

The BAC TSR2 – a historic overview from a personal perspective

By Ken Weaver

About the Author

Ken Weaver, born in Southampton in 1929, left school in 1947 and following army service, joined Supermarine at Hursley Park, Hampshire in February 1950. He worked as a weight engineer on the Pakistan Attacker and the prototype and all production variants of the Swift, ending as Section Leader. He transferred to take over the production Scimitar. In August 1957, Ken was moved to South Marston, Wiltshire, but within weeks was back at Hursley working on the TSR2 Feasibility Study. He returned to South Marston five months later, with the additional weight responsibility for the twin-engine version of TSR2. On 1st January 1959, Ken was transferred to Weybridge as a founder member of the Joint Vickers-Armstrong/English Electric TSR2 Project Team.

Several years later Ken was transferred to the Advanced Military Project Office at Weybridge, working on military applications of Vickers swing-wing technology, including both land and carrier (CVA-01) based fighter/strike aircraft. Ken's last aircraft project was not swing-wing, but the Airborne Early Warning aircraft for the CVA-01 carrier.

Following cancellation of TSR2 and transfer of swing-wing technology to Warton, Ken joined George Henson, the original TSR2 Project Manager, at the Vickers Shipbuilding Yard in Barrow-in-Furness in November 1965. George's task was to develop their design capability to obtain increased involvement on future nuclear submarines. Ken's initial task was weight aspects and led to a major reorganisation of that function at Barrow and the submission of specific weight-saving proposals for consideration by Director General Ships. The shipyard subsequently obtained a design contract, the SSN.0X Project Order for the next, deeper diving nuclear submarine. George was appointed Project Manager with Ken as his assistant.

As the resultant submarine (HMS Swiftsure) moved towards the production phase, George and Ken spent more of their time on other activities. Major projects for Ken were development of a Submarine Rescue System based on a Vickers Oceanics commercially operated Diver

Lock-out Submersible, and the setting up of an organisation to provide a commercial underwater design and consultancy service. The latter was known as Vickers Offshore Developments (VOD) and eventually became a separate company, with George as Managing Director and Ken as Project Director. However, after nationalisation of their shipbuilding interests, it became evident that VOD no longer fitted Vickers Ltd. long-term plans. Consequently, it was sold to British Shipbuilders, who had a poor reputation with oil companies - VOD's main customers, which led to Ken departing.

Ken rejoined Barrow Shipyard in 1980 as a planner for their SSK Combat Systems Design Authority Contract, but eventually became Head of Projects on the Combat Systems divisional board. He later became one of thousands made redundant in the Shipyard, in his case in November 1991. He then experienced a mixture of enforced holiday, paid and voluntary work before formally retiring in March 1996. His voluntary work for the local Furness Enterprise organisation continued for another six years, with one of his last projects, very fittingly for an ex-Supermariner, being an assessment of an amphibian.

TSR2 (Tactical Strike & Reconnaissance)

Author's Notes

1. In preparing these notes I have been becoming aware that my memory, especially regarding numbers, is not what it was. Since I have no sources available to refresh my memory but all my experience taught me that numbers and not just words are essential for design purposes, I have used figures that in some cases may be incorrect but certainly in the right 'ball-park'. Such numbers are quoted in square brackets, thus [].

2. The TSR2 design process was highly re-iterative. However, for these notes I have produced one write up for each technical area and include the start and finish, but largely ignore the intermediate steps. Most of these descriptions are included in Section 3, but one or two may occur elsewhere because they are used as an example to illustrate wider issues. A good example of this is the Air Conditioning System requirements, used to show what any designer would consider a major weakness in the Ministry handling of the project, discussed in Section 7.

3. Because of the Government cancellation instructions that everything associated with TSR2 must be destroyed, I suspect that security classification has never been reduced and hence much of the actual numbers may still be classified as SECRET.

1. BACKGROUND TO TSR2

The period 1950-57 has been described as 'The Golden Age' of the British aircraft industry. Many new designs had been produced, initially to implement lessons and new technologies learnt in WW2. However, the Korean War introduced a second wave of new requirements, primarily because both the USA and Britain were surprised by the performance of the North Korean Air Force, particularly the Russian produced Mig fighters. Further, existing new designs had been assigned super-priority status, and in many cases rushed into service too early.

In March 1957, the scenario was totally changed as a result of the Defence Review, when Duncan Sandys' White Paper concluded:

- a). No more manned fighter aircraft requirements for the RAF, who it was claimed had the capability to carry out the roles using ground-to-air guided weapons.
- b). The only new requirement for a bomber would be a replacement for the English Electric Canberra, known as GOR (General Operational Requirement) 339.

In September 1957 the Ministry called a meeting of all the British aircraft design companies who had expressed an interest in GOR 339. They repeated that it was the only new RAF requirement for a fighter or bomber at that time and requested formal proposals should be made by January 1958. They also introduced a new requirement: bids would only be accepted from companies prepared to fully integrate development with other companies (i.e. with organisations previously considered as competitors!).

There were a large number of submissions in response to GOR 339, since for many military aircraft dominated companies it was their only possible route to survival. Certainly more than 10 submissions were made.

2. VICKERS' RESPONSE TO GOR339

Thinking and discussions with Air Staff on a replacement for the Canberra had started by June 1956, with Supermarine acting on behalf of parent company Vickers. It had quickly become clear that a low-level strike-aircraft was required and the Scimitar, although designed as a fighter with a high rate of climb for the R.N. had been adapted to a low-level strike role. Key items studied by Supermarine covered many topics, including:

- flying at high sub-sonic speed near ground level over land (rather than over the sea).

- electrical power to be A.C. generated to suit high 'black-box' content.
- use of prototype aircraft versus pre-production aircraft for flight development purposes.

However, equally important for Supermarine was the need to build a new design team. Following the death of Chief Designer Joe Smith (early 1956), Vickers had announced that the design offices were to be transferred to the main production works at South Marston (Swindon – now Nissan Cars UK factory), a move that Joe had always resisted. This led to a large exodus of design staff. Firstly many of the senior staff who had been with the Company pre-War or since the early war years decided they would leave or take early retirement rather than uproot their families. Secondly, in early post-war years, many staff had been recruited from all over Britain. They had been attracted to Supermarine by a combination of factors, such as the magic of the Spitfire and the Southampton location with the New Forest and yachting facilities at Hamble close to hand (it certainly was not for financial reasons, where rates of pay were amongst the lowest in the aircraft industry).

Quite a large number therefore decided that Swindon was not for them and sought local employment instead. There were many aircraft companies based in or near Southampton, all of whom found recruiting from Supermarine attractive. At the time, particularly the Hamble based Folland Aircraft were engaged in designing their first major aircraft, the Gnat, a fighter for countries such as Jordan and India and an advanced jet trainer for the RAF. The early work on the TSR2 project was therefore vital in building a new advanced design capability, with strong emphasis on project and multi-team working.

When the formal contract was received in September 1957 for the study of GOR339, a project team some 30 strong was assembled at short notice to work at Hursley Park (A very large country house and estate near Winchester, taken over following the Supermarine Works being destroyed by German bombing raids in September 1940, as a home for the design office – now an IBM site). About two-thirds of the team would have been already at Hursley, the remainder being transferred back from their recent move to South Marston - in my case only a month previously.

From an organisational point of view the project start-up was straightforward. Everyone had previously been involved in some aspect of the project; we all knew each other (indeed from top to bottom on Christian name terms from Project Manager down – the first time in my experience) and were totally committed as a team.

Technically we knew the problem was the mission profile. It was to deliver a nuclear bomb, with a 50% C.E.P. (Circular Error of Probability) accuracy of [400] yards, on a target at a range of 1,000nm. The 1,000 nm was to

consist of three legs. The first 500nm could be at most economic speed and height (both out and home) and the last 200nm was to be flown blind at 0.92 Mach at 200 feet over rough terrain. Delivery was by LABS manoeuvre (See Note 1 below), then return to 200 ft and fly the 200nm at 0.92M on the home leg. The second leg of 300nm was different between out and home because of the state of readiness assumed for the defenders. Coming home it was at an altitude of [70,000] ft at Mach 1.7. The outward leg I do not remember, but believe it was high sub-sonic at more than 50,000 ft. Basically the mission profile combined the speeds normally only associated with high-performance fighters with ranges associated with high altitude bombers. A formidable task.

(Note 1) LABS – Launch Air Ballistic System was a flight manoeuvre designed to deliver a retarded nuclear store without nuclear risk to the delivery aircraft, or its crew. Because TSR2 would be flying blind, it demanded a pre-planned target and approach with a nominated IP (Initiation Point) that could be identified either before or after the target had been reached. If before, when the aircraft reached the IP flying at a pre-determined height, speed and direction, it would initiate the LABS manoeuvre by starting a constant 'g' force loop (on TSR2 '4g' preferred, at 0.92 Mach at 200ft that required a special 'g' suit for the aircrew).

At some pre-calculated position on the first quadrant, the retarded bomb would be released (on TSR2 it needed physical ejection using a Frazer-Nash gun) such that the bomb should hit the target. The aircraft could then complete the half-loop, be 'righted' by the pilot and then get as far away as possible from any nuclear fall-out, normally by flying as low and fast as possible. If it was necessary to use an IP after over-flying the target, a different delivery pattern followed. The retarded bomb would not be ejected until the aircraft was in the second quadrant on the loop, i.e. nearing the upside down position, and (Note 1 continued) hence the bomb would be ejected upwards relative to the aircraft. Once 'righted', the pilot could see the bomb above and behind him. Hence this was known as the 'Over the shoulder' LABS manoeuvre.

NB. The TSR2 was designed to fly 200nm into and out of the target area blind, using automatic (hands-off) control, which was also capable of performing the LABS manoeuvre. Previous aircraft, such as the Scimitar, had to rely on manually flying the controlled loop. I believe that normally it would use a '2½g' loop. Incidentally, the Scimitar nuclear store had been assigned the code-name Target Marker Bomb, TMB –bit of an understatement!.

However, a secondary role had been added to the GOR339 requirement, not previously discussed to my knowledge. The same aircraft must perform dispersed operations from an ill-prepared strip suitable for STOL (Short Take-off and Landing) with a radius of operation of 450nm.

Vickers (Supermarine) decided to study two separate designs; one for a single engine design, Supermarine's preferred solution and the other the Air Staff's preferred design for a twin engine aircraft. One of the main reasons for introducing these options was to formally analyse the penalties associated with the twin-engine approach, particularly in terms of weight. Rolls Royce repeatedly claimed to us (and we presumed to others) that they could produce two engines for the same weight as a large engine of equal thrust. That was probably true. However, some people were using this argument as being the same as saying that there was no weight penalty (hence cost?) for having a twin-engine version, which was a long way from the truth. Our studies showed that the twin-engine version was some 35% heavier than for a single-engine version of identical performance in terms of speed, range and payload. The two Vickers submissions were made in January 1958. The English Electric submission, known as P17, was also made in January 1958.

The first Vickers Aircraft/English Electric Aviation (VA/EEA) meeting at working level was held in April 1958. I am not sure of the politics involved but guess it started because someone from the Ministry had given at least an indication to each Company that there were similarities in their separate proposals that should give a good basis for their joint working. Vickers Ltd by this time would have already decided that Supermarine was to be finished as an aircraft design company, and Weybridge design staff were heavily over-committed to future airliners and hence no conflict of interest would exist.

English Electric Aviation would have considered that in the light of the Ministry statement regarding joint working by companies, it was probably their best option. The initial aim of both companies seems to have been concentrated on joint manufacture of whichever design was chosen by the Ministry. However, the Ministry decided that a Joint Design be produced, with the lead company to be Vickers. The team was set-up at Weybridge on 1 January 1959, consisting of the Supermarine team being officially transferred to the Vickers Aircraft Company payroll, and EEA members being 'seconded' as appropriate to temporary working at Weybridge. In addition to the previous company submissions, we now had the OR343 (albeit only in draft form until 1st Issue of 1st May 1959).

3. JOINT VA/EE RESPONSE TO OR343

The prime task of the Joint Project Team was to produce a joint VA/EEA design to OR343 in order that a formal contract could be obtained from the Ministry. This required not only all major design requirements to be amicably resolved, but agreements on common practices to be adopted for design, quality, planning and management, etc.. There was also a very important internal task to breakout the responsibilities and work for subsequent work sharing between the two companies. This subsequently became less relevant, especially commercially, when the British Aircraft Corporation was formed, initially 40% Vickers, 40% English Electric and 20% Bristol Aeroplane Co.

The design process is always complicated at the initial stages and in the end decisions depend on compromises between conflicting requirements by the customer and the design company's experience or preference. Potentially with three different independent design organisations involved, the TSR2 was expected to give major conflicts. In fact this was not a major problem because the full-time project team was 98% either ex-Supermarine or English Electric staff and both these companies respected each other. The major parameters were resolved as follows in approximately the same order that they were dealt with. However, the joint study only had to produce an aircraft specification and in most areas this did not need to have the design solution, only the undertaking to solve it. However, in the following details I often describe solutions that were not made until later, in some cases much later.

3.1 Wing, Tailplanes and Fin

The key new requirement was to fly at high subsonic speed at near ground level for a total of 400nm in and out of the target, relying entirely on instruments and navigation aids. Arising from this was a need to use a low aspect ratio wing to give minimum $\frac{1}{2}g$ bumps/minute for crew comfort and efficiency. The wing should be aerodynamically as 'clean' as possible because of potential problems at high speed/high 'g' conditions due to wing flutter and also fatigue.

EEA had proposed a Delta wing, for which they had carried out major development testing in their own wind tunnel facilities. Supermarine had proposed a low-aspect ration of 2.5 based on their actual flying experience, noting they had no wind tunnel facilities of their own for research and development purposes. The decision was easy, the delta wing was accepted for the joint proposal. Perhaps even more importantly, the discussions that led to this agreement resulted in acceptance that EEA should generally lead on all aerodynamic matters. (Note that the EEA Project Team members were heavily biased to aerodynamics by background). It was also agreed that roll should be provided by using the tailplanes differentially, and hence only low speed moving surfaces (flaps)

were required on the wings. The so-called 'Tailerons' were immediately agreed to be slab surfaces (i.e. no elevators) and after some discussions the same solution was agreed for the fin. The crew comfort criteria laid down by the Institute of Aviation Medicine at Farnborough could therefore be met when flying at 200ft at Mach 0.92 which was considerably better than any NATO fighter could perform.

3.2 General Structure Design Criteria

Decisions on the wing led directly to resolving other criteria, starting with Design Diving Speed (VD), and the associated maximum design 'g'. The speed was agreed to be 800kts EAS (Equivalent Air Speed). For comparison, the previous highest British aircraft was Scimitar at 728kts, with Lightning, Hunter and Swift around 660kt and the RN Strike Buccaneer [550]kts. The factored 'g' used for design was 10 (fighters normally 12g). The next decision was the main structure design temperatures of 128°C continuous and 146°C overshoot (i.e. for short periods – I do not recall the time). However, leading edges (wings, air intakes, windscreens, etc.) would be approximately 20°C greater. There was a further problem for wing design due to potential high thermal stresses that could occur between top and bottom skins of the fuel tank, i.e. the main structural box of the wing. The simplest solution was to use the wing fuel first (and fill it last), which was adopted, noting that only a small percentage of the total internal fuel could be housed in the wings.

3.3 Power Plant

The engine requirements were known in general terms. The Ministry required two engines and jointly the project team estimated that a total thrust/weight ratio of some 60% would be required, i.e. about 70,000lb of thrust at sea level with full re-heat. The engines would have to be mounted in the fuselage, side-by-side to maximise accessibility in-situ and ease of removal. The re-heat needed to be fully variable, plus variable intakes to control shock waves, etc. when aircraft go supersonic, along with variable exhaust systems, which would be essential to optimise fuel consumption. In addition, the worldwide operational requirements demanded auxiliary intakes (high altitude airfields) and water injection (high temperature airfields).

The project would require a direct drive for the electrical and hydraulic power generation, and air take-off for air conditioning, windscreen insect removal, flap-blowing, etc.. The engine needed to be designed for supersonic flight up to Mach 2.0 and for use with AVTAG, AVTUR and AVCAT fuels operationally. It needed to be of low dry weight but more importantly of low specific fuel consumption. Unfortunately there was no

proven engine that came anywhere near meeting the requirement; not surprising considering that the airframe design also had to start from scratch because the Operational Requirement was extremely different from any previously issued. Rolls-Royce had developed the Avon class engine with the main aim being to maximise thrust, leading to the RA24R (re-heat) for the Lightning, and for economy (essentially for civil aircraft) the by-pass Spey engine, due to be followed by the Rear Fan engine.

Bristol Siddeley Engines had been working on the Olympus engine, aimed I believe at the supersonic market (an all Bristol 'Concorde' perhaps). De Havilland had worked on a supersonic engine, the Gyron, due to be fitted into the Bristol Aeroplane Company's 188 supersonic research aircraft. In the event the aircraft flew with the 'Gyron Junior' engine but the project was cancelled nevertheless. The naval strike aircraft, the Blackburn Buccaneer initially had two Gyron Junior engines fitted. However, this combination resulted in an aircraft that proved to be underpowered, particularly for aborted landings on an aircraft carrier.

The Buccaneer was redesigned to take the RR Spey, a proven civil aircraft engine, designed for low temperature to give long-life and low specific fuel consumption, and this may well explain why the aircraft had a low Design Diving Speed of about 550kts.

The Bristol Olympus engine was eventually adopted for TSR2; I do not know who made the final decision. However, there were ex-Supermarine members of the Joint Project Team who had lost respect for the RR design team (but not their after-sales support organisation) as a result of Swift and Scimitar experiences.

3.4 STOL Capability

There were a series of separate design decisions that followed the late Air Staff introduction of a secondary role for the STOL operations from ill-prepared airstrips. In their submission against the GOR, English Electric had not attempted to implement this requirement into the basic P17 design, but had combined with Shorts who had proposed a separate lift vehicle that apparently carried the P17 proper into the air and launched it, and presumably recovered it similarly(?). To my knowledge it was not seriously considered as an option by the Joint Project Team. (When I heard about it later, I did wonder whether it was Short's who had invented the Mercury/Mayo Composite flying-boats, which as a young boy I had seen operating from Southampton Water). Therefore what is now described was based on the original Vickers proposal, originated at Supermarine based on Naval Aircraft practices, although of course, the 20kts or so wind speed over the deck due to the ship speed would not be available.

The first step was to increase the wing lift by means of a blown-flap, as first used on the Scimitar. Because no aileron was required on the TSR2 wing, the trailing edge flap could be extended over the wing net span. Also compared to the Scimitar, the leading edge flap, rather than being a simple 'droop-snoot' would be designed to also extend the wing forward when lowered. (This gave two advantages: firstly it increased the wing area and secondly, it increased lift at the front of the wing which at least mitigated against the aft shift of centre of lift that had occurred on Scimitar when the trailing edge flaps were blown).

The second step (Naval Aircraft practice) was to adopt their landing techniques, i.e. come down a constant glide path until it hits the ground, with no runway length therefore required for the unpredictable 'flare-out' used for normal airfield landings. The system to do this was simpler than the carrier landing mirror system, just place a transponder at the start of the runway and provide a pilot aid to give necessary information in the aircraft. Also, the undercarriage loads were considerably reduced without any moving deck considerations.

The third step of adopting Naval Aircraft practices was based on free take-off (without use of catapults) for Scimitar, i.e. essentially to rotate the aircraft immediately after take-off to give a high vertical upwards thrust element when resolving the engine thrust into vertical and horizontal components. At the lower take-off weight for the 450nm range STOL role, the TSR2 would have a thrust/weight ratio of some 75%, well over twice that of the Scimitar. With the delta wing form, some doubt existed whether the tail plane would be effective enough to start the aircraft rotation early enough to achieve minimum runway length.

The normal simple assessment of a tailplane's effectiveness was measured by calculating the TVC (Tail Volume Co-efficient), which only depends on relative geometric characteristics of wing, tailplane and their separation. By this method, the tail arm was too short but doubt existed whether this really applied to a delta wing because of the very large wing mean chord length. Therefore as a fall-back solution the nose undercarriage was designed with a built-in extension that allowed the pilot to initiate the rotation process by selecting extension at the required (pre-determined) speed. In fact, flight-testing of the first aircraft demonstrated that the tailplane was highly effective at low speed and hence the extension although built into the undercarriage, would not need to be used.

Also of interest is that for ship operations, short take-off of the Harrier was achieved by using the so-called 'ski-jump' as first used on HMS Invincible, as another method of achieving early rotation (the 'ski-jump' concept had been attributed to a Naval Engineer Officer, Lt. Cdr. D R Taylor- possibly FAA). The arrester gear landing system was not

applicable and was replaced within STOL requirements by use of a combination of a two staged braking parachute system and engine thrust reversal, followed by wheel brakes when speed had dropped.

There was one further aspect of operating from ill-prepared airstrips, which was the undercarriage wheel equipment. Traditionally development of higher speed and weight aircraft had resulted in higher tyre pressures in order to minimise the space required to house the retracted undercarriage. However, to select any wheel equipment it was necessary to know the LCN (Load Classification Number) of the runway, which could be measured by physical testing and defined the loading properties of the runway structure.

It took some time to agree this LCN because as far as we could ascertain none existed that could really support TSR2 STOL operations, even at the reduced range requirement. At the time, this meant a STOL Take-Off Weight of about 100,000lb, and an Emergency Landing Weight only slightly less. Additionally, the runway itself would need to cope with very high take-off thrust (2x[34,000]lb with full re-heat), associated temperatures and naval type landing techniques with extremely heavy braking (parachute, thrust reversal and wheel brakes). Eventually the LCN for these operations was agreed, but I cannot recall what it was.

The logistic problems of operating TSR2 from such airstrips would have needed a fundamental re-think by the RAF; TSR2 design incorporated a totally new approach to maintenance, etc. but it would have been unique and almost certainly resulted in two different support policies, either TSR2 (and subsequent new designs) or all existing aircraft. Implementing the new policy at a few major bases was one thing, but the demand on resources, both manpower and equipment, for dispersed operations would have been daunting.

It should be noted that the aircraft had, after a study of options, been designed to have a high wing, primarily to allow an internal bomb bay on the centre-line near to the aircraft's C of G, i.e. under the wing. A mid-wing option was also highly undesirable due to air intake/engine considerations. A wing mounted main undercarriage with its large total height would result in severe weight problems and therefore the main undercarriage had to be fuselage mounted with the widest track possible. The LCN requirement could only be solved by using both low pressure and low aspect ratio (i.e. wide) tyres. The complex set of space requirements under the wing centre-section of air-intake/engine, bomb-bay and main undercarriage could not be achieved with a single-wheel for each side. The optimum arrangement turned out to be a bogey-beam on each leg to give fore and aft separation, and the wheels to be mounted on either side of the beam to give lateral separation. The result was a complicated main undercarriage, noting that the permitted time for retraction was [8]

seconds. This had to include opening of the doors, rotating the main leg forward, while keeping the bogey-beam horizontal by rotating it relative to the leg, applying the up-lock and finally shutting and locking the doors.

3.5 Hydraulics

There were several requirements for hydraulics, the largest and most important being the flying controls and the raising/lowering of the undercarriage. The flying controls demanded high loads at high rates to power the surfaces during the 400nm continuous terrain-following mode (Mach 0.92 at 200ft), with many adjustments being required per minute with surface rates up to 20 degrees/second. The hydraulic oil would become very hot; calculations resulted in a high temperature requirement of 180°C. The requirements for the undercarriage were also very high but totally different in nature. Normally there would only be one up and down operation per flight, but each operation at high rate. However, the major problem was the O.R. called for operations at Arctic conditions, included take-off after over-night 'soak' with temperatures of -46°C.

Unlike the control surfaces, the undercarriage could not be exercised before take-off to warm up the hydraulic oil, and hence the low temperature requirement of -46°C also had to be satisfied. A totally new hydraulic fluid called DP47, produced by Monsanto Chemicals, I believe, was chosen. Four hydraulic pumps were fitted, two driven by each engine, each rated at 25g.p.m. at 4000psi.

3.6 Electrical Generation

Supermarine had long since decided that the advent of more and more 'black boxes' using A.C. power meant D.C. generation was no longer acceptable. At the time, the use of A.C. power would create a major problem because fuel pumps with individual speed control could only be achieved using D.C. power. After much investigation, it was decided that electrics would not be used on TSR2 to power the fuel pumps, for solution see 3.7 below. The aircraft was therefore designed using A.C., with 2x30KVA/55KVA alternators, one driven from each engine using a Constant Speed Drive. The double rating of the alternator was because the design of the alternator was top temperature limited. The ram-air cooling provided under high temperature ambient conditions allowed an unlimited rating of 30KVA. However, there was a need to provide de-icing, preferably electrical, for the air intake leading edges because of concerns that otherwise large pieces of ice could enter the engine with possible catastrophic effect. Icing conditions could only exist in low temperature ambient conditions, and this permitted 55KVA to be

produced without exceeding the permitted temperature limit of the alternator.

3.7 Fuel System

Two major problems dominated the design of the fuel system. The first was the 1,000nm mission profile demanded a total fuel capacity of 52% of Take-Off Weight, an amount unheard of in high speed, highly aerobatic design. The requirement was aggravated because the wing was small (high wing loading) and very thin, hence nearly all the fuel had to be carried in the fuselage. However, because of the major congestion of wing centre section, bomb-bay, intakes, engine bay and main undercarriage adjacent to the required aircraft C of G, the fuel would have to be carried forward and aft some 15ft away from the aircraft C of G. The fuselage tanks therefore needed to be carefully balanced, not only when full but also at all states of usage.

The second problem was how to drive the fuel pumps. Theoretical calculations had shown that because of the very wide range of pump rates required from maximum re-heat to engines idling, the use of hydraulics was more efficient than use of electrical motors. Because the individually variable speed pumps would be mounted inside the tanks, it was simple decision to use the fuel oil as the hydraulic fluid and to vary speed by bleeding off into the tank to reduce pump speed and hence rate as necessary.

3.8 Black Box Requirements

The proposed aircraft solution depended on major new requirements for the so-called 'Black Boxes', later to become better known as Avionics. The mission profile 200nm in and out of target at Mach 0.92 at 200ft above rough terrain, flying blind demanded new equipment, as follows:

3.8.1 Terrain Following System.

None existed in the free world; the best that existed was Terrain Avoidance, which used the traffic light system (red/amber/green) to give indications for pilot action. However, the Joint Project Team was aware that two students at M.I.T. (Massachusetts Institute of Technology) had produced a joint paper on the subject for their doctorate. The starting point had to be a very good forward looking radar, and the AI 23 intercept radar under development at Ferranti seemed a suitable basis for

the Terrain Following mode. It was relatively straightforward to bring the Americans and Ferranti together.

The next part of the system was automatic flight control of the aircraft during that leg of the mission. It was an adaptation of autopilot technology except for the extremely high reliability requirement since manual intervention was not possible in the available time and violent fail-safe avoidance would probably lead to a failed mission and possibly the loss of the aircraft. It was suggested to the Ministry that electrical signalling should be adopted for operation of the whole flight control system. However, they demanded an extremely low failure rate compared to the traditional manual controls and hence it was not acceptable from weight considerations. The overall system had to satisfy a crew comfort criterion of corrective action restricted to 0.5g.

3.8.2 Inertia Navigation System

There were many developments going on for aircraft, nuclear submarines, space/missiles, etc., but none had been designed to suit high aerobatic performance aircraft. However, even in the UK there was no difficulty in finding companies interested in producing proposals.

3.8.3 Sideways Looking Radar

The only method of updating the inertial navigation produced data was by use of low-level sideways-looking radar. Again there was considerable interest from potential suppliers, but considerable development would be necessary to satisfy TSR2 requirements.

3.8.4 Integration of above to give Navigation System

The very short time available for any action to be taken from the above three sensor sub-systems demanded pre-route planning for each specific target; production of resultant 'roller-blind' map, pre-setting of updates, correlation with Inertial Navigation System, and corrective action that could only be carried out by an airborne computer.

The best proven system available was the American Honeywell system. However, it would be impractical to split hardware and software designs for the new computer and many of the TSR2 capabilities would be given away or could be deduced from this software design. It was therefore considered essential to have a British supplier. Honeywell agreed to provide hardware and technical support to Elliott Automation, which took overall responsibility for the re-designed/package equipment for TSR2. The computer became General Purpose in that all functions best

performed by computer were integrated into the one computer complex. Reliability requirements were to be achieved by quadrupling essential functions.

3.8.5 Black Box Design

Supermarine had already established that the Embodiment Loan Item approach of producing items that were a common fit to a wide range of aircraft had resulted in major penalties on individual aircraft in terms of weight, space, power requirements, reliability and maintainability. They had therefore proposed that 'black box' design should be standardised on an aircraft basis for TSR2, which could only be carried out by a single design authority, the aircraft designer.

Since the Ministry had stated that no other RAF Operational Requirement for fighters or bombers would be issued in the near future, it would have been hard for them to produce any counter argument and they accepted TSR2 'black-boxes', etc. would be aircraft manufacturers' supply, not Embodiment Loan. To my knowledge, the only subsequent exception to this agreement was OR 948 (?), the pilot's standard instrument control panel. The Ministry's argument basically was they had spent a lot of time and money on this project and TSR2 could be the only opportunity to use it. The use of OR 948 was reluctantly accepted, even though some of the instruments used were technologically out-dated. However, our agreement was to my mind politically motivated to keep at least some of the 'specialists' in the Ministry sweet! The inclusion of already sunk costs still appears to be the basis of many wrong decisions, not solely restricted to Government!

Taking responsibility for the black boxes was a very major undertaking by Vickers Armstrong/English Electric. The main project team drawn from Supermarine and EEA had limited knowledge because 'black boxes' had previously been nominated and supplied as Embodiment Loan items. However, this was one area where the Vickers traditional aircraft organisation came up trumps. On the civil aircraft side, they had to provide aircraft to many different customers, operating in a large number of countries, and having to use airports with widely different facilities and particularly navigation and other aids. Although they did not design the equipment at Weybridge, they did know their way around the suppliers of equipment, etc., and indeed were continually courted by suppliers in an attempt to get their equipment into Vickers built aircraft. However, more importantly, there was a major division dealing with Guided Weapons. Probably as early as 1953, Supermarine had submitted proposals for the Swift to be fitted with the Vickers-designed air-to-air missiles. They were large/heavy and fairly expensive and not at all favoured by the Ministry. However, they were technically advanced but ahead of their time. The

reasons for their weight/cost were because their missiles incorporated self-homing and flight controlled devices with 'jump-up' and other characteristics.

When the two teams from Weybridge were put together they made an excellent job of becoming the controllers of electronic design on TSR2. Interestingly, when BAC (British Aircraft Corporation) was formed they inherited three Guided Weapons Divisions - from English Electric, Bristol and Vickers. It was considered only two were needed and hence the Vickers unit at Weybridge was dismantled. Some people were transferred with their projects to the units to be maintained at Stevenage and Bristol, but a good number were transferred to the aircraft business, combining with their so-called Electrical Department, to form a new division called Systems Division E (E for Electronic and Electrical). Prompted by the overall TSR2 project team requirements, they produced the system eventually adopted for TSR2, consisting of:

- All electronic equipment to be installed in one equipment bay except for sensors, displays, etc.
- Every box designed to common height and depth, and widths only available in quarter, half and three quarter or full unit size. These became known as V.E.Rs (Vickers Electronic Racking).
- Each box to have B.I.T.E. (Built In Test Equipment) and front face indicators to show cause of failure, and connectors to link it to a major ground test vehicle, a Hawker Siddeley Dynamics unit under development most appropriately called TRACE.
- Each box to be completely testable without being removed from the aircraft.
- Each box to be installed into a pre-prepared location by using mechanical guides and the rear of the box 'homing' into the necessary automatic locking electrical and cooling air connectors.
- Each box to be designed with layout to give optimum cooling requirements, using aircraft supplied cooling air.
- Front-line repair of each box by UXE (Upkeep by Exchange).

3.9 Fuselage and other design issues

Introduction All design related matters were the responsibility of the Chief Designer of the aircraft company. In the UK at that time, his organisation known as the Design Office was split into two major units known as Technical Office and Drawing Office. The previous sections 3.1 and 3.8 were primarily initiated by the Technical Office personnel, for action by the Drawing Office. However, some of the best designers were in the

Drawing Office and they had to initiate the most difficult task, the design of the fuselage. Particularly when a project requires knowledge or experience not known by that Drawing Office, or which is not freely available from others, e.g. Technical Office or contractors for specialist equipment, the task becomes very difficult indeed. This is because the major criterion for the fuselage is to be efficient as a container for all the items that must be contained within it, and being capable of structurally dealing with the major loads induced by wings, tailplane, fin, undercarriage, engines, etc. For high performance aircraft, the overall fuselage volume needs to be minimal and with a distribution that results in minimum overall drag.

However, the Drawing Office has two other major responsibilities. Firstly, they issue all specific design instructions to production departments, and hence they have to ensure that each part can be economically produced by their organisation or chosen contractors. Secondly, they must provide access for installation, maintenance and removal of all replaceable components, not only for company purposes but also, more importantly, for in-service use. Finally, their role is pivotal regarding the programme, particularly for prototype or first-of-type aircraft that are usually subjected to many late changes as part of the development process.

For TSR2 it was clear from the outset that the fuselage design would demand continual re-iteration, modification and in some cases, total re-start. This process needed to be controlled from the earliest stage in order that all parts of the project worked to a common design.

The following items illustrate some typical examples of the problems they faced:

3.9.1 Windscreen

a. The original requirement for bird strike was [5] lb bird at VD 800kts. Eventually the requirement was reduced to a 1lb bird, but only after a prototype was produced approximately 12 inches thick, capable of withstanding a [5] lb bird, which was agreed to be optically totally unacceptable.

b. Insect removal. The requirement was, in warmer climates, to deal with flying insect plagues of biblical proportion! Much work including testing was done in conjunction with RAE Farnborough. I believe the final solution was a hot, high-pressure air curtain ahead of the windscreen to deflect most of the insects, and then a washing system to clean the windscreen itself.

3.9.2 Ejector Seats

The new general requirement was for zero/zero seat (i.e. eject while stationary on the ground). Specific to TSR2 was ejection at any combination of height and speed within the aircraft's design flight envelope. The worst case was when flying at 800kts at sea level; neither the aircrew nor their personal equipment could withstand the associated wind load. The solution demanded a new seat concept, of rotation of the seat during launch so that a crew member's face was never exposed to full 800kts airspeed, and redesign of all crew clothing that included the lacing of the boots.

3.9.3 Cockpit

The cockpits for aircraft where the crew are confined to the ejector seats, are always difficult for designers primarily because the many demands for space within view and/or reach always exceed what is available. The matter is aggravated in that the many authorities with responsibilities for individual system cockpit items, commitment is mainly only to their system and hence reaching the essential compromises is a very long and drawn out process.

All Chief Designers to my knowledge considered the so-called Cockpit Conference meetings with its ever-increasing number of Ministry experts the *bête noir* of his life. There had been a major increase in attendees in my 15 years aircraft experience when the joint-project team had been formed. Swift less than 100, Scimitar more than 150 and Lightning I believe could not be accommodated in one forum, because about 250 needed to attend. I do not know the figures for TSR2 meetings, which were held in a series of sub-meetings based upon systems. The two common complaints made by the TSR2 team at BAC were that there were too many meetings and the number of attendees was excessive.

The cockpits for TSR2 also created major structural problems. Consider for example the hoods. They had to be ejectable at speeds up to 800kts; the design outer skin temperatures could reach 128°C continuous, 146°C for short periods. The inner skin temperature set by the Crew Comfort conditions could be about 10°C, causing thermal stresses. The difference between inner and outer skin air pressures was also significantly affected by the crew comfort requirement to provide a limited maximum rate of pressure change within the cockpit, that resulted in external pressure exceeding internal pressure following a fast dive to low-level. Finally both hoods were constructed with a combination of metalwork and transparency, notoriously difficult to design the connections, even without these much larger inner and outer temperature and pressure difference.

3.9.4 Equipment Bay

The structure over the equipment bay length would have to accommodate large access doors on each side and the sideways looking radar aerials and their radar transparencies also on each side, but below the equipment bay floor level. The nose undercarriage bay would extend under the equipment bay on the lower centreline. Immediately aft of the equipment bay would be the front bulkhead of the forward fuel tank group. Further the whole area will be heavily congested due to the services that need to be in that region. Obviously there were electrical cables and air supply pipe work that directly connect to the back of each individual 'black box'.

There would also be services running through the bay length, including air conditioning for the crew, hydraulic supplies for the operation of the nose undercarriage and doors, the opening of the cockpit hoods, and the retraction mechanism for the flight refuelling probe. There would also be the main fuel refuelling line, designed to accept 500g.p.m.; mechanism for operating the control surfaces; and many electrical cables, primarily to link the cockpit controls and indicators with the various sensors, etc. mounted throughout the aircraft. For these through services vulnerability requirements would demand separation. For example, the fuel line would be well separated from any source of ignition, such as heat or electrics. Similarly, any duplicated services such as electrical power would need physical separation to reduce the risk of a single incident losing both circuits.

3.9.5 Fuel Tanks

For the first time in my experience, the fuselage had to be designed to accommodate the huge capacity required, rather than fitting tanks into otherwise un-occupied space. Fuel tanks do need considerable access to permit maintenance. The top of each tank will need access to both high-level cut-off float-switches and the pressure relief vent valves. The bottom of each tank is more of an access problem requiring access to the fuel pumps, tank gauges, (minimum 6 per tank because of internal baffling, etc.) and low-level float switches. Further, the floor of the fuselage tank would not be the outside skin and hence double access is necessary.

However, we did successfully resist the normal Ministry requirement of fitting fuel caps to allow manual overhead refuelling (totally impractical because of the amount of fuel involved) and the new requirement to

provide gas tank purging (use of stored nitrogen, very heavy and space consuming and the Ministry suggestion of using a combustor would create an impossibly high risk).

3.9.6 Bomb Bay

The general problems of the space consideration in the fuselage centre section have been explained. However, the bomb bay had serious problems that had to be overcome, arising from the main mission profile, as follows:

- a. Externally mounted stores would create huge drag and hence restrict range.
- b. At high-speed normal longitudinal side hinged doors would create high lift loads on the 'store' when the doors are opened, and hence the use of high downward ejection forces would be essential.
- c. The delivery of a nuclear store from very low altitude used a retarded delivery to avoid the aircraft being responsible for its own, near certain destruction.

The eventual solution (not unique) was to use a rotating bomb-bay door, thus giving minimum drag penalty and minimum possible ejection force.

3.9.7 Rear Fuselage

Aft of the wing centre section, the major space or access requirements would be:

- a. Services to the rear wing, including trailing edge flap mechanical interconnection/drive, high-pressure air for flap blowing, and fuel connections, fuselage to wing tanks.
- b. Installation of engines, jet-pipes and variable exhaust units, plus associated items such as Constant Speed Drive with A.C. generators, hydraulic pumps and 'fueldraulic' pumps, water tank and system, Methanol tank and system and fire extinguishing system. The engine would have two major types of access/maintenance, for engine removal using a fuselage break-joint and a large number of doors, etc. for in-situ maintenance or replacement of engine mounted equipment items.
- c. Large fuselage mounted air brakes.
- d. Rear fuel tanks (similar requirements as Forward Tanks, (3.9.5 above).
- e. Mountings and actuators for taileron and fin.
- f. A considerable number of service runs for electrics, hydraulics, 'fueldraulics', high-pressure air and flying controls, etc.

3.10 The formal technical response

The official technical response was made in the form of an overall aircraft specification draft issued 3 June 1959. A study contract was then issued.

4. ACTIVITY LEADING TO FINAL SPECIFICATION

4.1 BAC In-house Activity

This was an intense study period. The teams were expanded at both Weybridge (Vickers) and Warton (English Electric) and the drawing offices started the process of their work that would ultimately lead to issue of detailed drawings for manufacture. Warton was eventually given the wing, tailplane and fin, plus the rear portion of the fuselage. Weybridge was responsible for the three other fuselage sections. The responsibility for systems generally followed geographical divisions, e.g. Weybridge on all electronics, air conditioning and undercarriages, etc., but some systems, such as the powerplant and hydraulics were jointly controlled technically, but with drawing office work performed in the company that controlled the space.

Overall Project Management, Structural and Weight responsibilities were allocated to Weybridge, with Warton being responsible for Aerodynamics and Flight Testing (including provision of Flight Test Pilots and Navigators). A Warton liaison man was permanently posted to Weybridge and regular joint meetings held at both Project and Systems level. In the early days travel was a real problem, e.g. from Weybridge, trains to Lytham St. Anne's arriving late at night, stay in a hotel for a couple of nights, then late afternoon train back South. Later, regular air flights meant flying to Warton leaving Vickers' Wisley airfield about 7a.m. and return leaving about 4p.m. the same day. These commercial flights were initially a shared function of the parent companies, i.e. Vickers Ltd and English Electric, not British Aircraft Corporation.

4.2 Obtaining Ministry Approval

Obtaining specification agreement on the TSR2 was a very hard task, in part because there was about 13,000 staff in the Ministry and TSR2 was the only new aircraft design. In fairness it has to be said that like the aircraft industry itself, the various parts of the Ministry would have also reflected on the problems that had occurred during the recent past and

would have looked at preferred ways in which improvement could be made from their point of view.

The over-riding problem had been the cost escalations that had occurred, particularly the development cost, where it was generally accepted that the escalation was just over 3 times the initial estimate. Some claimed that a factor of 3.14 should be expected from engineers, since they spent all their time running round in circles! Therefore it should not have been a surprise that the Ministry produced a list of objections to the Draft TSR2 Design Specification. In total there were nearly 100 items raised. Some were cleared either by amplification or amendment to the draft. However, about 50% were far more difficult to agree, although they only needed a change to one word to comply with the Ministry requests. Unfortunately, the word was 'should', which the Ministry wanted to change to 'shall'. Because there could be major cost implications to some changes from 'design-target' to 'must achieve', the subsequent agreement was a drawn out affair.

4.3 Ministry Request Reduced Take-Off Weight

There was from the basic design viewpoint a much more serious 'request' from RAE (Farnborough). Reduce the Take-Off Weight from some 120,000lb to less than 100,000lb. It was progressively suggested: adopt the single engine variant, which would achieve that; permit concessions on the 1,000nm profile; or delete the requirement for dispersal operations. All were turned down; the requirement would not be amended in any way.

5. TSR2 – WEIGHT REDUCTION

5.1 Target

Internally, the target was a reduction to 90,000lb or less Take-Off Weight, i.e. a reduction of 30,000lb, without loss of performance. It had been estimated that if a direct weight saving of about 5,000lb on the current design size could be achieved, then by scaling down the variable weight items (all structure, undercarriage, hydraulics, engines, fuel, etc.) that would give the overall saving of 30,000lb that was needed. Some further weight saving would accrue from reducing the volume where the design was dictated by volumetric considerations, e.g. the fuselage fuel tanks.

Further a target cost value of £80/lb. weight saving was accepted internally. In practice this meant that a weight saving proposal could only

be rejected on cost grounds if, on a per aircraft basis, the increase in cost was greater than £80 per direct lb of weight saved.

The possible weight savings were considered under four individual categories, although in practice specific savings could be due to more than one category. Note those discussed below are the most significant savings; many small changes were implemented to give the total.

5.2 Deletion/Reduction

The best way to save weight is by deletion of the function or item, because it will also save both space and money. TSR2 had already been designed 'tight' and certainly most of the functions were directly related to Ministry requirements and therefore sacrosanct. For items under direct control of the aircraft designer it was known that the deletion or reduction in joints (particularly structural) could give significant savings. Also to increase density by deleting unnecessary space was important. The main item of saving under this category was the gross volume of the fuselage fuel tanks, discussed in some detail later under Design Practices. However, one fuel tank saving was achieved by obtaining Ministry agreement that for deciding the total tank volume (based on the 1,000nm radius sortie), the use of navy fuel (AVCAT) could be used, i.e. 8.3lb/gallon instead of 8.0lb (or 7.7lb) for AVTAG and AVTUR. It was noted that for operations from ill-prepared strips in the STOL mode the tanks were only partially full and hence use of AVCAT not necessary.

5.3 Use of New or Improved Materials

5.3.1 Titanium

Supermarine had used titanium for the engine bay heat shield and later the blown-flap ducting on Scimitar. It had been considered as a main structural material for TSR2, but rejected because it was not weight efficient for thin plates (18 SWG or less), used widely in the fuselage and for 50% or more of the wing and empennage structure by area. There were also major production limitations of its use due to nitriding, (it will combine with nitrogen in the air at relatively low temperatures). Some titanium nuts and bolts were imported from the USA, but it was discovered that the main use, which was for access doors, etc. was totally unsuitable because titanium/titanium suffered what was called (I believe) 'Pick-up', i.e. they could be screwed up initially but very difficult to undo.

However, titanium was used for hydraulic actuators, but only for the cylinders, not the rams, to avoid possible 'pick-up' problems.

5.3.2 Maraging Steel (Maraging is a portmanteau word of martensitic and aging).

These steels have superior strength and toughness, without losing malleability. However, they are low carbon and derive their strength from a precipitation of inter-metallic components. The principal alloying element is nickel, with cobalt, molybdenum and titanium as secondary alloying elements. For stainless steel grades, chromium is required and the nickel content substantially reduced. The martensitic state is achieved using a carefully controlled heat treatment and cooling cycle. In this state the metal is strong and malleable and can be rolled, formed, machined or welded. Subsequent aging (precipitation hardening) is applied to give the finalised item. However, maraging steel is costly, due to both the raw materials used and the specialised treatments required.

On TSR2 a weldable version was used for the main undercarriage bogey beam, rated at Ultimate Tensile Strength of 100 tons psi. Although expensive the application gave very good weight saving, not only on the bogey beam, but also to reduced loadings arising from e.g. retraction/lowering of the undercarriage. However, probably the most important gain was the reduction in the space required for housing the undercarriage when retracted.

5.3.3 AM 350

A new material used for the 4,000 psi hydraulic system on TSR2.

5.4 Design Practices

The major change was the use of the computer, initially for stressing.

5.4.1 Fuselage main frames, etc

Traditionally even the heavy frames, such as wing, tail unit and engine mountings were fabricated. TSR2 changed to use computer-based strain-energy designs (later called 'finite element' technique). This computer program was then used to produce the inputs to the new Numerically Controlled (NC) machine tools. Considerable weight and assembly man-hours were saved. Logistically it created a problem in that instead of

using standard SWG plates, specially ordered billets had to be procured, requiring designs to be progressed much earlier than previously.

5.4.2 Fuselage fuel tanks

Traditionally wing tanks had been integral with the structure, mainly due to their relatively thicker skins, highly supported by ribs and spars. The much lighter fuselage structure consisted of thin skins, typically 20/18/16 SWG with longitudinal stiffeners called stringers riveted to them. When used as a fuel tank, further thin skins were attached to the inner flange of the stringer (or stiffeners on other structures such as bulkheads and floors). A flexible bag was then fitted inside the tank skin. Hence there was no need to seal the basic structure, particularly the rivet joints along each of the closely pitched stringers. However, there was a considerable loss in volume, usually about 1½ to 2 inches all round the tank boundaries. Because of the air intake/engines being in the fuselage, the tank perimeter so affected was considerable compared to the cross-sectional area it enclosed and the total loss of volume was about 10%. This lost space could be eliminated by using the main skin structure as the tank boundary, which had to be reliable from a tank sealing point-of-view. The only practical answer was to machine the outer tank boundary skins, including air intakes, etc., out of solid metal, starting with metal some 2 inches thick or so and ending up with full depth stringers. Between the stringers, the main area of skin was only 40 to 50 thou. (thousandths of an inch) thick, a very major machining task, with scrap cuttings totalling well in excess of 90%.

However, the total weight saving was considerable: all the tank supporting structure and bag tanks could be deleted; small savings could be made in the main structure weight due to the use of integral skin/stringer construction; and simpler tank access would be achieved. But, a much larger saving was due to higher density of stowage that together with use of AVCAT, was equivalent to reducing the fuselage by some 4 feet in length.

5.5 Manufacturing practices

5.5.1 NC Machining

The major advantages in terms of weight saving derived from either the deletion of joints, particularly where traditionally most of the assembly was constructed from plate, with many joints where thickness changes were required, or by incorporation of tapering thickness.

5.5.2 Machining tolerances

At Weybridge the standard machining tolerance was ± 10 thou. It was halved to ± 5 thou. (N.B. the average thickness of a 0.050 ± 0.010 inch machining would be 0.056 inches; for a 0.050 ± 0.005 inch machining was 0.053 inch; i.e. a 6% weight saving, both based on considerable measurements being taken over the years, usually just by weighing the items concerned).

5.5.3 Plate bend radii

Reduced from Weybridge standard bend radius equal to 2 times plate thickness to $1\frac{1}{2}$ times (or Supermarine practice).

5.5.4 Landings around holes

Again reduced, this time from 2 times hole diameter to $1\frac{1}{2}$ times.

5.5.5 Chemi-etching

Introduced at Weybridge, ideal for small items or where the basic SWG was light, e.g. 18g or 20g, necessary for edges because of butt or rivet holes, etc., could often be less for most of the plate, e.g. the nominal 20 SWG thickness of 0.036 inch could be thinned, other than the attachment areas to e.g. 0.020 inch. Also could produce tapered thickness by using time-controlled withdrawal from the bath containing the etching agent.

5.6 Re-design of aircraft based on weight savings described above

For constant performance, TSR2 was then scaled down and the result was a Take-Off –Weight to achieve the 1,000nm radius sortie of 88,500lb, with a fuel capacity of 45,000lb, i.e. within the RAE Farnborough requirement of less than 100,000lb. However, we had ended up with virtually nothing in TSR2 that had been previously used by English Electric or Vickers (Weybridge and Supermarine) other than the crew. However, they had to be clothed totally differently.

5.7 Retrospective discussion

Several years after the above event, probably shortly before TSR2 was cancelled and when I had been transferred to the Advanced Military Project Office at Weybridge and working on the aircraft for the new aircraft carrier, I held discussions with RAE Farnborough regarding the Technical Costing work I was doing on that project. During these

discussions the origin of the TSR2 100,000lb Take-Off-Weight requirement came up.

Apparently RAE was aware that the Ministry had a budget of £100m for the development of TSR2. RAE analysis of historic development costs for military aircraft, when adjusted for escalation, had given a figure for the Development Phase of £1,000 per lb. of Take-Off Weight. Hence they had concluded that the Take-Off Weight for TSR2 needed to be 100,000lb or less to satisfy the Ministry £100m budget.

My technical costing work (carried out about 4 years after the TSR2 decision) had led me to an entirely different conclusion; that the density of the aircraft was a much more powerful factor than weight itself. Certainly the reduced TSR2 had achieved higher density than the original design. Further, there would have been a high percentage of re-work, not just in the drawing associated work, but in items such as wind-tunnel testing, mechanical testing, etc. and doubtlessly the changes made in production requirements would have increased the Company overheads. I believe the last estimated development cost was £220m.

6. DESIGN DEVELOPMENT

The final specification of TSR2 was agreed and issued in August 1960. Following some further commercial discussions, a contract for 9 DB (Development Batch) aircraft was issued on 6 October 1960, i.e. as recommended by BAC (British Aircraft Corporation), the prototype approach was rejected because all evidence indicated it was a major factor in both extending the programme and the cost.

The use of 9 DB aircraft was based on an assessment of the necessary Flight Testing programme to achieve Acceptance by the Ministry against the Agreed Specification and the demonstrations required to show that it had been met. Also because many of the solutions were highly novel and Acceptance was largely based on 'shall' and not 'should' requirements, comprehensive recording of many functions were necessary. Nine separate programmes were produced and priorities assigned to each. The first aircraft obviously was assigned to the highest priority programme and so on.

However, each aircraft was assigned a back-up programme. The instrumentation, etc. on each of the 9 DB aircraft was capable of dealing with two programmes, but on board recording capacity for only one at a time (data transmission and ground recording of large amounts of information at high speed was considered but rejected for several reasons. The main reason was the ground receiving; the low-level high

speed testing data would need to be transmitted to a suitable aircraft at altitude to pass it to ground and environmental requirements would dictate testing in several different parts of the world where suitable ground recording facilities were unlikely to be available). It was anticipated that upon completion of full aircraft development, most of these DB aircraft would be brought up to full production standard before delivery to the RAF, noting during Flight Testing, aircraft would not be kept up to date with all design changes except where the change was essential for safety reasons or the performance of its intended flight-test programme.

On 28 June 1963 a contract for 11 pre-production aircraft was issued. I am not 100% sure of the difference between pre-production and production aircraft, but believe that the pre-production aircraft were for delivery to the RAF, but because the design drawings had not been frozen at the time of ordering, implementation of changes may require a repair action, or to be delivered with some temporary restrictions of a secondary nature, noting that at the time of ordering the first-flight was still 15 months away.

A contract for long dated material for 30 production aircraft was issued on 24 March 1964.

Prior to the first flight of TSR2, considerable testing was being carried out, culminating in flight-testing of key major development items in other types of aircraft. The most important was the Olympus engine, which was fitted to the bomb bay of a converted Vulcan bomber. During ground testing of the engine there was a catastrophic failure, resulting in a total write off of aircraft and engine, caused by (I believe) a shaft failure. Fortunately for BAC, Bristol Siddeley Engines had been taken over by Rolls Royce, who then proceeded to trace the fault and put the design right. Another major item that was test flown was the Ferranti Terrain Following Radar, the first of its type in the world. It had been fitted to a Canberra and the results were much better than expected. The trials system detected items as small as electric power cables strung between pylons.

The test flying of TSR2 had been a source of some friction between the Northern base at Warton and the Southern base at Weybridge, although it had been agreed that the ex-English Electric test pilots would do the flying. Senior BAC management wanted the first flight from Wisley, the ex-Vickers main airfield. The test pilots disagreed, stating its runway was not long enough for early flight. The compromise, which was probably the worst decision that could be made, was to use Boscombe Down, which had been used for that purpose by Supermarine. There were major problems just getting the aircraft there, meaning the aircraft had to be dismantled and then re-assembled and tested after its arrival. Major work

was also required in clearing the roads, requiring temporary removal of road 'Islands', traffic lights, posts of various kinds, trees, etc. in addition to a tortuous route to avoid the many low-height railway bridges. However, the major problem was that the two teams with all the background to deal with any problems arising and specialist workforce for implementing any changes were too far away.

Despite these delays and inefficiencies, the first flight was successfully made on TSR2 No. 1 (XR 219) on 27 September 1964, with the last of 24 flights made on 31 March 1965. I was long-since off the project, so not aware of all the details over this period. However, overall, most people had been highly impressed with the performance of such a novel aircraft, including how quickly it had gone supersonic. Its acceleration was demonstrated when with re-heat on one engine only, it had left its 'buddy' chase aircraft, a Lightning far behind, although the Lightning had its two engines on maximum re-heat. The only potentially serious problem to my knowledge was that the test pilot reported violent oscillations set-up due to main undercarriage vibrations upon landing, I believe on two or three occasions. However, the problem was analysed and corrective action successfully taken. (I did wonder if the basic problem had arisen from the use of very high strength maraging steel in order to save weight on the main undercarriage, particularly on the bogey-beam. Clearly if designed purely on strength considerations significant reduction in thickness would have resulted. But that could have produced the much more flexible structure that caused the problem).

On 6 April 1965, the project was cancelled in the House of Parliament as a part of the Budget Speech.

7. A 2009 REVIEW OF THE TSR2 PROJECT

7.1 Introduction

Two factors make this review highly subjective:

- TSR2 made only 24 flights before it was cancelled and therefore most elements are 'unproven'.
- The writer left the industry shortly after cancellation and is therefore generally unaware whether 'improvements' introduced for TSR2 were accepted or rejected in later aircraft designs.

7.2 Project Management

7.2.1 In the Aircraft Companies.

In the early stages, the Joint VA/EE (later BAC – British Aircraft Corporation) Project Team full-time members all worked as a team, with the attitude that overall design had to take priority over any individual company, department or discipline interests. The Project was controlled by the Project Manager. At Weybridge, although all the ex-Supermarine members had been transferred to the appropriate Vickers Aircraft departments, there was no obvious sign of interference by these senior managers in the work of the TSR2 Project Team.

Potential problems could have occurred, particularly at Weybridge, when development of the design started. These were reduced when due to national security considerations a separate TSR2 Design Office had to be established from the existing more 'open' civil aircraft facilities. However, the major step was by the introduction of project management procedures to deal with the control of the design when hundreds of design staff became involved. Internal specification requirements were written for each system, piece of equipment or task by the central Project Team, who were responsible for ensuring that they were totally compatible with the overall Ministry approved aircraft specification. This became Part A of that internal specification.

The second part of each internal specification known as Part B, was the detail design organisation's proposed solution to satisfy Part A, and had to be approved by the central Project Team before full implementation (e.g. production of drawings for manufacture) could commence. Finally, there was a Part C of each internal specification, which detailed the tests and trials, etc. that were necessary to demonstrate compliance, which could be prepared by anyone but had to be approved by both central and task designer. This procedure, which gave the detail designer considerable opportunity to inject his skill and experience into the ultimate design, appeared to be major step forward in controlling the design.

7.2.2 Within the Ministry

The Ministry appointed Project Manager was good at dealing with overall issues and acting as chairman of many meetings. However, at design level the Ministry relied on individual specialists representing Establishments, departments or committees.

Unfortunately, their major commitment was not to the TSR2 as a project, but to the organisation they represented. Hence, to achieve the essential requirement for a balanced design, the compromise was at best, difficult. Some of the worst examples, to my knowledge, are given below and arose via the large number of meetings held between the Ministry and BAC, noting the Requirements referred to are either specific project, i.e. the Operational Requirement and any resultant agreed documents, e.g.

the Aircraft Specification, or the general aircraft requirements detailed in Av.P. 970. The latter is often subject to interpretation and/or individual company custom and practice.

7.2.3 Example 1 – Air Conditioning System

The major requirement for this system arose from crew efficiency/comfort statements originated by the Institute of Air Medicine. This required the aircrew to be able to select various cabin temperatures within a range of about 20°, while the distribution system had to ensure that this temperature was maintained throughout the cockpit within a close tolerance [2°C?]. The BAC Project Team considered this requirement was a major step forward in their philosophy of a 'Total Weapon System' design. The O.R. included a requirement for worldwide operations, which could mean a high temperature combined with a very high humidity of [120%]. This was also a new requirement, believed to be only recorded while ground running of the Vickers Valiant during nuclear bomb testing from Christmas Island. This high water content would demand a lot of cooling and because it would occur infrequently, it was considered that some relaxation in the ideal cabin conditions should be acceptable.

Finally, there was a general requirement, somewhat vague and open to interpretation, regarding the allowable effects of a single engine failure. The Ministry, (I am not sure who, but believe the three separate requirements would have arisen from three different organisations) demanded that TSR2 Air Conditioning had to fully satisfy the crew efficiency requirement, operating in the high temperature/high humidity conditions after a single engine failure. Even when it was pointed out that the result of this combined requirement would be that under nearly all operating conditions, the 'bootstrap' type conditioner would freeze up, requiring by-passed hot air from the engine to de-frost it. This would mean that the eventual cabin air would have been super-cooled, then heated up to give the correct conditions, with significant penalties on the specific fuel consumption of the engines, they did not change their demand. I am not aware of the ultimate conclusion or how long it took to reach it, except that the 'disagreement' was outstanding for a considerable time.

7.2.4 Example 2 – Fuel System

I attended the first joint meeting on the fuel system in my role as responsible for the Fuel Balancing. The meeting was held in Warton and consisted of about 7 or 8 BAC and 50 Ministry representatives. Since TSR2 was, I believe, the first ever British aircraft with an automatic fuel balancing system, it was not surprising that there were a number of

queries related to that subject, although most of them were made by only 3 or 4 people. What did surprise me was the level of the questions, which demonstrated that:

- They apparently had not read (or could not understand) the technical information that had previously been supplied to them.
- They could not comprehend how vital the requirement was for a fuel balancing system on TSR2.
- They did not understand that balancing involved not only the amount of fuel, but also its distribution.
- They could not recognise the difference between absolute fuel tank gauging accuracy, included in the Av.P. 970 requirement, and the comparative accuracies that had been used for balancing calculations, e.g. Absolute values had to take into account a range of fuels and hence dielectric values and also high temperature differences which originated from refuelling in different environments; relative values only had to take into account temperature differences that could occur during a specific flight of one aircraft.

The meeting ended without any decisions being made, or even any actions being placed that would result in information being made available to support decision-making, i.e. in the design sense it was a non-meeting! (After the meeting, my colleagues told me that the vast majority of Ministry representatives understand the BAC proposal, but Civil Service protocol would prohibit any other Ministry person being seen to criticise another Civil Servant in public!).

7.2.5 Example 3 – Cockpit Labelling

The cockpit approval meetings also led to another example of the difficulty in obtaining acceptable agreement with the Ministry. A sub-committee with more than 50 members was set-up to decide the labelling that should be assigned to each cockpit instrument or control, etc..

After several meetings, a proposal was made by the Ministry that BAC representatives did not want. Subsequently the Ministry solution was accepted, possibly because the joint VA/EE Project Team had much earlier accepted the use of Ministry OR948 Central Control Panel (see Section 3.8.5). However, in the working-up towards the first flight, the nominated BAC test pilot stated that the fitted labelling was indecipherable and took the extreme step, supported by his navigator, of refusing to fly the aircraft unless it was changed. It was quickly changed to more traditional labelling. Not a good example of compromise by either Ministry or Contractor, but it does show the level of frustration that was being built-up within BAC by the Ministry approval process. (Since the pilot was not

subsequently dismissed by BAC, it has to be assumed that his action was supported by the higher level of management!).

7.3 Competitors' Project Management Systems

Before making any conclusions on TSR2 it is necessary to consider what our international competitors at that time were doing. The equivalent aircraft designs at the time were the French Dassault Mirage IV and the General Dynamics F111 in the USA.

7.3.1 Mirage IV

I was a member of a small Weybridge team sent to Paris late-1964, to assess the suitability of the Mirage IV as an option for BAC to offer to manufacture for the RAF as a replacement if the TSR2 was cancelled. On Project Management, our conclusions were highly favourable to their national system. The project had an overall Project Manager, a French Air Force Colonel. He was directly responsible to the President of France, General de Gaulle. A review of the project was held at the Presidential Palace on a regular monthly basis, I believe, normally without any one else, other than secretarial, being present. However, I doubt other French aircraft had the same 'political' support. The national policy of de Gaulle was French independence, which required an independent nuclear deterrent programme (Force de Frappe) and withdrawal from NATO. The key to the independent deterrent was the delivery system, viz the Mirage IV.

The contractor/designer of the aircraft, who owned the aircraft company, was Marcel Dassault. There was no French Scientific Civil Service and hence technical issues were decided between their Air Force and the Contractor. In the case of technical dispute, the arbitrator was the Professor from the French University École Polytechnique noting many of the senior technical people in both parties would have received their qualification there. The French Civil Service dealt with finance and contractual matters. Further, at that time (1964) the French had no equivalent of Av.P.970. Apparently when the Germans took over in 1940, they destroyed all French rules and Dassault, like most of French industry worked for the Germans using German rules. These were quickly ditched when German occupation ceased. (Without a Technical Civil Service it is difficult to imagine how a general rulebook could have been written from scratch).

7.3.2 General Dynamics F111

knowledge of the F111 at the time (1960-1965) was based on limited information that had been published in sources such as 'Aviation Weekly'. My impression was that the project was controlled by the United States Air Force (USAF) and that they had set up a total project system based on a multi-layered management system. Each manager within the system had his responsibilities defined. To be selected for one of these management roles was considered as a high accolade within the USAF.

However, the downside of that was that their individual performances were closely monitored and a failure to exercise their individual responsibilities was considered a serious default. Apparently, if any individual failed to make a timely decision within his remit, or attempted to pass it up the management chain, it was considered a 'sackable' offence (I suspect the 'sack' applied only to the project team, but the long-term prospects of an individual USAF officer would be severely damaged, i.e. 'a potential high flyer would become grounded!'). On the Governmental side they had no permanent Civil Service as such, but a complex political system based on the main lines of Federal, Senate and Congress control or oversight. On the Federal side this was implemented using Agencies, appointed by the President or his nominated senior representatives. The Senate and Congress powers were largely exercised by committees. However, in defence matters since the President was also Head of the US Armed Forces, the role of committees in the Senate and Congress was diminished, i.e. I concluded that technical control would be firmly in the hands of the USAF Project manager, which I considered vastly superior to the TSR2 system.

Recently I have looked at the F111 history and although it probably does not alter my conclusion on the project management by the USAF, the role of the Federal control is, I hope, something that could not occur in the UK.

The history of the F111 was that in June 1960, the USAF issued a specification for a long-range interdiction/strike aircraft able to penetrate Soviet air defence at a very low altitude and high speeds to deliver tactical nuclear weapons against crucial targets. (Nearly identical to GOR 339 for TSR2, issued March 1957). Meanwhile, the US Navy sought a long-range, high endurance interceptor to defend its carrier battle groups against long-range missiles launched by Soviet jet bombers and submarines (to replace the F4 Phantom, particularly requiring more powerful radar and longer range missiles). In February 1961, the new US Secretary of Defence (Robert McNamara) formally directed the Services to study the development of a single aircraft that would satisfy both requirements.

Early studies (not surprisingly) indicate that the best option was for the TFX programme to be based on the USAF requirement and a separate

version for the Navy. In June 1961, McNamara ordered the go-ahead on TFX, despite pleas by both the USAF and Navy to keep their programmes separate. The two Services could only agree on 3 things, the use of swing-wing, twin engines and two crew! On the latter, the USAF wanted tandem seating of crew and the Navy (because of length restrictions on carriers) side-by-side. Despite this, the USAF was ordered to issue a RFP (Request for Proposals) to which 6 responses were received in December 1961.

All were lacking but the best were capable of being improved with Study Contracts, with Boeing and General Dynamics the two chosen to undertake these. After 4 rounds of assessment, the selection panel decided in favour of Boeing, but in November 1962, McNamara selected General Dynamics on the basis they had a greater commonality between the variants and the resultant contract was signed in December 1962.

A Congressional investigation into this selection followed, but it did not change the decision to go with General Dynamics, who lacked experience with carrier borne fighters and hence teamed with Grumman for the Naval version.

I conclude that the USAF Project Management may have operated superbly, but it was unsuccessful in that it failed to stop the Federal Government from ordering an aircraft from a contractor, which neither they nor their US Navy counterparts ever considered to be the best option to satisfy their requirements!

7.3.3 Conclusions on Project Management

I conclude that the British system used on TSR2 was inadequate because the good contractor system was badly let down by the lack of technical support from the Ministry. The disappointment is greater because in my opinion, the Ministry had available to them some of the best technical and scientific brains in the world. However, to be fully utilised on any individual project, they would have to be organised into a project team, with their individual responsibilities being to their immediate superior in that project team and not to any specialist organisation.

Interestingly, apparently the French on the Anglo-French Concorde project used this well-known weakness of the British Ministry in making timely decisions to their advantage. The Concorde had been set-up on an equal share of both cost and value of work between the two countries. Because Rolls-Royce was the main contractor for the engines, the other airframe design aspects were led by France, using a Joint Project Team set-up in France (Toulouse, I believe). All non-engine proposals were therefore initiated by France. The procedure for obtaining joint Government approval included a clause that in effect meant that if the UK

did not submit a full counter-proposal within a prescribed timescale, the project would proceed on the basis of the original proposal, i.e. the UK rights were subjected to 'la guillotine'. I understand this was often exercised, even when the allowed period for approval was as long as 6 months.

7.4 Technical Aspects of the Competition

7.4.1 Introduction

At the same time as TSR2 was being developed, the two other aircraft that could be considered as competitors within NATO, were, as indicated above the French Dassault Mirage IV and the US General Dynamics F111 (which had originated as the TFX). A brief summary of each follows, concentrating on their suitability to undertake the British G.O.R.

7.4.2 Dassault Mirage IV

France decided to develop an independent nuclear deterrent and by 1956 work had commenced on a supersonic bomber to deliver it. A prototype was designed by Dassault, based on the Mirage III fighter aircraft, but with two engines and twice the weight. The first flight was in 1959. As discussed in para 7.3.1, it became a major National project and in late-1964 was assessed by BAC as a possible alternative for their manufacture if TSR2 was cancelled.

As such, it was considered to be unacceptable, due to four major factors:

- a). The Mirage IV had started with a mission profile that relied on high speed and high altitude penetration, while that option had been discounted by the UK due to its vulnerability to surface-to-air missile defences. When the Mirage IV was subsequently modified to suit low-level delivery, it was short in fuel capacity. Hence the requirement of range for the RAF could not be satisfied.
- b). Although two engines gave the Mirage IV duplication, other systems were not duplicated anywhere near the standard acceptable to the RAF. The emergency operation was to use the Martin Baker ejection seat. However, the French approach did reduce the defects and hence maintenance compared to e.g. Scimitar, where there were often 2 unreliable equipments, plus an even more unreliable indicator to tell the pilot which had failed.
- c). It had no black boxes for Terrain Following, Blind Flying, etc.
- d). The aircraft was not designated to operate worldwide or from dispersed fields.

7.4.3 General Dynamics F111 (In USAF nomenclature 'F' stands for Fighter, 'B' for Bomber).

Progressively, fighters have been used in Ground Attack roles since WW2, as they have also in the RAF and now are usually capable of what is termed Strike roles, while still operating within the Fighter Squadrons). The F111 had two main variants, the F111A for the USAF and the F111B, for the Navy. There was also the Australian F111C variant, of which 24 were ordered as a replacement for the Canberra (instead of the expected 30 TSR2s). Finally, when TSR2 was cancelled in 1965 the UK ordered 50 F111s in February 1967, which was known as the F111K. Two of these, which included British supplied missions systems, were in final assembly when less than a year later, in January 1968, the order was cancelled, due to higher costs and devaluation of the £.

The major development appropriate to the UK requirement was the F111A. Early models used 2x TF30-P-3 engines, each with 12,000lbs dry thrust and 18,500lbs with reheat, providing a maximum speed of Mach 2.3 at altitude. The aircraft had a maximum take-off weight of 92,500lb and empty weight of 45,200lb. The avionics suite included an attack radar mated to a separate terrain-following radar and an inertial navigation and nav/attack system. Terrain following was integrated into the automatic flight control systems to allow 'hands-off' flight at high speed at 200 ft altitude. Similar to TSR2, but I believe engine thrust a bit less and no mention of Sideways Looking Radar, essential for 'blind' flying the 200nm into the target at 0.92Mach at 200 feet as required of TSR2.

During development flying, major problems were experienced with the air intakes that caused engine stalls. That problem was not really solved until the F111D were ordered in 1967, in which the intake was located four inches further away from the airframe to prevent engine ingestion of the sluggish boundary layer air. In the meantime, the USAF had received delivery of the first batches of F111A in July 1967.

In March 1968 a detachment of 6 aircraft were sent to Vietnam for testing in real combat conditions. In a little over a month, three aircraft had been lost to malfunction (primarily with the terrain-following radar). This caused a political row in the USA, with Senators denouncing Secretary of Defence McNamara's judgement in procuring aircraft. The aircraft were not fully operational again until 1971. In September 1972 the F111 was back in South East Asia. The capability of the aircraft now began to show, with over 4,000 combat missions being flown over Vietnam, with only 6 combat losses.

Development of the USAF F111 continued, covering airframe, avionics and weapons fits, culminating in the highly successful F111F, which operated

from RAF Lakenheath, amongst other places. On 14 April 1986 it was 18 F111F that flew from Lakenheath to Libya, a round trip of 6,400 miles, lasting 13 hours. They were also outstandingly successful in operation over Iraq during Operation Desert Storm.

The Naval F111B, was a complete disaster. The Navy had wanted a 48 inch radar dish for long-range but were forced to accept 36inch for compatibility. They also requested a maximum take-off weight of 50,000lb, but the then Secretary of Defence forced them to compromise with 55,000lb. However, even this weight goal proved to be over optimistic. The prototypes were far over the required weight. Design efforts reduced the airframe weight but were offset by the addition of the escape capsule (to replace the two ejector seats. Lift was improved by changes to the wing control surfaces, but the aircraft was underpowered and a higher thrust version of the engine was planned.

However, the F111B had been designed before air combat over Vietnam in 1965 showed the need for better performance than the F4 Phantom, but the F111B, especially in the crucial medium-altitude regime, was decidedly inferior to the Phantom. During the Congressional hearings for the aircraft, Vice-Admiral Thomas F Connolly, then Deputy Chief of Naval Operations for Air warfare, famously responded to a question from Senator John C Stennis as to whether a more powerful engine would cure the aircraft woes with 'There isn't enough power in all of Christendom to make that airplane what we want!' By 1968 both Armed Service Committees of Congress voted not to fund production and in July the Department of Defense ordered work to be stopped on F111B.

The F111C was the export version for Australia, of which 24 had been ordered in 1963, the first of which was delivered in 1968. However, development delays and structural problems put back acceptance of the aircraft by the RAAF until 1973.

It would be interesting to know what the structural problems were. It should be remembered that the swing-wing was actively under development at Vickers, but no longer by Barnes-Wallis, who dreamed of producing a civil airliner that could fly non-stop to Australia at very high speed (Mach 5 to 8). However, later the development was aimed at fighter aircraft. The main structural problem was the fatigue associated with the swing mechanism. Vickers was concentrating on a single pin and track arrangement and found major problems in the fatigue of the lugs holding the pin. Traditionally, the method for dealing with fatigue was to reduce the stress level by increasing the thickness, but it was discovered by physical testing that above 3-inch diameter, increasing the lug diameter made no difference. It was believed this was because the actual pin to lug contact area was largely constant above that diameter. A large rig was built for testing, aiming to produce a 5-inch diameter lug with a

higher contact area to reduce the stress and considerable experimenting was being carried out to improve the fit. Aircraft generally used a Class A fit but some improvements had been achieved by using liners and selecting/matching on an individual basis. It was expected that a satisfactory 5-inch pin could be achieved (at a price). However, TFX had an 8-inch pin and it was predicted to fail very quickly if operating at low level with high 'g'. I note that the major failure was reported in the Australian version. Not surprising if it was fatigue induced because that version basically had the USAF fuselage but the naval wing, which had a greater Aspect Ratio giving considerably higher stresses on the inner wing and if the 8 inch pin had been retained, on the pin lug.

My general conclusion on the F111 is that it became a very good aircraft. Like many of the US aircraft however, the initial design was not their strong point. I think we Brits were better. However, they were better than us at 'improving' by testing than we were and because of their much bigger production runs could justify changes for future builds that would be impractical for us to retrofit. I had noted, for example, that their quoted reliability type data, usually excluded data for the first 100 aircraft or so, i.e. excluded Series 1 or Mark 1 data. A typical example in the early 1960s was the much-vaunted Freedom Fighter (the F5), a small aircraft (similar to the Folland Gnat) designed for US small country allies who did not have sufficient skills to maintain the US (or British) latest fighters. They made a huge saving in maintenance man-hours/flying hours when they reached the 101st aircraft (I vaguely recall by about 70%).

7.5 Financial Assessment

7.5.1 General

There can be little doubt that the major weakness associated with British aircraft development contracts throughout the 1950/60s was the financial aspects. Within the aircraft companies (almost certainly not unique to them however) the main reason for this was that the design organisations were divorced from the financial repercussions of their decisions, on the grounds of commercial secrecy. Equally on the Ministry side, their Operational Requirements did not contain targets in terms of costs, but solely in technical performance. This could only work in a cost-plus environment. However, the massive rate of increase of the demanded aircraft performance resulted in a corresponding huge increase in design man-hours on each succeeding aircraft. (When I joined Supermarine in 1950, they were just completing their first jet-powered aircraft, the Attacker. When I left the aircraft industry in 1965, BAC was halfway through the TSR2 development. I guess the increase in design man-hours when TSR2 was completed would be between 50-100 times those spent on the Attacker, for an empty weight increase of about 6 times).

However, the effect on labour costs would have been even greater due to three major factors:

- Labour rates, for example for draughtsmen, would have increased by a factor between 3 and 4.
- The ratio of design hours between Drawing Office and Technical Office was changing, i.e. the Technical Staff, a high percentage of whom were degree or Higher National Certificate qualified, were growing more rapidly and were higher paid. (NB. TSR2 was the first aircraft in my experience where even by first flight the Technical man-hours were greater than the Drawing Office man-hours).
- Major increases in Design Labour overheads due to many factors including permanent building replacing 'war time' temporary facilities, increased facilities for 'prototyping' and testing, education and training, etc., etc..

These effects on technical labour rates would have been considered as Labour Escalation and in total I 'guesstimate' would have been at least 500% between 1950 and (say) 1962 and hence given a total design labour increase of at least 250 times in total or 40times/lb empty weight.

The other aspect of development is the material cost, which can be considered under a series of major headings. Considering Flight Testing alone, TSR2 included 9 DB (Development Batch) aircraft programmed to fly at least 10,000 hours in total. The Attacker would be a maximum of one aircraft flying some hundreds of flight test hours, certainly less than 1,000 hours in total. The gross material cost difference between these two must be at least 200 times. All sub-contracts are considered as a material cost and due to the replacement of E.L.I.s these would also have increased by at least the 200 times factor in total. Hence, I conclude the total material cost on TSR2 was probably similar to that for design labour, i.e. the minimum of 40 times/lb empty weight would have probably applied for the total Development Cost compared to the Attacker, not just labour, a terrifying amount for those responsible for paying the bill!

7.5.2 TSR2 Development Costs

I have no details of the budget or actual costs, or even what was included in them. However, in retrospect, I believe the cost situation would have probably been as follows:

- a. Although internal company statistics would include the earlier stages, I would expect the Ministry would only have included the contract for 9 Development Batch aircraft, which was placed 6 October 1960, which would include the full development stage, i.e. production of all drawings

for manufacture as well as the manufacture and full testing of the 9 Development Batch aircraft.

b. When earlier RAE Farnborough had requested the major weight reduction (later stated to reduce the development cost to the internal Ministry target of £100m) they would also refer to that contract. I cannot believe anyone in BAC would expect to achieve it for that amount, but on the basis it was a cost-plus contract would put in a price that would not frighten the Ministry, say £125m!

c. It should be noted that any historic data based method of costing used by either the contractor (BAC) or the Ministry would have no basis for judging the various additional features of the TSR2 contract, viz:

- The 'sharing' of the contract between Weybridge and Warton
- The contractor to accept full responsibility for everything in the aircraft except the weapons proper. I am not sure however, if this would include the cost of the development flying of new equipment, e.g. use of a Vulcan for the engine and a Canberra for the Terrain Following System.
- The Ministry technical involvement, starting with making the Aircraft Specification change from 'should' to 'shall', then the excessively attended design approval meetings; and goodness-knows-what they would do when it came to 'proof of compliance' and its effect on flight-test hours.
- The manufacture and subsequent Flight Testing Programme associated with 9 development aircraft that would have to include at least some operations from ill-prepared runways and in environmentally different conditions. (I would expect the manufacture estimate made in 1960 would be low, possibly only 50% of the eventual out-turn). It should be noted that Weybridge had no experience of planning and manufacturing a fuselage with air intakes and engines buried within them, i.e. used to build the frames, then join them longitudinally by longerons, stringers, etc. then before adding plating for external skins, or internal floor. Thereafter, most work on completion of the fuselage was carried out from inside the large diameter fuselage.

At the time of cancellation, the general figure being quoted was BAC estimating £220m, but HMG expecting more increases to come. Although some of the costs due to the additional features discussed above would have been identified by then, others including the Flight Test Programme plus associated modifications, etc., would not. Other 'proofs of compliance' would also be largely unknown in cost terms and it was probable that some modifications would originate from change in Ministry requirements, with the most likely being related to weapons fit. I conclude that the final development cost would probably be near £300m.

When the new Government took over it was with an economy that was in a parlous state. It would appear to them that cancelling TSR2 would

probably save about £150m. There would be few other savings of that magnitude that could be achieved 'at the stroke of a pen'. Politically, of course, it could be played as correcting a costly mistake made by the other political party and would of course be welcomed by those members of the Government's backbenches who were anti-defence, anti-nuclear and/or pro-Russia!

7.6 Politics

7.6.1 Introduction

It is obvious from both the French and American situations described earlier, that the success of providing the essential Governmental support for both the French and the American competitors was highly political. In France they had Charles De Gaulle, the wartime hero of his Country, who then became a politician in order to lead his Country, which had become severely divided by WW2, to a position where it would become a dominant power in the world. His target for achieving this was very high; independency from the USA, via the independent nuclear deterrent and leaving the NATO club.

The Mirage IV was therefore not just an aircraft, but also the symbol of the new France. The American situation was also highly political, but in this case appeared to be kinder to the US Air Force than the US Navy, for whatever reason. The Congressional enquiries, etc., suggest that those elected bodies were of the same opinion, i.e. somewhere in the US process the politics were, or would appear to be, inter-service. Finally, there is also a possibility that there could be inter-company rivalries that get out of control and hence become political. For the situation in the UK at the time, it is best to deal with the politics in the reverse order to those above, i.e. consider the inter-company, inter-service and finally inter-political.

7.6.2 Inter-Company Politics

The one statement that was made after TSR2 was cancelled that gave me the feeling that everything I had done for the TSR2 project for about 10 years was not a waste of a large part of my working life, was that made by the man who was Chief Designer for the rival company, Sir Sydney Camm, who stated 'All modern aircraft have four dimensions: span, length, height and politics. TSR2 simply got the first three right'. I conclude there was no Inter-company politics.

7.6.3 Inter-Service Politics

Over the years there always appeared to be considerable tensions between the senior service (Navy) and the junior (Air Force) with the subject of air power being at the heart of it with e.g. topics such as Maritime Command. However, in the late 1950s early 1960s, the change in the Defence Programme from RAF (V-Bombers) to RN (Nuclear Submarines) seemed to create further conflict, not just between the services themselves, but in particular to the Members of Parliament who represented constituencies that gained or lost from such change.

Indeed, in regard to TSR2 some even claimed that the contract was given to the RAF as a consolation for losing the nuclear deterrent to the RN. If this matter had been confined to MPs, who it can be claimed are elected to represent their constituents (whatever that may entail) and if in opposition to the Government of the day, its duty is to oppose it either on principle or some lesser issue, that is to be expected from our democratic process. However, in the case of TSR2, in my opinion, the First Sea Lord (Lord Louis Mountbatten) behaved in an unacceptable way. For example, it was claimed that during a trip to Australia he produced from his briefcase 5 models of a Buccaneer and offered them for the same price as TSR2.

To me that was totally out-of-order, on three accounts. To begin with, technically, a flight of 50 Buccaneers could not have achieved the GOR339 requirement. Secondly, as Head of the British Navy, he should not have interfered in the decisions of either the RAF or the RAAF, they were not his business. Finally, he was in my opinion using his relationship with the Queen, who is also Head of State in Australia, for the purpose of commercial interests. Although we will probably never know, it could also be argued that his action led to the UK losing an order to our main competitor in the defence business, the USA.

However, although I may deplore the actions of the First Sea Lord in respect to TSR2, I do not believe it was critical in the decision to cancel TSR2.

7.6.4 Government Politics

For TSR2, the original contract had been placed by a Conservative Government and cancelled by a Labour Government, so it can be easily seen to be a party political issue. However, the reasons for the cancellation need to be considered more fundamentally than that and also the manner of its cancellation. Finally, there is the question have any lessons been learnt to reduce the root causes of the problem?

In Section 7.5.2 I concluded that it was an obvious target for cancellation with the prevailing National financial difficulties. However, it was not really cancelled because the outturn was going so high, but because the

increase in cost was too great. In the case of TSR2 this is almost certainly because the financial provision by the Government at the outset was too low. This could have been underestimated due to three major changes to previous aircraft procurement practice; the requirement(s), the use of two companies as the contractor and the Ministry control.

Dealing with each item in turn:

a). The requirement. The technical requirement was very challenging from a design viewpoint. Consider as an example only 200nm into (and out of) the target. It required five major developments together when I believe no aircraft in the world at that time had successfully solved one of them:

- Fly 200nm into the target at low level and high speed.
- Low level meant 200 feet or less over rough terrain.
- High speed was Mach 0.92
- Fly blind
- Deliver the store to 50% C.E.P. (Circular Error of Probability) accuracy of 400 yards

b). The Ministry decision to use two companies as a joint contractor. From a design point of view, the technical capability was considerably enhanced, but there was a significant penalty due to communication between the two sites. On manufacture, Weybridge was a major problem because they had little relevant experience, e.g. had never been involved with aircraft that had two engines buried in the fuselage. [If BAC had been formed before the closure of Supermarine, the logical decision would have been to integrate English Electric and Supermarine to form a Military Division at a single site, which could have only been Warton.]

c). The Ministry control. The technical control of TSR2 was by using large committees representing many separate organisations. The result was delayed decision-making or agreement. Certainly for the contractor, time means money.

The Ministry should have been aware that these would have resulted in higher potential cost growth than anything they had previously experienced and hence should have made some provision for dealing with it. (Perhaps a 3 time estimate for the delivery date would have helped them to understand the risk).

When considering the matter of the cancellation, my conclusion was a £150million saving for the design development contract. However, the total saving would have been much greater. The contracts for 11 pre-production aircraft (placed 28 June 1963) and the long dated materials for the 30 production aircraft (20 March 1964) would also be terminated and

the RAF must have already planned and initiated the new facilities they would need, e.g. training requirements for aircrew and maintainers would require major change and hence cost. Further, other major planned expenditure for production aircraft would be as a minimum delayed and probably reduced if a more limited successor was chosen.

The next question is if the decision was purely financial, why was it delayed compared to the other defence cuts introduced by the new Government. I would expect that the cost of delaying the decision would have been at least £5m per month (£2m for the development contract, another £2m for the other two BAC contracts and say £1m for additional RAF expenditure). A lot of money. This delay gave some credence to the claim that the cancellation was due to a secret agreement by Harold Wilson, the Prime Minister, during an earlier visit to the USA, to cancel TSR2 in exchange for their support for the IMF loan that the UK was seeking. If that were true, it would have to be hidden for political reasons and how better than to delay it and then introduce it later in the major annual budget.

Finally, regarding root causes, as a layman it appears that long delays and cost over-runs are still the order of the day, not only for Defence projects, but also in the other areas where HMG takes 'control', e.g. Wembley Stadium and 2012 Olympic Games. Also it seems it is now affecting not only large projects, but what are really small ones, e.g. body-armour for soldiers. Have any lessons been learnt?

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