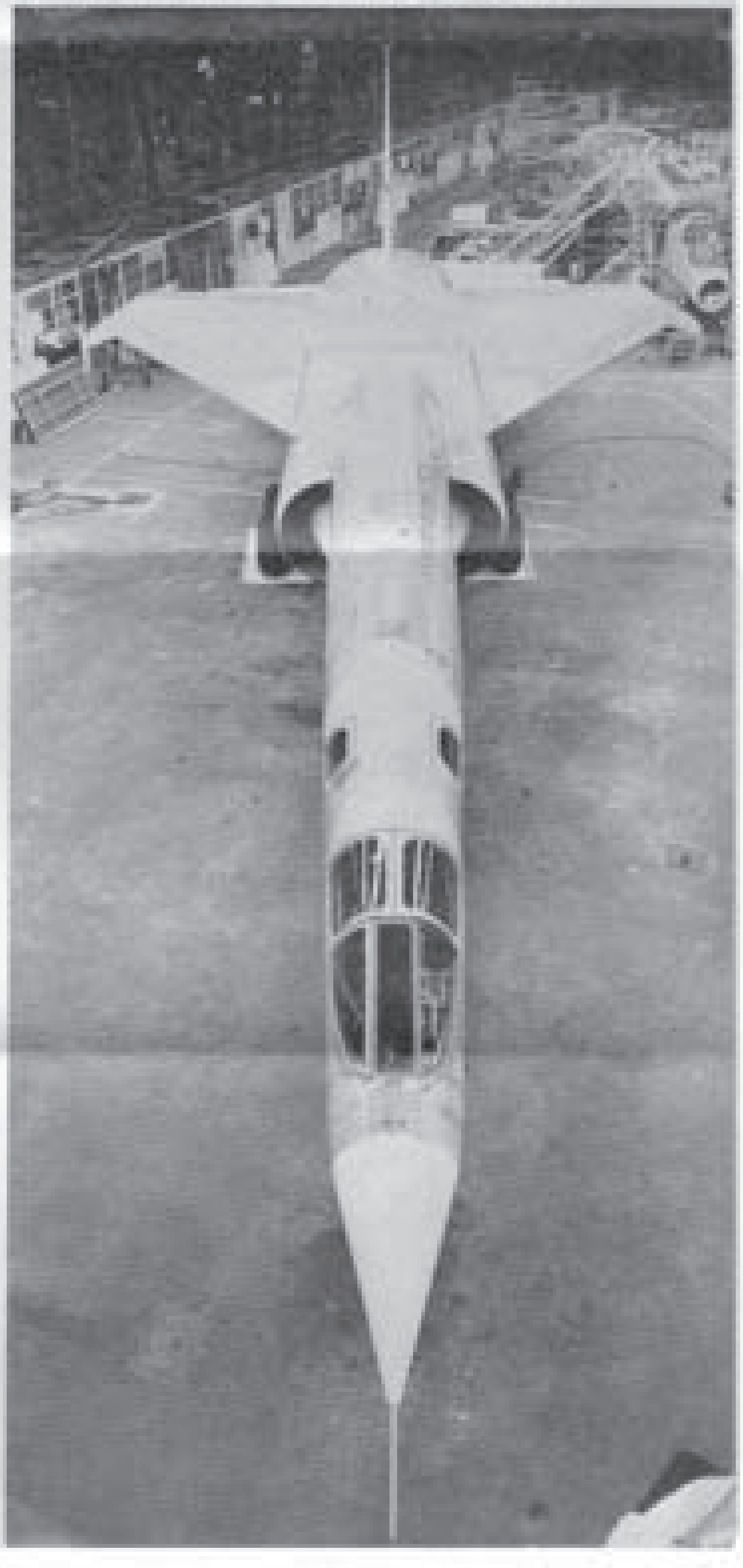
An outline of the way in which the TSR.2 has been designed to meet the GOR.339 requirement was given in the October 31, 1963, issue of *Flight International*, in an assessment by the Technical Editor. It is proposed in this article both to amplify that technical description and to consider the manner in which it has been created.

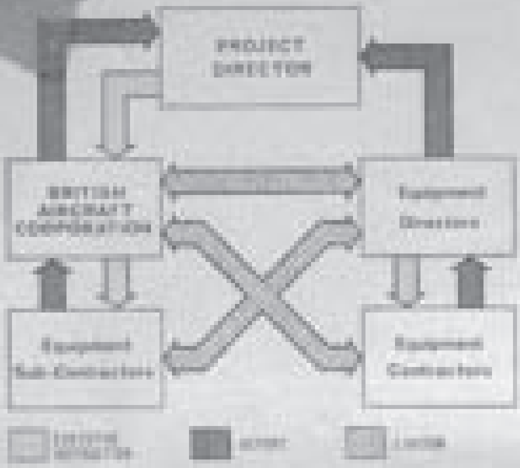
The configuration of the aircraft was determined by three factors: the performance specification for low-level penetration; STOL capability from rudimentary airfields and in cross-winds; and ferrying and operational range requirements, including the carriage of external stores. Thus, the thin 60° delta wing planform provides the optimum compromise of small area and low gust response, essential for low-level supersonic flight, with an aspect ratio adequate for STOL capability. The structure at the rear of the aircraft is kept as short as possible in order to permit the maximum ground incidence. To get adequate tail effectiveness for trimming out high lift at low speeds, the whole horizontal surface is set well below the wing, to avoid pitch-up, and is fully powered; port and starboard halves can pivot in opposition, for rolling and lateral trim. Thus the whole of the wing trailing edge is available for full-span blown flaps, bleeding air from the two large engines, apart from the turned-down wing tips which are provided to counteract the dihedral effect of the delta planform. An all-moving fin provides complete directional stability. It is under the pilot's control up to intermediate Mach numbers, but at high speeds automatic control stiffening and stability takes over.

The very effective blown flaps combine with a high thrust/weight ratio to confer STOL performance. With the flaps lowered, the centre of lift is well aft of the centre of gravity. In order to trim the aircraft at low speeds, without excessive tailplane area or deflection, a tailplane flap is fitted; and an extendable nosewheel is provided to increase incidence on the ground run. The landing gear (described later) enables TSR.2 to operate from semi-prepared surfaces, and for landing in very small fields a large braking parachute is provided. Since this could be an embarrassment in a cross-wind, there is provision for reefing it. It is believed that this is the first time that such a parachute—it is supplied by Irving—has been installed in an aircraft.

This summarizes the main external features of the aircraft; internally almost every cubic inch that is not occupied by powerplant, weapons, avionics and other necessary services, is utilized for fuel stowage. From the equipment viewpoint, the dominant feature is the adoption of the nav-attack system: the ultimate integration of aircraft guidance and control with weapons release

This photograph of one of the first of the 20 TSR.2 development aircraft was taken at British Aircraft Corporation's Weybridge Division last October. Further illustrations will be released following the first flight





This block diagram outlines graphically the administrative structure for technical management of the TSR.2 development and manufacturing programme. The arrangement was a new one for the British industry, with the prime contractor occupying the role of weapon-system manager.

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Organization

The main contractors for the TSR.2 weapon system, with overall responsibility for ensuring its workability and reliability, are British Aircraft Corporation. In the article previously referred to it was described how Vickers-Armstrongs (Aircraft) and English Electric Aviation—before their amalgamation into BAC—agreed to share the contract. The main contract was placed with Vickers at Weybridge, who were charged with the design and development of the fuselage and the electronic and armament installations (the nav-attack system); English Electric at Warton, now BAC (Preston Division), assumed responsibility for the wings, rear fuselage, engine installation, fuel system, powered flying controls and auto-stabilizers. As one BAC representative suggests, Weybridge are responsible for the TSR.2's "brains" and Warton for its "muscles."

This is the first British military aircraft in which the aircraft contractors have had such a high degree of overall responsibility for the equipment installed in the aircraft. In general, in the past the aircraft contractor has developed the airframe as a container for equipment which was developed for, and purchased by, the Ministry—the "embodiment loan" procedure. On TSR.2, the procurement of equipment falls into three categories:—

Category 1 embraces equipment purchased by the Ministry of Aviation contracts department to the Ministry's specification. The firms supplying this equipment are "associate contractors."

Category 2 equipment is specified and purchased by British Aircraft Corporation, subject to the approval of the Ministry, BAC being entirely responsible for its satisfactory development. Most of the nav-attack fall into this category.

Category 3 equipment also is specified and purchased by BAC, but in this case the Corporation have almost complete autonomy; no Ministry approval is required (except for a degree in the case of powered flying controls). Examples include the fuel system, hydraulics, powered flying controls, wheels and tyres.

On the face of it, Category 1 procurement appears to parallel embodiment-loan procedure, with the Ministry responsible for design, development, costs and supply. But for BAC the facts of life are rather different, because they are ultimately responsible for the integration of all this equipment into the airframe, and for its satisfactory working under very diverse flight conditions. The whole picture of TSR.2 development is one of constant liaison and co-operation between the Air Ministry, MoA, BAC, and the various subcontractors.

Airframe

Choices of structural materials for TSR.2 have been dictated by the high-temperature environment plus the problems introduced by low-altitude flying. The latter include rapid and severe reversals and vibration due to gusts, requiring high fatigue-resistance, and impacts from collisions with birds and insects. The high-temperature environment has introduced the fourth dimension, time, into airframe design (time as distinct from fatigue life). Thus, when evaluating the loads on the structure, the stress analysts have to consider the starting temperature and the size of the heat sink; in other words, the amount of fuel carried. A varied combination of transient conditions must therefore be added to the usual structural design cases. At Warton, to render the labour of stress analysis at elevated temperatures less formidable, a series of tests has enabled data sheets to be prepared which extend creep theory in such a manner as to be readily assimilated and applied as routine in the stress office. This is considered to be a major advance in design technique.

At Mach 2 plus, TSR.2 is working near the limits of light alloys. Some well-known light alloys have been developed to higher levels; and, at the "hot" end of the aeroplane, aluminium-lithium alloys—lighter, stiffer, and with better high-temperature properties than conventional aluminium-copper alloys—have been imported, through ICI Metals Ltd, from the United States.

Much of the structure adjacent to the engines is of high-strength heat-treated titanium alloy developed in Britain by ICI Metals Ltd, and having a strength/weight ratio about twice that of heat-resistant steel. Extensive use is made of very high-tensile steel in the undercarriage, as noted in the next section of this article.

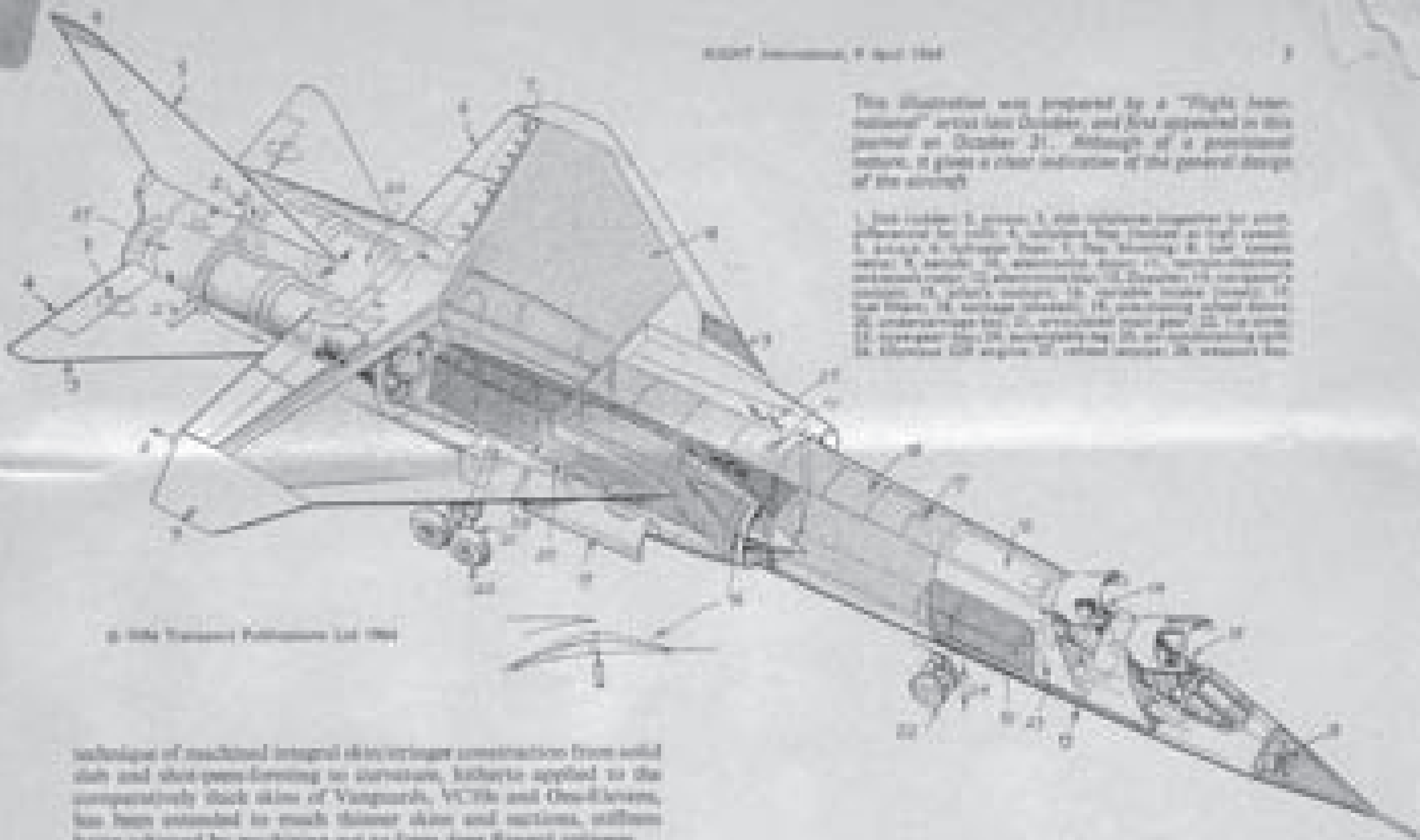
In general, the non-metallics have presented greater problems than have the structural metals. At the inception of the design BAC carried out a programme of detailed research on basic material properties in hot environments, and on the behaviour of small elements of selected materials.

Transparencies with new types of interlayer have been developed for the windscreen, canopies and radomes. High-temperature resins, imported from the USA, have been employed in the small amount of honeycomb structure in the aircraft. ICI's Silicodyne H (DP47) high-temperature fluid is used in the hydraulic system. Most of the fluid-tight seals are of silicone rubber.

Fuel-tank sealing at high temperatures has introduced a new problem. The tanks are of integral construction, and holes and cutouts have been held to a minimum, but there remains the problem of sealing where two stiff members meet. Sloshing has proved unsatisfactory. Interfaying techniques have had to be adopted, using specially developed sealants capable of withstanding elevated temperatures. These sealants are supplied by British Paints Ltd, under licence from Products Research Inc, of the USA. To secure effective sealing, the mating metal parts must fit closely, requiring tight machining tolerances and very accurate jigging.

Wings and fuselage of TSR.2 are largely of integral construction, with stiffened skins machined from stretched billet. The Weybridge

In this illustration a "Flight International" artist has superimposed a sketch of the TSR.2 on a map on which are marked major centres of TSR.2 manufacture and flight test. The tinted regions near the BAC plants in Lancashire and Surrey match with the corresponding shading on the portions of the aircraft manufactured in the factory concerned.



This illustration was prepared by a "Flight International" artist last October, and first appeared in this journal on October 31. Although of a provisional nature, it gives a clear indication of the general design of the aircraft.

[illegible]

technique of machined integral skin/stringer construction from solid slab and shot-peen-forming to curvature, hitherto applied to the comparatively thick skins of Vanguards, VC10s and One-Elevens, has been extended to much thinner skins and sections, stiffness being achieved by machining out to form deep flanged stringers.

This skin-milling technique, new to BAC's Preston Division, has been taken up in a big way by their "very preferred" subcontractor, the English Electric Co at Accrington, Lancs. Here, numerous Marwin skin millers have been installed specially for the production of TSR.2 wing and fuselage planks. It is planned eventually to apply Ferranti tape-control to these machines. At this works, also, an automatic-scanning ultrasonic testing machine has been installed for inspecting all incoming billets. This machine displays flaws on an oscilloscope, and also pin-points on the metal the approximate zone of the flaw.

Fins, tailerons and airbrakes are also made at Accrington, to a very high standard of interchangeability. The forming of the rolled planks to the required curvature is carried out by the main contractor at Samlesbury works, which is equipped for shot-peen-forming and presswork. The all-moving "taileron" surfaces are supported on plain bearings, since ball or even needle-roller bearings would occupy too much bulk inside these extremely thin structures. For these bearings, Ampep [illegible] now p.t.f.e.-based materials which minimize friction and breakout forces.

Production of TSR.2 is accelerating the introduction of numerically-controlled machine tools. The probability of their introduction at Accrington has already been mentioned. At the BAC Preston Division, Ferranti-tape-controlled Kearney & Trecker milling machines have been brought in. At one time the machining of hard titanium alloy presented problems. To get satisfactory results the cutting tool must have a very uniform speed. The tape-controlled machine provides the best way of achieving this improved control of cutter movement, resulting in longer cutter life, closer tolerances, a better finish on the workpiece and reduced tooling costs.

Landing Gear

One of the most unusual—if not unique—features of the TSR.2 undercarriage is the extending nose leg. This incorporates not only hydraulic retraction (forward) and steering, but also a hydraulic extension, shortening and locking capability which enables the TSR.2 to sit on the ground at two quite different angles. In the nose-high attitude both lift and drag are increased, to reduce the field-length required.

Each main gear has a single leg attached to one of the main fuselage/wing frames, carrying two wheels in tandem. The unit retracts forwards into a compartment close beside the armament bay and intake duct. Supersonic wave-drag considerations demand minimum cross-section in this region, and this has posed installational problems aggravated by the need to splay the legs out to give adequate track.

In order to achieve adequate strength for operating this very heavy aircraft from rough surfaces, without exceeding the severe restrictions on available cross-section, all major leg members are forged and machined in a very high quality ultra-high-tensile steel to an English Steel Corporation Ni-Cr-Mo-V, specification. This is the first time that steel of such strength has been used in a major production application in Britain.

It is no easy task to work in steels of this kind, and the manufacture of the complete units has been subcontracted to Electro-Hydraulics Ltd of Warrington, Lancs. EH have undertaken considerable development work in this field during the past few years, and have also installed a number of advanced machine tools necessitated by the high-grade materials. Heat-treatment methods have been developed in co-operation with BAC and English Steel Corp. BAC designed the legs to have very long stroke, in order to accommodate the undulations of long wavelength met with in semi-prepared surfaces. The oleo has a soft characteristic over most of its travel, but it stiffens towards the limit of its stroke.

To meet the requirement of withstanding high impact and single-wheel loads at high speeds while operating from soft dispersed areas, TSR.2 has relatively large wheels with low-pressure tyres. The latter have been under development at the Goodyear Tyre & Rubber Co (Great Britain) Ltd and the Dunlop Rubber Co Ltd since the original OOR.339 type of aircraft was first considered. From the outset it was realized that the tyre designers would be faced with new and formidable problems. The required type of tyre became known as the "high-speed puff bag."

It was necessary to devise a shape and type of construction which would operate at low inflation pressure without the formation of destructive traction waves in the tyre during high-speed and high-load conditions during take-off and landing. The take-off conditions are the most difficult to meet. Traction waves give rise to excessive shear, tensile and compressive stresses in the tyre carcass, and accelerations of a very high order are experienced on portions of the tread. All this generates considerable heat, and ply and tread start to separate. In these conditions tyres can disintegrate extremely quickly. These problems have now been surmounted, and Goodyear claim to have been the first to meet the TSR.2 specification during realistic and exhaustive dynamometer testing.

Goodyear and Dunlop tyres are being used alternately on the first batch of aircraft. The Dunlop contribution also includes

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Frank Munger, a "Flight International" artist renowned for his detailed cutaway illustrations, has prepared for this article two wash drawings giving a dramatic impression of TSR.2 operation at low level. This picture portrays the aircraft against a daytime sky filled with cumulus; that on page 9 depicts a run at dusk with full reheat.

wheels and brakes (incorporating axle-mounted Maxaret anti-skid units), brake-operating equipment and brake cooling. Each of the two split-type main wheels, for use with tubeless tyres, accommodates a plate brake and an air-cooling installation. The wheel rims incorporate fusible plugs which ensure controlled deflation of the tyre in the event of excessive heat build-up resulting from emergency braking. The air-cooling dissipates heat normally generated by the brake before it can soak into the rim and tyre beads. It consists of a fractional-horsepower electric motor driving a shrouded impeller, and the complete assembly is housed within the axle adjacent to the anti-skid unit.

Each Maxaret anti-skid unit is driven through a flexible coupling from the wheel hub, thus ensuring immunity to the effects of weather and any damaging material flung up by the wheels. Maxaret allows the use of maximum braking power in all conditions of weather and runway without resulting in wheel lock and consequent skidding.

Multi-plate brakes are used, incorporating jigsaw-type segmented rotor assemblies, and stator assemblies carrying inorganic pads. Automatic adjusters ensure that, as the pads wear, the working clearance remains the same, so that the displacement of the operating fluid is maintained at a constant figure throughout the service life of the unit. The principal brake structure can be of either steel or titanium. Problems arising from the high operating temperatures necessitated special test rigs at Dunlop's Aviation Division factories in Coventry, so that components could be tested under all conditions likely to be encountered in service.

Powerplant

Principal among Category 1 subcontractors are Bristol Siddeley Engines Ltd, responsible direct to the MoA for the supply of the Olympus 22R turbojet. This powerplant has a reheat thrust in the 30,000-33,000lb class, and two are installed in tunnels in the rear fuselage of the TSR.2. The company's Patchway division is well advanced in the development of this powerplant, which is developed from the earlier two-spool Olympus engines that have served so well in Vulcan bombers, and have earned a reputation for exceptional reliability.

The technical specification for the 22R, calling for a high maximum thrust and a very low specific fuel consumption, was a tough one; but it has been successfully achieved, with ample potential for further "stretching." Problems that have had to be overcome in the development include, on the one hand, those associated with operation at Mach numbers greater than 2: high-temperature lubrication and increased severity of vibration stresses. On the other hand there are problems of very-low-altitude operation: increased engine structural loads resulting from higher air density, and greater likelihood of damage from foreign-body ingestion. Bristol Siddeley's experience of low-altitude operation of the Orpheus turbojet in the Fiat G.91 has given them a good understanding of the difficulties. Damage by birds and other foreign bodies is minimized by the inherently robust design of the Olympus.

Basic strength requirements for a supersonic turbojet demand the use of guide vanes and compressor blading of steel. The use of specialized materials in some areas has demanded the evolution of new manufacturing techniques.

Technical data on the Olympus 22R remain restricted. However, it is known that the Concord's Olympus 593 engines are derived from the 22R. It has been stated that, compared with the Olympus 301 engines already in service with the Vulcan B.2, the mass flow of the Olympus 593 has been increased, and the thrust has been raised still further by a new high-pressure turbine, undoubtedly with cooled blades, allowing an increased combustion temperature.

In TSR.2 the Olympus 22R has a fully variable intake and variable-area nozzle, and a reheat system fully controllable over the entire range by a single lever. It is possible for both powerplants to operate under well-matched conditions in every phase of flight, and at low altitude the aircraft will cruise without reheat. The intake cone is moved by a Lucas jack with manual or automatic controls, and the intake lip has Dunlop anti-icing heater elements. Some eight years ago Bristol Aero-Engines entered a licensing agreement for developing and manufacturing the American Solar reheat system. The system now in use on the Olympus 22R differs widely, both thermodynamically and mechanically, from the original Solar system; materials, layout, construction and fuel-injection system are all very different.

A Rotax 12-joule high-energy ignition unit is fitted, and the engine fuel system is by Lucas Gas Turbine Equipment. Except for the flow distributor and nozzles, all fuel-system components are mounted on a single chassis, with consequent reduction in pipework and simplified installation and removal. The system incorporates two pumps, venturi meter and appropriate [illegible].

Flight trials of the Olympus 22R engine, installed in a Vulcan test-bed, began in February 1962. This aircraft, it may be remembered, was destroyed by a fire on the ground in 1962. Subsequent development of the engine has been carried out both at Bristol Siddeley's own facilities at Patchway, and by a Bristol Siddeley team in the high-altitude, high-speed test chamber at the National Gas Turbine Establishment at Pyestock. The Patchway test-bed is provided with an air intake heater for simulating conditions at speeds greater than Mach 2.

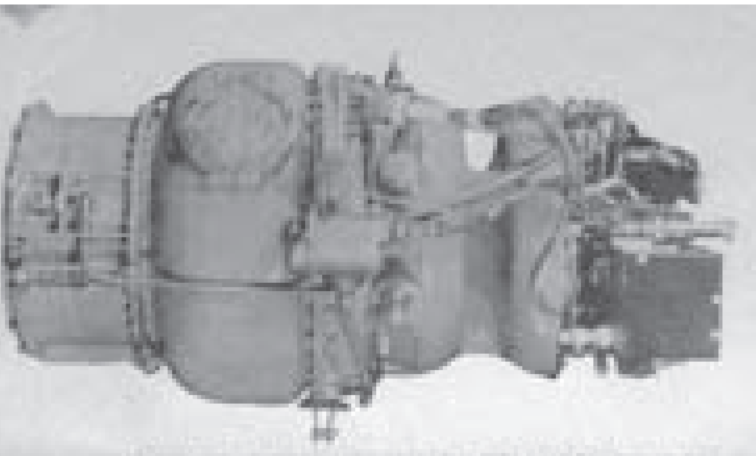
As well as the propulsive engines, Bristol Siddeley also provide TSR.2's on-board auxiliary power unit. This comprises a Cumulus turbo-compressor with power take-off. It is capable of providing pneumatic power for main-engine starting and cockpit and electronic air-conditioning, as well as shaft power for electrical and hydraulic services on the ground. The Cumulus is a 50 h.p. single-shaft gas turbine, with a single-stage overtip centrifugal compressor driven by a two-stage axial turbine. Compressed air bled from the outer casing of the annular combustion chamber provides a maximum flow of 2.6lb/sec for aircraft services.

Integrated Subsystems

Looking at the "brains" of the TSR.2: the Systems Division E (Electrics and Electronics), responsible for the whole of British Aircraft Corporation's activities in the fields of communications, radar, electric power generation, cockpit instrumentation, automatic flight control and flight instrumentation engineering, has the prime task of integrating the entire weapon system. The Division commands elaborate laboratories for carrying out rig tests, and comprehensive computing facilities. It includes a microwave division specializing in the design of suppressed aerials and the casting of waveguides, for outside customers as well as for BAC's own needs.

The nav-attack system specified for TSR.2 has posed new problems for the Corporation, and new solutions have been found. The high degree of accuracy necessary demands great complexity of equipment. This is accentuated in the case of TSR.2 by the versatility of the aeroplane and its exceptionally wide range of altitude and speed.

When the specification was issued no existing electronic equipment was capable of meeting the expected range of performance and environment. When terrain-following at exceptionally low altitudes it is important that the pilot should be completely happy, and confident in the reliability of the indications presented to him. The aircraft itself must respond immediately to pilot demand. Obviously, the forward-looking nose radar must be of the highest possible standard; and here, it is claimed, Ferranti have set a



On-board auxiliary power is provided by a Bristol Siddeley Cumulus a.p.u. which provides both shaft power and air bleed

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level surpassing anything achieved the other side of the Atlantic.

In fact the TSR.2 concept has involved a thorough review of the design of radar, airframe structure, handling characteristics, automatic guidance and autostabilization. An intricate chain of equipment has had to be co-ordinated to work reliably under exceedingly stringent conditions; and every phase of flight and variation of mission must be taken into account.

British Aircraft Corporation have approached this problem of co-ordination in a new way. In the United States, hitherto pre-eminent in the weapon system concept, it has usually been the practice for the airframe contractor to subcontract out to an electronics manufacturer the responsibility of integrating the various electronic systems. But because this is only one stage in integration it has been necessary to have an airframe team working in parallel with the electronics contractor, and this has involved unnecessary duplication.

BAC have themselves tackled the problem as a whole, and by this means, they claim, they have cut development costs by more than half as compared with American philosophy. They outline the system, agree the specification with the subcontractors, and ensure that the elements of the system work in accordance with requirements. This is done by carrying out detailed functioning tests in their laboratories on rigs representative of the aircraft. By this means problems of interference and cross-talk can be ironed out, and reliability of the system components can be ensured under every possible variation of working conditions. The rig tests also help tremendously in assessing the scale of the servicing problems, and in evolving checkout equipment suitable for RAF use.

As a result of the complexity of the electronic subsystems, and the vast number of inputs and outputs that require checking, BAC have introduced "integrated systems testing" in order to make servicing a practical and efficient possibility. In other words, they have specified *one* piece of test equipment which uses the working system as a simulator, and by running a test routine it will be possible to discriminate any faulty element in each system—which can then be withdrawn, replaced, and rechecked. All the major elements in the various subsystems are therefore fitted with pick-off points for automatic checkout. It is believed that this is the most comprehensive automatic checkout system yet developed, the integrated weapon system involving over 1,000 types of measurement.

Chief source of electric power in TSR.2 is a pair of solid-rotor alternators, each of which is driven by a main engine through a Plessey constant-speed drive. The alternator is by Rotax, and has a rating of 30/55kVA

Design of the automatic test equipment has been entrusted to Hawker Siddeley Dynamics Ltd, and it will be a development of TRACE (tape-controlled recording automatic checkout equipment), versions of which have already been supplied to the British and French Governments. The test routines are automatically switched through a taped programmed sequence to every subsystem element in turn. Any faulty element will cause a warning signal to operate, and will stop the test sequence. TRACE for TSR.2 will be included in a waterproof trailer designed for high-speed towing over unprepared surfaces. Complete environmental testing will be carried out on the equipment to ensure that it cannot be penetrated by dust or water, and that it will operate efficiently in all climates. Altogether the demands of TSR.2 for field support promise to be remarkably light.

Manual testing is also a requirement, and is catered for by using the same test pick-off points as are required for the automatic test equipment. These manual test sets are manufactured by the subcontractors responsible for the systems themselves.

Electrics and Electronics The electrical power system, for which Rotax are the principal subcontractors, has been tailored to the requirements of the electronic systems. The environmental temperature in which the generators have to operate—imposed by supersonic flight plus local engine temperatures—is well above the limits of previous designs. With the conventional salient-pole type of generator, mechanical difficulties are encountered under conditions of high temperature and vibration. Accordingly, solid-rotor air-cooled alternators, with no rotating windings, have been specified for TSR.2. This is believed to be the first time that solid-rotor alternators have been used in a major power-generating system. Another unusual feature of the electrical system is the adoption of solid-state voltage regulators for high-speed response; these have been subcontracted by Rotax to Mullard Ltd.

Each main solid-rotor alternator is driven by a Plessey constant-speed drive, and supplies 30-75kVA output for the two main a.c. generating channels. A solid-rotor alternator, with its associated regulator, is driven by a Lucas hydraulic motor and provides what is a constant-frequency supply for a third emergency channel. Rotax, who have vast testing facilities, have been responsible for the co-ordination of the generating systems, and over 2,500 hours development time has been spent in determining the various characteristics. In addition, the alternator and associated equipment have been subjected to environmental tests, including altitude and temperature.

TSR.2's subsystems, and the way in which they are integrated, can well be related to P. A. Hearne's "Digital Computers for Aircraft" in this journal's February 20 issue. A diagram in that issue illustrated a typical on-line central computing system for a military aircraft. In TSR.2, the central digital computing system is supplied by Elliott Flight Automation, Mr Hearne's company. Quoting from his article—with interpolations—"The sensor group, consisting of inertial platform (Ferranti), forward-looking radar (Ferranti), sideways-looking radar (EMI), Doppler (Decca) and air-data system (Smiths) provide 'raw' signals . . . to the computer. The computer processes these signals to provide outputs for the display of position and steering information (Smiths, Rank-Cintel head-up display) and also for the direct control of the aircraft through the autopilot (Elliott Flight Automation) and for the preparation and release of weapons."

While the computing system can be programmed by means of previously-prepared magnetic tapes for a very wide range of military missions, the crew are not, in fact, irrevocably tied down to a pre-programmed flight. Should local or tactical considerations demand a change of in-flight plan, the crew can feed in the necessary information and the pilot can at any time take charge manually. Outputs provided by the Smiths air-data computer include true airspeed, Mach number, rate of climb, altitude, indicated airspeed, dynamic pressure, static pressure, stagnation temperature and rate of change of height. Corrections for pressure error and Mach number are incorporated.

Ferranti's forward-looking radar provides terrain-following signals to allow the aircraft to approach its target at very low level, safe from detection by enemy ground radars. Ferranti have also provided the stable platform used in the Doppler/inertial navigation system, a three-gyro and four-gimbal system, fully manoeuvrable.

The Doppler radar, supplied by Decca Radar Ltd, measures ground speed and drift angle to a very high degree of accuracy throughout the complete flight envelope, and under extremely

"Moving-map displays . . . have been developed for TSR.2 by Ferranti Ltd." As described at the foot of column one below, the displays use a film-projection technique. This illustration shows one of Ferranti's mock-ups

severe environmental conditions. As with all TSR.2 subsystems, maximum reliability has been a prime consideration, and a high degree of fail-safe operation is included. Outputs are available in both analogue and digital form.

There are two sideways-looking radars in TSR.2, both supplied by EMI Electronics Ltd. One is for navigational purposes, for correcting Doppler/inertial fixes. The other is a new electronic aid to aerial reconnaissance: this radar looks sideways and downwards from the aircraft, with the radar beam fixed nominally at right angles to the fore-and-aft axis. As the aerial does not rotate and lies parallel to the axis of the aircraft, it may be made comparatively long, so giving a narrow beamwidth and better resolution. The time-base trace, which "paints" the picture on a radar screen, is kept stationary on a small display tube, and a long strip of film is moved past this display at a rate proportional to the ground speed. The film thus forms a complete record of what the radar has seen.

Such a radar can "see" through cloud and in the dark. The mapping picture can reveal geographical features such as rivers, lakes and hills, and will also define man-made features such as roads, canals and buildings. Moving-target indication can be provided, to make moving targets show up on the radar map in a distinctive fashion. Objects such as bridges and high buildings will screen the area behind them from the radar beam and will cause the formation of shadows on the film record. The films can be developed and processed rapidly on return to base, and skilled interpreters should be able to give the Command detailed information within a few minutes about the area which has been reconnoitred.

Line-scan is another form of reconnaissance device supplied for TSR.2 by EMI Electronics. This is an optical scanning system which can be likened to an "electronic eye" scanning the ground beneath the aircraft. It is possible to have both a passive and an active form. In the passive role the electronic eye scans without any illumination. In the active mode, a spot of light scans at the same time as the electronic eye, so illuminating the portion of the ground at which the eye is looking. The system can be used at night to give a performance comparable with that obtained during daylight, with little chance of detection. The output can be recorded in the aircraft or transmitted back to base by TV link.

TR unit for the reconnaissance radar is made by Mullard Ltd, and the IFF system is provided by Cossor.

The Marconi Company's contribution to TSR.2 include a high-power HF communications equipment, which will provide both single- and double-sideband transmission at high output power; and the instrument landing system from the Marconi Sixty Series. The latter, fully transistorized and incorporating new constructional techniques for maximum reliability in service, includes localizer, glide-slope and marker beacon reception; other recent aircraft using this series of equipment include the VC10, Trident and One-Eleven airliners.

Other electronic equipment includes communications radio by The Plessey Co (UK) Ltd, and a radio altimeter by Standard Telephones and Cables.

Instrumentation Moving-map displays, provided for both pilot and navigator, have been developed for TSR.2 by Ferranti Ltd. The displays use standard topographical charts photographed on 35mm colour film which is projected optically on to a ground-glass screen. As the aircraft moves over the ground, the projected map moves under a fixed marker which indicates the instantaneous position of the aircraft, and a pointer indicates aircraft track. The two displays are driven under command from a computer which accepts navigational inputs from the aircraft's central digital computer. A large number of maps can be stored on the film.

This Ferranti system is developed from an invention by RAE Farnborough, who have themselves done much work on the project. The film strip is driven along its length for change of Eastings, and across its width for change of Northings, by means of M-type repeater servos driven by a suitable ground-position computer. The display map can be either North-stabilized or Track-stabilized. With North-stabilized, North is at the top of the display and the rotating compass bezel, calibrated in degrees, is stationary. The track input drives the track line which rotates about the present-position indicator to show the track across the map. When track-stabilized, the track line is fixed on the vertical diameter, and the track input used to rotate the map and the degrees scale together.

In the Ferranti system, track stabilization is carried out optically by means of a servo-driven prism in the optical projection system, and the track input is in the form of a synchro transmission. An electro-mechanical computer accepts ground-speed information and contains an electro-mechanical memory system for storing resolved ground mileage information during a map-change sequence. A control panel on one display unit provides for selecting and accurately positioning the required map. North/South map changes can be made semi-automatically; East/West changes are made manually.

TSR.2 has a head-up display subsystem provided by Rank-Cintel division of the Rank Organisation. It presents attitude information in relation to the outside world, throughout the flight, by reflection on to the windscreen. Developed from earlier systems produced for the Buccaneer, it consists of two units: the pilot's display unit and display computer. The data input signals are provided by the aircraft nav-attack subsystems, and are processed by the display computer to provide bright-up and deflection voltages for the pilot's display unit. This unit contains a 3in high-intensity cathode-ray tube, on the face of which are written the symbols or combination of symbols that are utilized for a given flight mode. The display presented on the c.r.t. is collimated by a 4in f.l. lens and reflected directly on to the windscreen, so that the pilot is able to view the display, at infinity focus, from the normal head position.

This is the first head-up display installation designed to reflect the display directly on to the windscreen. In previous installations an intermediate 50/50 reflector has been necessary.

One of the largest periscopes built by Smiths, the TSR.2 navigator's downward sight, is servo-driven both in elevation and in azimuth. With ability to rotate through 360° in azimuth, the instrument provides a very wide field of vision.

The navigator's combined instrument display supplied by Smiths presents on a single panel three indications: vertical speed, altitude (by counter/pointer display) and airspeed information. The a.s.i. is servo-driven from the air-data computer. The servo-altimeter supplies information in digital form, so that data can be fed to other systems should this be necessary. The digital encoder can be set manually. Three indications are displayed on the a.s.i.: Doppler ground-speed transmitted by torque synchro link from the Doppler equipment; computed ground-speed fed by torque synchro from the navigational computer; and true airspeed fed by servo from the air-data computer.

Also supplied by Smiths, the pilot's altimeter is similar to that included in the navigator's display. The digital encoder, however, is replaced by a pressure potentiometer, and feeds altitude information to the head-up display; hence there is no manual setting facility. A stand-by altimeter is also supplied.

The pilot's head-down display, developed from a flight-data system designed by Smiths specifically for high-performance military aircraft, presents two instruments which combine the function of a normal set of flight and radio-navigation instruments. ILS, attitude, slip, localizer, compass and heading information is shown.

Flying Controls Since the powered flying controls are highly integrated with the aerodynamics of TSR.2, BAC (Preston) have set up a special joint management system with the system subcontractor, H. M. Hobson Ltd. Thus, should urgent changes in the agreed specification be required, under the joint management system these can be carried out with the minimum of delay.

TSR.2 . . .

Each powered flying control unit comprises hydraulic jacks responding to pilot control movements or autopilot demand via electronic signals. In developing the primary and auxiliary flying controls—namely, fin, tailerons, airbrakes, wing flaps, taileron flaps and pilot feel—H. M. Hobson were faced with a design requirement surpassing anything previously attempted in Europe. Control specifications were based upon the need to satisfy a high-speed, terrain-following capability within the environments evoked by supersonic all-weather conditions. The terrain-following mode dictated that positional accuracy of every surface, in response to a signalled input, should be of an unusually high order. The considerable inherent structural elasticity and control-surface inertia necessitated the development of powered controls with unique stabilizing systems. Special approaches were evolved to assess stiffness and mass effects. Manufacturing methods were refined to produce a new class of controls giving accuracies better than 0.1 per cent, and yet with parts having a useful service life. Extremes of environment demanded the use of new materials, techniques and processes. Much of the development programme carried out was to prove the capability under simulated flight conditions of special fluids, seal arrangements and treated materials. An extensive test laboratory was commissioned specifically for this purpose. The performance requirements supplied by the contractor were progressive, and left little or no margin for change. Only by insisting on such requirements could the necessary breakthrough in control engineering, compatible with the demand of the aircraft, be achieved.

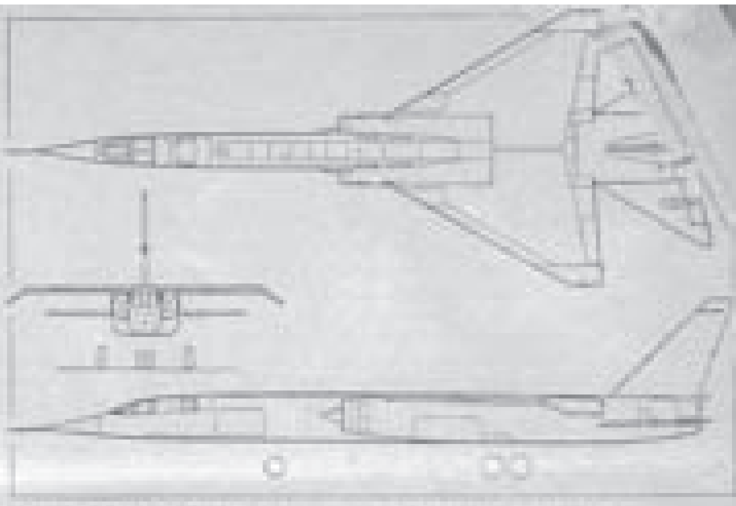
Hydraulics As already mentioned, the aircraft hydraulic systems operate on DP.47 Silicodyne H fluid. For weight-saving, an operating pressure of 4,000lb/sq in has been adopted. This has involved a development problem in itself, accentuated by exacting response requirements coupled with the inevitable contamination encountered in service and the high-temperature environment. Pumps and various valves for the hydraulic system are supplied by Lucas; other valves and selectors are supplied by Dowty-Rotol Ltd, who also contribute the two accessory gearboxes.

One installation problem encountered with the hydraulics was to achieve satisfactory pipe couplings. The traditional bell-mouthed pipe and screwed coupling proved inadequate to stand up to service conditions, and it was found necessary to develop a method of brazing *in situ* on the aircraft. This process, developed at Warton, demands precise dimensioning of the pipes to be joined. The two ends are closely mated, and the joint effected by brazing on a sleeve in an argon atmosphere both inside and outside the pipe. An expendable induction coil is used to raise the temperature to 1,000°C, the brazing equipment being by Radyne Ltd. The process has been used on stainless-steel pipes from 0.5in to 2.5in diameter.

Electro-Hydraulics Ltd has also been involved with the manufacture and development testing of many items of hydraulic equipment for the TSR.2. The main features in which these components differ from those generally in use are in the wide temperature range to be met and in the use of titanium. Titanium presents no difficulty in manufacture but an appreciable development programme has been undertaken to find materials which can be used in bearing contact with it. It has also been necessary to develop suitable seals for the extreme temperatures, and to ensure that all components work satisfactorily with DP.47 fluid.

Fuel The low-pressure fuel boost system, supplied by Lucas Gas Turbine Equipment Ltd, includes a centrifugal fuel booster pump, tank balancing valve and low-pressure warning switch. A number of other specialist companies have contributed—notably, valves have been supplied by the Saunders Valve Co Ltd, Normalair Ltd and Flight Refuelling Ltd.

Fuel-gauging has been developed by Smiths, the design being based on well-proven equipment which uses the capacitance principle. The system incorporates reference units which compensate for variations in fuel permittivity over a given range. Control and distribution of fuel to maintain a predetermined centre of gravity, and automatic control of refuel/defuel operations, are examples of fuel management performed by the system. The whole fuel system has been worked out at Warton on a full-scale rig to ensure proper sequencing of all the valves under every fuel combination and in every flight configuration. There is provision for refuelling in flight.



Dimensions of TSR.2 have not yet been disclosed, but this "Flight International" copyright three-view drawing is accurate to a high degree. Span and length appear to be approximately 35ft and 90ft, respectively

Air-conditioning Sir George Godfrey & Partners are the principal subcontractors for the TSR.2 air-conditioning system, which serves the crew-compartments, and also for cooling the equipment in the electronics bay. Subcontractors to Godfrey are Marston Excelsior (heat exchangers), Teddington Aircraft Controls Ltd (temperature control) and Normalair Ltd (pressure control). Two air-cycle bootstrap cold-air units are used, of which one is a standby automatically brought into operation should the working unit fail. The system is unusual in that mass airflow to the crew can be varied, as well as temperature. Another unusual feature of the air-conditioning system is the use of fuel-cooled heat exchangers.

The system has been designed to maintain the crew in comfort, at a mean cabin temperature of 15°C, without the use of special clothing. Nevertheless provision is made for fitting ventilated suits.

Crew-escape The escape system, including canopy jettison arrangements and mechanisms, together with two advanced rocket ejection seats, has been designed, developed and manufactured by the Martin-Baker Aircraft Co, in close association with BAC.

Since the operational role of this aircraft involves protracted high-speed flying at low altitudes, very exacting demands are placed on the emergency escape system. Among many new features of the seats and canopy jettison arrangements are the facilities for rapid exit, the power to obtain a high trajectory path, and maximum structural strength to endure ejection at high indicated airspeeds near the ground. Furthermore, extensive detail-design improvements have been made to the structures and mechanisms to ensure reliability, efficiency and to afford maximum protection against damage during ejection. Ease of servicing is obtained by providing for the quick removal of the seat pan, parachute and headrest assemblies, as well as time-delay mechanisms, whilst the structure remains in the aircraft.

An exceptionally high degree of comfort for the crew has been achieved, and the harness restraint is particularly effective. A hand-operated ratchet control positioned on the left side of the seat enables the pilot and navigator to obtain any desired degree of harness tightness instantly, as well as to slacken off for comfort; pre-tensioning of the harness is ballistically accomplished immediately before ejection. The navigator may jettison his canopy and eject at any time; if the pilot should operate his seat firing with the navigator still in the aircraft, then the navigator will be ejected first, followed automatically by the pilot. This arrangement eliminates the need for an abandonment command by the pilot and subsequent action by the navigator, thus reducing abandonment time, a vital requirement in emergency escapes near the ground.

Automatic harness pre-tensioning and effective head restraint bring both the pilot and navigator into a favourable posture before ejection at all times, and this facility ensures a satisfactory posture for the navigator when he is fired out by the pilot. Propulsion is provided by an ejection gun of proven efficiency and reliability, and the thrust thus obtained is augmented by the thrust developed by the Martin patented rocket motor fitted underneath the seat pan. Peak acceleration and onset of g have been held at a much lower level than in earlier types of seat. This propulsion system is being developed and verified by a most extensive test programme, including a number of live ejections.

Continued overleaf

TSR.2 . . .

Conclusion

Soon the first TSR.2 should embark on its flight-test programme, which, because of the very wide performance potentiality and complexity of the entire weapon system, is a development task of unprecedented magnitude. Indeed, British Aircraft Corporation consider the organization of this intensive programme to be as great a problem as the design evolution of the aircraft.

Airborne recorders have been ordered from Royston Instruments Ltd, designers and makers of the MIDAS range of flight-data recorders and data-processing systems, for installation in TSR.2 development aircraft. The equipment is ejectable complete with recovery aids: parachute, flotation bag, UHF homing beacon and marker dye. It can record 270 channels of information every [illegible].

TSR.2 development aircraft are likely to begin trials at the Aeroplane & Armament Experimental Establishment, Boscombe Down, where the first aircraft will shortly make her maiden flight. BAC have already appointed the first two flight-test aircrew. The initial flight is scheduled to be made by R. P. Beamont, deputy chief test pilot of the Corporation, and Donald Bowen, a senior navigator of BAC Weybridge Division. "Bee" made the first flights of both the Canberra and Lightning, and it is possible that his memorable demonstrations of these aircraft at past SBAC shows may be eclipsed at Farnborough next September. The second test crew will be J. L. Dell and P. J. Moneypenny, respectively chief test pilot and senior navigator of BAC Preston Division.

The bringing-forth of TSR.2 has been a very challenging task to a large section of British industry. Although it has cost many man-hours (and therefore much money), it is not in fact an expensive weapon system. It is so versatile that it combines in one aircraft the capability of dispersed-operation all-weather, low-level or high-level supersonic attack and reconnaissance roles, over extended ranges. From another viewpoint, it has contributed to industry in direct return to industry's contribution, improving our ability to produce modern structures, systems and components, in the raising of standards of engineering organization and skills, and in the development of new materials and methods. Without TSR.2 we should also be critically weakened militarily in our ability to react to any kind of world situation.

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