TSR2 with HINDSIGHT

Edited by Air Vice-Marshal A F C Hunter CBE AFC DL

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Royal Air Force Historical Society

A fine shot of TSR2 in flight bearing the signatures of all three pilots who flew the aircraft.

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Foreword

Air Vice-Marshal A F C Hunter CBE AFC MA LLB DL

This book is the result of a very ambitious seminar held at Filton in April 1997 to consider the history and lessons of the TSR2 project which so dominated the military aviation scene of the mid-'50s and '60s. The seminar brought together an extraordinary collection of those who had been deeply involved in the project, in Industry, in Government and in the Royal Air Force. Many of them had, until the seminar, chosen to keep their own counsel about TSR2 and their contribution to the day is of special interest.

The format of the day will be very familiar to those who have been members of the Society for any length of time and included formal papers and discussion groups which addressed various aspects of the project. These are reported in this book, as is normal. However, such were the interest engendered by the seminar and the huge scope of the subject that I was able to commission supplementary papers by some of those able to offer additional insights and perspectives on TSR2. These are included in this volume and will add greatly to its authority and interest.

The success of the seminar owed a great deal to the active support of Industry. Group Captain Jock Heron of Rolls-Royce and Ron Hedges of British Aerospace were great facilitators of the necessary arrangements. The day simply could not have happened as it did, had it not been for the indefatigable Chairman of BAWA, George Brown. He and his staff provided splendid facilities and the apparently effortless back up that always demands a great deal of extremely hard work.

The RAF Historical Society is also greatly indebted to Rolls-Royce and British Aerospace for their handsome contributions to the cost of producing this book. Publications are our enduring contribution to the recording of Royal Air Force History. We set ourselves high standards and that is, inevitably, an expensive business. The generous support and sponsorship that we have received have allowed us to attempt to record an ambitious and successful seminar in a volume worthy of the subject and the occasion.

Introductory Remarks by the Seminar Chairman

Marshal of the Royal Air Force Sir Michael Beetham
GCB CBE DFC AFC DL

President of the RAF Historical Society

The Royal Air Force and Industry have suffered many aircraft and equipment project cancellations over the years. I think that none caused as much anguish and debate as the cancellation of TSR2. It was a devastating blow to the RAF and it was a devastating blow to Industry.

I was in the Operational Requirements branch of the Air Ministry in the early 1950s when the Canberra was getting well established in service and the V-bombers were coming in. As a young squadron leader, I was told by my boss to pick up my pencil and to write the first draft of what became OR339, for a replacement for these aircraft, especially for the V-bombers in the strike role. I bit the end of my pencil and did my best and in due course I left that job and passed on to other appointments. I still feel, however, that the cancellation of TSR2 left a gap that was never satisfactorily filled.

The Society has assembled a unique gathering of those who were directly or indirectly involved in the TSR2 project for this seminar. Some will deliver papers which will later be published. There are many others who have a major contribution to make and I hope that they will take the chance offered by the discussion groups later, especially those who have not spoken on the subject before.

Today, we have a chance to assess TSR2 afresh. Was it a potential world-beater? Did we over-egg the specification? Was the cancellation 'political'? Where did the fault lie for the 'failure' to proceed with the project? What were the lessons to come out of it, for Government, for Industry and for the Royal Air Force? Did we take heed of those lessons? And, again, what did TSR2 leave behind in terms of R&D, systems and military thinking? These and many others are the themes of today's seminar and I very much hope that you will all contribute to the discussions and enjoy the excellent programme that has been brought together.

SECTION ONE

SETTING THE SCENE

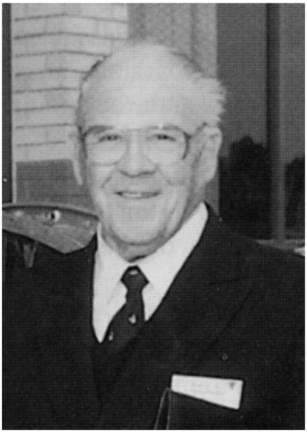
THE HISTORY OF THE PROJECT & THE OPERATIONAL REQUIREMENT

A SYSTEM STUDY OF TSR2

DISCUSSION

Setting the Scene

Wing Commander R P Beamont CBE DSO* DFC* FRAeS DL



Wing Commander Roland Beamont's name is synonymous with the great post war years of British test flying. He is highly regarded by those who know him, both as a brilliant test pilot and as a man who invariably sets out his views in a forthright and courageous way. For many, he is 'Mr TSR2', just as earlier he was 'Mr Canberra' and 'Mr Lightning'. His short introductory piece sets the scene for the wider debate of the TSR2 project.

The period following the infamous Defence White Paper of 1957 was one of confusion and indecision in the field of military aircraft procurement. Momentum in continuous development had been lost after the formal cancellation that year of any planning for future supersonic aircraft for the RAF. This momentum was not resumed until after a gap of two years when a major U-turn emerged from Whitehall in the shape of OR339 for a low level supersonic strike and reconnaissance aircraft for service in the 1970s.

This project required capability to penetrate the potentially highly sophisticated Iron Curtain defences in the 1970s-80s; and the contract was to be placed with a forced amalgamation of major companies in the British Aircraft Industry, only one of which had any experience of design and development of supersonic aircraft.

Even without the benefit of subsequent hindsight it could be seen with penetrating clarity by most people involved, except apparently by the government customer, that such an arrangement could only lead to administrative and technical delays which would inevitably result in difficulties, delayed deliveries and most probably cost over runs.

The practical solution of appointing one prime-contractor with the necessary experience to manage the whole project and subcontract-out where necessary under strictly controlled and disciplined conditions was, if considered at all, waved aside.

The resulting conglomerate then had to deal with the immense task of combining long-established administrations and design and works organisations and adapting them to form an entirely new management system, while at the same time starting out on the design, development and construction of the most advanced aircraft of its time in the world. That is, basing this new programme on a design and manufacturing system which did not exist at the beginning of the contract!

Gilbert and Sullivan might have had a word for it, but the government and their advisers apparently saw nothing odd in this arrangement which went ahead with the forced formation of the British Aircraft Corporation in 1960.

Over the next four years large numbers of the industry's best engineers and administrators battled with this challenge with determination and diligence, but despite their best and tremendous efforts cracks soon began to show when programme times fell behind and the planned First Flight became deferred for 'one year or more'.

Then in the last six months before flight massive technical problems began to emerge in many vital areas such as the engine, undercarriage and cockpit design.

Of these the first two were not resolved by the First Flight which had to be made with a conventionally unacceptable risk-factor in the only partially cleared engine, and with an undercarriage which had not been cleared for retraction and airbrakes which could not be locked closed!

Following a limited though successful Flight 1, rate of progress died away again due to multiple technical problems, and to the inability of the cumbersome management structure to accelerate this vital process.

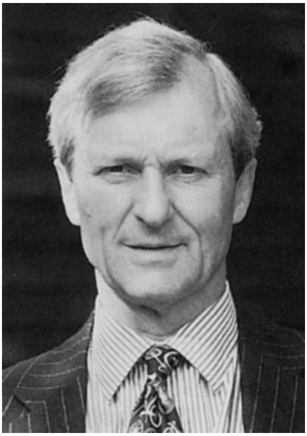
So Flight 2 did not occur until three months later and then further progress was prevented, by recurrent technical problems of a serious nature, until Flight 10 when correct undercarriage operation was achieved for the first time and then the flight envelope was immediately extended to 500kts on that flight – a clear indication of the rapid progress which was to be maintained over the next fourteen test flights until the programme's eventual assassination in April 1965.

With 2,500 hours testing to be completed before Service-entry the test programme had hardly started, but in a total of only 24 sorties BAC had established that from low speed to high speed at low level and to transonic at altitude this remarkable aircraft did not appear to have any aspects of stability and control needing major attention or modification. Its control qualities were already superb and it was right first time – an astounding advance for so early in the flight development programme. Its cancellation could not have been justified on any viable technical grounds.

That aircraft was the TSR2.

The History of the Project and the Operational Requirement

Group Captain W A Mears BA



Group Captain Wally Mears joined the Royal Air Force as a National Serviceman and trained as a navigator. He served on Canberra squadrons, first in the UK and then, in the low level strike and interdictor roles in Germany. He was an instructor on the Vulcan OCU and is a graduate of the Specialist Navigation Course. Later, he was a Flight Commander on No 83 Squadron and commanded No 44 Squadron, both with the Vulcan. He completed courses both at the RAF Staff College where he was later a member of the Directing Staff and the National Defence College. In later appointments, he was Air Attaché in Warsaw at the time of the crisis following the Solidarity strikes and commanded RAF Hullavington.

Wally Mears was a desk officer in the TSR2 Project Office of the Operational Requirements Branch at the time of cancellation after which he had responsibility for the still-born F-111K project. He was later a Phantom and Buccaneer project officer in RAF Germany. During his NDC course, he wrote a much acclaimed paper, 'TSR2 – Murder or Euthanasia?'

Within 6 months of coming into power in October 1964 a new Labour government had cancelled three major aircraft projects upon which the RAF of the 1970s was to be based. They were HS681, P1154 and TSR2, the Canberra replacement. Neither HS681 nor P1154 had flown and their cancellations aroused little public comment, but TSR2 became the centre of a political storm. TSR2 was claimed to be a world-beater. BAC's chief test pilot said: '. . . it can be said with certainty that TSR2 is a sound and satisfactory flying machine with superior qualities of stability and control and there is good reason to suggest that a high success rate may be achieved in the remainder of the CA Release programme.' This assessment was never publicly challenged and yet no use was found for the prototypes or any significant element of the aircraft project after cancellation. Perhaps today we can throw some light on this seemingly illogical set of circumstances.

The Origins of the TSR Requirement

The story of the TSR2 began in 1952 when there was a series of informal discussions between the Air Ministry and RAF Commands on the need for a Canberra replacement, although the Canberra was only just entering service. The first formal paper was a Proposed Air Staff Requirement circulated within the Air Ministry in November 1956. In it the Air Staff called for a tactical strike/reconnaissance aircraft capable of supporting a tactical offensive (possibly nuclear) in limited or global war. The intention was to exploit a combination of high speed with low altitude to ensure that all possible advantage would be gained from the difficulties which the enemy would face in producing an effective defence at those heights. They envisaged that the aircraft would also be able to carry equipment to permit alternative medium and high altitude strike and reconnaissance missions when the air situation was favourable. Thus the primary role of the aircraft was to be to deliver tactical nuclear and HE weapons from low altitude up to the maximum radii of action obtainable with minimum consideration for the prevailing weather conditions by day and night. It was also to be capable of meeting the tactical requirements for low and medium level photographic and radar reconnaissance by day and night.

This outline proposal was accepted by the Air Council and over the next few months General Operational Requirement 339 was drafted. At this stage several requirements were stated which were to have profound effects on the design. For instance, the basic size of the aircraft was determined by the range required of it. Because of considerations of possible targets in Europe and obligations under the Baghdad Pact and SEATO, the Air Staff stated a requirement for a radius of action of 1,000 nautical miles of which 200 nautical miles were to be at low level.

The vulnerability of the aircraft on the ground from surface-to-surface attack was considered and the requirement envisaged dispersed operations from short runway airfields. A take-off ground roll of 1,000 yards was stipulated (there were said to be 1,000 airfields of this size in Western Europe) and this was reduced to 600 yards for a short-range mission.

Invulnerability was also required in the air. To permit medium-level strike and reconnaissance missions to be flown in the regions defended by supersonic fighters, a requirement was stated for sustained flight at supersonic speeds.

These requirements each proved very significant in the development of the TSR2, but perhaps the most significant was the seemingly innocent statement that no single failure should prevent the crew from bringing the aircraft safely back to base.

Wider Consultation

Up to this stage no formal approach had been made to anyone outside the Air Ministry although informal discussions had been held with the Ministry of Supply. Early in 1957 GOR339 was formally passed to the MOS and submitted to the Defence Research Committee. In September 1957 it was submitted to industry for appraisal and by March 1958 the MOS had received brochures from English Electric, de Havilland, Fairey, Short Bros and Harland, Vickers, A V Roe, Hawker, Bristol and Handley Page, and from Blackburns a brochure for a proposed supersonic variant of the Buccaneer. These, together with research establishment reports on instrument and electronic systems, were studied by a joint MOS/Air Ministry OR339 Assessment Group and in June 1958 the DRPC approved a draft OR which set out the aircraft's characteristics in some detail and stated a target for Release to Service in 1965.

Over the next few months there was a great deal of discussion between the Air Ministry, MOS and industry and in January Vickers and English Electric were chosen as joint main contractors. Considering that Vickers and English Electric had not submitted a joint design proposal, nor even similar designs, this might seem an illogical choice. In fact the stimulus for this merger was political rather than aerodynamical! In 1957 a report of the Select Committee on Estimates had reported that 'Your Committee recommend that the Ministry (of Supply) should use the method of the selective allocation of contracts to bring about a measure of coalescence in the aircraft industry which they agreed was desirable.' This view was accepted and in December 1957 the Minister of Supply, in reply to a Parliamentary Question, said that 'the power of awarding contracts should (be used) to bring about a greater degree of integration.' In the case of the TSR2 it is clear that amalgamation was made a prerequisite for the award of the contract, and the choice of design was subordinated to the re-organisation of the aircraft industry.

By My 1959 the contractors (soon to become BAC), the Air Ministry and the MOS had all agreed exactly what was required and what was feasible. As a result of their consultations GOR339 was withdrawn and replaced by ASR343. It is noteworthy that all the changes were increased in the requirement. It seems that the Air Staff were persuaded that they had not set high enough standards, The most important of the changes were that the low-level height was redefined as 200ft or less, speed at 40,000ft was Mach 2.0 instead of Mach 1.7 (this was described as a cheap bonus as the thrust was available due to the take-off requirements), ECM was added, the ferry range was increased to 2,500nm (another supposed free bonus from the basic operational sortie requirement) and the Load Classification Number (surface load-bearing index) was reduced from 40 to 20, ie from concrete to firm grass, to be consistent with the short take-off dispersal philosophy.

I will leave it to other speakers to discuss the resultant aircraft and weapon system in detail, although I have of course my own views on what followed, but I would like to make three brief observations.

Given the undoubted ambitiousness of the OR, is it not strange that there do not appear to have been any voices arguing for a more cautious approach? Could it be that it was not in the industry's interests to be more realistic and not in the MOS's interests either?

The opportunity to try to accommodate the conflicting design requirements of high speed, low-level flight and short take-off (not to mention long ferry range and continuous supersonic flight) by use of variable geometry was given only passing thought and was not even proposed by Vickers for whom Dr Barnes Wallis worked.

No one, not even Hawkers, proposed using vectored thrust to mitigate the problems posed by the short field requirement.

A System Study of TSR2

Wing Commander G B Wilson BSc CEng MIEE

Wing Commander George Wilson was commissioned as an engineer in 1955. In this paper, he offers an account of the TSR2 project, as it appeared to the combined talent of members of his 1964 course at the RAF Technical College. He also describes the reaction of officialdom to the unpalatable conclusions of the course's system study of TSR2.

Background

In the late 1950s and early 1960s the RAF Technical College at Henlow ran a series of Weapon System Engineering courses designed to prepare officers for posts in the MOD, the Ministry of Aviation and the Research Establishments. The twenty-month course was spread over four terms and the last of these was spent on two projects, one involving the whole course and the other a personal subject chosen by the student. The Number 6 Advanced Weapons Course course project, carried out in the first quarter of 1964 was a System Study of the TSR2. Twenty students spent about two thirds of their time on the course project. This meant a total time of about 40 man months which should have given time for a reasonably detailed study.

The aim of the study was quite clear from the title – to examine the TSR2 design and projected performance as a complete weapon system. 'Systems' in service at that time were, almost without exception, actually collections of equipment developed as completely separate programmes and usually seemed to have been put together as an afterthought.

Conduct of the Study

We were briefed on the project by OR 24c in December 1963 and started in earnest in January 1964. Clearly, the first objective was to collect information on the programme organisation and the current state of the project. We had a reasonable degree of freedom in this part of the task but soon found that there was nowhere to go for advice on where information on the various sub-systems and equipments could be found. The systems approach seemed to have fallen at the first hurdle because nobody seemed to have an overall insight as to what was actually happening throughout the project.

In fact as the weeks went on we were able to collect a great deal of information but it was pretty obvious that the contractors, of whom there were quite a few, were not too keen on sharing information with each other. Often we were given information and asked not to tell one or more of the other contractors. In fairness, it has to be said that this was not confined to the contractors. MOD and the Ministry of Aviation (MoAv) were not always entirely forthcoming with each other and I will give some examples of this later on. By early March we had enough data to start our report and the first draft was submitted through the College Directing Staff for approval by the two Ministries. The reaction was not quite what we had expected. Nobody seemed to disagree much with the facts, only whether we should be allowed to put them on paper.

In the event, after a lot of negotiations, the study was completed and the report, with a few amendments to make it less controversial, was published. But the distribution, determined by the OR branch, was very restricted. The course presentation was made to an audience, again selected by OR, of less than half of what would normally have been expected. We had clearly upset the establishment although we were not told why – perhaps for getting too close to the facts.

Unfortunately no copies of the report seem to have survived. A search in the most likely of the many TSR2 files in the Public Record Office has failed to uncover a copy, although one may be lurking in one of the less likely files or in one of the few which have not yet been opened to public inspection. This means that this account of the contents of the report relies on the memories of the author and the other course members he has been able to contact. After over thirty years these could be suspect but the search of files at the PRO has uncovered enough material to suggest that they are fairly accurate.

So what did the report say that was so unpalatable to the Ministry? The study was, of course, concerned with the TSR2 as a system and not with the way the programme was being run but it was soon very clear that the project management was not capable of taking a systems approach with the result that the same old integration problems arose. There are over 150 TSR2 files in the PRO but not one looks at it as a total system. Although BAC was the main contractor, many of the sub-contractors were developing major systems such as the engines and Nav/Attack equipment under separate Ministry of Aviation contracts, ie, as Category 1 equipments. This meant BAC had little control over progress on these items but it also meant they could blame sub-contractors for any programme delays. The sub-contractors in turn postponed reporting any delays as long as possible in the hope that either BAC or another sub-contractor would declare a slippage and let them off the hook. This was one reason for the reluctance noted above to be open with each other in discussing problems.

As far as the actual design and projected performance was concerned there were several specific areas of concern.

Engines and Engine Installation

We were unhappy about both the engine and its installation in the aircraft. Since there had been eleven major engine failures in the fifteen months between December 1962 and February 1964 when we were writing our report this could hardly have come as a surprise to MOD. There were another three by July and two engines were fitted to the aircraft which were cleared for only the first flight on 27 September.

There were also major problems concerning the installation in the aircraft that were the subject of a report[1] by CSDE in June 1963. Like many contemporary aircraft the engine was installed through a tunnel from the rear end. During development the diameter of the engine had increased somewhat while the tunnel had shrunk because of a need to strengthen the fuselage frames. The clearance had become so limited that every aircraft was to have its own gauges to check that any particular engine would actually fit into that aircraft. On 30 September 1963 OR 24 sent a Loose Minute[2] to RAF/A2/MoA saying that jacking the aircraft for an engine change as currently proposed was unacceptable for a tactical aircraft. In a Loose Minute[3] to DCAS on 10th March 1964 DDOR 9 said that the clearance in the tunnel had gone down to 0.3 inches. In spite of this BAC were confident that this would prove satisfactory in service. However, BAC did agree with the DDOR 9 and CSDE that the engine accessories bay was unacceptable. Solution of this problem was likely to result in structural changes affecting the air brake configuration and reduce fuel capacity. These problems were never resolved before the first flight, or indeed before the project was cancelled.

A brief[4] prepared for the SofS for Defence in August 1964 for a meeting with the Minister of Aviation notes the following: 'At present the installation of an engine takes as long as 24 hours, while the accessory gear box is so badly placed as to create a flight safety risk.'

It would be unfair to attribute all the problems to the engines and DOR 3 had been warning of this for some time. In his report to ACAS(OR) on the TSR2 Progress Review Committee Meeting on 2 June 1964[5] he wrote: 'The aircraft itself is far from ready to fly; in particular the rear fairing and the ejection system have not yet been flight cleared. However, Walker (Resident group captain at BAC) is of the opinion that the standard reached for an August flight is no better than that laid down for the May flight and there will be even more work to do during the subsequent lay-up. It is apparent therefore that we shall get little effective test flying this year, a slippage of some 6 months over the confidential policy programme.'

Reliability

As engineers, one of our concerns about the TSR2 system was how easy or difficult it would be to keep it flying so that reliability was a matter of primary interest to us. The Staff Requirement, OR343, had no quantitative reliability requirement merely stating that the aircraft and its ground equipment were to be waterproof and remain serviceable with only the minimum of routine attention for 30 days in the open. This is not much help as a reliability requirement and a Reliability Sub-Panel was set up in April 1961. However, the first serious attempt to address the problem seems to have been a paper[6] by Science 3 produced in August 1962. This used a definition of 'failure' used by the main contractor, BAC, ie 'some shortfall relative to the requirement for a component, sub-system or system such that some unscheduled servicing action is required.' This is not really a satisfactory way of defining operational reliability but it did allow comparison to be made between the target for TSR2 and the achieved figures for in-service aircraft. The average MTBF for seven in-service aircraft, Valiant, Vulcan, Victor, Lightning, Scimitar, Sea Vixen and Buccaneer was 0.7 hours. Science 3 calculated the target MTBF for TSR2 to be 3.5-4 hours., an improvement of about five times. The only comparable figure was the 3.4 hours of the BOAC Boeing 707 which was a mature civil aircraft of considerably less complexity. The paper derived reliability targets for a number of sub-systems so as to give the overall figure required and, looking at the comparative figures in this paper, it is clear that the chances of achieving the targets were very low indeed. For example, the target for the Nav/Attack system was 21 hours while the forecast figure, using the current RRE component failure figures, was 6.1 hours. For most sub-systems the best in-service figure was close to, or better than, the TSR2 target although it has to be noted that the complexities were not necessarily comparable.

In spite of this paper, no serious concern about reliability seems to have been expressed for nearly a year and as late as December 1963 DOR(C) in a Loose Minute[7] to D(RAF)A, MoAv was still discussing a methodology for forecasting TSR2 reliability.

'I suggest a starting datum should be an overall TSR2 requirement of 80% success probability of completing a 4.5hr operational sortie but excluding in the first instance the weapon carried.' It is interesting to note that the 4 hours MTBF given in the Science 3 paper is equivalent to a 30% probability of completing a 5 hour sortie, although this figure may not be strictly compatible with the definition used by Science 3.

In spite of this late concern in the Ministry, it is clear that by the time we prepared our report the basic facts were well known to both MOD and Ministry of Aviation (MoAv) so that the concerns we expressed about reliability and the problems in maintaining the aircraft and hence the servicing costs could not have come as a surprise and should not have been regarded as controversial.

Nav/Attack System

The navigation system was an innovative and technically ambitious system with the outputs of a Doppler radar, IN platform and air data computer being integrated in twin Verdan digital computers to provide current positional information. In flight position updates could be input from the Forward Looking Radar, Sideways Looking Radar or visually. The drift rate of the IN platform would have required fairly frequent updates and the effectiveness of these would clearly have depended on the accuracy of available maps of the operational areas. We were not convinced that these would be good enough for many of the expected areas.

Accurate initial alignment of the IN platform on the ground was a painstaking process and depended on a surveyed site for the best results. Once aligned the system could be effectively locked in position but this meant that the aircraft could not be moved unless the system was run up again. This would have been very restrictive for an aircraft that was supposed to be able to operate in the field with minimal support of 30 days. Air alignment could be carried out after an initial coarse alignment on the ground but the accuracy of air alignment, like the updating procedure, depended on how good the radar or visual fixes were. For a tactical aircraft operating near the front line, finding enough good fixes might have distracted from the immediate task of getting to the target area.

As development proceeded it became clear that the required computing capacity had been grossly underestimated and would severely limit the aircraft's capabilities both for navigation and weapon delivery. The minutes of the Electronics System Management meeting on 20th February 1964[8] records that the visual fixing system needed an additional power supply and a knock on effect would be the need for an extra integrator in Computer No 1 and for two extra general purpose (GP) words in Computer No 2. In view of the shortage of integrators in the computers this was considered to be 'not the most acceptable solution.' Even earlier on 26 November 1963 a Loose Minute by OR 24b[9] had noted that the number of nuclear weapon delivery modes had been reduced from ten to six because of memory capacity limitations.

By the time the aircraft had flown and further work had been done on the Nav/Attack system the outlook had deteriorated even more. On 25 Feb 95 (*sic*)DCAS, sent a note[10] to the Air Force Board Standing Committee which was carrying out a TSR2 Costing Exercise which said, *inter alia*, 'At the present stage of development it would only be possible to programme one mode of weapon delivery (eg either lay-down or dive, but not both) and ten pre-set fix points for a given sortie.' This note went on to say that all the authorities expected the demand for computer capacity to rise by at least 10% during development trials and that this would mean there would be insufficient capacity for a complete operational sortie even without pre-set fix points. The proposed solution was to fit Verdan DSD-1 in place of the DSD but quite how much extra development time this would have taken was not discussed.

Project Management

Our study was a system study of the aircraft but it was impossible to ignore the effect of the project management on the failure to tackle many of the problems. The deficiencies in the effectiveness of the Ministry of Aviation, British Aircraft Corporation, Bristol Siddeley Engines Ltd and the Royal Aircraft Establishment were a constant theme of MOD papers from early 1963 until the project was finally cancelled. There were, of course, no MOD papers admitting to any internal management weaknesses!

In January 1964 ACAS(OR) wrote to DCAS[11]:

> 'I have no confidence in the ability of the management of BAC to give us the aeroplane we want, when we want it and at the right price. You will recall that many months ago I suggested the time was ripe for another confrontation between the Minister of Aviation and Sir George Edwards. I have been continuously discussing the situation with Ministry of Aviation and Sir Geoffrey Tuttle and was persuaded to take no action because we hoped the re-organisation of BAC might lead to some internal strengthening of the management and in any event, none of us could think of anything except possibly to put Freddie Page in charge of the Flight Development Programme.
>
> 'The real problem is, of course, that Sir George Edwards is the only man who can make anything of the mediocrity at his disposal and he has not the time. The VC10, BAC111, and now the Concorde are much more worrying and important to BAC and, in particular, to Weybridge than the TSR2. These are the aeroplanes which are going to pay the shareholders and BAC is not in sight of the break-even point on any of them. Nevertheless we must do all we can to improve the situation and you will, of course, have the opportunity of expressing your dissatisfaction at the Steering Committee Meeting which will presumably follow the Management Board.'

Some idea of the relationship between MOD and the MoAv can be judged from the tone of the note written by the SofS for Defence to the Minister of Aviation on 30 June 1964[12] which included the following:

> 'I need hardly say how disturbed I was to learn from your minute of 24th June of the further setback to the TSR2 (which, incidentally, was reported in the Daily Express a fortnight ago). When so much is at stake militarily, financially and politically it is exasperating to be told of yet another delay, especially when we have been saying for months that the aircraft's first flight is imminent.'

The briefing notes[13] for the Secretary of State's projected meeting with the Minister of Aviation in August 1964 have already been mentioned and it is worth quoting here at rather more length from a paragraph on management in that brief.

> 'In criticising past management of the TSR2 development programme, it must be recognised that good management cannot enable specific development snags to be foreseen. For example, the recent engine trouble could not be blamed on bad management, but it has become clear that BAC have been using this as a cover for their own delays since, in the event, the state of the aircraft and not of the engines has been the holding factor. This is an important illustration of the Ministry of Aviation's failure to achieve a grip on the overall programme. The forecast made by BAC and the Ministry of Aviation last February that the first flight would take place in May has been invalidated not by a single engine failure but by a completely false estimate of the amount of work remaining. The Ministry of Aviation's management is in fact culpable on three important scores:
>
> a. Failure to insist from the start that BAC had an effective management control and cost reporting and forecasting system;
> b. Failure to prevent the firm from incorporating undesirable features – eg at present the installation of an engine takes as long as 24 hours and the accessory gear box is so badly placed as to create a flight safety risk; the correction of these faults will take time and money which could have been saved by more effective control in the first place;
> c. Failure to develop an organisation capable of ensuring that manufacturing costs are not unnecessarily high.'

The final paragraph of the SofS's brief included the following:

> 'Although better management could not have avoided the TSR2 engine troubles, the whole project is characterised by deplorable technical delays, ineffective management and cost escalation (attributable largely to initial gross under-estimation of the technical problems involved and failure to ensure adequate cost control by the contractors), and by extreme tardiness in doing anything to remedy the Ministry of Aviation's own inadequate organisation.'

The System Study Report

The papers quoted in the foregoing paragraphs all provide evidence that the Advanced Weapons Course report did not contain any information that was not already well known to MOD. Indeed it is clear that the study only revealed the tip of the iceberg. The question then arises as to why MOD did not want it circulated in the normal way and why the presentation audience had to be so limited. The obvious explanation seems to be that while MOD were well aware of these problems they were not widely known by most others in the project and certainly by very, very few outside it. Every sub-contractor knew of his own problems but did not want them known, even, (or especially) by the main contractor until it became unavoidable. The mistrust between contractors and the MoAv and between MOD and the MoAv only exacerbated this culture of secrecy. The study report, if it had been circulated to all the contractors to whom we had spoken, could have given rise to all sorts of questions which could have caused an even wider breakdown in the already fragile relationships.

There may have been an even more pressing reason. The Air Staff had been declaring for years that the TSR2 would be absolutely indispensable to the future of the RAF and that it would be a world beater. Any admission that the aircraft was in serious trouble could not be contemplated. Furthermore the MOD seems to have been 'economical with the truth' in some briefings.

A contribution[14] sent forward by the Air Staff on 7 November 1963 for inclusion in the Secretary of State's lecture to the IDC course included the following:

> 'What I have to say about the TSR2 must be tempered by the fact that the aircraft had not yet flown – an event, however, which is not now very far in the future. But all the experts who have studied the aircraft and those who have been associated with its development are extremely enthusiastic about its potential as a military aircraft and, since its development has been accompanied by extensive testing on ground rigs, I believe they speak with both experience and authority.'

Further support, if any is needed, for this 'conspiracy of silence' theory is contained in a brief[15] prepared for the Prime Minister on 20 November 1963. A few of the more interesting extracts are:

> '2. If the Services are to conduct operations we must be able to create a favourable air situation and this entails an ability to destroy enemy air strength at source. For this we need a tactical strike/reconnaissance aircraft in NATO, CENTO and the Far East. This role has been discharged by the Canberra since 1951. But by 1968 the Canberra will be worn out and in any event could not survive even against second-class opposition. This means that our ability to strike at considerable- depth, using conventional or nuclear weapons, at targets behind the immediate battle area will have gone – and with it a vital part of the means to create the favourable air situation. Similarly, reconnaissance in enemy areas, politically vital in an emergency and essential in operations to Field Commanders, will be denied by an increasing enemy air and defensive power.
>
> 3. Thus unless we can find a replacement for the Canberra, of a quality which will enable it to live in a hostile environment of the sophistication which will be inevitable in the '70s, we will cease to be an effective air power.
>
> 4. This conclusion is reinforced by the very serious fall-off that will occur in our conventional air capability with the phasing out of the 'V' force in the early '70s . . . I mention it here merely to emphasise the importance of the Canberra replacement to our whole military position.
>
> 10. To sum up therefore:-
>
> (a) In the '70s the TSR2 will be the only British aircraft capable of fulfilling the first task of air power – to strike

in depth and survive.

(b) It will be the only aircraft capable of deep reconnaissance.

(c) In the same way as the Mosquito in the last war, it will be capable of fulfilling, in emergency, a strategic task.

(d) Its cancellation after rather more than £100M has been committed on it and a production order announced could put paid both to our use of air power and perhaps to the British aircraft industry.'

No 6 Advanced Weapons Course had considerable doubts about many technical aspects of the TSR2 system. Whether these could have been overcome given time and money – lots of it – we shall never know. However, given the way the project was being managed it must be very doubtful. As we have seen[16] by January 1964 ACAS(OR) did not believe that BAC was capable of providing the aircraft. Perhaps the project should have been cancelled then but who could recommend such a thing after that brief to the Prime Minister?

Notes:

1 AF/CT4671/64, Encl 56
2 AF/T788/64, Pt 9, Encl 87
3 AF/T788/64, Pt 10, Encl 61
4 AF/CMS/329/64, Pt 13, Encl 94
5 AF/CMS/329/64, Pt 13, Encl 47
6 AF/CT4671/64, Encl 56
7 AF/CT4671/64, Encl 51
8 AF/CT/4667/64, Pt 7, Encl 12
9 AF/CT/4667/64, Pt 7, Encl 2
10 AF/CMS/329/64, Pt 14, Encl 114
11 AF/CMS/329/64, Pt 14, Encl 10
12 AF/CMS/329/64, Pt 13, Encl 53
13 AF/CMS/329/64, Pt 13, Encl 94
14 RD/97/083, Pt B
15 RD/97/083, PTB, Encl 9
16 AF/CMS/329/64, Pt 14, Encl 10

Discussion

A number of issues concerning the origins of the project and the development of the Operational Requirement emerged in the discussion group chaired by Air Commodore Graham Pitchfork. Interesting comparisons were made with the Buccaneer and later Tornado.

Gp Capt Mears expanded on the view that the project may have been too ambitious for its time, 40 years ago. He noted first that the Operational Requirement came straight from the UK's Defence Policy of the day and to that extent, was not an exaggerated one. The problem, he felt, was that the requirement as it evolved could only have been achieved with either variable geometry or vectored thrust. The conflicting requirements of short field performance (demanding a high-lift wing) and low level operations (requiring a low gust response wing) should have pointed to the 'classic VG solution'. The installation of engines of sufficient power to meet the take off requirements led, in turn, to thrust in excess of what was needed in cruising flight and to high levels of jet pipe drag and to fuel consumption problems. The OR was appropriate but the effect of the forced amalgamation of the companies led to an aircraft with design problems which would probably not have been capable of operating in the environment for which it was intended. In his view, it would have had difficulties in terms of its short field performance, in dispersed operations and certainly in operating from grass strips.

Wg Cdr Beamont who 'flew the thing', said that it was by no means clear to him that VG would have resulted in a less dense and less complicated aircraft. The substantial experience of VG leads to the opposite conclusion. He had never understood why a speed of M=2.25 had been called for. The aircraft was intended to be a low-level transonic penetrator. The requirement for a sustained performance of M=2.25 at high level could only have led to a far more costly engine development. The job could have been done by optimising the aircraft's low level performance which would have resulted in a performance of M=1.7-1.8 at height. The aircraft would have been rather similar to the English Electric P17!

Wg Cdr Beamont described the English Electric P17 as a 'cheap but not nasty TSR2'. It was optimised – as it should have been in his view – for low level flight. The engine and airframe technology needed for an aircraft capable of arriving over the target at 200ft. at transonic speed, was available and affordable by comparison with TSR2.

Sir Michael Beetham had ‘picked up the first pencil’ as a squadron leader in OR to write the first draft of what became OR339. That followed extensive discussions with Industry as to what is possible. The OR staff had to look well ahead and could know what developments might be made by ‘the other side’. The staff could not be faulted, if they ‘asked for the best’. Suggestions from Industry of, say, a M=2.25 performance tended, therefore, to ‘creep into the OR’. There was always great enthusiasm to appear positive and never to say ‘no’. The danger, therefore was to over-egg the OR. That, coupled with the competition for the contract, resulted in offers or promises of performance which were almost irresistible. When some of the TSR2 requirements were now viewed with hindsight, it seemed clear to him that the industrial environment and concern on the part of the Service not to miss out on the fast moving technological developments in the aftermath of WWII led inevitably to TSR2. This was especially so in an aircraft that would not come into service for some time.

Sir Michael Beetham also suggested that the Intelligence community was reluctant to be left behind – or to be seen to have under-estimated the enemy capability. In such circumstances, great care would have been needed not to over-state the requirement. He said that it was important in writing an OR, not to be confined to one flight regime, especially if the aircraft is not due to come into service for some years. If the enemy had solved the problems of defence at low level, the aircraft might be driven to operate at higher levels. At the time, OR330 (a high level supersonic bomber) had just been cancelled, therefore the Air Staff would probably have been concerned to build in as good a high level performance as could be achieved.

Neville Beckett of BAe who had worked at Brough (on the Buccaneer) and, later at Warton, queried the specification of supersonic speed for TSR2, noting that the Buccaneer had, by and large, satisfied the RAF. Two aspects of the TSR2 OR caused him concern. First, the compromise made necessary by the need for supersonic flight. The high level subsonic cruise efficiency of TSR2 in a Hi-Lo profile is 30% less than that of the Buccaneer. TSR2 reflected the compromises largely brought about by the requirement for supersonic performance and 'the myth' of ride quality at low level requiring high wing loading. TSR2 did indeed have a small wing and very high wing loading, about 50% greater than Buccaneer, and lift dependent drag and induced drag were poor for the high level cruise case. Other penalties followed the decision to build a supersonic aircraft, including SFC penalties due to the use of reheat and nozzle drag. Was it really thought that TSR2, cruising at M=1.7 at altitude, using 60% more fuel per nautical mile than an aircraft flying at M=0.9 at low level was any safer?

Mr Beckett could not understand why, in the name of low level ride, the wing loading argument was taken to the extreme in TSR2, as it was. The Buccaneer, by comparison, had a wing loading of around 2/3 that of the TSR2, a higher lift curve slope and a 'decent' span producing good lift (C_LMax of 2, compared with probably 1.5 in the TSR2). The whole balance of the aircraft had been adversely affected. All in all, in his view, the TSR2 had been the 'wrong' aircraft.

Air Cdre Pitchfork declared his interest as Chairman of the Buccaneer Aircrew Association and noted that it was not he who offered the comparison!

Wg Cdr Beamont responded to what he regarded as a 'piece of special pleading' by noting that the TSR2's low level transonic (M=0.9-1.1) could not be approached by the Buccaneer which would probably have achieved only M=0.85 carrying external stores.

Gp Capt Mears described how the OR had also been intended to give the RAF a reconnaissance capability at medium level, at least in limited war. It had been intended to operate in areas, outside the NATO area, which were defended by supersonic fighters, not necessarily densely defended by SAM systems. Supersonic capability was needed in such scenarios and Industry had said that a M=1.7 capability was 'easy', given the engine thrust available. The reconnaissance community had been anxious to operate at medium level, with a sustained supersonic dash capability. The high-speed, low level case had been just one of the options, essentially for the strike role. The Buccaneer could not have offered such performance.

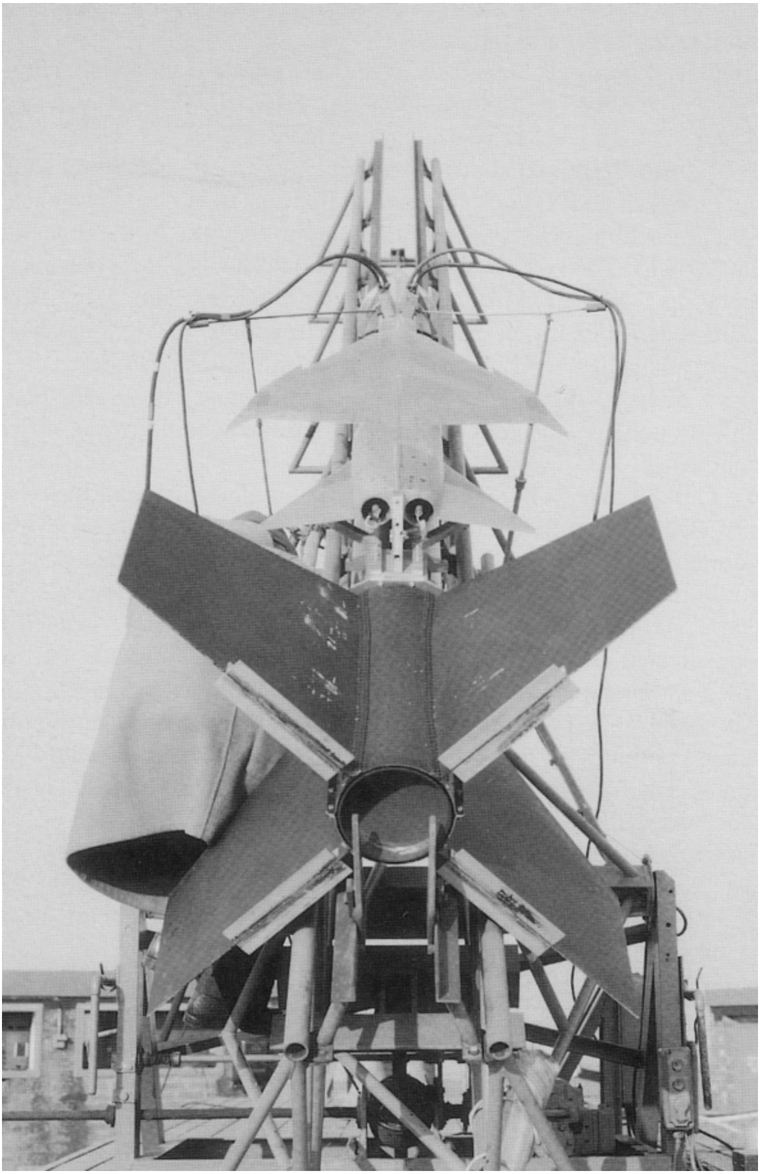
The Ministry of Aviation's attitude had been exemplified in the early days when a supersonic variant of the Buccaneer had been offered as a solution. An un-named Director in the MoA had written that the Buccaneer could not be made supersonic even if two Atlas missiles were strapped to it! (Air Cdre Pitchfork interjected that it could have carried them!) Later, when TSR2 had been cancelled, the same Director had proposed a supersonic Buccaneer and Gp Capt Mears concluded that the MoA had played a game that was of no assistance either to Industry or to the Service.

Air Cdre Pitchfork came back to the OR, asking if the two conflicting requirements of 600yd. LCN 20 take off performance and M=2.25 at high level were ever reconcilable.

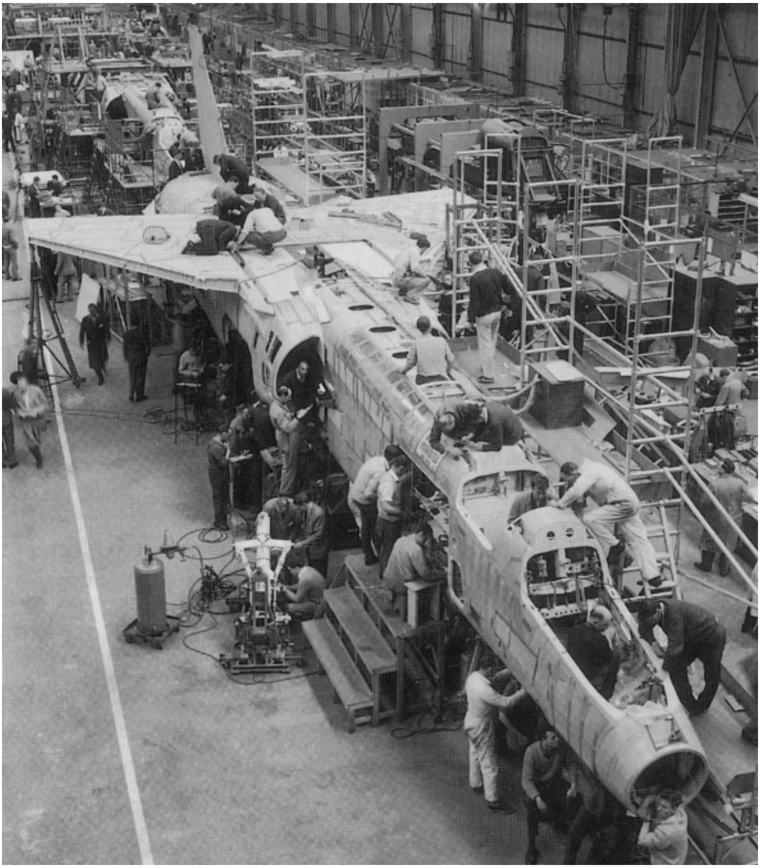
AVM John Price had also been a 'pencil chewing squadron leader' in the days of TSR2. Later he flew the Buccaneer. He had always had difficulty with the short field requirement in the OR. At the time, the Hawker P1154 should have taken on that role. The logistic problems of operating from 1,000 airfields in Western Europe had never been addressed. Problems of refuelling and rearming the aircraft were never satisfactorily answered. All sorts of difficulties had been introduced unnecessarily when the use of well found bases with good runways and adequate damage repair facilities would have obviated them.

Wg Cdr Jimmy Dell who had shared the majority of the test flying with Bee Beamont said that he had always been puzzled with the requirement for '650kts out of a semi-prepared strip'. Who, he asked, would have flown the aircraft into such a strip in the first place, let alone providing the sort of logistic support necessary for such a sophisticated aircraft? He still had a copy of the Flight Manual for TSR2 and has shown it to Tornado pilots of today whose reaction to it is to say that TSR2 was just a longer range Tornado, an aircraft which continues to serve well in the front line of a number of air forces. The flight envelopes (800kts; M=2.2) are nearly identical yet TSR2 was cancelled over 30 years ago.

Gp Capt Mears agreed that the short field performance requirement had created one of TSR2's major problems. He doubted that the aircraft could have been operated out of the sort of short strips postulated: stopping it from an aborted take off would have been extremely difficult. There had already been talk of retro-fitting the aircraft with a hook. Knowing whether full thrust would have been available for take off was complicated by the inability to hold full power against the brakes and the ‘thrustmeter’ which measured 9 parameters could not tell the crew whether enough power for take off was available before they had started rolling. The engine installation was totally incompatible with field operations. It had to be inserted into a 25ft. tunnel with a clearance of only 0.1ins. The RAF specification for an engine change to ground run was 3 hours; the average of the best three engine changes achieved by BAC was 68 hours – in a hangar!



An early test model of TSR2 is prepared for flight



TSR2 under construction at Weybridge

TSR2 at the time of final assembly

SECTION TWO

TSR2 AND WHITEHALL

POLITICS *OVER* STRATEGY – AUSTRALIA'S REJECTION OF TSR2

DISCUSSION

TSR2 and Whitehall

Rt Hon Sir Frank Cooper GCB CMG PC

Sir Frank Cooper was a pilot in the Royal Air Force from 1941-46 and, after graduating from Oxford, joined the Civil Service in which he was to have a distinguished career. Most of his Whitehall career was spent in Defence and he was Permanent Under Secretary at the MoD from 1976-82. He held Air Ministry appointments as Private Secretary to USofS (Air), to the PUS and to the Chief of the Air Staff before becoming Head of the Air Staff Secretariat in 1955 and AUS (Air) from 1962-66. He was therefore at the centre of affairs as the TSR2 story unfolded and at the time of cancellation. His paper considers the political backdrop against which the project finally foundered.

GOR339, OR343 and the TSR2 were with us from March 1957 until April 1965. They were rarely free from controversy. This whole period was fraught with change and full of argumentation. It is difficult to recall any post World War II period in Britain when so much happened and the problems were so complex.

The Context

The Empire was falling apart fast. More than 20 colonial countries became independent members of the Commonwealth or changed their status within a period of a few years. After Suez, Britain and the RAF were kicked out of Iraq, having already left Egypt. EOKA in Cyprus, Oman, Jordan, the Lebanon, Kuwait, East Africa, Aden, Indonesia all required operational involvement of British Forces. It became increasingly difficult for military aircraft to move about the world. Hence the search of an 'all Red Route'. As an aside, when the USAF built the airfield in Ascension Island the Air Staff insisted on 'Free Use' – fortunately for the Falklands conflict in 1982.

The enthusiasm for permanent bases; the pressure on mobility;

the need for transport aircraft; the growing importance of flight refuelling and the emphasis on aircraft range and take-off characteristics in hot climates were all by-products of this rapidly changing world.

The strength of the Soviet Union, and its technical prowess, grew. The Anglo-American alliance prospered. Thor missiles were introduced into Britain with their nuclear warheads under 'double key' arrangements, similar to those applying to RAF Canberras in Germany. There was a Berlin crisis in 1960. The Cuban missile crisis erupted in 1962. President Kennedy was assassinated. The US became involved in Vietnam.

The Sandys' White Paper of 1957, written in 11 weeks, was designed to substitute technology (particularly missiles) for people wherever possible. Blue Streak and Blue Steel Mk 2 were cancelled and when the Americans decided to cancel Skybolt Macmillan persuaded Kennedy to make Polaris available for Britain's strategic deterrent. Conscription was abolished and there were no conscripts in the Armed Forces after 1962.

More than 30 weapons systems were cancelled over a short period of years. Costs, complexity, and knowledge were all escalating wildly. The functional costing system was brought in – an adaptation of the American system which McNamara had introduced in the United States and subsequently urged on Thorneycroft.

The Ministry of Defence was reorganised. The Ministry of Supply was seeking to rationalise the aircraft industry – no less than nine airframe companies responded to GOR339 in 1957. They were told in September of that year that GOR339 would go only to a group of companies. The Ministry of Aviation was created in November 1959 and was required to cover the whole spectrum of military and civil aviation.

There were major inter-Service rows about Army helicopters, air transport, Coastal Command, and aircraft carriers – all of them damaging. The Services' Works Departments were removed from them overnight.

This brief sketch is meant simply to illustrate a few of the factors and the times through which the TSR2 argument ebbed and flowed. But perhaps above all the country was financially in dire straits for much of the time and financial crises were a recurrent theme.

Systems of budgetary control were crude and for complex projects the arrangements for forecasting, monitoring and controlling expenditure were inadequate.

Conception

The requirement for a Canberra replacement – initially GOR339 – was controversial from the start in 1957. The Royal Navy pressed, at the highest levels, that the RAF should take the Buccaneer (NA39) and leave GOR339 to be developed in a later time-scale when it would not clash with the peak period of developing what became the Buccaneer. They argued that the time-scale and costs of GOR339 were optimistic and that it would be best for the two Services to move and work together.

These arguments were rejected by the Secretary of State for Air (George Ward) primarily on operational grounds – notably range and take-off performance in hot climates. It is only fair to add that George Ward himself questioned how long it would take GOR339 to materialise and asked whether NA39 could not fill a gap. Exchanges between Ministers were icily polite – a forecast of what was to come.

The Defence Research Policy Committee, under Sir Frederick Brundrett, was sceptical about GOR339. The Brundrett view was that NA39 could comfortably fill the tactical strike/reconnaissance role in support of the Army. The Ministry of Defence, at that time a very weak department, was also sceptical and rather pro NA39. One question it asked (prophetically) of the Air Ministry was whether the RAF had considered any foreign aircraft.

The back-biting rumbled on with the Air Ministry line toughening and the inter-Service arguments with the Admiralty intensifying. The breach between the views of the two Ministries was complete by the summer of 1958. They went their separate ways.

The Navy made good progress with NA39. The Defence White paper of February 1958 had mentioned (in the Sea Power section!) that a low-level tactical bomber (NA39) was being developed for the Royal Navy and that 'its adoption by the Royal Air Force . . . was being considered.'

The necessary approvals began to be obtained for GOR339. The hurdle of the Defence Research Policy Committee was overcome in June 1958 with the DCAS arguing that the requirement was vital for the three Services; vital to the aircraft industry; vital for the UK's balance of payments; and to the British position in NATO. He is recorded as saying that 'it would probably be the last military fighting aircraft developed in the UK.' He stressed the urgency. But it was December 1958 before an unenthusiastic Minister of Defence gave his approval to the project.

The Air Ministry took all this to mean that there was a continuing drive to force the RAF to take at least some NA39s and put off GOR339.

So, by the end of 1958 quite a number of the main ingredients for the TSR2 fight were visible.

Problems

One basic problem was that, even within the Air Ministry itself, there were nagging questions about GOR339. Doubts grew over the years. The primary cause was lack of confidence in those concerned with research, development and production of the aircraft and the constantly changing forecasts about timing, performance and, above all, cost.

From the start the overall management of the project was regarded as suspect – to put it at its highest. In some ways this was not surprising given the shot-gun nature of the industrial consortium coupled with the fact that Whitehall itself spawned committees, the consequence of which was to make matters worse. At no time was the project management system well regarded. To add to the confusion the operational requirement was 'upped' on several occasions.

There was no doubt that relations with the Ministry of Supply/Aviation and the Air Ministry went from bad to worse and that these poor relations spread increasingly to the Ministry of Defence as a whole. The breach itself was of long-standing. The basic cause was lack of trust, particularly as regards the information received by the Air Ministry. The trust was lacking because the Procurement Ministry stood between the Air Ministry as the customer, and industry as the supplier. Moreover, nothing seemed to arrive at the right time and at the right price, let alone with the desired performance. The lack of trust was exacerbated by the financial arrangements under which the Ministry of Supply/Aviation recovered production costs from the Air Ministry but was left with the research and development costs. Hence, there was no clear objective against which the supply department could assess performance and value.

The continual slippage of the forecast in-service dates added to the general air of despondency. All the change was in the wrong direction and it hurt. Slippage contributed to the ever-diminishing credibility of the Ministry of Supply/Aviation and, indeed, of industry. Delays in the first flight of the TSR2 and the delay after the first flight were damaging. The engine problems – not least the blow-up of three engines – further sapped confidence. Internally, there was no doubt that the Air Ministry's own budget was over-stretched, particularly in the equipment field.

The traumatic, confusing and never to be under-estimated effects of the Sandys' White Paper of 1957 which pushed for greater mobility and increased emphasis on air transport capacity, coupled with the rising cost of equipment, offer at least a partial explanation. One of the oddities was that throughout the eight-year period the need for a Canberra replacement was never seriously questioned; the need for tactical reconnaissance aircraft for NATO, CENTO and SEATO was always accepted; and, despite Suez, in 1956, East of Suez did not become a crunch issue until after 1965, though the argument about how to project power – particularly air power – overseas ran strongly throughout. It is fascinating to recall that Harold Wilson told Parliament in December 1964 that 'we cannot afford to relinquish our world role . . . sometimes called our East of Suez role.'

The Australian attitude and the Australian decision – highly costly for them as it turned out – to buy the F-111 have been the subject of considerable speculation. In 1963 the RAAF sent an evaluation mission to Europe to look at possible aircraft purchases, including specifically the TSR2. It was known that the F-111 was a potential contender. While the mission was in progress in Europe the Australian Government announced that it was to buy the F-111. There is no doubt the Australian decision severely damaged the prospects of the TSR2. Industry had tried hard to interest the Australians. The Ministry of Aviation and the Air Ministry were open to the criticism that they could have tried harder in the early stages though no doubt they were inhibited by the fact that there was no good story to tell or much of a belief that the Australians would be buyers. Both Ministries tried hard before the Australians came to a final decision and in the evaluation process.

There was always speculation about the influence of Lord Mountbatten and Sir Solly Zuckerman and their closet activities in casting doubt on the TSR2. Mountbatten actively discouraged Scherger – his Australian opposite number. But talking to members of the Australian RAAF mission, it was difficult to believe that there was much enthusiasm for the TSR2. The most potent factor, however, was the determination of Australia to move visibly closer to the United States in a military sense, based on their increasing doubts about Britain's military capacity to act significantly in the defence of Australia.

What about the Ministry of Defence as a whole? The Royal Navy and the Army, though always concerned – and increasingly so over the years – about cost, tended to adopt a policy of live and let live. Successive Ministers of Defence and Secretaries of State for Air fulminated about delay, about vacillation and cost increases but stayed steady about the requirement and the means of meeting it – until the arrival of the Labour Government in 1964 and its subsequent decision to cut defence expenditure.

The Chiefs of Staff in general were supportive largely because of the need to live and let live but also because the RAF at that time was fortunate enough to have outstanding Chiefs of the Air Staff, Vice-Chiefs, Assistant Chiefs and Directors of Plans. The roles of Lord Mountbatten and Sir Solly Zuckerman have always been regarded with suspicion by many. There is little doubt that both would have liked to abolish the TSR2 – indeed never to have started it (a view shared by Sir Frederick Brundrett who was Chief Scientist at the start). There is equally no doubt that both encouraged frequent reviews and indulged in what one might call clandestine operations. But it was mostly sapping and mining and in real terms curiously without much impact. Lord Mountbatten was unwilling to come out into the open and tackle the issue head on, not least because it looked like disloyalty to his military colleagues (with whom he was having a tough time on other matters) though he was more than willing to encourage others privately, for example, Harold Watkinson, to 'have a go'. Eventually, Watkinson instructed him formally never to raise the matter again.

The small Ministry of Defence central secretariats and scientific staffs were never enthusiastic about the TSR2 and most became hostile. But over the years most came to accept the TSR2 as water over the dam.

The Ministry of Supply/Aviation who in many ways were the progenitors of the project, forfeited the trust of all, primarily because of the inaccuracy of their forecasts and their inability to oversee and organise the management of the project as a whole.

The Treasury sought every opportunity to express doubts and misgivings about costs and to encourage review of the project and its management. They were worried that by some means or other, which they could not clearly discern, the role of the TSR2 was being extended and the specification increased upwards. Basically, however, they accepted the need for the Canberra replacement and it would be difficult to argue that they held the project up seriously on financial or other grounds.

What is surprising is how ineffective were those who believed wholly or partly that the RAF should adopt Buccaneers. Some of the critics were in positions of great responsibility but were incapable or unwilling to exercise it.

Costs

Major defence changes are rarely the result of internal policy initiatives. They stem in the main either from external influences or from economic and financial factors. It was these factors that broke the TSR2's back.

The cost history of the TSR2 was horrific. It is worth remembering that the Air Ministry's total budget averaged little more than £500 million a year over the eight-year period and that of the Ministry of Aviation about £200 million. To put these figures in today's terms merely multiply by 10 plus a bit.

The first figure informally bandied around for GOR339 was around £16 million – that was a guesstimate. In July 1958 the Ministry of Supply told the Treasury that the in-house estimate was £35 million to CA Release. In November 1959 it was £62 million up to CA Release, with plus possibly £15-25 million on top. In 1960 there was much discussion in Whitehall about astronomic costs. Confidence was beginning to sag.

Costs, again to CA Release, went in mid-1962 to £137 million and in December of that year the figure quoted was £175 million. The Minister for Defence (Peter Thorneycroft) commented ‘a remarkable figure for a light bomber replacement.’

In January 1963 the cost was informally bracketed at £175-200 million and the £175 million figure was used in April 1963 when the Prime Minister (Harold Macmillan) asked: ‘What will it cost? Will it ever fly?’ In the Air Ministry the Defence Secretariat commented that ‘the cost increases of the project continued to break all records.’

In June of 1963 the figure was refined to £175 million/£222 million. About the same time it was thought that production costs would be about £2.3 million per aircraft. In January 1964 the cost to CA Release was revised upwards once more, this time to £240/£260 million and the production price went up from £2.3 million to £2.8 million.

There is no doubt that during the first half of 1964 there was a change of attitude in the Air Ministry among some senior people, (including CAS, the Director of Plans (Air) and the Secretariat), and the Air Ministry began to question seriously whether the RAF programme could bear the cost of the TSR2 and about its effectiveness in terms of performance. One consequence was that the Air Ministry decided to ask the Ministry of Aviation in March 1964 for a fixed price contract. Another was that CAS, after discussion with a very limited circle, took a note from himself to the Secretary of State for Air (Hugh Fraser), who showed it to Thorneycroft expressing doubts about the project. The paper was torn up and CAS told that this was not a matter to be discussed before an Election.

The arrival of a Labour Government in October 1964 was quickly followed by instructions to review the aircraft programme and look at foreign alternatives. It was also decided to review the ‘big’ carrier requirement. Finally, there was a decision to bring down defence expenditure to a level of £2,000 million at 1964 prices to be reached by 1969/70. This was expected to be about 6% of GNP. The previous Government’s costings forecast showed a Defence budget of £2,400m. in that year.

In December 1964 an Air Ministry team went to the United States to look at American aircraft, including the F-111. The background brief suggested that the research, development and production costs of the TSR2 were forecast at just over £740 million of which £160 million had been spent or committed. In truth by this time most of the Air Ministry had lost confidence in almost anything to do with the TSR2.

In January 1965 the Defence and Overseas Policy Committee virtually wrote the death knell of the TSR2 not least because, 'US aircraft were available at fixed prices and with fixed delivery dates; they cost much less and would be in operation earlier.' But the Committee asked for a further review of costs and prices of the F-111 and also asked the Minister of Aviation to review the consequences for the aircraft industry. On 1 April at a late night and somewhat mixed-up Cabinet meeting the decision was taken to cancel the TSR2 and to take up an option on the F-111, provided such an option involved no commitment at that stage to purchase any aircraft.

What has almost certainly been under-estimated was the impact of the favourable financial terms skilfully presented by the Americans – Henry Kuss – and which included a potentially favourable impact on the RAF programme as a whole.

At the time of the October 1964 general election the cost of the TSR2 had gone through the roof. It was arguable, to say the least, that the same fate would apply to the HS681 and the P1154. It was certain that to contain the cost of those three aircraft, within an overlapping time-scale and within even a highly optimistic view of the money likely to be available for the RAF, under any government, would have been impossible.

The Americans had put forward proposals for offsets covering the three American aircraft (the F-111, the Phantom and the Hercules) plus a deferred payment scheme, to be financed by the US Export Import Bank. The bill was to be met by 14 half-yearly instalments, with interest at 5¾%. The consequence would be to flatten out the hump in Air Ministry expenditure and defer much expenditure for several years.

The decision was announced in the Budget Speech in April 1965. The Minister of Aviation gave instructions to break up the existing completed and incomplete TSR2s.

The public justification was based virtually totally on cost – both escalatory and absolute – including the failure to secure a fixed price plus 'the stark fact that the economics of modern military technology' ruled out 'British development of this type of aircraft for a purely national market.'

It is extraordinary how little space the cancellation of the TSR2 takes in Harold Wilson's autobiography (even less in Pimlott's biography); in Healey's autobiography he states that the 1960 estimate had tripled four years later to a sum of £750 million; the delivery date instead of being 1965 had slipped to 1968 or 1969; and £250 million, he claimed, would have been saved over ten years by buying the F-111, which was itself axed from the programme in 1968. Roy Jenkins was also brief but it is perhaps worth quoting what he said:-

> 'The Australian Air Force had early in 1964 delivered a nearly final blow to the TSR2 by opting for the F-111. By early 1965 the British Ministry of Defence, Air Marshals as much as Ministers, wanted to do the same. The TSR2, good plane though it was, had few friends outside the aircraft industry and the military chauvinist political lobby. I did not think we should keep it going, although I was not convinced that the automatic alternative was to buy the F-111. My scepticism about a continuing British East of Suez role pre-disposed me in favour of doing without either. This divided me from Healey, who was determined to buy the American plane.
>
> 'The Treasury were naturally in favour of saving money, although their voice was rendered uncertain by Callaghan being as an instinctive East of Suez man as I was a sceptic. But he certainly wanted the TSR2 axed.'

An extraordinary and complex story. Cancellation was inevitable.

Politics *over* Strategy – Australia's Rejection of TSR2

Phil Strickland MA

Phil Strickland is an Australian with a particular interest in modern history, especially in relation to air power. He graduated from the Australian National University with a MA in Strategic and Defence Studies in 1994, after preparing a thesis on the role of air power in the 1991 Gulf War. He is currently preparing a doctorate on Australian-Indonesian relations during Indonesia's Confrontation of Malaysia in the 1960s.

For many people, the decision by the Australian Government not to buy the TSR2 for the RAAF sounded the death knell of the project. Phil Strickland examines the basis on which the decision was made. His paper sheds a fascinating light on the complex domestic and international politics that surrounded the decision making process.

> *'All weapons have political implications and the biggest weapons have the biggest implications.'* Peter Calvocoressi

Introduction

On 24 October 1963 the Australian Government announced its purchase of 24 F-111 strike/reconnaissance aircraft from the United States to replace the Royal Australian Air Force's (RAAF) Canberra bombers. The government rejected the British TSR2 aircraft which, until April 1963, was the only aircraft in contention to eventually replace the Canberras.

In April 1965 the British Government cancelled the TSR2 project entirely, and Australia's earlier rejection has been seen as a significant step towards this decision. Stephen Hastings wrote in 1966 that 'the failure to sell the TSR2 to Australia was a bad blow to the prospects of the project . . . (and) a serious setback to British aviation as a whole in the longer term'.[1]

While the history of Australia's rejection of the TSR2 inevitably contains highly specific and, to a non-technical eye, almost 'microscopic' elements, this rejection also entailed broader strategic implications beyond the fate of the project itself. It appeared to epitomise Australia's strategic reorientation away from Britain to the

United States in the 1960s. As the *Daily Telegraph* wrote in November 1963, 'Australia's switch from British to American military aircraft is a powerful reminder of the tenuousness of the Commonwealth and of our own strategic and industrial limitations at its centre'.[2] This was an ironic comment on a decision by a government led by Sir Robert Menzies, avowedly one of the Commonwealth's most ardent Anglophiles.

Had an Australian sale for the TSR2 been secured it is very likely that it would have provided a powerful, and perhaps decisive, counterweight to the many influential British critics of the project. In 1963 these included HM Treasury and the Chief of Defence Staff, Lord Mountbatten, as well as the Labour Opposition, which was expected to win government in the 1964 General Election. A foreign order might have placed the TSR2 on something like an equal footing to the Anglo-French Concorde project, which was also to come under the threat of cancellation in 1965, but survived this threat. At the very least, an Australian sale of the TSR2 would almost certainly have made the decision to cancel the project considerably more difficult.

The question of whether an Australian sale could have 'saved' the TSR2 can, of course, never be answered with absolute certainty and, by way of comparison, the F-111 itself came close to cancellation on at least one occasion in the 1960s. However, the importance which the British Government had attached to a foreign sale to assure the prospects of the TSR2 was well known to the Menzies Government. According to Alan Stephens, the Queen herself had lobbied Menzies' Minister for Defence, Athol Townley, on behalf of the TSR2.[3] The Australian Treasurer, Harold Holt, was fairly pointedly advised by his Department in September 1963 of comments in *The Economist* that, 'the only hope of placing a ceiling on TSR2's alarming cost lies in selling it to other countries so that development overheads can be spread over longer production terms'.[4] In 1963 there were no 'other countries' apart from Australia who were interested in buying the TSR2.

Shortly after the F-111 purchase was announced, a senior adviser within the Australian Prime Minister's Department, Allan Griffith, wrote to his Department head, John Bunting, that an 'Australian purchase of the TSR2 might have built in . . . a factor which would have perpetuated production' of the aircraft in the event of a Labour victory in 1964.[5] Finally, the significance which the British Government attached to an Australian sale was explicitly conveyed to Menzies by the British Prime Minister, Harold Macmillan, in 1963. Macmillan said that the importance of this sale exceeded that of a normal commercial transaction, for events had demonstrated the premium strategic value of modern air power, and the concurrent operation of the TSR2 by the RAF and the RAAF would therefore fortify the Anglo-Australian strategic connection in the South-East Asian region.[6]

Despite its understanding of these issues, the Menzies Government nevertheless rejected the TSR2, and this in itself provides a very significant confirmation of Australia's drift from a British strategic orientation.

As discussed below, an examination of the decision-making process through which the Menzies Government chose the F-111, and of its perceptions of the strategic and (especially) the political contexts within which this decision was set, adds further support to the 'strategic reorientation' thesis. Menzies himself justified the purchase of the F-111 to Prime Minister Douglas-Home as a means of sustaining American 'interest in this corner of the world'.[7]

Nevertheless, some aspects of this decision-making process appear to contradict the strategic reorientation thesis. Some of Menzies' senior advisers showed considerable reluctance to reject either the TSR2 specifically, or the British strategic connection generally, in the final weeks before the selection of the F-111. A further and ironic contradiction to the reorientation thesis is how, in at least one critical instance, the close relations between British and Australian service chiefs provided a conduit for undermining the prospects for an Australian sale of the TSR2. In April 1963 Lord Mountbatten expressed his doubts about the TSR2 ever going into production to the Chairman of the Australian Chiefs of Staff Committee, Air Chief Marshal Sir Frederick Scherger (see below). Scherger had previously been the TSR2's most important proponent in Australia – according to Stephens his confidence in the project was shaken by Mountbatten's comments.[8]

In February 1966 – well after the decision to reject the TSR2 – Australia continued to value its British strategic connection highly enough for the Holt Government to enjoin the British Minister for

Defence, Denis Healey, that 'a British presence is vital not only in the Malaysian area but in the region generally.' Nevertheless, Australia's Deputy Prime Minister, John McEwen, warned Healey that, while Australia would understand the necessity for a British withdrawal under economic or political duress, Australia would then 'feel a need to turn to the United States.'[9]

Australia's wish to prolong Britain's strategic presence 'east of Suez', and her military support for Britain's stand against Indonesia's Confrontation of Malaysia, show that Australia's strategic reorientation towards the United States in the 1960s was not a tidy and even transition. However, McEwen's comments are a reminder that this reorientation continued nevertheless. This shift, which the F-111 purchase had emphasised, had paid a political dividend for Menzies in the November 1963 Federal Election and would do so again for Holt in December 1966, with the assistance of a visit from President Johnson and Holt's pledge that Australia would go 'all the way with LBJ' – a slogan that has frequently been recalled with derision in Australia since but which was generally applauded in 1966.

While Australian, American and British strategic interests generally overlapped in the early to mid-1960s, it is, and was, apparent that Australia underwent a kind of strategic 'continental drift' away from Britain towards America during this period. The events relating to the Menzies Government's decision to buy the F-111 – one of the most expensive and significant individual strategic purchases in Australia's history – occasionally illustrated the contradictory attractions of Australia's American and British links. In the end, however, this decision illustrated the dominance of Australia's shift to America over Australia's strategic connection to Britain.

Strategic and Political Considerations

The Menzies Government's fairly rushed consideration of the 'new bomber' issue in 1963 was shaped by a number of strategic, political and alliance factors. These were in turn partly shaped by perceptions of the increasing strategic threat that Indonesia, under the adventurous regime of President Sukarno, posed to Australia. John Bunting noted to Menzies in September 1963 that: 'I would expect to find that there is a real military case for a new bomber. I also expect that there is a political compulsion to have one'.[10]

The selection of the F-111 was driven at least as much by political compulsion as by military need. One of the clearer indications of this was the Government's decision in 1964 not to acquire an interim replacement for the Canberras pending the delivery of the F-111s. The re-election of the Menzies Government in late 1963 removed the political urgency of the new bomber issue – in the absence of political compulsion, the RAAF's case that it was strategically desirable to *immediately* acquire more modern bombers failed to convince the government.

In the early 1960s RAAF doctrine was based on the need to acquire modern strike bombers in order to provide Australia with an effective strategic deterrent. Although the RAAF envisaged that these bombers would be primarily intended to deliver conventional ordnance, this doctrine borrowed heavily from American theories of nuclear war-fighting. The RAAF's doctrine could not be implemented with the Canberras, which lacked any non-visual bombing or electronic counter measure (ECM) capability, had a very slow speed (350 knots) over target, and generally had slight prospects of survival over the highly defended targets the RAAF might engage in South-East Asia or Indonesia. The RAAF also estimated that the Canberra's airframes would only remain airworthy, assuming drastically reduced flying time, until 1970 at the latest.

The RAAF accepted that the cost of re-equipping its fighter squadrons with the Mirage IIIC appeared to preclude any acquisition of new bombers until the mid-1960s – although the Chief of the Air Staff, Sir Valston Hancock, opposed a decision to increase Australia's order of Mirages in March 1963 on the grounds that this 'could prejudice all possibility of seeking a replacement for the Canberra'.[11] The RAAF had been keenly interested in the TSR2 since 1959, and there was a perception, at least within the Prime Minister's Department, that the Australian public expected that the TSR2 would eventually replace the Canberra.[12]

However, until 1963 there was considerable inter-Service and bureaucratic resistance to the RAAF's objective. The navy pressed, for instance, for a new aircraft carrier as a better alternative to land-based bombers. The Treasury was consistently hostile to the acquisition of either aerial or naval offensive capabilities; it claimed in 1963 that Sukarno probably envied Australia's investment in economic infrastructure such as road and rail links, despite his massive investment in his armed forces.[13] Treasury argued that long-range bombers could not be justified because any Australian operations in South-East Asia would take place under US air cover – ironically, this argument would be revived in 1964 as a major reason for rejecting an interim replacement for the Canberras.

As late as March 1963, following a review of Australia's defence needs, Bunting noted that new bombers did not 'qualify as a first priority' for the Government[14] The Government made no decision on Townley's recommendation to agree in principle to acquire 24 strike/reconnaissance aircraft, and to then send an evaluation team abroad to investigate aircraft in production or under development. However, it is likely that this absence of a decision reflected a normal delay in translating the government's current imperatives into the bureaucratic and inter-Service complexities of the defence review cycle, for by March 1963 the RAAF's desire for a new bomber had received assistance from some unexpected quarters.

Australian apprehension about Indonesia's future intentions had been heightened by Sukarno's success, through a combination of military threats and diplomatic pressure, in forcing the Dutch to withdraw from West New Guinea in 1962. Australia was sympathetic to the Dutch but American support for Indonesia's claim had made the Dutch position untenable. Among other things, the Dutch withdrawal gave Indonesia, which was seen as increasingly susceptible to both internal and international Communist influence in the early 1960s, a common frontier with Australia's New Guinea territories. In January 1963 Indonesia announced a policy of Confrontation against the proposed Malaysian Federation, which was supported by Britain and Australia. This announcement was followed by a statement from the Australian Federal Opposition Leader, Arthur Calwell (Labour), that the Indonesian Air Force could destroy any Australian city at will 'even if they allowed 24 hours notice to the RAAF to concentrate for the defence of that city'.

Other things being equal, Australia's alleged vulnerability to Indonesian air attack might have provided a more urgent justification for fighter rather than bomber aircraft – and indeed in March 1963 the Government decided to double Australia's order of Mirage fighters, as noted above. However, Calwell's statement attacked the Menzies

Government at perhaps its most vulnerable point. During the 1961 election campaign the influential *Sydney Morning Herald* newspaper switched its support from Menzies Liberal-Country Party Coalition to the Labour Party. This switch was almost decisive and Menzies was returned with a majority of just one seat. The *Herald* subsequently maintained its criticism of the Menzies Government's alleged appeasement of Indonesia and its neglect of Australia's defence forces – especially of their offensive capabilities.

In Bunting's words, Calwell's statement turned the acquisition of a new bomber into a 'political compulsion' for the Menzies Government. On 7 May 1963 Cabinet decided to send an RAAF evaluation team abroad, headed by Sir Valston Hancock, to investigate suitable aircraft on a no commitment basis. However, this did not dispel the political sensitivity of the bomber issue, for the Labour Party committed itself to the purchase of a new bomber at its July 1963 biennial conference. This decision made it virtually certain that if Menzies sought an early election to enlarge his small majority he would see that there was a need to trump Labour's bid. Given that Menzies was actually in office, and therefore could play such a trump, Labour's persistence with the bomber issue ultimately proved to be self-defeating.

Australia shops for a new bomber

Bunting noted to Menzies in September 1963 that the evaluation team had conducted its investigations without a clear directive specifying the strategic requirements that a new bomber was expected to fulfil.[15] This in itself may be indicative of the haste with which the Government was moving on the bomber issue. In the event, the RAAF drew its own strategic guidance from a very broad statement in the March 1963 defence review that 'some increase in the present scale of defence programming will be necessary [so] that we can make an effective and sustained contribution to South-East Asia and, at the same time, deter Indonesia from possible activities inimical to our strategic interests'. This statement was incorporated into Air Staff Requirement 36 (ASR 36) for a new strike/reconnaissance aircraft.[16]

ASR 36 stipulated that a new RAAF bomber should, *inter alia*, have an all-weather capability in both its primary strike and secondary reconnaissance roles; a capability for delivering both conventional ordnance and 'special stores' (nuclear weapons) – although Townley later advised Cabinet that the RAAF's new bombers would only be armed with conventional weapons; a speed of Mach 2 at 50,000 feet; a desirable radius of action (ROA) of 1,100 nautical miles (nm); and be in service with the RAAF by June 1966.[17]

The evaluation team defined two basic missions for a new bomber. These involved, firstly, joint operations under American command against targets in southern China and North Vietnam, in the event that China chose to repeat its intervention in the Korean War in a limited war in South-East Asia. Secondly, the new bomber was expected to provide an Australian deterrent against Indonesia 'embarking on activities inimical to our strategic interest' and 'to act with certainty' from both overseas and Australian bases against any Indonesian target system 'under all circumstances'.[18]

Although the RAAF's F-111s were delivered too late for service in either the Confrontation or Vietnam wars, these mission profiles anticipated Australia's later involvement in both conflicts. Hancock later claimed that these profiles originated in two alternative scenarios developed by the RAAF in late 1962 or early 1963. One was 'based on the concept of forward defence with allies', the other on a situation where 'we were reduced to virtually a fortress Australia, when we would need a strong deterrent to ensure our survival under more difficult circumstances'.[19] The two mission profiles were, however, clearly consistent with the defence review statement quoted above.

Between June and August 1963 the evaluation team investigated the French Mirage IV, the TSR2, and the American F-4C Phantom, RA-5C Vigilante and the TFX (redesignated later in 1963 as the F-111). While these aircraft represented an extensive menu, a key issue is whether or not the team was already predisposed against the TSR2 even before it went abroad.

In April 1963 Air Chief Marshal Scherger had met with Mountbatten and 'left London sceptical that the British chiefs of staff fully supported the TSR2 project; in particular, he believed Lord Mountbatten opposed the aircraft because of the drain it would make on the total defence budget'.[20] Mountbatten's opposition to the TSR2 went beyond its cost and also reflected his belief that the Polaris submarine-launched nuclear missiles were a better deterrent than air-launched nuclear weapons. While noting that Mountbatten's preference for Polaris was probably technically correct, his biographer, Ziegler, states that he 'pushed his campaign against the TSR2 to the limit of the scrupulous, some would say beyond it.'[21] However, Mountbatten's behaviour was certainly not unique among the principals associated with the selection of Australia's new bomber, for one of the sorrier aspects of this process proved to be the fairly high degree of disingenuousness many of them displayed.

The evaluation team's report noted that it had received 'verbal assurances from the Secretary of State for Air and the Minister for Aviation that the TSR2 was a firm Service requirement and that they could see no reason why production orders would not be approved.' However, the report also reiterated the allegations that Lord Mountbatten 'is strongly opposed to the continuation of the TSR2 project and has sought to reduce its numbers if not eliminate it altogether.'[22]

It is an interesting ethical question as to whether the views of a Service chief – even one of Mountbatten's high standing – on a defence procurement issue should have been given equal weighting to those of government Ministers. However, Mountbatten's prognosis certainly made an impression on the Australians. Almost 30 years later Hancock recalled that 'I heard that Mountbatten was completely against [the TSR2] . . . I believe he felt that the drain on the defence budget would be too high, and so he was against it.'[23]

This comment was bracketed with Hancock's recollection of his discussions in mid-1963 with George Edwards of the British Aircraft Corporation, the manufacturer of the TSR2. Edwards asked Hancock, 'Is there anything more that we can do to persuade you to support the TSR2?' Hancock replied, 'Yes, get a production order from the RAF, because there's no way that the RAAF are likely to support this as the sole purchaser.' Hancock said that the failure to secure a production order for the RAF 'forfeited any support' he was going to give the TSR2.[24]

As discussed, a foreign order was crucial to the prospects of the TSR2 entering service with the RAF. The TSR2 was therefore caught within a very difficult maze indeed when the representative of the only likely foreign customer for the aircraft required an RAF order before he would support the project. The British Government's authorisation of a production batch of 30 TSR2s in September 1963 came too late to influence the evaluation team's findings. Interestingly enough, when Australia agreed to purchase the F-111 no firm production contract had been agreed to by the US Government with the General Dynamics Corporation.

In mid-1963 neither the TSR2 nor the TFX had made their maiden flights. The evaluation team's report noted that there 'was some doubt about whether either aircraft will go into production', although it expressed high confidence about the TFX's prospects. The report considered that if both aircraft were produced the TFX would prove to be a far more flexible weapons system and, as it would be built in larger numbers, it would have a lower price. The team found that, while both the TSR2 and the TFX would meet the RAAF's requirements better than any of the other aircraft it investigated, the TFX 'considered in isolation', was its preferred choice.[25]

This was in some respects a surprising judgement, because the report noted that 'the TSR2 has progressed rather more than had been thought' and there was 'no great evidence of TFX manufacture'. (One very clear indication of this was the inclusion in the report of a poster-sized photograph of a TSR2 being assembled. In mid-1963 it was not possible to produce an equivalent photograph of a TFX, but in this case a picture was not worth a thousand words). Indeed, the team found that much of its discussion of the TFX had perforce to centre on its anticipated performance. Nevertheless, the team found that the TFX was superior to the TSR2 in terms of its expected range, reconnaissance capability, short take-off and landing characteristics, weapons-load and cost.[26]

Some of these findings were questionable even on the basis of the data available to the team. Their report included a table which showed the ROA of the TFX and TSR2 as, respectively, 2,000nm and in excess of 1,100nm. This appears to have been a deliberate presentational exercise because the TSR2's ROA was described in the text of the report as greater than 1,600nm. The text also described the TFX as designed for a basic mission of 800nm – it could achieve a ROA of 2,000nm only through reducing its dash speed from Mach 1.2 to 500 knots and through the addition of external tanks.[27]

The operational range of an aircraft is directly related to its payload weight and apparent shortfalls in the F-111's weapons-load:range characteristics, compared with those advertised in the evaluation team's report, came to light later. The report described the TFX's maximum bomb payload as slightly under 50,000 lbs., compared with up to 16,000 lbs. for the TSR2. However, in 1966 the United States advised Australia that modifications were required to enable the F-111's bomb-load to be increased from 7,500 lbs to 12,000 lbs (with a ROA of 1,100nm) or to enable carriage of a maximum load of 37,500 lbs with a ROA of 700nm.[28]

In mid-1963 the TSR2's development had advanced to the point where precise data could be supplied to the evaluation team on key items such as the aircraft's cost – £A122 million for 24 aircraft – and its availability for entry into RAAF squadron service – mid-1969. By comparison, the team was unable to obtain a satisfactory estimate of the TFX's price and was advised by the US Department of Defence to ignore the figures supplied by General Dynamics. The team estimated that the TFX could enter squadron service with the RAAF by September 1970, about a year later than the TSR2. However, the team's report downplayed some of the TSR2's more favourable or more certain characteristics. It noted that the TSR2's price could blow-out from £A122 million to £A150 million if the RAF only ordered 50 of these aircraft rather than its planned batch of 100, and that the estimated date of entry into RAAF squadron service could be delayed 'for many months'.[29]

The degree to which Mountbatten's meeting with Scherger predisposed the RAAF against the TSR2 is reflected in such editorial bias. It is quite clear from Hancock's comments noted above that, by August 1963 at the latest, the RAAF's early interest in the TSR2 had evaporated as a result of its doubts about the TSR2 entering production. Given the degree of opposition within Britain to the TSR2, the team's preference for an aircraft with better production prospects may have been entirely defensible. However, by basing its preference for the TFX on the somewhat loose presentation of technical data in the evaluation report the RAAF was being much less than frank.

Given its preference for the TFX the evaluation team's recommended selection – the US RA-5C Vigilante – was therefore somewhat surprising, for the Vigilante was superior to the TFX and the TSR2 in only one respect. It was already in production and one squadron of 12 aircraft could enter service with the RAAF by

December 1966. Hancock later recalled that, 'I was less than honest there because I didn't indicate that I reckoned [the Vigilante] as an interim aircraft . . . But having a good deal of experience with politicians, I was quite convinced that after all the uproar over replacing the Canberra had subsided, if we didn't have an aircraft in place, we'd never get a strike aircraft at all. That was why I made no mention of treating it as an interim aircraft'![30]

And so to Cabinet

On 5 September 1963 the Minister for Air, David Fairbairn, recommended that Cabinet agree to the purchase of 24 Vigilantes and 'subject to the latest information about the development and production of the TSR2 and the TFX', to consider, by March 1965, the purchase of an additional 12 Vigilantes to re-equip the third Canberra squadron.[31] Bunting noted to Menzies that the proposed re-examination of the TSR2 and the TFX was clear evidence that 'the RA-5C would have turned out to be a tide-over aircraft!' – a point precisely in accord with Hancock's private view.[32] Fairbairn's submission combined the immediate acquisition of a 'third-best' technical choice with the possibility of a further heavy financial commitment to a more advanced aircraft in two years time.

Taken together, a number of apparent defects in Fairbairn's submission raise the question of whether the Vigilante was ever anything more than a 'Trojan horse' for the TFX. These include the wide gap between the Vigilante's actual capabilities and the expected advanced specifications of the TFX and the TSR2; the manner in which a junior Minister rather than his senior colleague, the Minister for Defence, made the initial running in the Cabinet on a highly expensive and strategically significant acquisition – 24 RA-5Cs would have cost around £A88 million, a higher price, as it turned out, than the estimated best price of the TSR2 in October 1963; and the transparently hybrid nature of the proposal, as evidenced by Bunting's comment above.

Indeed, on the day the F-111 purchase was announced, Bunting noted to Menzies that 'instead of leaving the RAAF with their third choice – which is what the Vigilante boils down to – we have made it possible for them to get their first choice'.[33] The recommendation of the Vigilante may have proved to be something of an embarrassment for the RAAF. When the government considered the issue of an interim replacement for the Canberra in 1964 the Vigilante was not one of the candidate aircraft because 'Cabinet had already rejected this aircraft'.[34]

The Government's consideration of the Vigilante purchase was a point of balance for the TSR2's prospects in Australia – thereafter, they were to decline dramatically. On 16 September Bunting informed Menzies that 'the RA-5C proposal does not stand up to scrutiny, the TFX is too far into the future, and the TSR2 is therefore indicated, especially as orders placed soon would presumably satisfy the political requirement'.[35] However, on 7 October the Government finally rejected the Vigilante proposal, 'concluded that the TSR2 ought probably to be excluded from consideration . . . for the present at least' and decided that Townley should undertake 'a discussion with the United States Administration at the political level, concerning the problems of [the Canberra] replacement and the way or ways in which the Government may deal with them'.[36] This included investigation of the prospects of obtaining an interim replacement for the Canberras, probably to offset the Labour Party's pledge to acquire a new bomber, if elected.

These decisions reduced the TSR2 to a 'second best' choice. On 11 October Bunting advised Menzies that he needed to be 'less than frank' in responding to financial concessions on the TSR2 offered by Macmillan on 3 October because, if Townley's negotiations proved to be unsatisfactory 'we will want to reopen the possibility of choosing the TSR2'. Moreover, 'it will do Mr Townley's talks in Washington no good if it trickles down that we have firmly turned the TSR2 down'.[37]

Allied actions

The most critical historical question associated with the selection of the F-111 is what firmly turned the Menzies Government's mind towards this aircraft after mid-September 1963. A note from Bunting to Menzies on 22 October stated that the American offer for the sale of the F-111 'seems to achieve what was the unexpressed core of Cabinet's decision to send Mr Townley to the United States, ie almost to get the Americans to tell us what we should have and thus link them to our defence'.[38] However unattractive its apparent sycophancy, it is difficult to find a more concise description of the Government's thinking than this. Ironically enough, in his comments on Townley's proposed negotiations with the United States, Bunting's subordinate Allan Griffith had cautioned against 'the proposition that we place ourselves entirely in the hands of the Americans . . . we should therefore leave our position somewhat more open than is proposed'.[39]

In September 1963 the British Government intensified its efforts to sell the TSR2 to Australia. The British Secretary of State for Air, Hugh Fraser, visited Australia coincident with Cabinet's consideration of the Vigilante purchase. Fraser told the government that an order for 30 TSR2s had been placed and that Britain sought to conduct the TSR2's weapons evaluation and training in Australia. Macmillan reinforced this pitch on 3 October in an offer to Menzies to waive the TSR2's development cost charges.[40]

Macmillan left office in early October 1963 due to illness. Menzies' reply to Rab Butler on 14 October was, as noted above, deliberately 'less than frank'. Menzies wrote that 'you may feel that [Townley's mission to Washington] amounts to a virtual decision on our part to prefer one or other of the American varieties of aircraft to the TSR2. I can only say again that we have not made any decision [and] Townley's exercise is essentially investigatory'.[41] Menzies' statement was technically correct, for Cabinet had only gone so far as to conclude that 'the TSR2 ought *probably* be excluded'. However, on 14 October the British Minister of Defence, Peter Thorneycroft, conveyed an offer to Townley in Washington to lead a team to Australia to negotiate terms of sale for the TSR2. This offer was not taken up – the British were not given an opportunity to match or better the American offers. It was perhaps no small wonder that the lack of official comment in Britain on the purchase of the F-111s 10 days after Menzies sent his letter to Butler appeared to arise from 'bewilderment rather than understanding'.[42]

In the early 1960s there may have been no greater difficulty for any western government than to compete with the United States for an arms sale. Hancock's evaluation team had already undertaken 'exploratory' discussions in July and August about the funding arrangements that might be available for the purchase of an American aircraft. They were informed that the US Secretary of the Treasury and the Secretary of Defense, Robert McNamara, would ensure that

Australia would receive 'whatever financial conditions [she] wanted'. Moreover, 'but for the absorption of the President at that particular time in his family affairs, he would have been able to give the same assurances from that level'.[43]

What motivated these apparently generous intentions? Allan Griffith prepared a paper for Bunting in November 1963 titled *American High Policy and the TSR2*, which claimed that McNamara was hostile to the TSR2 because it would have advanced British claims to a nuclear deterrent outside centralised NATO control. 'The Americans have . . . a theory that if nuclear wars are started they should start as a result of action or reaction by the Soviet Union and the United States' – not by the actions of the superpowers' allies. Griffith asserted that McNamara regarded the cancellation of the TSR2 as desirable not only in itself but also as an indirect means of curtailing development of the French *force de frappe.* Accordingly, 'McNamara would have seen that the Australian purchase of the TSR2 . . . would have perpetuated production of the TSR2 and made it more difficult for Britain to resist the temptation to relinquish her national deterrent'.[44] Griffith's note implies that McNamara therefore had very cogent reasons for seeking to forestall an Australian purchase of the TSR2.

Griffith's analysis could be regarded as excessively conspiratorial although, whether or not it provides an accurate explanation of US motives in 1963, it certainly provides a fascinating insight into the world-views of some of the Menzies Government's senior advisers in the early 1960s. Mr McNamara has denied that Griffith's claims have any substance. He indeed maintains that the Kennedy Administration offered Britain access to Polaris when Macmillan made an impassioned appeal to Kennedy at the Nassau Conference in December 1962, after the cancellation of the US Skybolt project, that the lack of a modern British nuclear deterrent would ruin both the Conservative Party's electoral prospects and Britain's ability to sustain an effective defence.[45]

Mr McNamara also denies that the Kennedy Administration sought to provide the Menzies Government with any electoral assistance, as part of the F-111 package deal, in the form of the free offer of 24 B-47s as an interim replacement for the Canberras. Soon after this deal was announced Menzies called a snap election for 30 November and three B-47s toured Australia during the election campaign. However, according to McNamara his only underlying motivation throughout the F-111 negotiations was his perception that Australia was paying insufficient attention to Indonesia in defence, diplomatic and foreign aid matters, and that the deal was partly an attempt to ensure that Australia was in a position to redress this balance in relation to defence.[46]

Menzies provided the new British Prime Minister, Alec Douglas-Home, with a personal explanation for Australia's rejection of the TSR2 on 24 October, and noted that 'for your private information, there was a considerable degree of US initiative' in the F-111 deal.[47]

It is clear from this comment that, whatever its motives, the US Government was highly receptive to Townley's mission. Indeed, Townley's comments to Menzies suggested that the Kennedy Administration was engaged in a virtual 'Dutch auction' in negotiating a price that was acceptable to the Australians. 'There was a real desire to meet us in every way. Fortunately, the President himself, after his conversation with you recently, had told McNamara that there was to be no quibbling, and these instructions were followed to the letter'.[48] It had taken the Government seven months to move from the position where the acquisition of new bombers was not (formally) one of its highest priorities, to its despatch of Townley to Washington to seek just such an acquisition. This was in itself a fairly rapid policy reversal, but it took only a little over two weeks more for Townley to then negotiate the purchase of an aircraft which was still more than a year away from its expected maiden flight.

It was therefore a remarkable and even comical indication of the government's lack of hard information about its prospective purchase that, as late as two days before the F-111 deal was closed, there was some alarm within the Defence and Prime Minister's departments about the reconnaissance capabilities of the F-111. This arose from a cable despatched by Townley that noted that the US had designated the specialised reconnaissance version of the F-111 as the RF-111. The government had been under the impression, since the evaluation team's report, that the F-111 would combine reconnaissance and strike capabilities in the one aircraft. Bunting was concerned enough to advise Menzies on 22 October that 'if there is insufficient reconnaissance capability in the F- series, I would feel that the TSR2 must come back into the picture'.[49] A subsequent cable from Townley provided sufficient reassurance.

By this point the marvellous electoral opportunity that the F-111 purchase represented clearly impelled Menzies to close the deal. In the same note that set out the reconnaissance issue, Bunting indicated that 'the Government will find itself in a caretaker mode from 1 November' and that there was 'therefore a need to finalise the F-111 decision before then'. In a cable to Townley on 24 October Menzies wrote that the announcement of the F-111 deal 'would be a good thing for us . . . [because] . . . much may be made of your remarkable achievement' during the election campaign![50] Much indeed would be, in 1963 and in later years.

Under the terms of its agreement with the United States, Australia purchased 24 F-111s for £A56 million, with an initial delivery date in 1967, and had the option of borrowing 24 B-47s from the United States pending the delivery of the F-111s. The RAAF did not want the B-47s, which it regarded as essentially equivalent to the Canberras, and advised the Government of this as early as 22 October.[51]

However, McNamara's demurral notwithstanding, the offer of the B-47s appears to have been an important part of the government's political consideration of the F-111 deal.

The government may have decided to acquire a new bomber, but its delivery was several years away. Calwell had responded to the announcement of the F-111 purchase with accusations of government duplicity in regard to the rejection of the TSR2, and promised to immediately acquire a new bomber if the Labour Party won office. However, the flights of the B-47s around the country visibly offset the Labour Party's charges that Australia would still be exposed until the F-111s arrived. Cabinet did not formally decline the US offer of the B-47s until 14 May 1964 and also rejected an alternative RAAF proposal to acquire the Phantom as an interim aircraft two weeks later. It accepted the argument that 'the military necessity [for the acquisition of the Phantom] does not exist'.[52]

What price the F-111

While the F-111 purchase helped resolve Menzies political difficulties in 1963, it remained a controversial issue in Australia for many years afterwards. Subsequent difficulties with the F-111's cost overruns, development problems inherent to the production of technologically advanced aircraft, and a series of American F-111 air-crashes in the late 1960s enabled Calwell's successor, Gough Whitlam, to describe his Shadow Minister for Defence during the 1969 election campaign as 'a brave man who had fought at El Alamein and flown in the F-111'. Whitlam's jibe illustrated the devaluation in the F-111's electoral appeal over the previous six years.

The F-111s did not enter operational service with the RAAF until 1973, six years later than scheduled, by which time their price had inflated from their original quotation of £A56 million ($A112 million) to $A344 million by 1971.

The Menzies Government tried to make much of the claim during the 1963 election campaign that it had purchased the F-111s very cheaply. Townley said that the price of the F-111s was half what Australia would have paid for the TSR2s. On 10 November 1963 his Departmental Secretary, Sir Edwin Hicks, felt compelled to intervene with the observation that this was a potentially embarrassing line for the government to pursue, for the price differentials were much closer than Townley had claimed – £A81 million for the TSR2 compared with £A56 million for the F-111.[53]

Hicks' estimate coincided with the publication of an article in the *Sunday Times* that claimed that the British Government was about to formally offer Australia a 10 per cent reduction in the TSR2's price when Menzies announced the F-111 purchase. Bunting wrote to Hicks that 'there is a good deal of circumstantial evidence that some proposition was about to be put to us, but we never saw it.[54] The Australian High Commissioner in London, Allen Brown, cabled Bunting on 13 November. Brown agreed with Bunting 'that the weakness in the government's public relations case is that the British government were never given the opportunity of doing better than the Americans cost-wise. This is unfortunate seeing that we have chosen to make the disparity in costs a primary reason for the decision. [The F-111 purchase] has not been a great success from this end from the public relations point of view'.[55]

Conclusion

Sir Valston Hancock later remarked that 'the decision to purchase the F-111 turned out to be the most fortunate one in the event because had we bought the Vigilante I don't think we'd ever have replaced it because the political heat would have gone off the decision by that time. But by taking the decision to buy the F-111 for political but not strategic reasons, we have now acquired a tremendous deterrent force with the modernised F-111'.[56]

There is much in Hancock's analysis of the Menzies Government's primary motivation for acquiring the F-111s, and something in his arguments about their ultimate strategic benefits. The process employed to select the F-111s was extremely flawed. Not only was the TSR2 denied a 'fair day in court', but the Government failed to appreciate that both cost escalations and development problems were likely to be encountered with an aircraft that employed untried technologies, and which had not yet advanced to any significant pre-production stage. Had these issues been squarely addressed in 1963 it is arguable that both the subsequent political costs of the purchase, and the organisational strain that the F-111 imposed on the RAAF during the 1960s, may have been greatly reduced.

Hancock's report briefly canvassed the production difficulties inherent with advanced aircraft such as the F-111 and the TSR2. His report was flawed, however, by its emphasis on the escalating costs that the TSR2 was likely to face without a similar caveat on the F-111.

In this respect his report made too much of the prospect that large production runs – of up to 3,000 F-111s! – would reduce their unit cost.

Nevertheless this flawed process led to the acquisition of an aircraft which, despite its early difficulties, is scheduled to remain in service with the RAAF until around 2020 – almost 60 years after its original investigation by Hancock's team – and which has been successfully adapted to Australian operational requirements.

The strategic and political circumstances of 1963 provided the RAAF with a unique opportunity to advance its doctrinal claims for strike aircraft. This was a very brief window – as the RAAF's failure to acquire the Phantom in 1964 demonstrated. The TSR2 appeared to be the only prospective replacement for the Canberra before 1963 but Australian political circumstances did not favour an early decision to acquire it. It is a supreme irony that when political circumstances finally favoured the purchase of a new bomber in 1963 the RAAF's perception of the TSR2 was quickly devalued.

Moreover, and whatever the TSR2's objective merits, it is difficult to see how the Menzies Government could have derived the same political advantages from advertising Australia's British connections through the purchase of the TSR2, as it did from the purchase of the F-111. For that matter, it is difficult to see how a barn-storming visit by V-bombers would have had the same electoral impact as the government derived from the B-47s in November 1963.

The lengths to which the Menzies Government went to ensure Australia's strategic value to the United States have been heavily criticised since. However, and like other western governments in the 1960s, the Menzies Government was conscious of two overriding factors – the dangers of the Cold War and the strictly limited means available to Australia to defend herself against these threats. Given these perceptions, the efforts that Menzies and his successors made during the 1960s to align themselves as closely as possible with the United States are not surprising.

However, in the case of the F-111 purchase, the Menzies Government can be faulted for its naive trust in the ability of the United States to solve Australia's strategic problems without any significant effort by Australia to relate her own strategic requirements to such a highly expensive strategic procurement. In this respect Bunting's comment that Townley's mission was intended 'almost to get the Americans to tell us what we should have and thus link them to our defence' reveals both a cringe in Australia's strategic culture and a reciprocal Australian confidence in the consistency of American strategic wisdom. It is no accident that Australia only came to see the necessity for an independent strategic outlook after her confidence in American strategic guidance was greatly shaken by the demonstration of American strategic fallibility in Vietnam and – in a much smaller sense – the difficulties associated with the early F-111s.

From a purely financial aspect the Menzies Government can also be faulted for its failure to undertake negotiations based on rigorous bargaining between the American and British offers for new bombers in 1963. Allan Griffith recommended that Australia should undertake such bargaining in September 1963, but nothing came of this proposal.[57] Had the Menzies Government undertaken such negotiation with America *and* Britain it would have been less open to the charge made by Calwell in 1963, and confirmed by the historical record, that it dealt less than frankly with a major ally in relation to the TSR2.

The strategic significance of modern weapons systems frequently lies as much in their symbolic value as in their actual employment on the battlefield. This symbolic value can have both national and international political dimensions. The strategic symbolism of Australia's F-111 has already gone through at least three evolutionary stages. Between 1963 and 1966 the F-111 symbolised Australia's eagerness to be identified with the United States and, in declining the TSR2, her rejection of at least part of her British strategic connection. In 'Stage 2', the difficulties encountered in the latter 1960s in bringing the F-111 into service with the RAAF appeared to many Australians to reflect the costs to Australia of the American alliance itself. In Stage 3, and as Australia adopted a more independent defence policy from the 1970s on, the F-111 came to be seen by some of Australia's regional neighbours as a potential strategic threat to themselves and a justification for their own strategic procurements.

There are now indications of a fourth stage which completely reverses the original symbolic Strategic role assigned to the F-111 – to deter Indonesia. In July 1996 an RAAF F-111, with a Bahasa-speaking navigator, flew to Djakarta to participate in an Indonesian air show. According to the Department of Defence, this first display of an RAAF F-111 in Indonesia was in line with Australia's closer defence ties with that country under the bilateral security agreement negotiated by the Keating Government.[58]

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Discussion

Air Vice-Marshal Nigel Baldwin chaired a discussion group on TSR2 in the maelstrom of Whitehall, in the course of which some unexpected views emerged about the ultimate commitment of the Royal Air Force to the project. The realities of what had probably been an over-ambitious procurement programme in the mid-60s were also discussed.

In 1956-57 **Sir Freddie Sowrey** was Staff Officer to the Air Force Member of the Defence Research Policy Staff. He recalled that the NA39 [Buccaneer] was quite incapable of meeting the Air Ministry requirement for speed, range or short field performance with the loads specified. Later, as Personal Staff Officer to CAS in 1961-62, he had seen at first hand Sir Thomas Pike's efforts to see if one aircraft might serve both the RAF and RN. CAS was a great supporter of Sir George Edwards and his efforts at Vickers. During that time, however, Skybolt was cancelled and he believed that the long term retention of a nuclear capability by the RAF may have come under political scrutiny then and have played a part in the ultimate cancellation.

Air Cdre Henry Probert wished that he had had the benefit of the day's discussions when, some years ago, he interviewed the three Chiefs of Air Staff of the time surrounding the TSR2 story. Sir Dermot Boyle, Sir Tom Pike and Lord Elworthy had had much to say about the project. Sir Dermot allowed him to see the draft of a short personal memoir [*My Life*] and asked for his comments [as the then Head of the Air Historical Branch]. Only one point concerned Air Cdre Probert and that was where Sir Dermot referred to the period when he was Vice-Chairman of BAC and watched the first flight of TSR2, performing perfectly in Bee Beamont's hands before it was cancelled in a most scandalous way. He wrote:

> 'It would be hard to imagine a more wilful destruction of a great national asset. I felt it very badly, having as CAS fought it through least two Defence Committee meetings and persuaded Duncan Sandys to accept it. The RAF did not recover from its loss until Tornado arrived in service.'

He went on to say that he blamed the Labour Government and said that he was sure that Lord Elworthy had done all he possibly could to defend it. At that point, Henry Probert felt that he had to do something, because he had also spoken with Lord Elworthy at a later stage. He said that he personally had accepted cancellation as CAS. Costs were escalating rapidly, the numbers to be purchased were being steadily cut and he feared that it would run the whole of the RAF budget dry.

Air Cdre Probert called Sir Dermot Boyle and reported this news. 'There was a little silence and he undertook 'to think about it'. When the book was published, the reference to Lord Elworthy's defence of the project had disappeared.

Henry Probert had not heard at that time, that CAS [Elworthy] had recommended to Hugh Fraser [Minister (Air)] before the 1964 General Election the cancellation of TSR2. He suspected that, had another Conservative Government been elected in 1964, TSR2 would still have been cancelled.

AVM Nigel Baldwin said that Sir Michael Quinlan, PS to CAS in 1962-65, had reported [in a letter to AVM Sandy Hunter] that Lord Elworthy had indeed recommended cancellation to Hugh Fraser on the grounds that the cost of TSR2 was out of control. He had suggested the substitute purchase of the US TFX [F-111] Fraser declined to forward the idea to Peter Thorneycroft, then Minister of Defence. Sir Michael had also written:

> 'On the same out-of-control theme: I recall Sir George Edwards coming to see Sam in the final crucial days, when everyone knew cancellation by Denis Healey was in the offing, to make a last appeal; yet even then he did not feel able to promise to keep costs below specific figures (I think I recall that Sam suggested to him, as a challenge, £300M R&D and £3M per copy – vast figures in money of the time, and substantially above the estimates then theoretically current).'

Sir John Barraclough was Director of Public Relations for the RAF at the time and said that he did not believe that PR, good or bad, would have made that much difference to the outcome of the TSR2 project. He did believe that it was worth remembering that much PR and lobbying activity had been going on, much of it of a very secretive and sophisticated nature. The Air Ministry 'line' on the aircraft was 'remarkably and outstandingly feeble' which was surprising, given that it came after an audacious and courageous PR gambit by Sir Dermot Boyle (CAS 1956-60) in the shape of his Exercise PROSPECT which had been 'one in the eye' for Duncan Sandys. TSR2 was the phoenix emerging from the [Sandys] ashes. His own experience was that 'if the trumpet gives an uncertain sound, who will prepare himself for battle?' and that there had been no [RAF] 'line' on TSR2.

At the time, the RAF was pushing the V-Force in the context of massive retaliation and his own task had been to gain publicity for the Force and the coming Skybolt. Journalists had had considerable difficulty with understanding what the TSR2 would do in the context of a 3-day war! TSR2's capabilities did not fit in with any NATO strategy; some years later, it would have matched the demands of flexible response perfectly. It had not been sufficient for Julian Amery, a great patriot, to say that a world-class air force needed a world-class aircraft. The 'sceptical press' would not be convinced by such assertion. It had then been necessary to go to the East of Suez and Island strategies which resulted in a confrontation with the Royal Navy and the aircraft carrier programme.

Sir John added that, for the future, any OR should include a public affairs statement by way of justifying any project which must be kept up to date throughout the programme.

Professor John Law of Keele University offered some thoughts. First, he was not sure that English Electric could have done the job as defined in GOR 339. The specification had been ratcheted-up to a point where he believed that the systems expertise of Vickers was essential. Second, he had interviewed Roy Jenkins [Lord Jenkins of Hillhead, Minister of Aviation 1964-65] in the last five years or so and said that he was no longer certain that the Government had made the decision simply on cost grounds, rather than for any wider political reason. Third, he believed that the skills available at the time to people in Whitehall and industry did not overlap sufficiently. A project of such complexity demanded a range of skills (technical, operational, administrative and financial) and these may not have been present in combination.

Peter Hudson was Head of the Air Staff Secretariat in the early '60s and, later, Head of the MoD Programme & Budget Division. He agreed that CAS had decided that TSR2 could not be proceeded with, some months before the October 1964 election. The Labour Government then found before it an extremely ambitious and probably completely unrealistic programme including the TSR2, HS681 and the P1154, each of which was technically demanding and uncertain in terms of cost. Cancellation of TSR2 was likely to be a political hot potato but the fact remained that there were three highly attractive American aircraft covering the roles of the three British types. The F-111, the Hercules and the Phantom promised to cut several hundreds of millions of pounds off the projected programme and the terms of purchase were very attractive indeed.

Sir Patrick Hine said that the Royal Navy had already opted for the F-4K Phantom, having failed to harmonise requirements around the P1154. While the RAF continued to look to the P1154, the RN broke ranks and opted for the Phantom, although not at that time with the Rolls-Royce engines. The Labour Government, therefore, could have seen a certain synergy in the RAF accepting the Phantom also.

Sir Frank Cooper believed that insufficient emphasis had been placed on the impact of the Sandys Defence Review on Whitehall as a whole and also on industry. The focus of Sir George Edwards' attention on the VC10 and other civil projects was mirrored in Rolls-Royce where the anticipated dearth of military orders changed the company's emphasis to civil engine development. Sandys had sent a culture shock through both Whitehall and the Industry.

He agreed with what Peter Hudson said about the impact of the terms of purchase of the American aircraft which had 'flattened out' the entire programme until well into the 1970s. Besides the cost of the aircraft (Phantom £0.9M and Phantom complete with R-R engines and radar £1.6M; Hercules £0.75M), the spreading of payments (at 5.75%) over 7 years very much eliminated peaks in the programme. TSR2 could not be taken in isolation. The US Programme Planning Budgeting System had been successfully adapted [by Peter Hudson] for use in the Air Ministry and much had been learnt thereby.

SECTION THREE

A PROJECT OVERVIEW

DESIGN AND DEVELOPMENT OF THE AIRFRAME

TSR2 - A WORM'S EYE VIEW OF EVENTS

THE ENGINE FOR TSR2

DISCUSSION

A Project Overview

Sir Frederick Page CBE FRS FEng Hon FRAeS

Sir Frederick Page joined Hawker aircraft after leaving Cambridge in 1938 and went on to an extremely distinguished career in the British and European aircraft industries. He became Chief Engineer of English Electric Aviation in 1950 and a Director and Chief Executive of the company from 1959-65 when he was appointed Managing Director (Military Aircraft) of the fledgling British Aircraft Corporation. He was later Chairman and Chief Executive of the British Aerospace Aircraft Group until 1982. During the latter appointment, he also served as Joint Chairman of SEPECAT (Jaguar) and as Chairman of Panavia (Tornado). His intimate familiarity with the TSR2 project and, especially, with its English Electric antecedents make him uniquely qualified to present an Overview of the Project.

After 1946, two factors emerged which were to have a great influence on the TSR2 project.

Firstly, the period in office of Ministers concerned with aerospace equipment for defence became about one twelfth of the overall timescale of a successful project, yet each felt that he had to leave his mark on it even if his experience of aerospace was negligible. Because the true value of a project to the RAF and to the economy of the UK via exports is mostly concentrated in the second half of the timescale, the first few Ministers only see expenditure and development problems. Is it any wonder that, coupled with technological, international and political developments, the ups and downs in procurement policy made the Big Dipper at Blackpool look like a level playing field! Figure 1 lists some of them. A further complication was that there were two separate Ministries involved and, of course, the Treasury.

The second factor was the eminently sensible need to amalgamate industry into fewer and more effective units. On 16 September 1957, at a meeting attended by senior industry representatives who had just received the first issue of GOR 339, ultimately TSR2, Sir Cyril Musgrave, speaking for the Minister of Supply, emphasised that need and said 'the only power the Department possessed was in the placing of the contract and it was intended to use this as a means of encouraging the association of firms.'

In his 1982 Hinton lecture, Sir George Edwards aptly describes three aircraft projects used in this policy as 'golden welding flux'. Two of the three were cancelled before they flew, but TSR2 XR219 survived to fly satisfactorily until the programme as cancelled by Denis Healey on 6 April 1965. By then, the second aircraft, XR220, was ready to fly at Boscombe and the third, XR221, fully equipped for systems development, was at Wisley and ground tests had proved that the complex electronics had been satisfactorily integrated into the airframe; the opportunity to test the airborne systems performance was wasted because Healey's decision was enforced so strictly. A BAC

PROCUREMENT POLICIES

1945-46	'No new aircraft needed for 10 years'	
	B3/45 Canberra initiated	
	'Supersonic aircraft too difficult for UK' – Miles M52 stopped	
1947	ER103 issued for new supersonic research aircraft	
1948-58	Combat, supersonic and research aircraft	
	started	18+
	cancelled or stopped	8+
1953	F-86 fighters imported from USA	
1957	Duncan Sandys' Defence White Paper	
	'RAF will not require fighters more advanced than P1 and fighters will in due course be replaced by missiles'	
1959-60	TSR2, HS P1154 and HS681 initiated	
1964-45	New Labour government defence review cancels P1154 and HS681 and finally TSR2	
Note:	Civil aircraft, helicopters, engines and missiles similarly affected.	

Derek Wood's book *Project Cancelled* gives more detail.

proposal for a very limited programme on that aircraft was rejected and all mock-ups, aircraft, components, jigs and tools had to be destroyed, or, in a few cases, used for testing ammunition and explosives or as museum pieces.

I assume that this seminar is intended not only to establish the facts but also to see what lessons might be learned.

The first lesson is that a contract for a complex and technically demanding project should only be awarded to a firm that has adequate strength, management ability and structure, facilities and relevant experience and can devote an authoritative, comprehensive and suitably experienced project management team full time to the project. Properly organised, Vickers and English Electric had the necessary strengths and experience to have produced a successful TSR2 more cheaply and more quickly; separately, they both had significant weaknesses.

The strength of Vickers was that its aircraft business was completely integrated under the control of an able and forceful character, Sir George Edwards, and it had got the Valiant into service quickly. Its weaknesses were lack of any experience of, and facilities for, the design and testing of supersonic aircraft and preoccupation with some difficult and unprofitable civil aircraft. It also lacked adequate definition of the relationship between project management and specialist departments, particularly finance.

The strength of English Electric Aviation was its experience of the very successful Canberra programme and proven expertise and facilities for the design, development and flight testing of supersonic aircraft plus a clearly defined project management system. Its weakness was that it had no properly integrated control of manufacture which had to be sub-contracted to the main English Electric organisation and it was also heavily involved in getting the Lightning into service. Moreover, because some of its contacts with the customer challenged the increasingly severe requirements in OR339, it was possibly seen as somewhat uncooperative. Its geographical distance from Whitehall was also a handicap in the intense lobbying.

Both companies recognised the need for rationalisation and earlier informal contacts ripened into top level discussions and detailed technical exchanges during 1958. In my view, the premature announcement on 1 January 1959 of the award of the TSR2 contract to Vickers with the work shared on a fifty-fifty basis with English Electric only served to prevent the formation of a properly balanced project team and led to delays and increased cost. The formal contract for 9 development batch aircraft to Specification RB192D was not placed until October 1960, after the formal merger in July 1960.

Vickers had clearly won the battle in Whitehall and the uncompromising terms of the January 1959 announcement followed by the award of all subsequent contracts to Vickers only, even after the formal incorporation of BAC, inevitably meant that all definitive aspects of the project were controlled by Vickers men. For example, the Project Director, Chief Project Engineer and all leaders of specialist design, manufacturing, finance and procurement activities were Vickers men. The flight test aircrew were led by English Electric because Vickers had no one with any substantial supersonic flight test experience.

Thus English Electric Aviation was firmly treated as a sub-contractor but this had one beneficial side effect which outlasted TSR2. As previously mentioned, English Electric Aviation did not directly control manufacture and Vickers personnel monitoring the build programme found some difficulty in obtaining a clear picture and voiced fears that the wing and rear fuselage units from Preston would delay final assembly. Sir George Edwards, Lord Caldecote and I reviewed the situation in late 1962 and I promised that if the whole aircraft manufacturing and associated financial, administrative and commercial departments were brought into English Electric Aviation, no Preston units would delay assembly. Things moved quickly and, by early April 1963, the amalgamation had been completed formally and all Preston units arrived at or before the time Weybridge needed them. This was a key TSR2 achievement and the foundation of the successful Military Aircraft Division of BAe at Warton and Samlesbury.

The second lesson is that the customer must also devote an authoritative, comprehensive and suitably experienced project management team full time to the job and it must have full knowledge of the available budget and contingency margin, preferably shared with the contractor's team, otherwise there will be cost over-runs. I wonder if this lesson has yet been fully absorbed but at least there is

DEVELOPMENT OF TSR2 SPECIFICATION

Feb	1957	English Electric P17A proposal submitted formally
Mar	1957	GOR 339 1st issue
Sep	1957	GOR 339 formal issue to nine companies
Mar	1958	OR 339 1st draft
Aug	1958	OR 339 2nd draft
Nov	1958	OR 339 3rd draft
Dec	1958	OR 339 4th draft
Mar	1959	OR 343 draft issue
May	1959	OR 343 formal issue
Aug	1960	Specifications RB192D final contractual issue after three drafts
Feb	1961	OR 343 2nd issue

now a unified MOD containing the procurement function.

In the absence of such arrangements, the prolonged and competitive gestation period of TSR2 provided ample scope for costly embellishment by enthusiastic OR officers in MOD and equipment specialists in MOS and their suppliers. The various issues of the requirement are shown below, from the original English Electric P17A proposal in February 1957 up to the contractual specification RB192D in August 1960, each being more demanding than the previous one.

To illustrate the growth in size, complication and therefore cost in this period, in 1957 English Electric envisaged a M=1.6 twin-engined aircraft weighing less than 70,000 lb and Vickers even proposed a less than 50,000 lb single-engined aircraft. We ended in 1965 with a 110,0001b twin. Although the sea level speed, take off distance and radius of action requirements remained roughly the same, the altitude speed for design and test was increased from no specific figure to M=2.25 and 825 knots IAS at maximum world wide temperature. The low level penetration height dropped from 1,000/1,500ft to not more than 200ft and the runway classification number dropped from 40 to 22 with a tyre pressure less than 80psi. The new equipment specified increased greatly, the initial interim fits of mostly existing items proposed in P17A were ruled out, twin Olympus 22R engines instead of 15R became mandatory and, at a late stage, the main computer installation was doubled.

In the comprehensive three-volume final proposal submitted under intensely competitive conditions in January 1958, English Electric limited the supersonic dash speed at altitude to M=1.7 and maximum design speeds to M=1.9 and 750 knots IAS in a standard atmosphere,used as much existing equipment as possible and 190psi tyres. Even so, timescale and costs were identified as problems although later development based on service experience was envisaged.

However, the Vickers project management team accepted all the increased demands spread out over many meetings with officials. At one, when the design speeds and temperatures were increased, I said, 'Gentlemen, I hope you realise that what you have done will ensure that this project will cost the earth,' but this was dismissed as coming from a disgruntled sub-contractor.

Most of the major new equipments and the Olympus 22R engines were supplied under the MOS embodiment loan procedure and Vickers did not control, and were not aware of, the true costs until it was too late. In 1964 when the first assessment of production cost was being made, Henry Gardner, the Vickers Project Director, said to me with some anxiety that the estimated production cost of a set of equipment for TSR2, not including engines, was more than the production cost of a complete Lightning including engines. The third lesson is therefore give the main contractor as much control of total cost as possible.

Everybody knows the fourth lesson that new, or virtually new, engines are costly and cause delays. In his autobiography *Not Much of an Engineer*, on pp 146 to 148, Sir Stanley Hooker emphasises that the basic Olympus 15R was good for M=1.8, adequate for the original P17A, but it had to be largely redesigned to cope with the increased weights and temperatures previously mentioned. He also reinforces some of my other points and mentions the HP shaft vibration which blew up the Vulcan test bed and also delayed TSR2 flight testing.

The fifth lesson is that, for an advanced supersonic aircraft, the development batch procedure with no preceding prototype phase ensures trouble and increased costs. Contrary to some published statements, there were no TSR2 prototypes. The contract was for 9 development batch aircraft plus 2 structural test airframes, an idea imported from the Americans who have long since dropped it. An early limited prototype programme is essential.

The sixth lesson is that the contractor should be able to assemble and test fly the aircraft *ab initio* either at his own airfield or at another suitable airfield where permanent fully staffed final assembly and flight test teams are maintained. Vickers chose Weybridge for an initial assembly and then the aircraft had to be dismantled, moved to Boscombe Down or Wisley and reassembled. In this process, one major sub-assembly was damaged. Although Boscombe personnel were very helpful, and long hours were worked, it was not always possible for Boscombe, Vickers and English Electric and Bristol Engines to arrange for all the appropriate people to work 24 hours, 7 days a week when required as had been done on their own local airfields. This caused further delays as did engine and undercarriage problems.

After the engine problems had been partly cleared, TSR2 XR219 made its first flight on 27 September 1964 with some engine limitations and with the undercarriage locked down. The flying qualities in that limited flight were good but there was a strong lateral vibration at the pilot's station at touchdown which interfered with vision at that critical moment.

The main undercarriage, a Vickers responsibility, had to cope with two large low pressure tyres on a fore and aft bogey offset on the outside of a long stroke, widely splayed, sliding tube oleo-pneumatic leg and the bogey had to rotate during retraction. The complex movements during retraction and the offset moments and loads at touchdown were a recipe for trouble. It took over four months and nine flights before the undercarriage could be retracted on flight 10. In this period there were some very difficult incidents but the retraction problem was finally solved. However, on any but the gentlest touchdown, usually achievable by skilled test pilots, the lateral oscillations remained. On several occasions, foam had to be laid at the touchdown area to reduce spin up and lateral loads. This problem, although reduced, had not been completely solved by the time the programme was cancelled. My opinion is that, to avoid trouble in service, the undercarriage should have been a rigid leg levered suspension design like the Jaguar.

Sir George Edwards necessarily had been much occupied with the setting up of BAC and the Vanguard, VC10, Super VC10 and BAC 111 programmes but near the end of 1964 intervened to put me in charge of the TSR2 programme. This was a doubtful honour as it was by then clear that a new Labour government aided by several powerful figures behind the scenes in Whitehall were determined to cancel the project. However, we did succeed in getting XR219 back to Warton, reaching 30,000ft and M=1.12 and proving that, up to those limits, performance and handling were either as forecast or better and the flying rate doubled. Then the project was cancelled. Many thousands of people in industry lost their jobs but I am not aware that the politicians, civil servants and Service personnel responsible for over-specification and lack of control suffered equally.

Finally, it is my firm belief that, if the original P17A proposals had been accepted, TSR2 to a very advanced standard might well still be in service with the RAF today and with several other air forces as well at considerable profit to the UK.

Design and Development of the TSR2 Airframe

B O Heath OBE CEng FRAeS

Professor 0llie Heath played an important part in all the major projects of English Electric Aviation in the two decades following the Second World War. He was a stressman on the Canberra and aerodynamicist on the Lightning before undertaking a very significant role in the TSR2 project, ultimately as Project Manager. Later, he had similar responsibility for AFVG and MRCA. Until 1981, he was BAe Technical Director (Warton Division) and he held the Chair of Aeronautical Engineering at Salford University from 1983-89. His paper shows clearly the depth of his personal involvement in the TSR2 project and the nature of the difficulties encountered in the design and development of the airframe.

Until accepting this invitation from the RAF Historical Society, I have declined to contribute to books (and a video) on TSR2, not wishing to express my views where a direct balancing response was not possible. The nature of the Society's seminar has allayed this concern. Some modern logic advises that black and white are shades of grey! I shall endeavour to present my subjective views as objectively as possible – but they will still be subjective. I have written down my recollections in some detail and have described my feelings at the time and in retrospect. This expanded paper, based on the verbal version delivered at Filton, allows more background to be provided and some extrapolation to Tornado.

My TSR2 appointments involved living from problem to problem (hopefully solution to solution) so my account does not reflect the general progress being made: in 1956, I was Principal Project Engineer at English Electric (EE), Warton, responsible to the late R F (Ray) Creasey. From 1960-64, I was 'Oppo' to G S (George) Henson (Weybridge ex-Supermarine), responsible to Mr H H Gardner and to (then Mr) F W Page as Project Manager Canberra and TSR2. In 1964, I became Project Manager TSR2 with Development responsibility to F W 'Freddie' Page, a responsibility which continued through 1965 for Jaguar and AFVG.

The Early History of TSR2

On 29 October 1956, Ray Creasey gave details of discussions he had had with Mr Handel Davies (then Scientific Advisor to the Air Ministry), concerning a Canberra replacement. Parameters for study included a radius of action of 600 nm at 0.9M at sea Level and 1,000 nm at 1.5M at altitude; ferry range of 2,000 nm; HE or Target Marker loads or photographic or electronic reconnaissance equipment; and an in-service date of 1964. Ray Creasey suggested a twin-engined, Canberra-sized aircraft. He quoted the anticipated Rolls-Royce Conway engine thrust of 16,500lb cold and 26,500 (2,000°K) in reheat, with the engine stressed to M=1 at sea level and M=2 in the stratosphere. Initial weight estimates resulted in an AUW of 80,000 lb and no less than 8 variants were to be studied, including conventional bombing, interception, interdiction and various forms of recce.

In 1957, English Electric issued a report entitled 'Possibilities of a Multi-Purpose Canberra Replacement P17' [Report P103], based on this advice. The Report considered that there was a requirement for a manned aircraft in the tradition of the Canberra, even in a ballistic missile era, able to reconnoitre and strike small targets accurately with a variety of weapons; adaptable to local conflicts and with maximum flexibility for unforeseen circumstances. Low level attack to aid navigation and strike accuracy, flying subsonically to the target areas where transonic performance would be adequate; this capability would readily give M=1.5 at altitude without intake or equipment temperature problems. Above M=2 performance and timescale penalties were likely.

800yds was the best envisaged ground run: Normal margins – 900yds (LCN 40 for take off and LCN 20 for landing). Such performance would require highly rated engines with large amount of reheat, giving benefits on climb, altitude and supersonic performance, but the penalties on subsonic/transfer operations using larger airfields or RATO needed to be justified. The continued need for high level operations was detailed.

An operational (Lo-Lo-Lo) radius of 600 miles would require the use of drop tanks and specially designed engines, even at subsonic speed. A radius of 1,000 miles (Hi-Lo-Hi) was possible assuming M0.9 above 30,000 ft and a short low level run to the target.

Alternatively, a similar radius could be achieved (Hi-Hi-Hi) with a supersonic burst of several hundred miles. Ferry range, with bomb bay tankage, could be at least 3,000 miles.

Report P103 also mentioned fighter possibilities, starting with adequate endurance and performance at long range approaching that of possible enemy bombers. It gives a flavour of the emergent requirements of the OR/GOR and it will be seen that GOR339, OR339 and OR343 are characterised by their increasing severity.

Submissions to GOR339

Several companies were invited to respond to GOR339, generally to be regarded as a Canberra replacement and certain companies were requested to give commentaries on such topics as Naval applications (Supermarine) and VSTOL through to VTOL (EE, with Shorts finally).

English Electric (Warton) Submission

Aircraft Density and Engine Installation. EE's experience of the P1 and Lightning raised one major factor of caution, namely fuselage density. The earlier designs had minimised frontal area to give sustained supersonic capability, even had reheat been reliable, and this resulted in problems with engine and systems installation, hydraulic pipe chafing and suchlike, and difficulties of accessibility. Range and avionic development were limited. Despite that, the Lightning was successful – even popular – and provided valuable experience of high Mach No and high EAS realities.

My first involvement with 'TSR2' was in response to a request from Ray Creasey in 1956, to see how a fuselage engine installation could be avoided. Two possibilities were finally explored. Each involved podded engines, either wing-mounted with a T-tail to allow the use of re-heat, or rear-fuselage side-mounted with a canard. Wind tunnel tests showed that the tailplane of the former could never be mounted high enough to avoid pitch up, a popular bogey of the time. A tailless delta configuration was barely even sketched out because of the problem (then) of trimming the lift of TE flaps. We missed the later SAAB close-coupled wing-canard solution and, in the absence of artificial stability, could not reconcile take-off nose lift with stability. Thus, reluctantly, we adopted fuselage engines. A dedicated Design Office was established under George Parker, to ensure practical installation, and a mock-up was built.

Aircraft Density and Spare Volume for Development. The Canberra, with wing-mounted engines, had room to accommodate equipment for its multitude of roles both in RAF service and overseas. It was suitable also for many equipment Trial Installations. Although the Martin B-51 was already flying and incorporated many advanced features, the USAF chose the conventional Canberra which, as the B-57, saw substantial development and re-equipment. The Martin company wanted EE to participate in a joint development programme, progressively thinning and sweeping the tail and wings, with (finally) podded engines and updated avionic fits. EE declined the invitation, preferring to concentrate on the RAF Canberra replacement. So it was for American industry to fit all manner of new sensor and electronic equipment and to re-engine (twice) and re-wing the aircraft but all employing the same basic fuselage. This Canberra and later Lightning experience all led EE to favour the creation of some volume margins for development in initial design.

Gust Response. The Canberra was one of the largest aircraft to be flown at high EAS at low level and in turbulent air. This gave crew and equipment a very rough ride of which several members of the Design team had experience at first hand, in the search for reductions to acceptable levels. This was reflected in the EE choice of wing for the P17 submission, namely a 60° delta ('Lightning with the notch filled in') with its low lift slope. Space in the fuselage was allowed for sprung equipment mountings and explored for the crew seats.

STOL. The short take off requirements were to be covered by the use of blown flaps, although double-slotted flaps were used in wind tunnel tests as a simulation. The delta platform gave the best fixed wing value of C_L/a_l [TO/Gust Response].

Work with Short Bros & Harland

EE was concerned that extreme demands of STOL, let alone VTOL, would escalate costs and preclude supersonic capability. The joint submission (with Shorts), which ran to three volumes, explored a range of designs (some in detail), including the use of lift engines and nozzle deflection, a pure VTOL solution and the combination of a conventional P17A with the P 17D lifting platform for VTOL and dispersed supply. This was intended to dissuade the customer from opting for STOL at too early a stage, yet providing the best advice on this aspect from Shorts.

Summary of EE Views and Position:

- Avoid high density and leave room for development
- Delta wing for best balance between high lift and low gust response
- Avoid undue STOL but meet stated requirement
- Modest M and EAS targets
- Make low speed and supersonic wind tunnel tests to M=1+
- Keep integral tanks simple (Canberra and Lightning experience)
- Use existing equipment as far as possible, at least initially
- Plan progressive development of equipment and avionics
- Start detailed work to define weight, practical volume, economies
- Check strength, stiffness and dynamic response to turbulence

Vickers (Weybridge) Submission

The Vickers team consisted of two aircraft elements at Weybridge, namely the basic Vickers-Armstrong (VA) organisation and a Vickers-Supermarine (VS) team recently arrived from South Marston (which acted as their GOR339 project team), and a Guided Weapons element. Vickers Production and Design activities were under the same direct management of Sir George Edwards.

I cannot portray first hand the experience which VA thought the most important but the main expression of it to EE was that from the Scimitar by the Supermarine team. They made a strong appeal to reverse growth-factor concepts and to maximise the use of space. Some comments will illustrate their approach which may have been conditioned by the possibility of a naval application:

> 'We can't afford to drag fresh air about! Until every panel is dished and all clearances minimised, we shall not be happy with the design.'

> 'It is worthwhile spending between £250K and £1M to develop

a new pump [to pump hot fuel used as a heat sink].'

The suggested undercarriage design suggested that naval use may have been behind the VS thinking. VS had developed effective blown-flaps for the Scimitar and used high-tensile steel, titanium and chemi-etching to reduce weight.

The Weybridge emphasis on maximum exploitation of reverse growth factor to achieve minimum size, weight and unit cost involved:

- High density generally and modern avionic racking
- Miniaturised equipment tolerant of high temperatures, accepting associated R&D costs
- Powerful blown flaps
- Advanced materials
- Integration and management by Systems Engineering Techniques

Aircraft of the (Jan 1958) Submissions

VA submitted two project designs, one single-engined at 40,220 lb AUW, and the second twin-engined at 81,222 lb, claimed to be capable of meeting or exceeding GOR339 respectively. They offered M=1.1 at sea level and M=2.3 at altitude. EE's twin-engined two-seat P 17A at 66,000 lb AUW claimed M=0.95 (725kts EAS) at sea level and M=2.0 at altitude. All aircraft were two-seaters. Besides difference in overall characteristics and performance claims, the main differences were:

VICKERS	**ENGLISH ELECTRIC**
Slightly-swept wing; tip tanks	**60° delta with blown flaps**
Ailerons	**Tailerons**
Blown Flaps	**Blown Flaps**
Intake forward of wing	Intake under wing*
All-moving fin	Fixed fin and rudder; ventrals
Engine and jet pipe in tunnel installation	Engines installed through u/c bay; jet pipes rearwards through frames
Forward retracting u/c with low-pressure tyres	Rearwards-retracting u/c

Large side doors for avionics access	Vertical access into avionics bay
Many integral fuel tanks	Wing and semi-integral tanks
Short tail arm (on twin)	Long tail arm

* On advice from their Aerodynamics Department the EE intake was moved on to the fuselage sides with a consequent weight increment.

The features in bold type were incorporated in the final TSR2, despite which the aircraft overall still bore a strong resemblance to the P17A.

In April 1958, brochures were exchanged – three thick volumes from Warton which included the STOL/VTOL input from Shorts; and one single slim volume from Weybridge. The Warton team could hardly believe the small and apparently superficial amount of work done by VA in support of its claims: 'The fin is strong and stiff for reasons of strength and stiffness'! VA later admitted that only a month had been spent on the designs but the arguments on integration and inverse growth-factor were fully expressed.

In mid-1958, the two project teams met at Boscombe near Bournemouth and began a mutual appraisal of the designs, focusing specifically on weights, drag, high lift potential and power demand. Mostly, they related the (escalating) OR339 to their own designs.

Vickers views on the PI7A proposal:

> 'VA have stressed the weapon system in their design with the bonus of considerable performance development. EE are relying on conventional design practices hoping that these will meet (marginally) the specified performance with generous volume allowances, capable of accepting major equipment changes. But balance considerations will restrict these.'
>
> And:
>
> 'The importance of STOL has not really sunk in at Warton: the current OR implications are not fully accepted by EE, some of whom stress that it is thought wrong when the aircraft will operate mostly from long concrete runways. The P17 is not a STOL aircraft, not fitted with balloon tyres or a long stroke

undercarriage. Its view is poor compared with the VA proposal.'

And:

'VA packaging is similar to that of AI 23 in the Lightning. EE have allowed room for miscellaneous personal and picketing items etc in the equipment bay.'

And:

'EE have a pedestrian approach to airframe heating and are reluctant to accept integral tanks: use conventional zoned power plant installation; use conventional cockpit displays.'

And:

'EE haven't used the fuel as a heat sink and are unaware that both R-R and BSE accept up to 150°C engine inlet temperatures.'

And:

'EE use a conventional air-cooled system, assume maximum steady conditions of M=1.7 (Max Temp Atmosphere), peaking at M=2 (36,000ft ISA) for short periods kinetic temperature of 146°C with a warning light.'

English Electric Views

EE could not understand how such claims could be advanced when so little work had been done to support them. EE summarised its biggest difference with VA as:

- EE's preoccupation with minimised cost and time based on some experience of volume saving on P1
- VA's approach whereby reduced aircraft costs were claimed as offsetting the time and cost of re-engineering equipment.

English Electric Report – 'The Economics of GOR339'

In 1958, EE issued a report which reviewed R&D and unit costs for airframe, engines, new and existing equipment. Whereas VA had quoted cost estimates in its submission, EE was only prepared to quote against a firm specification.

This report continued the theme of avoiding undue density and included a graph showing the upturn in £/lb when this condition was approached, based on an analysis of current military aircraft. It concluded that increase in size above that of P17A increased cost without worthwhile gains in immediate or potential performance. Size reduction gave increased cost and loss of development potential. The largest savings in airframe costs would result from using past experience from aircraft with comparable missions or performance (Canberra and Lightning).

The report emphasised the general benefits of using existing equipment where possible; 'The greatest economy stemmed from the use of an existing engine and reheat, but if a single-engined aircraft were stipulated, a new half-size engine (*cf* RB 142) would be economical overall.' The use of existing equipment, and the omission of equipment not required for the primary role would give economy (Linescan for navigation and even terrain clearance was questioned). The cost of improved inertial navigation equipment might be justified.

The 'Economics Report' listed detailed economies emerging from P17A, including the simplification of structural joints (eg constant angle or right angle); the use of straight lines (wing contour spar-wise); and the use of flat skins, as on the flaps, of localised camber and of parallel fuselage sections. The elimination of an undercarriage joint, the simplification of tank sealing and of system runs, and the use of reduced fin attachments, all could achieve savings. The use of ductile alloys and the reduction or elimination of special steels, titanium and magnesium alloys also made for economy in construction.

Escalation of the Requirement

The requirement progressed by stages from GOR339 (Mar 57), through OR339 (Dec 58) to OR343/RB192D (May 59). Throughout the process, the demands became more and more severe as may be seen in the range and sortie radius requirements Each specified a 2,000 lb warload and fuel reserves.

The first draft of GOR339 called for a hi-lo-hi radius of 1,000nm including a 200nm low level segment and a ferry range of 2,000nm. OR339 tightened these requirements, initially allowing the use of overload fuel but later calling for a clean aircraft, to include a 100nm dash at 1.7M at altitude with 200nm at low level, at not less than 0.9M. GOR343 confirmed these parameters and increased the ferry range to 2,500nm, without overload fuel tanks or air-to-air refuelling. OR343 introduced the so-called 'Army Sortie' with a hi-lo-hi profile including 100nm supersonic cruise at altitude and 200nm at low level, at not less than 0.9M.

Mach Number requirements at low level settled at 0.9M but supersonic performance at low level was for a short burst only, 'if this did not affect the design of the weapon system.' The requirement Mach No at altitude began at 'not less than 1.7M' but was subsequently increased to 2.25M at 40°C, giving 180°C ram temperature. The final diving speed was to be 800kts EAS.

Take off requirements initially (GOR339) were for 'practical operation' from 3,000ft or less – and allowed the use of unconventional means of improving take off and landing performance. The final draft of OR339 specified 'take off to 50ft' in 3,900ft for the 1,000nm sortie but abandoned the use of rocket boost for all other cases. OR343 called for 3,900ft take off roll distance for the 1,000nm sortie but less than 3,000ft roll at ISA+30, for dispersed operations.

The minimum landing roll requirement started at 800yds but finally called for 600yds on a wet surface with 35kts crosswind. LCN started at 40 but was finally to be as near 20 as possible, with tyre pressures such as to minimise rutting.

The effects of the progressive enhancement of the requirements inevitably led, sooner or later, to demands for more thrust, lift and fuel capacity and for less drag. They also led to the use of massive tyres on a complex undercarriage and to a hot structure, fuel and systems. At the time, it appeared to many that the 'Army Sortie' was specified in an attempt to win Army support for the project. The supersonic requirement was said by some to have been included 'to keep the NA39 out' but it may have been to cover a fighter version of the aircraft later. Indeed, EE did propose the P22 to that end as 'the antidote to enemy P17s'.

The Award of the Contract

The enhanced requirements and Weybridge's undamped enthusiasm ['Mach 2 from a cabbage patch'!] – doubtless helped to secure the go-ahead on 1 January 1959 with Vickers as prime contractor, 50:50 with English Electric as sub-contractor. Although this was most disappointing to EE in view of the detailed work that we had done at Warton, it was nevertheless a major achievement since every relevant Western aircraft had been assessed by the Ministry. That process doubtless resulted in 'enhancing' the requirement, to satisfy doubts as to whether the aircraft was potent enough for the project to be started.

It was never really clear at working level what the agreed basis of the joint work was to be in aircraft terms. Were the companies to work together to develop jointly the P17A configuration, to combine the VA fuselage with the EE wing, or, jointly to define a new aircraft (which might have the EE wing)?

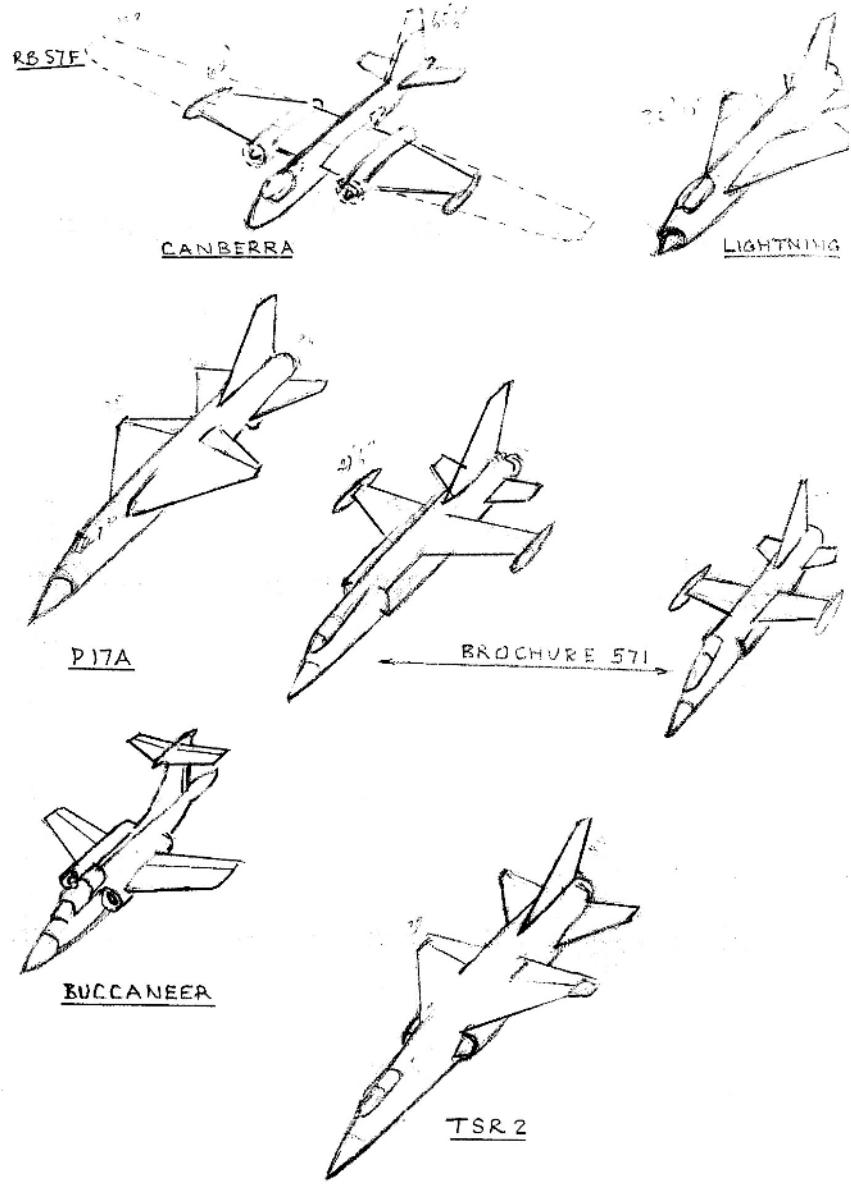
In the event, a joint team was formed at Weybridge which spent several months on the difficult task of defining scheme drawings, reflecting the tight requirements of the specification.

The way in which the main undercarriage retracted became a key issue to which all other issues seemed to be geared. This was resolved by the personal decision of Sir George Edwards, that the gear would retract forward, to help emergency lowering.

A joint review of weights revealed a discrepancy between VA's empirical methods of prediction and those of EE, based in detailed work. The former predicted a much higher wing weight but an EE analysis of existing delta-wing weights against strength and stiffness parameters confirmed the accuracy of the EE work. In the event, the wing was the only component to meet its weight estimate with a slight margin. It also had useful fuel capacity and was confirmed.

The enhanced take-off requirements meant that only the Bristol Olympus 22R could provide the thrust required. The guarantees secured on the 15R were lost and it is understood that the official specification of the 22R was compiled without reference to its prime use on TSR2.

To their credit, the joint team and its associates in the parent companies presented an agreed GA in mid-1959 (using the VA571 notation). It was agreed that VA would design and build the 'front half' of the fuselage and EE the wing, tail and rear fuselage. With that the EE team returned to Warton. An attempt was made to establish Design Authorities in each company but this was not very successful, particularly for EE since VA, as main contractor, often had to overrule EE when proposals were judged to be unacceptable when translated into performance terms (ie weight, heating and power demands). The only direct EE project office return to the Ministry was the return to the Resident Technical Officer.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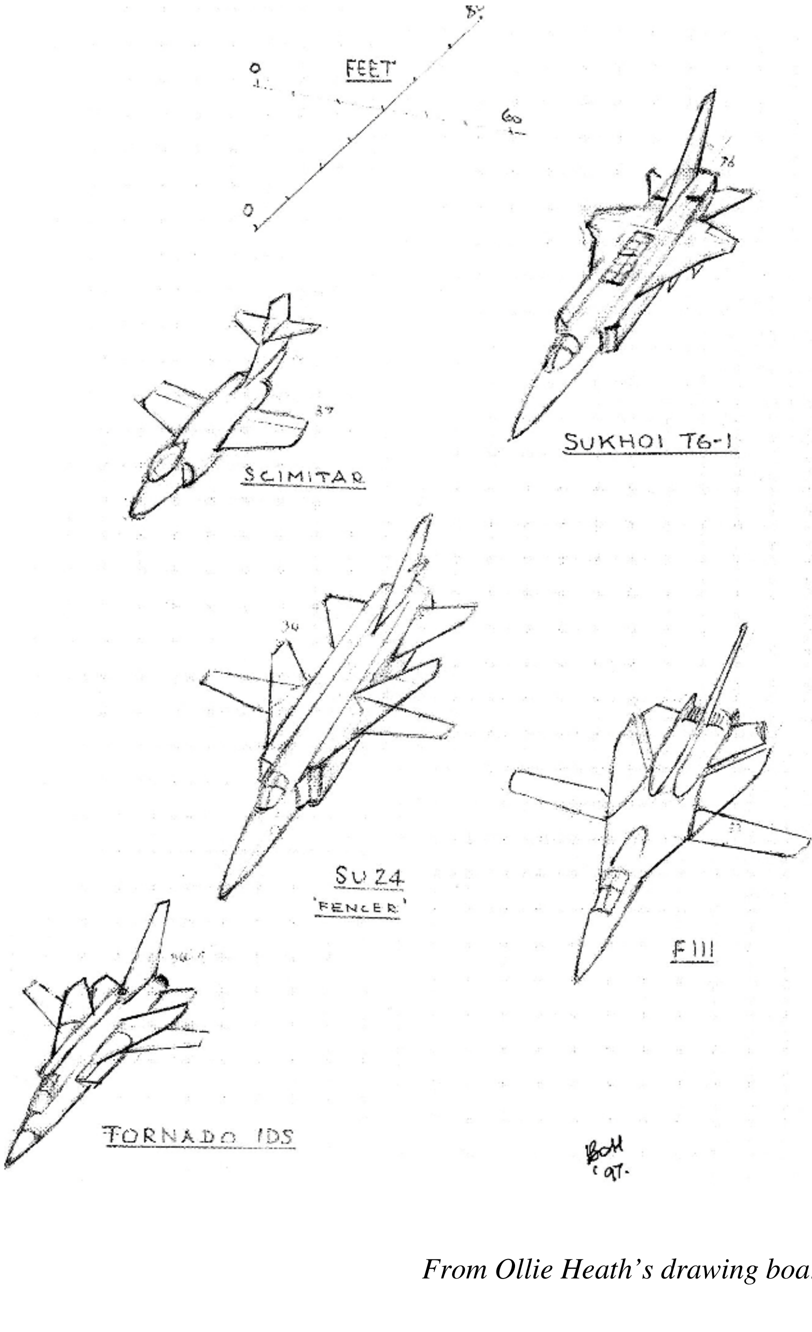


From Ollie Heath's drawing board

Repercussions of the Performance Demands

I now have to give a rather dreary account of a rising tide of difficulties which occurred as design progressed. Weight growth generally could not be contained and the demands of high temperature led to delays and to engineering and production difficulties with materials, including their supply. With great dedication these were largely overcome, leading to successful flights in which key guarantees were demonstrated as met, notably AMPG both sub- and supersonically.

Rear Fuselage

Many of the problems experienced were seen by me at first hand in the engineering of the rear fuselage for which EE had direct responsibility. In common with most military aircraft with rear-mounted engines, balance considerations put a premium on saving empty weight in the rear fuselage, yet achieving maximum fuel capacity, notwithstanding the requirement for low afterbody drag. Thus the rear fuselage had to be built without major joints and engines and jet pipes housed in tunnels surrounded by integral fuel tanks. The 22R was not a cool by-pass engine. There were thousands of holes of close tolerance to be pre-drilled, assembled and sealed – 'a watch-maker's job' the works said.

It was not until March 1960 that supersonic wind-tunnel test results were again available and one effect of the resultant design re-freeze was further refinement of the rear fuselage lines. This created further pressure on fuel capacity and a request for the engine final nozzle diameter to be reduced by 2" which, surprisingly, was rather readily accepted by Bristol Siddeley Engines (BSE). In contrast the transfer of the rear fairing to BSE was very formally defined and implemented.

BSE wanted an inch clearance round the engine envelope on withdrawal. This was very tight but was made more so by the late introduction of a heat shield in the tunnel which, very understandably, had to contain a torching flame from the engine for several minutes until the extinguishing system overcame it. This was proven by a fire tunnel made specially for the purpose at Warton.

Initially, the Ministry would not accept a single-zone engine installation and insisted on all fuel and hydraulic items in the engine auxiliaries bay being enclosed in a box carried on the engines (the 'meat tray'). It was found that the pressure load on this could not be carried by the engine carcass; reversion to the single-zone bay was then allowed but only subject to the fitting of double-walled pipes on both engine and airframe. These made further demands on space and were costly, involving high-grade materials with problems of their own. Space had to be found for water injection equipment, to enhance engine thrust.

Heat from the engine installation enhanced high zone temperatures and meant that high-temperature sealants had to be used on the tunnels. The necessary interfaying seal demanded very accurate fit and jigging and, even where fillet sealing was possible, very accurate sub-assembly jigs, master templates and tooling were needed. Sixty percent of the rear fuselage was integrally machined, by comparison with 20% on the Lightning. To take full benefit of this in weight-saving terms, close grading of thickness to follow the stress pattern was adopted, sometimes with chemi-etching (new plant), demanding very close tolerance control. To meet timescale demands, temporary tooling had to be installed at both Warton and Weybridge.

VA's experience of sculptured machining was applied to TSR2, including tunnel skins and surface panels. The skin cutters used were controlled by cam bars which became very complicated due to discontinuities in this military application, for example for external store stiffening. Spare capacity allowed the car industry to manufacture cam bars. Difficulty was experienced in defining acceptable mean surface finish roughness with normal cutter marks and accidental scratches. Many hours were expended in polishing the bases of stringers, for example, 400 hours on each set of tunnel skins. Sample rubber castings finally gave a usable guide. The replacement of milling by routing was partly adopted. The first large tailplane frame was made without fault.

As design and testing progressed it became apparent that 3-D subtleties not always apparent to the draughtsmen were causing leakage through unsuspected leak paths between machined members. Many small rubber mouldings had to be designed and made as a 'fix'. As a result, the number of drawings required increased to an issue rate of 320 per week at Warton. A further heavy manpower load was caused by the need to define systems, electrics and instrumentation installations and runs to loft accuracy which were then confirmed on the metal mock up.

The selection of materials also posed problems. Titanium alloys were used extensively but were in short supply and even flat panels had to be hot formed for nominally straightforward applications. Being aware of the likely problems set by the flap-blowing tubes 'which tapered in every direction', EE made them successfully. A visit to the USA in 1959 (to see, *inter alia*, the A3J Vigilante and the extraordinarily complex B-58 Hustler) did not change the level of endeavour on TSR2. The merits of the Al -Lithium alloy X2020 and reassurances on brittleness were not confirmed by use on TSR2 where replacement by conventional light alloy had to take place. The trip also prompted the use of a certain type of panel fastener which proved most unsatisfactory.

To help relieve the load on EE, VA took responsibility for the fin and tailerons later in 1960 but EE covered fin flutter using American dampers which themselves caused delays due to random deficiencies even after rigorous cleaning.

Although I am not asked to cover systems in this paper, it must be mentioned that, to meet high-temperature requirements with 4,000 psi hydraulics, Inconel X was chosen for the hydraulic pipes and DP47 for the fluid. Problems with seals were anticipated so brazing *in situ* in jig was adopted. This itself resulted in problems, some of which seem trivial in retrospect but did not seem so at the time. The use of DP47 sometimes seemed to give a useful fall-back excuse for delays and difficulties.

Forward Fuselage

Because the front fuselage and avionic responsibilities were allocated to VA, I am personally far less aware in detail of their difficulties – and of their achievements – than I am of those affecting the EE components. The forward fuselage was not much affected by the re-freeze of 1960 and the avionic and weapon systems were programmed for the third and later aircraft anyway. However, it was found that allowances for basic and instrumentation cabling were inadequate. The electric circuitry had to be redesigned to avoid phase differences. Delays on the power controls delayed switch on of the Automatic Flying Control System (AFCS).

I have always believed that the standard of avionics and instrumentation and their comprehensive integration established on TSR2 gave a very good basis for applications by British Industry on later programmes. There was continued pressure to reduce the extent of instrumentation specified but analysis of flight records after cancellation showed its worth.

Vickers certainly had their weight problems but, when area-rule calculations showed that cross-sectional area could be increased in the avionics bay region, they did not take this up, suggesting that density could not have been such a pressing issue there. EE had warned that the juxtaposition of undercarriage, intakes and weapons bay would result in insufficient cross-sectional area and these warnings were borne out in complicated fuel tanks and undercarriage. There were consequent bomb bay constraints and winged stores had to be transferred to wing pylons. This aggravated the loss of stability shown on later wind-tunnel tests with the shortened tail arm.

The disappointments of the Al-Lithium alloy, X2020 also affected VA. Heat treatment and machining difficulties occurred on the windscreen forging and there were furnace constraints on 120-ton steel for the undercarriage (which later proved to have sequencing and vibration problems). Although not due to the tight specification, there were problems with the auxiliary intake doors and with the gold-film windscreen. A variety of comments were made by the crews on cockpit controls and instruments.

The Wing

Compared with the rear fuselage, the wing had an easy ride but was certainly not without problems to be overcome, including those with machined panels. The introduction of 450 gallon tanks and 'other stores' contributed to the complexity of ribs and panels, as well as overall aircraft stability effects.

At re-freeze, the wing was moved, its planform changed slightly and the tips given anhedral to reconcile lateral and longitudinal stability requirements; a very complex joint rib resulted. The wing already had a centre-line joint but only after great resistance from the weight-saving auditors.

Interchangability requirements stipulated even on aircraft 1-9 were severe, particularly as affecting the wing leading edge. Even trim on the final fit of the closing end panel was not permitted.

Engines

Shaft-belling vibration and longitudinal vibration due to a changed reheat fuel valve spring have to be mentioned.

Power Controls

The development of the power controls demanded time-consuming intrusion by EE into the suppliers where modifications, basic production and experimental or theoretical solutions to test and rig arisings had all become intermingled. For example, two-stage valves had to be introduced to rectify taileron-jack judder on the return stroke with one supply system failed. The titanium jack bodies were difficult to forge and the selection of that material caused delay. Later, it proved impossible to plate the titanium rams of the taileron jacks and steel substitutes had to be made.

The dynamic response demands on the all-moving fin jack were very high. Nose-wheel lifting was basic to aid STO but jacks for the taileron trailing-edge flaps were an addition, to keep the taileron angle compatible with fuselage lines and ground clearance. The airbrake drive shafting had backlash such that with the valve tolerances attainable, closure could have meant over-closure, so the aircraft flew during the test programme with the airbrakes set slightly open.

Systems Engineering

The VA brochure made a full appeal to the benefits of integration and system engineering concepts but I have no personal recollection of (say) AVP970 requirements being waived in pursuit of them. (Most of those with supersonic content were from the P1 (Lightning) anyway where, by RAE direction, EE had derived their own rules. Later, on Jaguar, Jim Hamilton ruled that Air Norms would be a guide but that the judgement of the engineers would be paramount. On Tornado, against some UK protest, Mil Specs were imposed but even then some flexibility in application and interpretation obtained.) On TSR2 there was little concession to the application of AVP970, the 'small print' if anything being tightened up, Although US achievements had to be recognised or bettered in the OR, it was UK not US margins on diving speed, for example, which applied. Some weapon system ethics may have applied to TSR2 avionics but on the airframe systems side there was little evidence of this.

The Advisory Design Conference was almost entirely devoted to confirming aircraft performance requirements. For example, a ceiling of 56,000ft was defined although some equipment specs had called for a zoom to 70,000ft. There was an awareness of weight growth 'into service' but an offer by the Ministry to relax the 3,000ft take off run was declined by the firm 'so as not to prejudice weight saving pressure'. There were minor ADCs and specialist meetings, often beset by changes in personnel and apparently unconstrained levels of attendance – inversely proportional, it has been said, to the gravity of the issues under discussion.

As an aside, a combined ground service trolley was developed but had difficulties which, significantly, were the subject of the first newspaper paragraph on the TSR2. Whatever their later views, the press at the time did nothing to sustain the aircraft through its difficult times.

Requirements Post-OR343

Even after the issue of OR343, additional requirements were stipulated which compounded the difficulties already identified. A demand for sustained cruise of 45 mins at M=2.0 introduced such varied problems as near-boiling fuel and oil, the introduction of an intermediate engine reheat rating, the need to bias intake design to the supersonic regime. Supersonic lateral auto-stiffening was emphasised; the benign temperature rise lag was lost inducing system and structures penalties and complexity. Range requirements for the strategic role introduced 450 gall wing tanks and a 1,000/1,500 gallon ventral tank, resulting in more wind tunnel testing and practical repercussions. Conventional weapons requirements increased from 4 × to 12 × 1,000 lb bombs and the carriage of 22 was studied. Changes to the weapons fits on which the design had been based included NATO twin suspension, Bullpup, Microcell rockets and others.

An emergency arrestor hook fit was deferred and 'buddy' refuelling and gas purging were deleted. The original (Palouste) APU was replaced by a Cumulus. More severe interpretation of the airbrake requirement led to a fully variable system with 'in and out' emergency selection. This was later criticised for over-complexity by the OR staff. Fuel tank jettison was specified as 'safe forced jettison', interpreted as at any fuel state, speed, height or 'g' loading within flight envelope. After many wind-tunnel tests, cost reduction led to free jettison at a limited range of speeds and heights, involving yet more wind-tunnel tests. Limitations due to the carriage of external stores were initially stated as acceptable but later only as they affected range. Some provisions made were outside the temperature or 'g' capabilities of the stores themselves.

Three later additions gave particular problems. A Thrust Meter was originally intended to give a thrust comparison between the two engines at take off but the Ministry experts finally demanded a measurement of thrust at any altitude as a percentage of sea level thrust. Although this was Cat 1 (Government Furnished) equipment, much effort was demanded of EE, BSE and the supplier. The Ministry insisted on automatic cover for fuel system failures, especially of wing fuel transfer, and this demanded sophisticated, expensive valves. The effect on CG of carriage of external stores resulted in the scrapping of a simple system with fuel flow proportioners and its replacement with a sophisticated transfer and gauging system. An emergency alternator was specified belatedly '. . . not to cover double engine failure but it was necessary to cover failure of the main running-engine alternator with the other engine failed'.

The system employed for categorisation of equipment was a major departure from both Systems Engineering concepts of authority and traditional bought-out procedures. Cat 1 equipment was Government Furnished Equipment (GFE); Cat 2 was a mixture of Ministry approval and Company procurement; and Cat 3 was Company-only procurement. The EE procurement departments could not believe that they could be involved in securing equipment not controlled by them [Cat 2] and it took a series of in-house seminars for the Company to evolve and define selection and ordering procedures for use by men and departments schooled in the rigour of the traditional system.

Pressures on the Project

Further negation of Systems Engineering concepts was provided by the fluctuating priorities accorded to performance, time and cost. Political pressure 'to convince the Treasury' appeared to make it necessary to eclipse the **performance** <u>envelope</u> of many existing and projected types such as the F-105, A3J, NA39, Mirage IV and F-106, in order to get the go-ahead and this was reflected in the escalation of the GOR and ORs. To 'secure the Army vote', very short take off and landing runs were stipulated – and quoted in Hansard – and the supersonic performance was progressively enhanced, including the 'small print' not normally the province of either the OR staff or the Treasury.

By the end of 1961, **timescale** was the top priority despite delays in the granting of the initial contract. Unfortunately, some suppliers increasingly began to fear that the aircraft would not go into production and began to assign higher priority to other projects involving their products. A self-fulfilling prophesy.

Computerised Critical Path Analysis 'PERT' was instituted but took some time to register the 'holding items' already identified from bar chart formats. This was not surprising since the Management Charts were very comprehensive and showed a breakdown from overall major events such as first flights, CA Release, through jig stages to equipment deliveries, test-rig plans, drawing issue and so on. Plans and achievements were continuously updated and reviewed.

Whilst it is true to say that **cost** became top priority as cancellation increasingly became a threat, this would by itself be misleading. Certainly, Value Engineering was introduced – but was hard to implement – and considerable efforts were made to record and control costs within the aircraft companies. In 1966-67, the Treasury stated:

> 'The methods of management and of recording and reporting costs against physical progress on TSR2 were a considerable advance on anything which had been attempted before in this country. Their effectiveness was in the event nullified by the inadequacy of the original technical programme and cost estimates.'

It concluded that the scale and technical difficulty of the problems involved and to the time taken to solve them were the main cause of the cost increases.

The Public Accounts Committee was somewhat more critical. It referred to a weakness in linking expenditure to physical process or to the original estimates. I recall this criticism from the time when it was made but it was hard to establish what more was required. The Ministry had admitted to the PAC that:

> '[we] had been too ambitious in expecting to make spectacular improvement in performance within the cost contemplated at

the time – longer and more intensive studies were needed before embarking on such a project.'

Activity before First Flight

A great deal of senior management time was spent on issues such as trying to prove in anticipation that 10 hours per month flying per aircraft was possible and on evaluating the benefits of tropical trials at Colomb Béchar. We were involved also in negotiating guarantee points capable of unambiguous demonstration when the whole aircraft was defined and capable of giving 'only' what it could. Senior managers also devoted much time to attending and travelling to a hierarchy of meetings. I recall that these, with their associated briefings and minutes were very demanding and rarely added to action already in hand. Some of these meetings seemed to have overtones of personal antagonism.

Most important of all, much senior time was devoted to early flying at Boscombe Down and the preparation for it. In the run-up to the first flight, in around September 1963, Roland Beamont issued a note about aircraft complexity and as TSR2 Project Manager (EE), I was charged by (then Mr) F W Page to run a series of meetings to clear the items of concern.

Flight Operations staff combed through the minutes of each technical meeting and every obtainable report and surfaced again all problems affecting flight whether believed solved or not. These were referred to me to detail, with the aid of the Warton project office and appropriate technical authorities, the way in which they had been resolved. This was a long and sometimes frustrating task where it was known to the project office that a problem had long ago been solved and put to the back of one's mind. Nevertheless, the sheer professionalism of the Flight Ops exercise was impressive and served to strengthen one's own confidence in the prospect of first flight. Having eliminated – or defined and reduced – the dangers of flying the aircraft for the first time, the flight test crew were prepared to do so in a calm and businesslike manner.

The first meeting was held on 25 September 1963 and covered more than a dozen significant items, including in-flight emergency procedures and crew briefing matters. By the time of the first flight, these earlier problems were overcome. A year later, on 9 September

1964, points raised in anticipation of first flight numbered 14 and included (as a first item) queries about engine life totals and about shaft life. In the week of the first flight [on 27 September 1964] five essential points were raised, including the need to clear the engine relight drill, to extend the flap blowing limit from 5 to 15 minutes and to rectify a reheat problem experienced on ground runs.

My own contribution on the morning of the first flight was resolving a problem with the parachute brake door. On taxi trials, this door had shown an increasing tendency with taxi speed to foul the fin but manual analysis of each individual oscillation showed that landing was safe in this respect. A slide-rule and ruler had their uses still. The story of the first flight is well known and it resulted in an enthusiastic report, notwithstanding undercarriage vibration problems on landing.

Cancellation

Shortly after the first flight, the aircraft went on to a lay up. After Harold Wilson became Prime Minister, he gave the company some sort of reprieve – a last six months to show what TSR2 could do. Under these pressures, the aircraft was flown again, Bee Beamont and the flight test crews contending with undercarriage and excessive longitudinal vibration problems which caused eye blurring. It flew supersonically on flight 14 to Warton, high and low performance checks validating two range guarantee points, sub- and supersonically. It handled very well, without trim change, 'I recognised the simulator all the way round', said Bee.

The 24th and last flight was on 31 March 1965 and resulted in a number of relatively straightforward snags, beside engine and undercarriage vibration problems. The aircraft had 'progressed well [with] only one system causing delays – the undercarriage and it was believed that its problems were resolved.' It was understood that the third aircraft, yet to fly, had successfully simulated an operational sortie. Despite this success and the promised six months' reprieve, the TSR2 was cancelled in the Budget Speech of April 1965.

I am not personally and directly aware of the high-level machinations and let-downs of this period. The Australians who had visited Warton many times and expressed enthusiasm for the TSR2, bought the F-111. It is said that they were offered TSR2 for a fixed price of £2.1M. The PAC minuted a liability agreed with BAC/BSE of

£650M, including a price of £332M for 110 aircraft, or £3M per copy.

John Stonehouse (Minister of Aviation), visited Warton and saw a film of the simulator and rigs. 'That's where the money goes', he said. There was a great respect – a fascination – with things American and even when the Americans were in difficulty, it did little to help us. A Ministry man, normally a good friend of ours, said, 'If these people are in trouble, what chance do you lot stand?'

We were asked later to check performance claims for the F-111 and found them optimistic. Nevertheless, a combination of Lords Mountbatten and Zuckerman, the NA39 and the F-111, George Wigg, Richard Worcester, Mary Goldring, 'Nothing East of Suez' and, finally, Denis Healey prevailed. 'We are not here to support overgrown mentally-retarded schoolboys', he said.

The Aftermath of Cancellation

The cancellation of TSR2 was bad enough but almost worse was the ban on all flying and the rejection of a proposal to carry out a £1M flying programme, to confirm calculations on the intake, on drag, surface flutter and auto-stabilising. In addition, information on engine operation and supersonic operating experience would have been amassed. 'It would cost £2M', said the Ministry and rejected it. Lack of this very experience put BAe engineers in a poor position when negotiating with Dassault on AFVG. Perhaps partly to justify continuing with the Mirage IIIG, but undoubtedly with some sincerity, they said ''Ow can we believe you – you had everything – the engine, the airframe, and the avionics – and still you did not proceed: in the end you will just buy more Phantoms.'

After cancellation, the instructions within Warton were very clear: the run-down was to be conducted with dignity and professionalism. The run-down terms, ie penalties for late compliance, were set down in standard AP documentation and were applied with rigour. Some people emerged to apply them – it seemed almost with alacrity. 'Where were they when we were building up?' I wondered.

Within the allowances, I was able to encourage, for example, Department Heads, to recall their experiences and lessons learnt on TSR2 for the unlikely event, as it seemed then, of being assigned future aircraft. Some work was obtained from RR Derby and Windscale (Adour test rig and AGR instrumentation) but it wasn't aircraft work and it wasn't received with much enthusiasm at Warton. And so the 'day of reckoning' arrived: it brought no sense of even grim satisfaction. Two initially rival teams had worked loyally together and had overcome many difficulties to create a fine product. Despite a march by thousands down Whitehall, there were thousands of redundancies throughout the industry which seemed to be doomed. TSR2 was not the only project to be cancelled.

The first aircraft was used as a target to test munitions and the second was used at length as a noise generator at Boscombe Down, to simulate Concorde. The reheat worked perfectly.

Reflections on the Lessons of TSR2

It is now forty years since I was first involved on a task associated with what became TSR2 and over thirty since its first flight and cancellation. What are my feelings now after Jaguar, AFVG, Tornado?

Out of TSR2 came such lessons as the need to achieve a fuller linkage between overall postulations and detailed manifestation, through demonstrator programmes and avionic hack aircraft. A proper awareness of true full cost of programmes – and the need to tailor initial requirements to cost – were other important lessons which were applied to the full in the MRCA programme. The need to achieve better matching between engine cycle and airframe performance was recognised – and achieved in the RB199/Tornado combination.

The attitudes of people involved became more positive towards co-operation, delegation appropriate to Weapon System concepts. Closer and more friendly contacts were achieved between firms and officials. Arrangements for decision taking, assignment of Technical Authority and check functions were secured, complemented by flexibility on drawing systems, specifications and standards. Collaborative working depends on good long-distance communications, including modern electronic systems, and communications aircraft were made available.

Valuable engineering experience came from TSR2 such as: large-scale digital computations for stressing, thermal stressing, temperature definition, flutter and vibration analysis of structures reaching and sustaining high temperatures. Successful engine-airframe integration by rig and wind tunnel testing was anticipated and the application of theory to intake and afterbody/nozzle design developed. Similar attention must be paid to external store carriage and release. The usefulness of large rigs for testing fuel, power controls, electrics and avionic systems was shown.

Such lessons, and others concerning the practical manufacturing aspects of the use of advanced materials and, for example, integral machining techniques, were invaluable in later projects. Much was learnt about the importance of extensive instrumentation with airborne magnetic-tape recording and ground playback equipment, allowing high-speed automatic analysis of large quantities of data.

A further generation of experience beyond Canberra and Lightning was achieved, showing what was not feasible, quite as much as what was. Great progress was made in the development of safety in Automatic Flight Control Systems, employing two and three control channels and involving response monitoring and precise power controls. Digital and analogue computing and hardware were developed successfully as were rig simulation and techniques for 'calibration' by simulating and matching previous aircraft. The use of such techniques as a design tool and to anticipate the flight characteristics of new aircraft was also pioneered. Automatic fuel management was developed as was the use of hydraulic systems with new fluids, seals and pumps to accommodate high temperatures.

All in all, I can say, from direct personal experience of the projects that followed, just how much was owed to TSR2 and its lessons. Having been styled Systems Engineer (Warton) on Tornado, I cannot now deny the fundamental soundness of the integrating concept, nor of the benefits of reverse growth factor as emphasised by Vickers. On Tornado, the GAF wanted priority for small size and low approach speed; the Italians wanted supersonic manoeuvrability; the RAF and the German Navy wanted range. Because the necessary detail work had been done, Systems Engineers could give them these. TSR2 was a few years ahead of its time but not all the supporting ground work had been done. This caused unrealistic cost estimates and delays to the programme – but the required performance was attainable.

The density and % fuel volume of aircraft such as the F-16, F-18, Jaguar and Tornado were about three-quarters those of TSR2. Soviet experience in developing the T6-1 delta into the swing-wing Su-24 shows what might have been done by UK had the P17A been adopted and progressively developed.

TSR2 – A Worm's Eye View of Events

A T F Simmons

Tony Simmons was another member of the English Electric Project Team which inspired the P17A and later helped give birth to TSR2. His account of the origins and gestation of the project lends a great deal of atmosphere to what, inevitably, was a very human story. Rather sadly, he agrees that 40 years on, in an age of double-glazed and air-conditioned rolling stock, he could no longer sketch a first design on the steamed up windows of a railway compartment!

First Thoughts

For me it began one summer's day in 1956 when a letter was passed round the Project Office at Warton, for us all to read. A schoolboy in the West Indies had written to English Electric HQ in London offering polite praise for Canberra and Lightning but saying that it was about time for a supersonic Canberra. The rest of the page was decorated with sketches of possible configurations for this beastie. The letter had been forwarded from London to the Chief Engineer at Warton and thence to Ray Creasey and his henchmen. I remember being very impressed that everyone read that letter and looked at every picture with respectful interest. We soon realised that the Canberra replacement project was already a twinkle in Ray Creasey's eye.

In later summer and autumn Ray Creasey started to tour the Air Ministry and Ministry of Supply looking for support for a Canberra replacement. Eventually he found that support. He sent Ollie Heath home in October 1956 and told him to come back in a week with some possible designs. At the end of the week Ray got us together – Ollie, Tom Campbell (Structural Design), Frank Roe (who ran all the Warton wind-tunnels then and all Warton later), Alan Pennington (power-plant) and me (thermodynamics, equipment, Kinematics, electrics, etc – the sweepings from the design office floor).

We all sat there looking at Ollie's 3-view plan for his most favoured designs, each one on- a piece of foolscap paper. None of them looked much like a P17 or a TSR2, but the ideas were there. However, a little time and a few laps round the circuit soon created the familiar shape. Each lap consisted of guessing the weight and the frontal area and the power plant and then designing the structure and shape to suit. Then we all worked out the weight and performance.

Then we all started again with better guesses. Each circuit took more time and involved more people. Eventually every department had a finger in the pie . . . but that was much later.

Low Flying

It was some time before GOR 339 was published. The Warton Project Office team made intermittent progress whilst the requirement settled. However, we did have time to ponder on the blind low-flying requirement needed to avoid detection by enemy radar defences. We had seen stories about developments in the USA where a forward-looking radar had been adapted to give a view of the hills ahead so as to enable an aircraft to fly up a valley (a terrain-avoidance radar). However, a good long look at a map of the world shows few valleys with steep sides up which an aircraft could fly at five or six hundred knots. Most hills have shallow sloping sides. Very few faces have a gradient as steep as 45°.

It follows that up and over is the way to avoid hills – but not too far up. I had this problem on my mind in February 1957. Tom Campbell and I were travelling down to Euston in the evening of the 19th in the steam-hauled train of the day. Tom had a good book. I hadn’t. So I gradually worked out the technical requirements for a terrain-following radar using the steamed-up window as my scribbling pad.

Ray Creasey was interested in these ideas later, when I’d tried them out on a map of the Western Highlands. One day, Donald McCallum and Mal Powley of Ferranti had been visiting the Lightning Development team at Warton. They and their aircraft were trapped by stormy weather. They got together with Ray and I was fetched down to trot out my ideas. I hadn’t got past the need for a large forward-looking dish but Donald McCallum had the solution at once with a split beam radar (like AI 23) and the terrain-following radar was on the stocks.

Two Diversions

At about this time there was a lull in our activities. Ray Creasey’s ever-inventive mind had been turned on to the problems of ground-control of interception by Lightnings fitted with Firestreak (which had to be fired from well within the rear hemisphere of target aircraft). He invented the Vectogram. This was a transparent overlay for the ground controller to enable him to tell the Lightning pilot when to accelerate and when to turn on to the target so as to avoid wasted time catching up the target and getting within Firesteak launch range. I learned a lot about ground radar and GCI. The Vectogram (and whatever Fighter Command made of it) was all happily rendered obsolete once the Lightning Mk 3 entered service with its collision-course weapons.

And there was the P10D! By this time the Warton supersonic ramjet project had manifested itself as a long-range flying bomb – on paper only. I remember that Ollie Heath and I joined two boffins, senior and junior, from English Electric, Luton. We visited the Air Ministry at Whitehall Gardens and discussed global politics and oversize deterrents. We four came out of the Air Ministry and held a discussion in Charing Cross Gardens, sitting in a row on one side of the main promenade. A band was playing the grand march from Aida. Ollie talked with the principal Luton man (should the missile fly at Mach 3 or 4) and the words seemed to fit in with the music. The other Lutonian and I lost touch with the conversation, separated as we were on the end of a row and watched goggle-eyed whilst an obliging lady (who had been passing through the gardens) sat on a customer's lap, covered herself with a mackintosh and would have provided complete satisfaction in full view of the public had a park-keeper not seen them and had he not stood there whilst they disentangled themselves (under the mack).

I don't remember much else about the P10D.

The Brochure

The GOR 339 project got underway again then. John Nathan had joined our gang and at last I had real help in developing our knowledge of navigation and weapon-aiming accuracy, particularly in the blind loft-bombing sortie which was the main theme of the GOR.

By this time (autumn 1957) English Electric had made friendly overtures to Short and Harland. I was dispatched on a wild goose chase to get help with systems engineering from Shorts design team. I got intelligent and friendly conversation and a look round Belfast before it was spoiled by civil strife but no more.

Finally we worked the last spell from Christmas 1957 to the 31st January 1958 at between 70 and 80 hours each week and produced the P17 brochure. I do remember rushing about and writing all the bits that no one else would write and wondering whether I should have been journalist or novelist!

Partnership and Shotgun Marriage

We carried on working on the P17 for the rest of 1958. We talked to friendly electronics companies – Ferranti, Marconi, EK Cole and Elliott Brothers. The world carried on too. Six days after the brochure deadline a BEA Elizabethan crashed at Munich and killed and injured many of the Manchester United football team that were aboard. On 11 April I saw Sputnik II cross the sky in the evening.

The situation began to change in April. On the 29th I went with Ray Creasey and Ollie Heath on a confidential visit to Vickers-Armstrongs at Weybridge. Ray had worked at Weybridge as a very young man during World War II but for Ollie and me it was our first visit. Hundreds more visits were to follow. I know that I spent some time being entertained with great kindness by Jeffrey Quill in his office. I asked rather flat-footedly what his job was and learned that he had been a Spitfire test-pilot in his time. Later I learned that he was *the* Spitfire test-pilot. I still blush when I think about it!

This was the beginning of the long uneasy relationship between Warton and Weybridge. People like Jeffrey Quill helped to turn rivalry into teamwork.

My next encounter was with Jock Graham at Hurn in late June when we told each other about the equipment and systems in the Vickers 591 and the English Electric P17. Other exchanges of information had been going on in parallel. Each technical organisation was convinced that it had the right answer and that the other group was mistaken. Nevertheless the boards of Vickers and English Electric had read all the signs and had decided that a joint project was good for our health. On 1 January 1959 the TSR2 contract was awarded jointly to Vickers and English Electric but Vickers-Armstrong was nominated as the prime contractor.

Evolution of the TSR2

An enormous amount of work had been done at Warton and Weybridge during 1958 (for Weybridge read South Marston as well) and the Vickers-English Electric consortium was the proud possessor of two separate and distinct projects neither of which in truth could totally satisfy the contract. For the first few months a joint team was formed at Weybridge led by George Henson (Vickers, ex-

Supermarine) and with Ivan Yates from Warton as second in command. Between them, and with regular inputs from Ollie Heath's gang at Warton, a new design was created which was a sensible (and practical) compromise.

The Vickers Type 591 was a straight wing aircraft of small size and high wing-loading. It had room for the necessary avionic equipment only if new equipment of very small size was developed.

The P17 was a much larger aircraft in overall dimensions with the inevitable Wartonian twin-engined layout. It had a robust delta wing and plenty of room for power-plant and equipment. It assumed the minimal amount of special new avionics because new avionics seldom turned up on time. In the words of George Edwards it was pedestrian. It would also have met the in-service date.

From the moment the contract had been placed the project was under threat of cancellation. It survived for 6¼ years only because the arguments for its continuation were more convincing than those mounted by its detractors. George Edwards was the project's quite brilliant champion. He was often forced to think on his feet and to claim capabilities for the TSR2 that would end argument, at least for the time being. MoD added each new claim to the project specification and an inevitable increase in cost and timescale. The sensible and practical compromise aircraft slowly moved towards the limits of possible development. A particular killer was the requirement for sustained flight at a Mach number above 2 in a maximum temperature atmosphere. One felt that the cost of the whole project might have been reduced by 20 or 30% by simply limiting the specification to Mach 2 in an ICAN atmosphere and slower if it's hotter.

One might think of the P17 concept as in the tradition of the Hawker Hurricane – sturdy, easy to develop, easy to build and to repair and likely to be delivered on time. The TSR2 in its eventual form was a design like the Spitfire in which almost everything was sacrificed to performance, particularly cost and timescales. It was also elegant and beautiful and somehow crept into people's hearts.

Avionics

The job of developing the overall avionic system went to the Guided Weapon department of Vickers-Armstrong at Weybridge. John Clemow had overall charge and applied all his considerable leadership qualities to the task. He had with him some very capable and strong minded people who were nevertheless very ignorant of manned aircraft and their problems. John Clemow managed to build a very effective team which nevertheless heard and acted on advice and ideas from outside. I remember particularly John Lambie, John Lattey and Dennis Harris – respectively for diplomacy, for well-placed enthusiasm and J-band radar and for solid results.

Warton played little part in procuring the avionics but we did write (and rewrite) the specification for the Verdan digital computer that was chosen (made by Elliott Bros under licence from North American Autonetics). This specification consisted largely of the fifty-odd equations involved in navigation and the various weapon-aiming modes. For John Nathan and me it was a wonderful exercise in getting everything exactly right.

There is a big blank here because for the next four years I was immersed up to my armpits in the overall Lightning weapon system OR 946, radar, guns, rockets and missiles.

The Achilles Heel

One other Warton job was the calculation and recalculation of the total probable error in blind weapon delivery. The sortie would depend on reconnaissance records of a hard target and a recognisable ground feature some 30 miles away. The attack would be at the end of a thousand-mile sortie. The estimate of accuracy took into account a loft-bombing attack, wind-shear and every likely equipment and crew error.

It became obvious that, against a hard well-defended target, the attack must be blind or else the vulnerability of the aircraft would be too great. The probable delivery error was going to be hundreds of yards (2 to 4). High explosive weapons might have seriously damaged the enemy's equivalent of the NAAFI but would not touch, except by a stroke of good luck, a properly prepared missile silo. So an attack of this type would have needed the kiloton atomic bomb being developed for the RAF.

Of course, there were a number of visual modes of weapon delivery (live dive-bombing for instance) which would have been accurate enough for 1,000 lb HE bombs, but no one in his right mind would have dreamed of exposing a multi-million pound engineering jewel like the TSR2 to the hazards of light anti-aircraft and small arms fire at close range.

Therefore the TSR2 as a weapon of war was tied to the kiloton bomb.

When Harold Wilson became Prime Minister in 1964 he was dependent for his majority upon a spectrum of Labour MPs whose left-hand end had strong reservations about nuclear weapons (to put it mildly). They could just about tolerate the concept of the ultimate deterrent but the idea of a proliferation of smaller atomic bombs must have been anathema to them. This meant that the kiloton bomb was doomed.

No kiloton bomb: no TSR2. QED.

Cancellation and After

And so 6 April 1965 came and went. I see on looking back that there was a Lightning Weapon Systems Trials Sub-Panel meeting all day that Tuesday. I only learned about the TSR2 cancellation when I emerged from the meeting.

As I remember it, a condition of Government support for the staff redundancy scheme (generous by 1965 standards) was that Warton, Preston and Samlesbury on the one hand and Weybridge and Wisley on the other should make some 15% of their staff redundant. At Weybridge it was straightforward because that sort of percentage of the staff were employed on sub-contract and could be quickly laid off. There were no personal choices to be made and tears were few. The avionics team left en bloc and joined Elliott Brothers as a new division called EASAMS, able to make a major contribution to Tornado development.

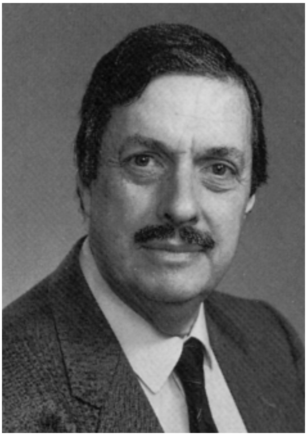
At the Warton end by contrast the 15% redundancy was real. Freddie Page of course led us from the front and very carefully delegated the task to us department managers. We were disciplined into parting with the 15% of our staff which we could best do without – easy to think of 2 or 3% but 15% eats into the basic strength of any department. Anyhow we did it and the scars took some time to heal. But the eventual effect was to weld the whole of Warton, Preston and Samlesbury into a determined team.

Freddie also announced to us his six-pronged attack to bring in new work. He gave us his hope that at least three of these projects would come to fruition. In fact, over the next 3 years all 6 came off, one after the other.

Cancellation of the TSR2 killed Weybridge in the end. A new cost-conscious Warton recovered in a few months and went on to extraordinary success (though BAC Luton was sacrificed in the process).

The Engine for TSR2

J D Wragg CBE CEng BSc(Eng) FIMechE FRAeS Hon DEng



John Wragg retired from the Board of Rolls-Royce plc as Director, Military Engines in 1989. He had joined the Engine Division of he Bristol Aeroplane Company in 1952 as a development engineer after Army service, practical training and gaining a degree in mechanical engineering. He is a Visiting Professor at Bristol University. His recollections as project engineer in charge of engine development for the TSR2 allow him to present a uniquely informed account of that programme.

It is a pleasure for me to be able to talk about the engine which powered TSR2 and I have at least one advantage I suppose, and it is that I was appointed at the time of the launch of the TSR2 engine as the project engineer in charge of the development programme, and so, in those terms, I was responsible for the introduction of design changes to resolve the various problems that were encountered; that is half the story. The other half is that I was also instrumental in having most of the papers on the engine for TSR2 destroyed when I was in a somewhat more senior position in Rolls-Royce; the consequence really is that my sins have come back to haunt me on both fronts, on the subject of the development of the engine and on the subject of the papers not being in existence to support what I have to say.

But I really do want to concentrate on the engine that was selected; there has been a great deal written about the political reasons why the Bristol-Siddeley engine was chosen, and there has also been a lot of discussion and debate about what would have happened if other engines had been selected for this aircraft. I do not propose to talk about that because I am afraid that my mind was focused on making the particular engine that did go in TSR2 a success and in looking at the problems and their solutions which were to carry this through into an engine that went into production.

When the decision was announced in January 1959 that the Olympus turbojet was to power TSR2, the engine had already been in service with the Royal Air Force for two and a half years powering the Vulcan B Mk 1. In its original form as the B.Ol.1 of 9,140 lb thrust, the Olympus first ran in 1950; nine years later it became the subject of the first major contract to be awarded to Bristol Siddeley Engines on the company being formally established as an operating concern in January 1959.

The variant of Olympus which powered the TSR2 was sixth in line of development from the B.Ol.1. The Olympus 593 engine in service in Concorde, is the seventh member of the family. First to enter service in mid-1956 was the Olympus Mk 101 of 11,000 lb thrust. This was followed successively by the Mk 102 of 12,000 lb and the Mk 104 of 13,000 lb, each of these 100-series engines powering the Vulcan B Mk 1. The first major change in design was the Mk 201 of 17,000 lb developed to power the Vulcan B Mk 2. A second re-design occurred with the B.Ol..21 Mk 301 of 20,000 lb thrust, also used in the Vulcan B Mk 2. The B.Ol.22R Mk 320 engine for the TSR2 stems directly from the B.Ol.21, the Olympus 593 being evolved from the 22R.

The Olympus was Britain's first twin-spool turbojet, and undoubtedly this choice of configuration was an inherent factor in the engine's outstanding handling characteristics and exceptionally low specific fuel consumption. In the Vulcan the Olympus proved itself one of the most rugged and reliable engines in service with the Royal Air Force.

These features and the valuable operating experience accumulated in service with Bomber Command were important considerations when the Olympus was chosen for TSR2, although I do not now think that there was an appreciation of the changes required to achieve the TSR2 requirement.

We can perhaps today look critically at the limited amount of demonstration work that was done to support the changes in design to suit the needs of TSR2. In fact; the background which convinced the customer that it could form a successful engine with development in the areas of sustained supersonic flight and reliability and good handling qualities came from somewhat limited testing with the reheat system and no testing at all in terms of operation at sustained high intake temperature; not perhaps the best basis on which to commit an engine for the task that TSR2 demanded.

From an engine manufacturer's point of view of course TSR2 was every man's incentive in terms of the development of a gas turbine engine. It was demanding in every sense; it was seeking things that had never been done by an engine before and all of these were naturally pursued with vigour. But perhaps not early enough and the preparatory work was not done successfully enough to be able to say that the engine would be fully developed at the time when it was required for production aircraft.

The reheat system for the engine had emerged from work that had been done with a Solar reheat system developed partly in the United States, and partly here at Patchway on various Olympus engines; an infinitely variable reheat system, combined with a variable nozzle which was later pneumatically operated, was the basic standard chosen and developed for the TSR2, and indeed was in its successful demonstration the basic reason why this particular engine was selected and why that particular reheat system was chosen. Infinitely variable reheat systems are quite difficult to design and develop and of course they need a variable nozzle of a degree of complexity.

So that was one step forward, the thrust required to make the aircraft go supersonically was something which had been demonstrated.

Also of course a great deal of attention too was put towards what was required of an engine that needed to undergo sustained operation at high Mach numbers; a condition which amounted to an intake total temperature of 146°C (Concorde demands 127°C today). Much of the design to do this had to be attacked on an analytical basis; there was no evidence which could be looked at and of course the Olympus engine designed for the Vulcan did not have to deal with this sort of condition. The fact that air, oil and fuel temperatures were much higher in TSR2 was a new task and new challenge and demanded a changed construction and new materials within the engine; the new arrangements for the shafting to move bearings out of the very hot areas of the engine, were more or less adopted off the drawing board. Although analysis work was done to identify that with the design changes throughout the engine it should be able to operate at the much higher temperatures that were required for supersonic flight, it could not be demonstrated until the first Olympus 22R bench engine had run.

And then of course the idea of doing sustained endurance running at very high intake temperatures was one which required a novel test bed. The Pyestock cells which were in the process of building at that stage and being worked up, were no sort of vehicle to test whether an engine would live for long enough at the supersonic conditions that were required; and so there was built, with some difficulty, an intake heater made of engine combustion chambers and this required a good deal of development before it could be risked in front of a scarce development engine.

Industry and the military customer had been accustomed to validating an engine for entry into service, and hence production, primarily by passing a 150-hour endurance test, known as a Type Approval Test. This had naturally become the focus of a successful development programme and the bench testing for a new engine type mirrored the Type Test schedule; this schedule had been an adequate validation for subsonic engines but had no relation to TSR2. The testing requirement of the Olympus engine for TSR2 were such that, in effect, a new schedule with many new mandatory additional tests was evolved.

The Committee sizes and structure for deciding on the overall requirements of the elements of the production TSR2 would today be unbelievable. The nearest real equivalent in recent years to the enormous programme that emerged from that examination by Committee, is the evolution of a new information technology system. And it was as if today we were to say to everybody at the launch of the specification for an information system 'what would you like to have out of this system' and there was nobody who ever said 'no you cannot have that'.

Not at all; there was an enthusiasm for more and more and so the engine had new tasks placed upon it and for every new requirement in terms of the specification of the build standard for the use of water injection, the ability to run at high intake pressures, high intake temperatures, the ability to provide a dual cycle engine in effect that had a very good SFC at subsonic conditions but was able to run at sustained supersonic conditions without any damage, that could withstand sand ingestion tests, salt ingestion tests to name only a few.

On some of the most difficult elements of the engine, as they subsequently emerged, the weasel wording was by today's standards, absolutely appalling. The phrase used was that the engine should be 'compatible with the aircraft intake'. But what standard is going to be met and by whom? There was no mention of what testing had to be done to demonstrate that the combination was adequate.

Testing was specified to prove that the engine could operate at high intake temperatures for prolonged periods and for many other aspects; there emerged out of all this a long tortuous programme of testing which was required, including flight testing, before the engine should fly in TSR2; so the development programme was set out to satisfy that testing. In doing that of course we were not merely finding out how to develop the means of testing, but we were trying to find out too how the engine responded to the conditions to which it was subjected, and why it responded in the way that it did.

And naturally there was a fair number of surprises. This was a new area, something which was not properly understood and where the only way one could do so was by investigative testing and measurement. In a number of respects this was not done in the early days of developing the engine. The reason I think in retrospect is because it was believed that by writing a schedule of precise tests you could actually demonstrate the integrity of the engine satisfactorily. Whereas what happened was that those formal tests dominated the pattern of the testing for the engine rather than perhaps to have done much more instrumented testing and to make sure that the design concepts were correct.

Indeed the worst problem that dogged the engine for TSR2 in its development programme was the behaviour of the low pressure shaft. A much longer LP shaft was fitted to the 22R than had been in use on earlier Olympus engines and that was, in part at least, as a result of trying to keep the engine bearing compartments as cool as possible in the much hotter environment that was going to be encountered in supersonic flying.

But unfortunately that change also resulted in a design of shaft which was capable of being excited in vibration by a number of stimuli, one of the most significant being the resonance of a shaft mode with over-fuelling of the reheat system; this had been discovered immediately prior to the first flight of TSR2. It was necessary to revise the fuelling of the reheat system at that stage and subsequently to introduce a completely new schedule to ensure that the over-fuelling and the consequent excitation was avoided. That was done and was successful, but there were, as I am sure many people here today know, many flights that were carried out before those changes had been fully introduced.

So how do we sum up the experience of developing the engine for TSR2? Well it achieved delivery of an engine, deficient in a number of areas agreed, but adequate for the early flying of TSR2. Subsequent development of Olympus for Concorde shows that there was still very much to be discovered at that stage and the cancellation of TSR2 prevented the Olympus 22R engine being developed to match fully the requirement of the aircraft. But it has been shown in terms of the subsequent Concorde programme that the engine was perfectly capable of achieving the full specification that was required by the aircraft's operational needs.

If ever an engine suffered from the lack of a demonstrator programme carried out ahead of launch, then it was the Olympus 22R. The first engine to benefit from a full, combined customer/industry funded, demonstrator programme is the EJ200 for Eurofighter, and all the evidence points to an extremely successful validation programme as a result.

Discussion

Parts of the discussions in each of the groups chaired by Air Vice-Marshal Baldwin and Group Captain Jock Heron shed light on the TSR2 project, the design of the airframe and the development of the engines demanded by the OR.

Handel Davies was a Director General [Scientific Research (Air)] in the Ministry of Supply from 1957-59 and had the 'invidious task' of organising the design competition for TSR2 between the nine companies which submitted designs. In the course of the study made, the line was agreed to force the amalgamation of the aircraft industry. For that reason, the decision made was to award the contract to Vickers, on the condition that the company 'got into bed with' English Electric. He thought then, and still believed, that this was a fundamental mistake which later played a very major part in the decision to cancel the aircraft. The OR called for the most advanced aircraft ever attempted by British industry. The combination of that and the bringing together of the two companies and their [quite separate] teams in a massive reorganisation had presented them with 'a virtually insuperable task'.

The 'ludicrously fragmented state of the industry' at the end of WWII when no fewer than twenty-seven companies had existed had had to be addressed and that was Government policy. However, no less than twelve years had been allowed to elapse before anything was done to remedy the situation and that was, perhaps, understandable, given that the industry was then headed by 'magnificent buccaneers – from Handley-Page downwards'. Resistance to collaboration on the part of industry was matched by a failure on the part of Government to take action earlier. Not until the 'famous' meeting held in 1957 by the MoS had the riot act been read and a warning issued that no further orders would be placed until something had been done to bring industry together. It was on that basis that he and his colleagues decided that, although English Electric had produced the best design, the project demanded a leader of the stature of Sir George Edwards. This presented the merged companies with a superhuman task and led inevitably to the escalation of the cost of the TSR2.

Sir Patrick Hine suggested that it would have been better to have selected the preferred English Electric design and to have stiffened the management expertise necessary to drive such a sophisticated project, by bringing in the top management judged to have been lacking by the MoS, perhaps as some sort of rationalisation process. The problem had been one of putting together the best of two designs, at the same time as merging companies of different cultures and managing a very sophisticated programme. To attempt all of these things probably made it impossible to have maintained what should have been more rigid cost control.

Handel Davies said that the decision had been made for reasons of exploiting Sir George Edwards's very special capabilities. That was not to say that such qualities were not available in English Electric but George Edwards was an engineer, as well as the then Chairman of the company and had the ability to lead the design team. In the event, it did not work out as hoped, given his preoccupation with, *inter alia*, the VC10, their BAC 111 and other civil projects. He added that he still had a conscience about his recommendation but recalled that it had been faithful to the Government line of using the TSR2 contract to force amalgamation on the industry.

David King was at Boscombe Down in 1962, on acceptance trials of the Vulcan and Victor. He was later invited to join Vickers as a TSR2 project navigator. He had a 'worm's eye view' of the differences of culture evident between Vickers and English Electric and of the clashes between the flight test organisations of the two companies. Brian Trubshaw of Vickers had wanted to take the lead but it had been given to Bee Beamont and friction ensued. He also questioned the directness of control at Vickers where he believed that the VC10 was the company's major preoccupation.

Jack Gordon, General Manager of NEFMA, looking after Eurofighter and Tornado, agreed with David King about the relationship between Vickers and English Electric during that period. He attended a number of meetings between Vickers and English Electric, his first experience of a collaborative programme. The relationship between them was quite shocking! The engineers approached almost every problem from a different angle and seldom agreed on anything. He had spent the last 25 years on European collaborative projects and had never experienced anything as difficult – or as acrimonious – as the relationship between Vickers and English Electric.

He recalled that he inherited Handel Davies's office in St Giles Court, 30 years later, and found some old working papers there, relating to the disposal of TSR2. The papers showed that costs had been changing faster than the systems used for approving them could handle. The decision to cancel had been inevitable and absolutely right! He believed that if TSR2 had gone ahead, it might have cost at least three times as much as the pessimistic projections used at the time.

Sir Patrick Hine said that the culture differences spoken of were to be seen long after the formation of British Aerospace and its privatisation in the mid-'80s. The [old English Electric] Warton culture was very different to that of the former Hawker Siddeley Aircraft Company at Kingston/Dunsfold. The mistakes of TSR2 had not been repeated by producing aircraft as a product of the two cultures, putting two companies together, adopting a hybrid design and creating a joint management structure. Nonetheless, Warton has produced Jaguar and Tornado and Kingston Harrier and Hawk. He found it hard to understand why English Electric, designers of the P17 and with a successful track record with the Canberra and Lightning, had not been thought to have the management expertise to drive through the TSR2 project.

Handel Davies said that it was clear that lessons were learnt. The very same people, in collaboration with MBB had produced Tornado and collaboration over Concorde was successful, too. The lessons learnt covered every aspect of procurement, design, development, engineering, technical and political.

Mike Salisbury gave his view of the Vickers approach to project management as Prime Contractor, by comparison with the approach of English Electric. He had been in charge of aerodynamics at Vickers, Weybridge, at the time of TSR2 and had brought up the Supermarine or Vickers part of the design to Warton. There had been a rigid project management approach within the design teams, with technical authorities at one end or the other [Weybridge or Warton] and 'shadows' at the other end. He could not, therefore, recognise the major problems raised by others on the design front. However, he could not speak for the financial and overall project management areas. By way of comment, he said that he and a number of his colleagues went to Avro Canada after the cancellation of the Arrow to see what might be learnt from that and put forward proposals for a limited flight test programme and exactly the same thing happened as with TSR2. The Canadian Government decreed that every trace of the aircraft must be destroyed.

Bob Fairclough late of BAe, Warton, said that the parallels between the Avro Arrow and TSR2 were very apparent and the projects were very close in time. Sadly, the Canadians had failed to learn the lessons and when they were a prospective partner in Tornado, what they wanted in the Tornado specification was just as extravagant as those of the TSR2 and the Arrow. Had the Canadian input to a Tornado specification gone ahead, the aircraft would have been killed off as surely as the others had been. He recalled that Canada had wanted something in the order of M=3.0 at 70,000ft in a ground attack bomber! Lessons were not always learnt.

Prof Ollie Heath reflected that it may not have needed instructions from a high ministerial level to ensure the destruction of the aircraft and jigs. Once the instruction to stop had been given, there were volumes of standard procedures for running down. The spirit of so many people in the company had been so broken that they feared penalties for not adhering to the letter of the law! He recalled people from the company coming into the project office to make sure that things were being run down fast enough – people who had never been much in evidence when the project was being built up! The procedures for run-down had been more clearly expressed than those for building up. People had been scared of penalties!

John Wragg noted that there was a period of so-called run-down of the project during which there was a technical invitation as to how the assets could be used for the furtherance of knowledge for future projects. Just as with the airframe, well worked-out proposals were developed and endorsed but these were pruned down to the point that none of the work was allowed to go ahead. It was not a qualified judgement allowing some activity to go ahead: nothing was done. New production engines were shipped to Shoeburyness in response to instructions where they were used in firing tests for ammunition and many of them were there for a number of years. The number of engines delivered was far in excess of what was needed for the tests at Shoeburyness and these were apparently carried out more to destroy the engines than to gather data.

Ivan Yates of English Electric,. BAC and BAe, reported that he had had an absolute denial from Denis Healey himself, which he accepted, that he had given the instruction to destroy all trace of TSR2. Given the structural and organisation 'shambles' of the project, it was conceivable that almost anyone within it might have given the order. In fact, given the organisation scenario described by Sir Frank Cooper, it was amazing that anything ever happened at all! Anyone at the time who wanted anything to be done and funded, be it new aircrew equipment or whatever, could put it down to the TSR2 project. The system had been completely out of control. Even if Industry had had a first class project management scheme, no one can be identified as having been in charge in the Ministry. The combination of a wholly new engine, coupled with performance demands involving high temperatures, had cried out for the building of a prototype or two but the disordered state of affairs within the Ministry had made it almost inevitable that the very sensible things suggested by English Electric were never heard or acted upon. It was 40 years ago that much attention had been devoted to sorting out project management within English Electric, resulting in principles and rules which had since stood the test of time.

John Wragg said that a situation in which the base-line moved significantly during the life of a project and the whole programme and income for a company depended on actions preceding could not lead to particularly adroit project management. It did not encourage people to say that 'We can't do that' – or that 'We will need £xM extra to do it'. From the engine point of view, the company appeared to be so scared of adding to the bill that some quite improper undertakings were given in relation to enhanced performance. He did not believe that any project structure could have withstood such pressures. In those days there had not been the visibility of spend and commitment that exists in aerospace companies today.

Gordon Lewis, formerly of the Bristol Engine Company agreed broadly with his former colleague and reflected on whether there had been any project management – and, if not, whether it would have made any difference to the outcome. He attributed the failures to the shifting of the goalposts and the lack of resistance to those shifts or any exposure of their consequences. One of the huge burdens on the TSR2 had been the step by step movement in the Requirement from the P17 through to the ultimate TSR2. It had had a very profound effect on the engine because the Mach No. requirement was extended to the point when the engine had had to suffer a very considerable redesign. Most of that had happened after commitment. Management systems today would quickly set out the consequences of the changed requirement in terms of cost and time. In those days, engineers had seen the Requirement as absolute and their response had been to do what was necessary to satisfy it – without making too much fuss, for reasons of lack of security. The consequences had been to contribute to the ultimate failure of TSR2. It was not true to say that there had been a lack of project management in the sense that the engine development itself was badly managed. On the contrary, there was a great tradition of development engineers running engine programmes. But the visibility and understanding of what was being done within the context of the total project had been 'pretty thin'. In hindsight, the Company should have said that the Olympus was suitable for a M=1.7 aircraft and that they could have committed to such a programme. It should have said that for M=2.25 performance, the engine would take 3 years longer in development. It would require the introduction of new materials and a redesign of shafting and bearings – and would cost three times as much as the original bid!

Gordon Lewis distinguished between 'fault' and 'responsibility' in the failure to ensure effective project management. He said that Sir Freddie Page had long argued that the project should have had a prime contractor, a notion with which he broadly agreed. In such a case, the prime contractor should have said what could or could not be done – and how much it might have cost. In the absence of such an arrangement for TSR2, it should have been for 'the Ministry' to understand the effect of changes, asked for by some parties and agreed to by others. As a final point, he said that TSR2 in his recollection was the first major example of a 'project managed' programme. He recalled George Henson at Weybridge who was 'the Project Manager'. It might not have been possible to carry out the duties implied by the label but there had been an awareness of the need for active project management.

Professor John Allen, now of Cranfield, had not been on the TSR2 project but was a member of the BLUE STEEL project at Avro and at Hawkers with the Hawk, said that it might strengthen the argument for him to report similar experience from Hawker Siddeley. He fully agreed with Sir Frederick Page that the need is for project leadership by one man who can take the ultimate responsibilities. The politically inspired amalgamation between English Electric and Vickers had destroyed the 'creditworthy' project leadership arrangements built up, as they must be, over many years. That destruction must have been an added and contributory difficulty, besides whatever others might have arisen. About 90% of the irrevocable decisions on a project are taken at a very early stage, an aspect which, Prof Allen argued, is seldom discussed. At the point of making such decisions, little is available by way of reliable data and, effectively, the company is managing ignorance. Management experience, accrued over perhaps 40 years, is needed to allow the application of collective wisdom and 'feel' to such uncertainty. Amalgamation can destroy such experience and the lesson is as true today as it was in the 1960s – here and, notably, in the USA over the next 20 years where the problems have yet to come.

Sir Frederick Page agreed with these sentiments which highlighted again the key issues on management of TSR2. In his paper, Sir Frank Cooper had given a first class account of the confusion and lack of control in official circles, given the various officials and ministries involved. Equally, on the industrial side, there had been a great deal of 'rearrangement' going on at the same time, in the course of the mergers for which TSR2 had been, quite simply, a blackmail – only Sir Cyril Musgrave [Permanent Secretary at the Ministry of Supply 1956-59] put it slightly more tactfully! The key issue was that both the official side and the industrial side had been in a 'pretty considerable state of flux and muddle'.

Mike Salisbury picked up the point made by Gordon Lewis about the constant changing of the specification which had been true of the aircraft's equipment. However, on the aircraft side, a submission had been made in July 1959 and the basic performance requirements had not changed after that. Thus the requirements for the engine, in terms of Mach No should have been known by that date. TSR2 had been the first example of the workings of the Zuckerman Committee on 'how to order aircraft' and one of the early stages of that process was a feasibility study. He recalled that most of the questions that were addressed at that time had concerned what was technically feasible in the timescale of the project (although the timescales had subsequently been found to be optimistic). Few questions had been asked about what the technical achievement was going to cost. Finally, Vickers (or BAC as it became) had had very little control over much of the equipment, for example the Category 1 equipment which included not only the engines but the inertial platform, the forward looking radar and the reconnaissance system. Each of these equipments had had an equipment director (a Ministry man) who had had to report [to D(RAF)A] on any matter where he believed that Vickers-Armstrong was not doing the right thing at the right time! In short, although Vickers had been appointed prime contractor, the firm had not been allowed to exercise the authority implicit in such an appointment.

Gordon Lewis agreed with Mike Salisbury's views. Commitment to the engine project had been clear from about the beginning of 1959. What had not been clear was the nature of the contract. It had been in the previous two years that the project had moved from step to step to step, without the consequences being understood and evaluated at the time.

Sir Frederick Page said that the final issue of the specification [RB192D] had been in August 1960 and there had been changes right up to that date. He emphasised that it was not true to say that all the detailed requirements, which were very important in terms of the cost, had been settled by early 1959. The changes had gone on until August 1960.

Mr D L Pinn, had been a member of one of the teams in the Ministry of Aviation under D(RAF)A, Freddie Cook, when the programme started. He had been involved in the writing of the project management plan which was the first time any such plan had been written. The Project Director, Freddie Cook, had not had complete control of the programme because the Ministry itself was split into functional and project departments. He was a project department manager and the engine, for example, was not under his control, being a Cat 1 item and falling under DG Eng. Similarly, the forward looking radar and the inertial system fell under different directors. There had been co-ordinating meetings every three months but these were very large meetings. The theoretical management structure within the MoA at that time had been clearly defined and all responsibilities written down and documented.

Gp Capt Heron asked if there had been a 'single point of contact' with power to say 'yes' or 'no' to all the disciplines involved and **Mr Pinn** said that had been the case. The project team, in the shape of Mr Freddie Cook had the ultimate say and 'the technical money'. He had had ultimate responsibility and ultimate authority. Mr Pinn had seen that authority actually exercised on more than one occasion within the project, for example, when a new camera had to be developed and Freddie Cook had authorised the contract worth c.£1M. However, the day to day running of the Cat 1 items was the responsibility of the functional directors within the MoA.

Sir Frederick Page said that Mr Cook and John Heyhurst had been the main points of contact with the MoA (or MoS) at the time. But no one in the Ministry had had the authority to over-rule a new Air Ministry requirement. And that had been the problem! He had not been aware of a firmly stated Air Ministry requirement having been rejected. Messrs Cook and Heyhurst had had the job of putting into practice in the best way possible the solutions to the stated requirements.

Gp Capt Ainsworth had had some experience of project management as the first RAF 'Rayner' project manager. He said that he did not recognise Mr Pinn's Ministry but that he did recognise Sir Freddie Page's! The situation pertaining before the introduction of the short-lived Rayner system had been one in which no one in the MoA or MoS would argue with a stated OR. The job of the technical people in the MoS was to try to do what the OR staffs wanted. The only check or balance in the system was from a finance branch to which an explanation had to be given. At no point in the old system had there been anyone who could say 'This is absurd!'

Ivan Yates returned to Prof Allen's earlier remarks about the building up of industrial trust and competence over a period of, say, 40 years. He suggested that it was not just a matter of time and, indeed, Sir Freddie page had built up the English Electric team in just over 10 years. It was as much a matter of depth of experience as, for example, was found in the unique supersonic experience of the Warton team. That factor had been ignored in the industrial consequences of the `blackmail' referred to by Sir Freddie. Mr Handel Davies had told him that, effectively, things had been done in the wrong order. The companies had been put together and a contract issued to Vickers before any of the groundwork had been done. There had been no experience of supersonic aircraft at Vickers and the 'wise warnings' from Warton were 'inappropriate' in the atmosphere created by the systemic failures of the Ministries.

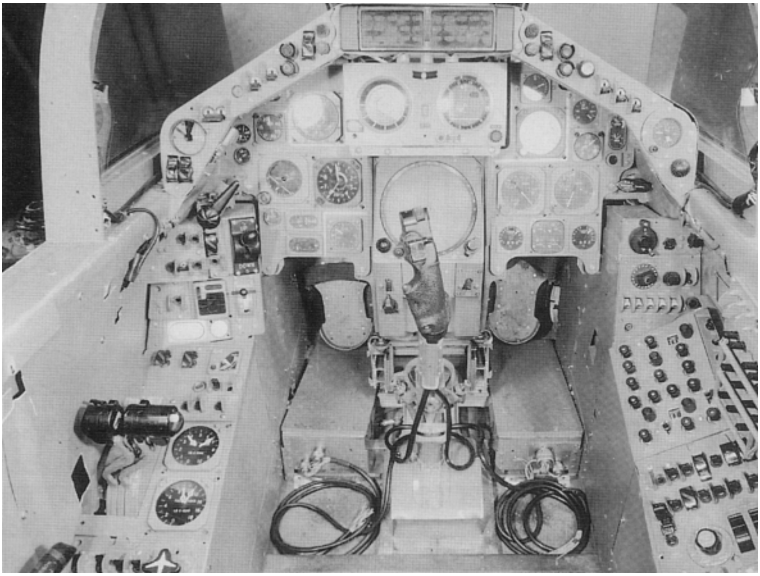
Preparation had been inadequate and rushed. **Ivan Yates** recalled that he had been seconded to Weybridge in 1959 and, by the time that the 'July Brochure' was being put together, the aircraft [design] was neither stable, nor did it meet the requirement. Only 6 weeks before the brochure was due to be submitted had the Weybridge team been able to conduct wind tunnel tests, to remove the planned anhedral from the wings and to add leading edge devices to bring the lift coefficient somewhere near the requirement. It was only in the Spring of 1960 that by moving the wing aft and introducing anhedral tips that a viable configuration had been achieved. Despite the over-complexity of the aircraft and the mistiming and consequences of the amalgamation, some marvellous engineering had resulted.

Gordon Lewis was uneasy about the way that the discussion had gone, in the sense that it had revealed considerable problems and weaknesses in the management of the TSR2 project. Those like himself with extensive experience of other projects would agree that a similarly critical view might be taken of many of these. He wanted to suggest another perspective on the project. He noted first the context of the overall timescale and achievement of TSR2, with a decision in principle made in early 1959 and aircraft flying in 1964 and, also the complexity and severity of the requirement. That achievement, set against all the problems of companies coming together and inadequacies in management structures, made it very important not to loose sight of the enormous engineering achievement of TSR2 which was carried out in a timescale which compared extremely favourably with anything achieved today. TSR2 was got to the point of flight testing in a fraction of the time needed today for Eurofighter 2000 and that should never be forgotten. And it had compared especially favourably with the progress of other projects, notably in the USA.

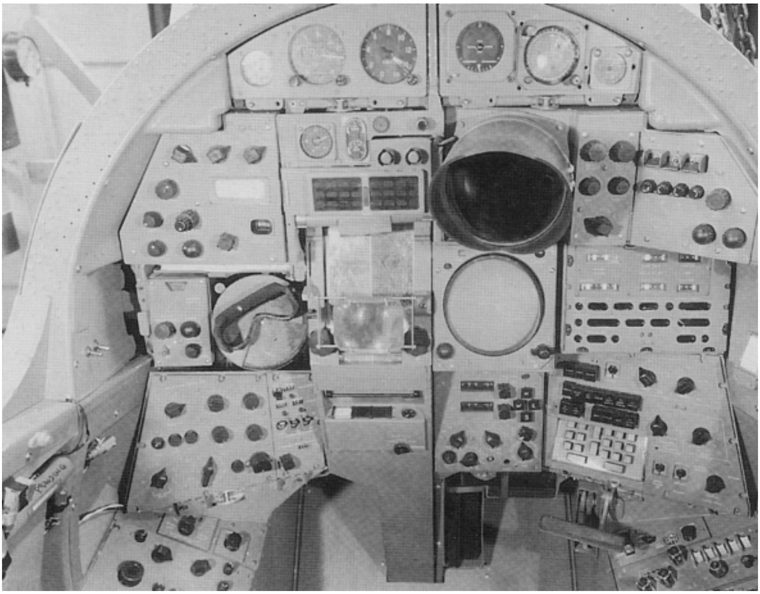
As a footnote and by way of summary, **John Wragg** said that matters had gone awry simply because there had been nobody in a position to say 'no' to anything!

Press briefing at the time of TSR2's first flight. Bee Beamont and Don Bowen face the cameras

The undercarriage that caused so much trouble in early flights



TSR2 front cockpit



TSR2 rear cockpit

SECTION FOUR

AVIONIC SYSTEMS FOR TSR2

FERRANTI AND TSR2

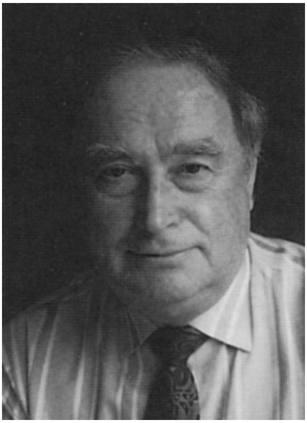
THE COMPUTER SYSTEM

AUTOMATIC FLIGHT CONTROL SYSTEM

DISCUSSION

Avionic Systems for TSR2

C M Stewart BSc



Greg Stewart graduated with an Honours Degree in Electrical Engineering from Glasgow University and joined Ferranti Ltd in Edinburgh in 1955, after postgraduate studies at the University of Strathclyde. Appointed to the Instrument and Fire Control department, he worked on AI 23 and AI 23B radars for the Lightning. Later, as Chief Engineer of the Radar Division, he was responsible for the design of radars for Sea Harrier, Lynx and EH101 Merlin. He is now Technical Support Manager of the Radar Division of GEC Marconi Avionics.

Having been Project Leader for the Forward Looking Radar for TSR2, Greg Stewart is well able to describe the enormous scope of the avionics systems required by the OR.

The Requirement

The TSR2 represented a challenge to both the aircraft design and its avionic systems because of the requirement, unlike its predecessors, to operate this large aircraft in low level interdiction and strike missions, combining the roles of attack and reconnaissance in long distance penetration of enemy territory.

The scope of the innovative developments, which were called for in the avionics systems if the aircraft was to satisfy this requirement has perhaps not been sufficiently recognised. It could indeed be said that these innovations represented a significant milestone in the evolution of avionics and they are worth reviewing to highlight those aspects which justify this claim. This is especially so in the light of developments which were to follow.

The Technology

The project was an ambitious one, particularly in the context of 1960's avionics technology. The potential advantages to be gained from the application of semi-conductors to avionics were already appreciated but although they were by then in widespread use, the integrated circuit was a relative novelty incorporating perhaps a few transistors against the million or more which is typical of current processor chips. However, the avionics world at that time was predominantly an analogue one and perhaps the most obvious difference between avionic systems of the TSR2 period and more contemporary ones, was the absence of the digital bus as the primary means of transferring data and control signals between individual avionics equipments. Instead, individual wires each dedicated to a single purpose were required leading to the major burden of large and heavy cableforms running the length and breadth of the aircraft and, perhaps even worse, the associated large number of multiway plugs and sockets.

Let us first look, however, at how the roles of the aircraft dictated the type and form of avionics required.

Aircraft Operating Modes and the Avionics System

Four of the operating modes of TSR2 gave rise to particular requirements for the avionics system:

- Long distance operation, navigating without external aids.
- High speed flight at high and low levels (down to at least 60 metres) with minimum exposure to enemy ground fire.
- Reconnaissance to record details of ground and man-made features over a wide swath centred on aircraft track.
- Accurate delivery of ordnance to predetermined targets and targets of opportunity.

The principal equipments which were employed to meet these requirements were:

Principal TSR2 Avionics Equipments

Equipment	Supplier	Now
1 Forward Looking Radar (Terrain Following)	Ferranti	GEC-Marconi Avionics
2 Inertial Navigator	Ferranti	GEC-Marconi Avionics
3 Doppler Radar	Decca	Racal-Thorn

4 Central Computer (Verdan)	Elliott Bros	GEC-Marconi Avionics
5 Moving Map	Ferranti	GEC-Marconi Avionics
6 Radio Altimeter	STC	STC
7 Head-Up Display	Rank Cintel	GEC-Marconi Avionics
8 Flight Control System	Elliott Bros	GEC-Marconi Avionics
9 VHF/UHF Radios	Plessey and Marconi	GEC-Marconi Avionics
10 Sideways Looking Array Radar (SLAR) – X Band Navigation Radar	EMI	Racal-Thorn
11 Sideways Looking – Q Band Reconnaissance Radar	EMI	Racal-Thorn
12 Optical Line Scan	EMI	Racal-Thorn
13 Stores Management	Vickers Armstrong (Weybridge)	British Aerospace
14 Head Down Display	Plessey and Marconi	GEC-Marconi Avionics

System Design

Flying low over long distances in hostile territory presented considerable difficulties and demanded complex solutions. The ability of the navigation system to operate without external aids was an important attribute for deep penetration into hostile territory. To have good knowledge of present position and track placed heavy emphasis on the reliability and accuracy of the navigation system. This was to be met by the then latest technique, a Doppler-Inertial mixed system in which, as well as keeping the platform inertial velocities correct, the Doppler Radar helped keep the platform to the local vertical. The first stage of the computation, converting acceleration to velocity was to be accomplished by electromechanical integrators but the second stage (velocity to position) was to be the responsibility of the central digital computer. The earliest trials of this system, in a Comet, were encouraging with performances of around 6-8 nm/hr CEP in position and about 0.25°/hr in azimuth.

Perhaps the most novel feature of the aircraft's avionic system, and the one which required considerable determination to implement, was the decision to use a pair of digital computers as the aircraft's central computers. These equipments were assigned the tasks of carrying out the navigation and bombing calculations.

Digital computers, although beginning to appear in civil applications such as payroll processing had not been used in a British military aircraft before and, as it was considered that no suitable computers were available in Britain, Verdan computers from the US company Autonetics were chosen. (These were virtually the only non-British avionics on the aircraft). Their use however, presented several major problems. Although powerful for their time it quickly became evident that their capacity to satisfy all the demands placed on them was distinctly limited. This was aggravated by the fact that the remainder of the avionic system was analogue and therefore inputs and outputs had to be transformed through A to D and D to A converters, creating something of a bottle-neck and inevitably great competition for the available resource.

It is perhaps significant that this early use of the digital computer in such an avionic system did not immediately encourage its widespread employment in later aircraft. Increasingly complicated analogue systems with their electromechanical instrument servo systems continued to be employed, for example in the bombing system of the F-4 Phantom several years later. It is interesting to speculate whether the continuation of the TSR2 programme would have hastened the introduction of digital systems and caused such analogue techniques to disappear much more rapidly than they did or whether the limitations in the then current digital technology would have been a sufficient discouragement.

Low Level Flight in all weathers

The key to safe low level flight over a variety of terrains with minimum exposure to enemy ground fire is the ability to determine the contours of the ground along the aircraft's flight path and to provide steering control signals in the vertical plane which enable an optimum profile to be flown.

In the case of TSR2 this was to be done by the use of a Terrain Following Radar (called the Forward Looking Radar – FLR – to differentiate it from the other radars carried) operating as part of a system which included a radio (as against the modern radar) altimeter, measuring the distance to the ground or water directly below the aircraft, angular stabilisation signals from the inertial navigator, an airstream direction detector or ADD to determine the aircraft's velocity vector in the vertical plane and azimuth drift angle, once again from the navigation system, to ensure that the radar scanned the ground along the aircraft's future track. Some early work on the use of a radar for this purpose had been done by Cornell University in flight trials over the Appalachian Mountains and whilst this provided some reassurance as to the viability of a radar sensor for this purpose, the actual system adopted by Ferranti for the TSR2 differed considerably from that used in this early work.

The eventual intention was to couple the steering command signals computed by the radar to the AFCS with the Head-Up Display providing the pilot with a monitor of tracking performance. However, manual control using only the HUD was also possible and was used during the flight trials, which utilised initially a Dakota, then a Canberra and finally a Buccaneer, in extensive flying over rugged terrain in the Scottish Highlands.

It is interesting to note that some of the features of the system which were recognised as necessary from the beginning did not appear in later US systems until the situations they were designed to accommodate had been encountered in trials. An example is the transition from flight over land where good radar returns are obtained to flight over water where returns can be weak or non-existent and height information is supplied only by the radio altimeter. When this transition occurs when the aircraft is flying down a slope towards the water, there is a danger of the pull out command appearing too late.

It is important to realise that the system concentrated on determining the optimum flight path in the vertical plane, with no ballooning over peaks to minimise exposure of the aircraft to ground fire and no attempt was made to present a situation display which would permit a choice between flying around obstacles or over them. However, in a subsequent development, after the cancellation of the TSR2, a ‘terrain avoidance’ system displaying ground contours over a wide angle centred on the azimuth track of the aircraft did give the aircrew this ability whilst simultaneously retaining control of the vertical steering to ensure the chosen ground clearance was maintained. It seems possible that this system would ultimately have been used to upgrade the TSR2’s capability.

Despite this apparent limitation, the Terrain Following Radar System did provide safety in turning flight by arranging that the radar’s vertical scan leaned into the turn to scan the correct area of ground along the future track.

Although it was never possible to test the whole system with the AFCS, since the trials aircraft did not have a suitable one, there is no reason to believe that performance would have been any worse than that achieved by manual control and many miles of flight over very rough terrain at heights down to 30 metres without hazarding the aircraft are a testimony to its success.

It is worth noting that this was probably the first time that a radar had been so intimately linked to the flight control of the aircraft. Fail safe was therefore a requirement and to meet this the single channel was covered by a parallel monitoring system which applied a number of different methods to ensuring that the radar performance was adequate and that the steering signals were sensible and safe at all times. A film has survived which shows some of the flight trials of the FLR.

Other Operational Modes

The Forward Looking Radar provided other modes which could contribute to the operational roles. These included ground mapping for navigation and target identification and beacon homing to assist in rendezvousing with tanker aircraft. With a pre-planned target, or one selected in flight by the navigator, transition to the attack mode from terrain following was accomplished by automatically injecting a climb command into the vertical steering signals inducing a gentle bunt to achieve the right position for visual acquisition of the target by the pilot. By flying to place the aiming mark of the HUD over the desired target on the ground, the radar, with its boresight slaved to the aiming mark, could then measure the range along this boresight to the intersection with the ground. From this range and range data, the weapon release point could be computed.

An interesting example of adapting the designs of the avionic equipment to the particular operational exigencies of the TSR2 is the Forward Looking Radar Display located in the rear cockpit. To offset the expected high turbulence which would have made it difficult and tiring for the navigator to focus his eyes on the display, the CRT was viewed indirectly via a lens and a mirror forming a long folded optical path and which had the effect of making the image on the display tube appear to be at infinity and therefore quite steady to the observer despite any ambient vibration of the display or himself.

Radar Navigation and Reconnaissance

The Forward Looking Radar and the Doppler Radar were not the only radars on the aircraft. A sideways looking X-band navigation radar from EMI, utilising two long arrays, one on either side of the aircraft, was fitted for the purpose of presenting a detailed view of the ground and a method of allowing 'fixes' to be obtained which could be used to correct the prime Inertial Navigator.

The transmissions were switched alternatively from one array to the other to give a complete ground picture centred on aircraft track. This was to be presented to the observer by an unusual, one might almost say bizarre, display system or Rapid Processor as it was also known.

Since SLRs utilise the forward motion of the aircraft to scan the ground, the picture must be built up by a series of adjoining strips or lines on the CRT display, each representing the returns from an individual or group of transmit pulses. These lines must be integrated continuously to show the complete map and in the case of TSR2 this was to be done by exposing the lines on the CRT to a photo sensitive strip of film which was being moved past the CRT and then instantaneously developed using a series of chemicals contained in bottles attached to the display. The complexity of the mechanisms which must have been required to operate this system successfully in the ambient conditions of the cockpit is remarkable.

A further aid to navigation provided on the aircraft was a projected

Moving Map Display, also from Ferranti. This held a large area of Europe on 35mm film and was driven by the Navigation Computer to present position in the centre of a ground glass screen. Zoom and look forward facilities were available by selection. A repeat display was provided in the front cockpit. In its initial form the Moving Map Display was independent of those of the radars but later developments allowed these to be combined so the map overlayed the radar display and made it easier to recognise ground features and update the navigation system by bringing the two displays into coincidence. Again this might well have been a future upgrade to TSR2.

To meet the requirements for gathering data in the reconnaissance role, a special underbelly pack was to be provided. This contained, besides a panoply of cameras, a very high resolution Sideways Looking Radar operating in Q-band (37GHz) and an optical line scan unit. Both developments by EMI. The outputs from these units were to be held on a separate photographic recorder although it is interesting to note that studies were started of a ground processing and replay facility which was to have data relayed by video link from the aircraft in flight. It is difficult to see, in the absence of satellite communication how this broadband link was to be maintained over long distances and with possible terrain masking. However, in the event these studies were not carried through to full development.

AFCS

The Automatic Flight Control System (AFCS) provided two separate functions:

1. Three axis autostabilisation involving control of both fin and tailerons.
2. Autopilot/flight director control in a number of modes involving control of the aircraft in azimuth and elevation.

The AFCS had the distinction of being one of the few systems to be tested, in part, at least, on board the TSR2 aircraft itself.

It was completely analogue in design which leads to the interesting question of whether such systems were easier to qualify and gave as high a standard of airworthiness as the modern digital systems with their well publicised software problems, even though their scope for implementing sophisticated aerodynamic control laws was more limited.

By the time the TSR2 project was prematurely terminated, most of the avionics equipments described were in an advanced state of development and probably all of them had been subjected to flight trials although sadly a complete avionics system was never flown in the TSR2 itself. Many equipments, however, including the Forward Looking Radar, had been installed in the No 3 TSR2 prior to flight test when the end came.

Some elements of the development work on avionics equipments were allowed to continue although much of the valuable experience which would have come from the TSR2 flying was lost. An example was the increased interest which was taken in both measuring and improving the reliability of avionic equipments by formal testing and assessment programmes. In the case of the Forward Looking Radar, for example, this allowed the development batch of 18 radars to be finished and the extensive testing and improvement programme to complete many hundreds of hours of testing.

It is probable that not many of the equipments were allowed this stay of execution, although they undoubtedly formed the basis for further developments, reappearing in new forms in later aircraft projects, some of them in the US, the Head-Up display being a notable example, suggesting that the technology of the TSR2 avionic systems was, in many respects, ahead of its time and fully in step with the advanced nature of the aircraft itself.

Acknowledgements

I would like to thank the following people for the supply of information and their assistance in the preparation of this paper:

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Ferranti and TSR2

Sir Donald McCallum CBE FEng FRSE DL

Sir Donald McCallum was educated at George Watson's School, Edinburgh, and Edinburgh University where he graduated BSc in Electrical Engineering in 1942. After wartime service with the Admiralty Signal Establishment, he joined Ferranti Ltd in 1947. He became Project Leader on airborne radar and was responsible for teams developing AI 23 for the Lightning and BLUE PARROT for the Buccaneer. He was General Manager Scottish Group Ferranti and a Director of the parent company. His account of Ferranti's involvement in TSR2 sheds light on the systems involved and his observations on project management are especially revealing.

The three major programmes that Ferranti was involved with for the TSR2 were the development at Bracknell of the Inertial Platform designed by Barnes of the Royal Aircraft Establishment (RAE) and the design and development of the Forward Looking Radar and the Moving Map Displays at Edinburgh. Until early 1968 I was Manager of the Electronic Systems Department in Scotland responsible for these two projects. Before concentrating on the Forward Looking Radar (FLR) and especially on the terrain following mode, one aspect of the Moving Map Display deserves at least a mention. Later the computer was modified slightly to become the attack computer for the Nimrod and continued unchanged into the Mark 2 Nimrod. Even in 1962 it was extremely old-fashioned in its technology, ball and disc resolvers, not a digit in sight. Maybe there is a moral somewhere.

In 1957 Mal Powley and I went to a meeting at Warton to discuss missile integration for the Lightning with Hawker Siddeley Dynamics. Their aircraft was delayed several hours and in the waiting period Tony Simmons told us of some of English Electric's forward thinking. The high altitude which the Canberra had used was no longer a safe defence with advances in guided weapons. The best defence for future strike aircraft seemed to be in very low level flight where advantage could be taken of hills and valleys to provide concealment and the task of the guided weapon made technically more difficult because of ground clutter. However, it was clear that such a path could not be flown visually, certainly not in the night and bad weather conditions which gave extra security. Simmons then told us of a proposal for a radar system scanning in the vertical plane and using Q-band (0.8cm wavelength) to get adequate resolution. Immediately we both exclaimed that the work Ferranti had done on monopulse (static split) air-to-surface ranging at X-band (3cm wavelength) would give more accurate information and reduce the weather problems inherent with Q-band. Within a few minutes we had outlined the so-called angle-tracking system in which the radar tracks the ground ahead of the aircraft and determines by measurement of the difference between this angle and the aircraft's flight vector the appropriate flight path.

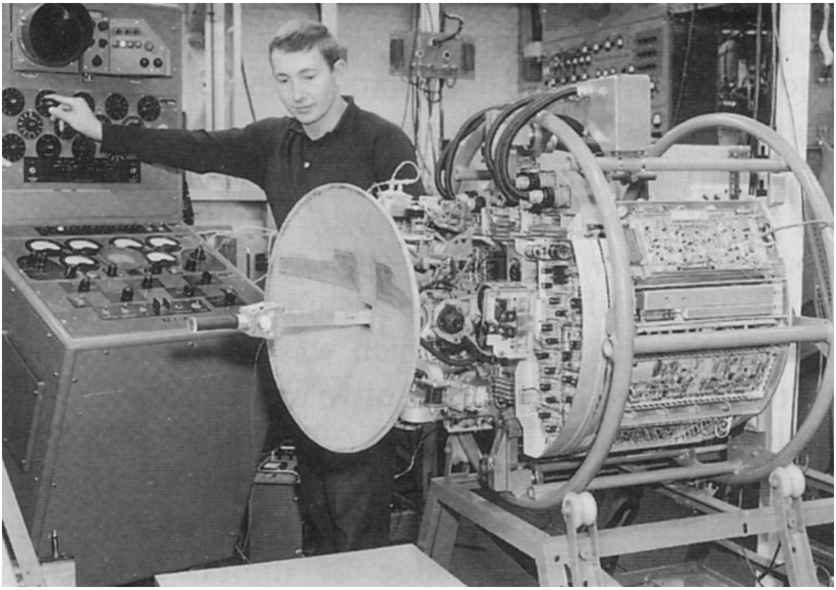
Very little happened for some time after this until a meeting was held in, I think, 1960 at Castlewood House to discuss the problems of low flying for the TSR2. We put forward our proposal and the representative of the Royal Radar Establishment (RRE) described their preferred solution, which involved a pre-planned tape recording of heights along the planned route with voice instructions to the pilot on change of height. Although this may be regarded as a primitive version of the Tomahawk system it found little favour, especially with the pilots present. The Director of Electronic Research and Development (Air) (DLRD(A)) in the Ministry of Aviation then provided funding for work to be done on the Ferranti proposal. A detailed system study was done and existing information on radar returns from ground surface and obstacles was studied. Accurate information proved to be very scanty, in fact virtually non-existent, and a programme to establish quantified information had to be established. This involved detailed measurements from a ground site at Linlithgow near Edinburgh which included a wide range of targets, including a palace, and flight observations from a Dakota to determine the type of echo from, *inter alia*, television towers and power lines. These showed, in the case of trees, for instance, that while some echoes appeared to be from below ground level there were always echoes during a series of a few pulses from the top or higher than the actual tree. This gave confidence to continue with the system design. While this programme of basic measurements was proceeding RRE had discovered the work at Cornell Aeronautical Laboratories on an angle-scanning system. The system had many similarities to the original ideas described by Tony Simmons but using an X-band monopulse radar. What can be described as a battle of the systems then took place between RRE and Ferranti. It was brought to an abrupt end by a letter from DLRD(A), prompted doubtless by John Mills of RRE, stating that Ferranti must adopt the angle-scanning system or the contract would be cancelled. While an effective method of settling the controversy, unfortunately the technical arguments were never debated in a non-partisan fashion. Looking back I think the right decision was made, as the scanning system had a reduced risk of the aircraft hitting the ground. On the other hand it did give a greater and distinctive warning to ground defences of its approach. I must admit, however, that after more than thirty years I still feel nostalgia for the elegance of the tracking system compared to the brute force of the scanning system.

The Forward Looking Radar (FLR) used many components from the AI 23 and AI 23B radars fitted to the Lightning including the mechanically roll-stabilised scanner. This was to prove of great value in turning flight. The transmitter power was reduced from 250kw in the AI series to 50kw which was still considerably higher than competing equipments and a considerable safety advantage at very low levels of flight. The electronic circuits were, of necessity, a new design using sold state devices. The argument, a true but unfortunate one, that integrity was absolutely vital allowed the computation for the so-called 'ski-toe' flight path computation to be carried out in the radar and avoided the central digital computer which was at the heart of the 'system concept' strategy which dominated the thinking on the aircraft. An important part of this computation aimed to eliminate any 'ballooning' when the aircraft crossed a ridge.

There were powerful voices in both the Ministries of Defence and Aviation and also at Weybridge which wanted to adopt the American Texas Instruments radar (the Texas Ranger as it was known in Ferranti) under development for the F-111 instead of the Ferranti radar. This would then have been procured under sub-contract from BAC Weybridge as were the other main equipments. The Electronic Directorate in the Ministry of Aviation was, however, determined to support the British development. At times the relationship between CGWE (Controller General Weapons and Electronics) and the Director of Operational Requirements (DOR) was at an extremely low ebb. I remember on one occasion being asked by the then CGWE, Sir Steuart Mitchell, to act as a go-between with DOR as normal relations had broken down.

Ferranti was thus, for both technical and political reasons, somewhat of a cuckoo in the system concept nest. Indeed we were uncertain what the words 'system concept' meant or what they added to achieving a successful aircraft. In our previous experiences on the Lightning and the Buccaneer the aim had clearly been to develop and produce a total system to meet the operational requirement. In both of these aircraft there was no question who was responsible for the overall design, Freddie Page on the Lightning and Barry Laight on the Buccaneer. In the case of the TSR2 this was never clear to me nor, I think, to my colleagues. The enthusiasm which the earlier programmes generated was absent. The 'system concept' meetings isolated us from the aircraft and I never saw a TSR2 airframe during the entire programme. These meetings had an unreal air, perhaps in line with the dictionary definition of concept as 'an abstract idea'. There was a magnificent block diagram which Howard Surtees of EASAMS had produced which was the definitive plan of the system and which was much in evidence at early meetings. Initially, the meetings were chaired by George Henson and were long on discussion but short on decision. For instance, there was a problem with transients on the 115 volt 3 phase 400 hertz supply which took many man-hours of talk on the possible causes of such an annoying problem when all that was needed was for the designers of the power supply to be told to fix it; which they eventually did. Later Clemow took the chair which raised the intellectual level of the discussions but did little to accelerate decisions. In the last year or so of the programme Sir George Edwards put Harry Zeffart in charge of equipment. 'Twenty eight volt Harry', as the system concept men called him, quickly brought realism to the situation. Having been through the fire of getting the Valiant and other aircraft into service, he knew the hard grind which is essential and that repeating the words 'system concept' as a kind of mantra was no substitute for action. His appointment two years earlier would have transformed the equipment situation.

Despite the growing evidence that the development of the FLR was going well there was continuing pressure from various quarters to drop the FLR and use the Texas equipment being developed for the F-111. During one session in 1964, when George Henson was supporting this proposition, Mal Powley said to him, 'George, you



Forward Looking Radar under test

ought to be careful advocating the superiority of American equipment because the customer might think that applied to the whole aircraft.' To which Henson replied, 'You know, Powley, I have heard you say some stupid things in the past but that exceeds them all.' At 2am on 6 April 1965 Ferranti engineers completed testing the first FLR installation in a TSR2 and in the afternoon of the same day James Callaghan, Chancellor of the Exchequer, announced the cancellation of the TSR2. A decent interval was to pass before the planned purchase of the F-111 was made official.

As nearly three-quarters of our defence design effort was committed to the TSR2, this created a degree of concern in the Edinburgh management. The fact that the FLR programme was directly with the Ministry and the determination of the then DLRD(A), Air Commodore Frank Tyndall, to complete the Buccaneer trials were invaluable helps. The twenty or so development models under contract were finished and some of these were used for many years at RRE for various research activities. The whole FLR programme reflects great credit on the team led by Dick Starling and Greg Stewart and on our chief test pilot, Len Houston, who flew the flight trials manually using the steering information displayed in the Head-Up display. A film, now nearly 30 years old, recorded some of these tests including a low-level flight lasting the best part of an hour.

When the Buccaneer flight trials were completed and analysed and the results shown to Frank Pelton, the pioneer of terrain following at Cornell, he told us our achieved performance where we had demonstrated flights at 100 feet over the Scottish Highlands compared to the design target of 200 feet was several years ahead of the rival work in the States. The turning flight performance was unique.

The Computer System

Peter Hearne FEng MSc and Paul Rayner BSc

Peter Hearne had a distinguished career in the aviation industry and retired as Chairman of GEC Avionics in 1994. Earlier, as an engineer, manager and later director of Elliott Flight Automation, he played a major part in the development of computer systems for TSR2 and other aircraft. He was President of the Royal Aeronautical Society in 1980 and is a keen glider pilot.

The reliance of TSR2's systems on computer power was just one of the novel and demanding aspects of the project. This paper, written by Peter Hearne in collaboration with his colleague Paul Rayner, shows the extent to which later projects benefited by the work done for TSR2.

Choice of Contractor

At the time of the realisation of the TSR2 the need for precision calculations in inertial navigation systems and the increasing difficulties of combining large numbers of different analogue electronic subsystems in an overall integrated multi-function system had become increasingly apparent in the development of the Navigation Bombing System Mk I (NBS1) for the V-Bombers and the BLUE STEEL inertial navigation system.

These difficulties led to the TSR2 specification of a system based upon a central digital computer to be used to give the precision of calculation and improved capabilities in the integration and multi-function aspects of the system. Although GEC Stanmore had developed a prototype digital computer/differential analyser (called Dexan) in association with RAE Farnborough the prototype unit was far from mature and lacked the necessary software development infrastructure, even for the 'small' (by modern standards) amount of programming required; some 4K to 8K words! It must be said, it appeared a major task to us at the time. It is worth commenting that for TSR2 some 90-95% of the development effort was devoted to hardware associated matters, most of which was entirely new and unfamiliar technologies, and 5-10% to software matters. (On the Jaguar it became more 80-85% hardware 15-20% software. In 1997 for Eurofighter and F-22 it is probably 5% hardware to 95% software).

Although RAE preferred their own Dexan machine, Elliotts had considerably greater overall knowledge of digital computing stemming from their work in this field since 1949-50 when they produced the first real time UK digital computer for a highly ambitious Royal Navy fire control system. Additionally Elliotts were the prime contractor for the BLUE STEEL inertial navigator and the NBS aircraft interfaces. Putting this background together with an aggressive campaign to licence and market the North American Aviation Verdan computer, Elliotts won the contract for the central digital computing system, the first in a European aircraft.

The Verdan Computer

Verdan had originally been designed to carry out inertial navigation calculations and platform control on the earliest US Navy nuclear submarine (*Nautilus*) and on the Navajo cruise missile. It was later adopted for the Hound Dog cruise missile and for the NA A3J Vigilante's integrated system, known as REINS, where it performed a central computer task not unlike but considerably less complex than on the TSR2.

Verdan was a combined General Purpose/Digital Differential Analyser (GP/DDA) implementation. The computer operated in serial mode and had very limited capability compared with even the most modest PC today. To allow it to operate in real time, a DDA (the digital equivalent of an analogue computer) and a general purpose CPU shared a common rotating disk memory. There were a number of simple analogue (voltage), serial digital and switched input and output channels.

We originally attempted to programme the whole task in the DDA, emulating the approach that would have been taken with an analogue computer, with the GP being used to set up initial conditions and to handle the operator interface. However the DDA is subject to drift when handling trigonometric functions (which was most of the time), and needed constant resetting. Eventually the computational approach changed to carrying out all the functions in the GP with the DDA being used for extrapolation between successive computational cycles.

Interface Equipment

A number of additional boxes of electronics had to be designed by our team at Borehamwood to integrate the computers into the aircraft system. The main ones were an Interface Unit whose primary task was to translate from servo signals to digital and the reverse, a Navigator's Control and Display Unit and a Reconnaissance Buffer Store. Each posed its own unique problems and none of the design tasks were as straightforward as may have appeared at first sight.

The Interface unit, known as the IOU, housed six digital servos and electronics to harmonise a motley array of signals from other system components, converting them to match the signal channels provided by the computer, and similarly to match the output signals from the computer to the rest of the system. Servo inputs were fed to a servo receiver, the output shaft of which was connected to a digital encoder through suitable gearing to get the required resolution. The characteristics of digital servos were not well documented at that time and a considerable amount of experimental work was required to characterise the servo, to investigate its stability and ultimately to come up with an optimised design.

Probably the most difficult design task was the Navigator's Control and Display Unit (NCDU). We had been allocated a space about eighteen inches high at the right hand side of the cockpit spanning the junction between the upper and lower sections of the cockpit structure. The mechanical design of the unit was a nightmare. The box had some twelve faces of which only two met at right angles and at least one was curved – this was in the days before computer aided design. The fixings provided for the unit were at its base with rear mounted connector to allow it to be jacked in and out for maintenance purposes. These fixings proved to be inadequate for a unit of its size and weight and a top fixing was added.

The unit then became a structural member linking the top and bottom sections of the fuselage which brought additional complications. Ultimately the top fixing was replaced by a 'steady'.

Suitable keyboards were not commercially available in the early 1960s so we had to design our own. The result bore more resemblance to a typewriter keyboard with its mechanical levers than the modern membrane keyboard.

The only alphanumeric display elements available then were neon discharge devices called Nixie tubes. They had a stacked set of cathodes, each in the shape of a number or letter, which were selected individually and viewed through the end of the tube.

The NCDU was connected to the computer by a digital data bus.

Again nothing like this had been attempted before so we designed our own which worked well. It was another ten years before the digital data bus became the transmission standard for military digital systems.

The design of the NCDU was commenced in about 1960 using germanium transistors (as did Verdan). Silicon transistors did not become generally available until a year or so later and I recall an agonising decision as to whether we should change to the new silicon components, which meant changing the polarity of all the circuits we had designed. I am pleased to say we took the right decision (for once).

The Reconnaissance Buffer Store (RBS) was used to pass navigation data to the reconnaissance pack. The requirement came along relatively late in the development of the project and technology had moved on. Without letting it be widely known at the time, because of the potential risk and increased cost, the decision was taken to use the newly available Integrated Circuits (four gates in one package) in its design. This must have been another 'first', in the UK at least.

One of the major unsung contributions of the TSR2 programme was the introduction into the UK of the 'high quality burnt-in component' concepts which had been developed for high reliability requirements in US 'strategic' weapons systems. Commonplace today it represented a major advance in avionic equipment reliability in the UK at that time.

System Mechanisation and Installation

The central computing system was required to carry out all of the special weapon bomb delivery calculations and all of the outer loop navigation calculations together with the integration of all of the navigation sub-systems. This required the tying together in a common time/spatial reference of the Ferranti inertial platform, Decca Doppler and Thorn EMI sideways looking radar. This enabled such functions as Fix Monitored Azimuth waypoint storage and steering, Doppler Inertial mixing and similar modes to be implemented. As well as outputs to the navigator's displays, additional outputs went to the AFCS, moving map, HUD and at a later date the Forward Looking Radar. At this time also a conventional bombing mode was put into study.

The critical dependence of the aircraft's operational functions on the central computing system caused Elliotts to propose a duplicated system whose concept was based in part on the fail operative philosophy of the automatic landing system then in development for the Vickers VC10. The solution chosen was to allocate 'primary navigation plus secondary bombing' to Number 1 computer and 'primary bombing plus secondary navigation' to Number 2.

The Autonetics company, who were necessarily privy to some of our design decisions, were impressed with this 'graceful degraded redundancy' idea and, without our knowledge, adopted it for the General Dynamics FB-111's all singing and dancing system configuration, which has only recently gone out of service.

Although a central digital system had been specified for the TSR2 nobody, including Vickers, had any hands-on experience concerning the 'codes of electrical engineering practice' necessary to avoid signal corruption or equipment damage from power supplies or signal or other spikes and radiated interference. We learnt as we went along to pay particular attention to common signal earthing systems, spike suppression on relays, power supply interrupts all of which were essential engineering solutions to obtaining a reliable functioning installation.

A further difficulty imposed by Vickers was their insistence on repackaging the Verdan computer in a slightly different form factor so that it would meet Vickers requirements for a common modular standard of back-connected shelf-mounted equipment. This was a costly, time-consuming and wasteful exercise and at the end of the day there were still many other systems equipments which had not been repackaged to this modular standard. Moreover, we had begun to encounter very high connector 'loads' associated with the large number of back pins. It is doubtful whether this type of extravagant 'preference' would be allowed in today's world.

The Outcome

Experimental systems flew in Hastings and Comet aircraft at Boscombe Down, the latter ultimately forming the test bed for the later Elliott development of its indigenous 920 computer which, in various forms, went into the Nimrod Mk. I and Mk. 2, some 300 Jaguars and many other UK military programmes.

Although a complete system was ready to fly in the third TSR2 the cancellation prevented this from happening.

The TSR2 central computing system was not only a first for the UK and Europe but in its concept and functionality was in fact a world first as witness the adoption of the configuration by the FB-111 programme.

More importantly it spawned generations of new digital avionic systems for the UK and Elliotts, in particular the Jaguar, Nimrod 1 and Nimrod 2.

Perhaps its most effective outcome was to cause the Elliotts team to realise the problems of cost effectiveness and reliability associated with large centralised computer systems and to encourage us to develop a single function digital computer which, according to the simple minded specification, should be 'no heavier, no larger and no more expensive than the single analogue computer it replaces'.

This concept led to the first practical implementation of a federated system, as opposed to a centralised one, another UK first which began in the Tornado and is currently the accepted avionics norm. Elliotts (now GEC-Marconi Avionics) alone has produced more than 30,000 of the type of federated computer units which emerged from these developments and they are widely used in flight control, air data, head-up displays and navigation systems in such diverse aircraft as the F-16, C-17, F-111, Eurofighter, Phantom and Tornado to name but a few of the twenty-five distinct types of airframe to which they are supplied.

Post Meeting Comments

A number of the system group discussion members criticised the complicated technologies used in the analogue/digital interfaces and the lack of capacity of the Verdan computer. I hope this account will show that we were well aware of these problems and were actively working towards a Mid Life Update type of solution. Vickers and ourselves calculated some 2,000 lbs of cabling weight would be saved by a digital highway implementation; something not possible in the initial fit which used so many 'existing' GFE equipments which were almost all 'strongly' analogue. However we did have our own internal digital bus in the computing sub-system which worked well as did another innovation, the integrated circuit group in the Recce Buffer Store.

Computer storage capacity was always a problem from Day 1. However in early 1959 there were very few rugged computer stores of any type and the drums and core systems of the, then emerging, computer industry were in no way suitable for the TSR2 flight envelope. We did have in mind to use the doubled ‘two faced’ disc of the marine version of Verdan (which also went into the UK Polaris boats) as an interim Product Improvement Programme for the early production aircraft. This would have given us 8,000 words total.

Our longer term solution was based on a ‘soldier proof’ computer which Elliotts had designed for a tank AAA fire control system which had a ruggedised 1 microsecond core store, unheard of in those days; alas! with only 500 words of memory. This computer suitably shrunk and micro-miniaturised together with the other digital technology improvements of the early 1960s became the 920M of which some 400 went into various Jaguars. These grew in time from an 8K to a 64K store and formed the heart of an airborne computing system which drew heavily, and successfully, on the background of TSR2. A further benefit was the 920ATC used in all the maritime Nimrod 2s and in many ground installations, which weighs in with 256K of storage. However, none of this was available in mid-1959 and Verdan had the unequalled and unique advantage of being available as a fully qualified unit. There were not <u>any</u> others, except for the emerging Hughes system in the F-106.

I believe the discussion showed that the Vickers/contractor integration team worked in a very harmonious fashion which did in fact produce a very effective systems integration. The Vickers ground rig was a precursor of today’s digital ‘iron birds’ and came together with remarkably few problems. Inter-contractor relationships were undoubtedly helped by the lack of contract squabbling which almost inevitably happens on today’s fixed price programmes, particularly when the price is being squeezed below a reasonable level to do the job. However, the downside was a lack of cost targets and cost control. Change control in terms of costings did exist but customer requested changes in the technical specification seemed to have a much greater priority than the maintenance of cost targets. The balance between the customer’s wish (or even dream) list and his bank account was definitely not being properly monitored by the various Ministries.

Hopefully all sides learned from the experience. I know that some 20 years later as a prime contractor on the F-16 we were able to have an equally harmonious relationship with General Dynamics and at the same time exercise well-planned budgetary control on a sensibly profitable programme – of some 6,000 systems!

Automatic Flight Control System

Douglas Gemmell BSc

Douglas Gemmell graduated in Aeronautical Engineering from Glasgow University in 1958 and has worked exclusively in the avionics industry since then. He was part of the English Electric team working on the flight development of avionic systems for the Lightning. Later, he led the systems design team at Elliott Flight Automation for the TSR2 automatic flight control system. Since cancellation, he has been involved in the development of automatic flight control systems for Concorde, of fly-by-wire and V/STOL aircraft control systems, and of large CRT 'glass cockpits'.

The TSR2 automatic flight control system broke new ground and included many advanced features which are well described in Doug Gemmell's necessarily somewhat technical paper.

Health warning

This note has been created without the availability of any documentation written at the time of the development and hence has relied totally on my memory. If any reader spots what they consider to be inaccuracies or important omissions, not only do I apologise but I congratulate the reader on their special powers of retention of such technical detail.

Introduction

The design and development of the Automatic Flight Control System for the TSR2 aircraft was a co-operative effort between British Aircraft Corporation, Elliott Automation and HM Hobson.

The Weybridge Guided Weapons team of BAC had overall 'Nav Attack System' responsibility. The Warton team having responsibility for the aircraft stability, control and handling qualities had the major role in working with Elliotts on the autostabilisation system. HM Hobson was the hydraulic powered flying control supplier and had a major contribution to the design of the multiplex first stage actuation system.

The System was a revolution in the design of autostabilisation and autopilot systems in terms of both system's architecture and control laws as a result of the following requirements:

(a) The aircraft was directionally unstable above about Mach 1.5.

(b) The natural aircraft pitch manoeuvrability at subsonic speeds was inadequate for low level ground attack.

(c) The low speed dutch roll characteristics were such that a conventional yaw damper was ineffective in improving handling qualities.

(d) A wide range of autopilot capability was required including automatic terrain following at heights down to 200 feet above ground level.

Aircraft Control Surfaces

Aircraft pitch and roll control was by two horizontal all-moving surfaces, called tailerons, which operated collectively as an all-moving tailplane to provide pitch control and differentially to provide roll control. There were no ailerons on the wing, the complete wing trailing edge being used for flaps. Directional control was provided by an all-moving fin, rather than a rudder on the trailing edge of a fixed fin.

For convenience, the terminology used in this paper includes aileron (for differential taileron) elevator (for collective taileron) and rudder (for all-moving fin deflection relative to the fuselage).

Lateral-Directional Autostabilisation

The directional instability at high Mach Numbers necessitated the provision of artificial stability and demanded that a single failure would not result in loss of control. A triplex architecture was selected with majority voting between the three lanes. The voting arrangement was incorporated on the output of the triplex first stage electro-hydraulic actuator which drove a duplex tandem primary hydraulic power control unit of the all-moving fin control surface.

The majority voting implementation comprised hydraulic pre-loaded 'spring boxes' between the output of the three individual electro-hydraulic actuators and the consolidated mechanical input to the fin power control unit. The spring boxes allowed limited movement between the three actuator outputs and a microswitch was operated should any spring box limit be reached, thereby providing to the pilot a warning of a lane failure. Within the limits of the spring box travel, the outputs of the three actuators were averaged by a summing linkage; as soon as the spring boxes 'bottomed' force coupling allowed the majority voting to come into effect. Under normal conditions the pilot would then decelerate into a stable flight regime.

Sensing of slide-slip, which was the fundamental requirement to provide artificial directional stability, was from triplex lateral accelerometers. The accelerometers were mounted forward of the centre of gravity so that the lateral acceleration resulting from rudder application was approximately nulled by the lateral acceleration due to yaw acceleration.

The accelerometers were also positioned, taking into account the position of forward nodes of the fuselage first and second lateral bending modes; to ensure that the autostabilisation system did not destabilise these structural modes – a very real problem for a high performance autostabilisation system when the frequencies of the 'quasi-rigid' aircraft dynamic modes were less than a decade separated from the structural modes.

Triplex yaw rate gyros provided the basic dutch roll damping. These were mounted ahead of the anti-node of the fuselage lateral first bending mode. In addition to careful positioning of the accelerometers and gyros, notch filters were also included to attenuate feedback at structural mode frequencies with minimum phase lag at lower frequencies.

The aerodynamic characteristics resulting from the small high-mounted delta wing and the low roll inertia resulted, particularly at low airspeed, in a conventional yaw damper using yaw rate via a wash-out filter being ineffective. Not only did this conventional system provide inadequate damping but with the high gains required, large amounts of transient adverse yaw occurred on entering turns. A 'sideslip-rate' or 'beta-dot' control system was implemented which was highly effective in both dutch roll damping and in turn co-ordination since it provided pro-turn rudder on initiating a turn.

Sideslip-rate could not be derived satisfactorily either from a lateral accelerometer, because of the risk of destabilising a structural mode, or from a sideslip vane, because of the effects of turbulence. A close approximation of sideslip rate was derived by computation.

$$(\dot{\beta} = -r + p\alpha + {}^{g}/v \sin\varnothing \cos\vartheta$$

Where: r = Yaw rate Ø = Bank angle
p = Roll rate ϑ = Pitch angle
α = Incidence v = True airspeed

Because many of the sensors required for the necessary computation were single sourced the full control law for sideslip-rate was single-lane limited authority with only the yaw rate being triplex; and, in the event of a failure of the single lane computation, the yaw damper reverted to a conventional yaw rate with 'wash-out' filter – which was adequate at high airspeed/low angle of attack flight conditions.

Pitch Autostabilisation

Ground attack was one of the roles required of the TSR2. As an inevitable result of the high wing loading – a deliberate design feature to minimise the response to turbulence during prolonged low altitude cruise and interdiction – at typical ground attack airspeeds of 400-500 knots the pitch response was poor.

To provide good normal acceleration response to fore/aft pilot 'stick' movement a 'manoeuvre boost' system was provided. This was, in effect, a simple normal acceleration manoeuvre demand system where control column input was fed to the autostabilisation system as a normal acceleration demand and compared with actual normal acceleration from accelerometers. This autostabilisation control was subject to 'wash-out' so that the steady-static 'stick-force' per 'g' was unaffected and determined by the design of the mechanical control and hydraulic feel system. This system was operative only at subsonic speeds.

Pitch rate feedback via a wash-out filter was introduced throughout the flight envelope to improve damping of the short period pitch oscillations. As in the case of the lateral-directional autostabilisation system, the positions of the rate gyros and accelerometers were chosen carefully in relation to the fuselage vertical bending modes; and notch filters were incorporated in the sensor signals.

The Autopilot System

The TSR2 autopilot system provided the most comprehensive range of flight control system modes of any aircraft of its generation. The system architecture was determined by the most critical mode –

automatic terrain following where the design objective was full automatic flight control at altitudes down to 200ft above the local terrain. Subsequent experience may well have suggested that to be an ambitious objective but that symbolises the overall ambition of the TSR2 project. However ambitious the objective may have been, the implementation and safety design were quite realistic and pragmatic.

The Terrain Following System

The Terrain Following System was based on the Ferranti forward looking radar system which made a vertical scan of the terrain ahead of the aircraft. Also included in the sensor system was a radar altimeter.

The fundamental concept throughout the terrain-following system was to follow the 'more nose-up' command of duplex sensor and computing lanes. Thus the 'more nose-up' command between the forward looking radar and the altimeter determined the signal which the autopilot (and flight director) took as the command signal.

Similarly in each radar scan the 'more nose-up' flight path command was determined. In order to avoid high terrain at longer range causing the aircraft to fly at unacceptably high altitude above the local terrain the forward looking radar signals were subject to a 'ski-toe' filter; which meant that the longer the range ahead of the aircraft the higher the terrain had to be before its signal was taken into account. The shape of the ski-toe was therefore the actual factor in determining how close the command flight path was to the local terrain and how early the commanded flight path responded to the terrain profile ahead of the aircraft.

The forward looking radar system provided to the autopilot a flight path angle command signal, via duplex output stages with duplex limiters on the command flight path.

The Pitch Autopilot System

Safety Architecture

The 'more nose-up' concept was maintained throughout the pitch autopilot inner loop system with duplex computing lanes and a duplex electro-hydraulic actuator driving the tandem taileron powered flying controls. The electro-hydraulic actuation system comprised two duplex actuators, ie acting simultaneously in parallel. A 'more nose-up' mechanism was incorporated between the mechanical output of the electro-hydraulic actuators and the input to the tandem flying control.

In the autopilot mode the taileron electro-hydraulic actuation system was reconfigured from the limited authority mode used for autostabilisation into a full authority system. Although manoeuvres were limited by pitch rate demand electrical limits an independent 'manoeuvre monitor' was provided which cut out the autopilot if normal acceleration limits were exceeded.

Pitch Manoeuvre Control

The lane pitch control system was based around a pitch rate manoeuvre demand 'inner-loop'. All autopilot 'outer-loop' commands were converted into pitch rate command signals via an appropriate gearing and a lead-lag filter to provide outer loop stability. The pitch rate command was limited as a function of flight envelope – essentially true airspeed – to provide a normal acceleration limit for the specific flight conditions.

The pitch rate command included the turn co-ordination term:

$$q_D \; {}^{g}/_{v} \sin \varnothing \tan \varnothing$$

to provide highly responsive turn co-ordination before developing any outer loop errors, eg terrain following flight path, height etc.

The inner loop pitch rate demand system was a classical 'proportional plus integral' control system – but until this time not used in autopilots.

Thus $q_D = \frac{1+ST1}{1+ST2}$ (outer loop error function), with q_D limits

and $\eta = G_q \left(1+\frac{1}{ST3}\right)(q-q_D)$

This provided a tight response to commands, responsive elevator application to trim changes and as referred to above, good turn co-ordination.

The complete inner loop system, except the turn co-ordination command, was implemented as a duplex 'more nose-up' architecture.

Other Pitch Autopilot Modes

In addition to terrain following, a full range of autopilot modes was provided:

- Height Lock and Height Acquire
- IAS or Mach No Lock – under elevator control
- Automatic Bombing Manoeuvres
- ILS Glide Slope acquire and hold as an integral feature of the auto-approach mode.

Autothrottle

An 'autothrottle' function was provided as part of the auto-approach system, to provide control of airspeed which was particularly important as the approach speed was well below minimum drag speed.

The 'throttle' command signal was fed via limiters into both the Olympus engines' electronic control systems.

Roll Autopilot

The autopilot modes provided included:

- Bank angle command from a command knob on the cockpit AFCS control panel.
- Heading acquisition and hold.
- Track acquisition and hold, the track lateral deviation being provided by the 'Verdan' navigation computer.
- ILS localiser acquire and hold as part of the auto-approach system.

The control law architecture comprised a roll rate control inner loop implemented in duplex architecture with duplex roll rate command limits, the roll rate command being a function of bank angle error; and a bank angle control loop with variable bank angle command limits depending on flight conditions and autopilot mode.

The command bank angle was a function of the outer loop error i.e., heading, track and localiser.

ie $\xi_D = Kp\,(p - p_D)$ with ξ limits

$p_D = pK\text{Ø}(\text{Ø} - \text{Ø}_D)$ with p_D limits

and Ø_D either from the autopilot controller, heading error, track error or localiser.

Electronics

Previous generation military autopilots in the UK, for example those for the English Electric Lightning and Blackburn Buccaneer, had suffered from being implemented with magnetic amplifiers. Fortunately, the silicon transistor had become available before the design of the TSR2 AFCS.

The electronic implementation was based upon DC operational amplifiers utilising individual silicon transistors, the individual amplifier modules being constructed in a 'log-pile' or 'cordwood' arrangement. The multiplication functions, including control law gearings, were implemented by electro-mechanical servo multipliers. Actuator position feedback was from carbon film potentiometers.

The complete electronic design had to be sensitive both to the need to minimise phase lags in the implementation and to accurate matching of lanes in the multiplex parts of the system.

Conclusion

With the abrupt cancellation of the project in April 1965, little flight experience was obtained of the many novel features of the system. Extensive ground testing of the structural feedback from the rate gyros and accelerometers had been carried out to verify frequencies and node positions.

However, several of the concepts and much of the experience were used in the design of the AFCS for the Concorde by which time integrated circuit DC amplifiers were available providing a major reduction in electronic component count. The triplex actuator concept was further developed by Elliotts in a quadruplex configuration which was the basis of the Tornado electro-hydraulic actuator. Beta-dot stability augmentation has gradually found its way into a number of aircraft often not from the 'beta-dot concept' but from a 'how do we fix this' approach.

The Concorde and Tornado were perhaps the last systems to benefit from a continuity of experience from Lightning, Buccaneer, VC10, BAC 111 and TSR2, all these projects being undertaken within a period of not much more than a decade by the Elliott team with many individual engineers, either common to more than one project, or sharing their experience freely between the projects.

Discussion

TSR2 was an aircraft which attempted to exploit and integrate a large number of systems, most of which were at the cutting edge of contemporary technology. The discussion group led by Air Vice-Marshal George Black explored a number of aspects of this very complex area.

Peter Hearne [then of Elliott Flight Automation] said that the reason that Elliotts had gone for a digital central computing system lay in the accuracy needed for inertial navigation calculations. In addition, the experience of integrating the Navigation Bombing System Mk 1 with BLUE STEEL [for the Vulcan and Victor] had shown the extreme difficulty experienced with analogue computing systems of any degree of complexity. What turned out to be a dual computing system had been selected, in which, even following the loss of one computer, the aircraft would have had a good mission capability. It became a standard computer configuration for American aircraft, as well as British.

The TSR2 flight control system had gone on to form the basis of the system for Concorde and reliability advantages of analogue technology had dictated its use in this application. Tornado had been half-digital and half-analogue but aircraft such as the Eurofighter, Boeing 777 and F-22 employ digital systems and all can trace their origins back to the TSR2 systems.

Responding to an enquiry by **George Black** about the cost control on the part of the Ministries, **Peter Hearne** said that no figure had been allocated but that the company had offered its own quotation. The 'up-front' licence fee for the computer had been substantially less than the costs that followed. What the process had introduced to this country [for the first time] was the high reliability electronic component concept, a spin-off from the US strategic weapons systems and that had certainly raised costs. No major cost disciplines had been imposed on the company.

Wg Cdr George Wilson repeated his belief that TSR2 had not been 'a complete weapons system'.

Peter Hearne rejected that suggestion, citing the work of Brigadier John Clemow who had been appointed Chief Systems Engineer at Weybridge, charged with the systems integration of TSR2. He had run a systems integration panel which met monthly at Weybridge, attended by all the relevant contractors [including Elliotts]. Vickers engineers working for Clemow had provided systems integration. It had been one of the first examples of a good main contractor/sub-contractor integration method with very little contractual squabbling.

Denis Harris, ex-Vickers-Armstrong, had been an employee of Brigadier Clemow, along with colleagues present at the seminar. A large system engineering group had been established at Weybridge, to undertake the specification, design and development of systems and to participate in software production for TSR2. Its members had worked closely with colleagues at Warton. These teams had developed the philosophy of the approach involving rig testing on the ground, airborne trials in other platforms, leading to testing in the aircraft itself. That approach carried on into the Nimrod Mk 1 programme and Tornado. Capacity problems had existed but that reflected the complexity of what had to be fitted in to a [relatively] small machine. The computer itself had been an interesting hybrid, having been designed to solve differential equations and, as a result having within it a digital differential analyser as well as a general programme computer. At the time of cancellation, the installed systems had been 'stimulated, simulated and thrashed to death in terms of testing' and were ready to roll in the third aircraft. That experience was fed forward into the RAF's other programmes.

John Goodwin, who had worked with Denis Harris, said that the Weybridge team had been well placed to influence other groups, by virtue of its extensive knowledge of what was going on in America and of the problems then affecting American programmes, especially over fixed price contracting which, he suggested, resulted in contractors blaming each other for failure. Such problems had not surfaced during the TSR2 because of the ability of the team to feed back problems and to help cure them at source. Equally, some of the problems experienced because of lack of integration in US programmes such as Hound Dog or A3J had been averted because of the ability to cure at source conferred by the system approach.

George Wilson said that he had been talking of the 'entire TSR2 weapon system' and not just the avionics which he readily conceded had been performing extremely well. Other parts of the total aircraft system had not been as successful.

Dr Jim Drury, who had not been involved with TSR2 himself, said that it was important, especially for those who had no experience of such programmes, to remember that this was the first major programme in which this systems engineering approach had been applied. As in all such cases, it would have been wrong to expect perfection at the outset.

Greg Stewart also recalled the system meetings at Vickers. They had been true system meetings and had not concentrated on individual pieces of equipment. The [forward looking] radar, for example had been involved in the flying of the aircraft and its engineers had had to work in harmony with those dealing with other aircraft and avionic systems. Replying to an enquiry by George Black, he confirmed that flight testing by Ferranti in other aircraft had involved the use of other linked parts of the TSR2 system.

Air Cdre John Burke, as a squadron leader, had been seconded to Weybridge to look after the in-service support aspects of TSR2 for the RAF. He commanded the Electronics Introduction Team which was responsible for the support aspects of the nav/attack system and the recce pack. He referred to the Stage 1 rig on the shop floor at Weybridge in which all the parts of the nav/attack system were integrated, a very successful exercise. There had been a very proper systems approach to that part of the [overall] system. **Tony Simmons** paid tribute in passing to the pioneering work of Blackburns who had built the first system test rig from which, through the Lightning could be traced the origins of the successful TSR2 rig.

John Burke was inclined to agree with George Wilson's view that the overall weapon system had not been tackled in the same way. This had been the first time that the RAF had got in on the ground floor of a development aircraft, working on a day to day basis with the contractor. In later service, he had served in MOD(PE) and saw systems tracing their origins back to TSR2. In his view, it had been a criminal act to kill it off.

Air Cdre Dennis Reader had also been a member of the RAF team at Weybridge. As a nav/attack system specialist, he recalled his tremendous admiration for the development ingenuity that had gone into the TSR2 system. However, he had had great misgivings about how the average RAF technician would have coped with it in-service. Each bit of information from the central computer had been exported via encoders, requiring one wire per bit. These wires (a spaghetti) and the digital-to-analogue converters would have posed huge maintainability problems. He had concluded that the RAF would have faced great difficulties for the first years of TSR2 but that, after a 'mid life update', 'there would have been no stopping it' !

Peter Hearne, said that it was important to remember that the project had represented the leading edge of digital technology. The TSR2 integration system had been considerably more elaborate than the partial integration achieved, for example, on the A3J, the Hound Dog or in the Nautilus submarine. The Americans had not had the experience of such elaborate integration as the TSR2. The fact that they had subsequently chosen to incorporate systems and configurations such as had been developed for TSR2 in the FB-111 showed just how great had been the advances made in UK. As a footnote to Dennis Reader's reference to cabling, Peter Hearne said that it had been calculated that around 2 tons of wiring had been needed for analogue signals which would have been reduced significantly by the use of digital interfaces. Although the computer system had had an internal digital highway, it had been impossible to modify Government-supplied equipment.

Tony Simmons, who had been part of the Warton team, suggested that, at the time of the design work on P17A at Warton, the main role of the aircraft had been to deliver a one-kiloton nuclear weapon. The weapon system had been designed to achieve that, with a specified accuracy, given a stated number of opportunities to update the equipment en route. For security reasons, the details of the one-kiloton bomb were not made available to those designing the bombing system, but for some release unit requirements. Otherwise, a system approach had been taken to the bombing system.

Peter Hearne said that there had been an extremely successful systems integration group at Warton for the Lightning. This had brought together products from Ferranti, Elliotts and Smiths Instrumentation, in the radar, flight control, air data and MRG systems and was probably the very first example of successful systems integration in this country. That background experience at Warton had played an immense part in developing the philosophy for TSR2. Where the bombing system had been concerned, at the time of cancellation when an increase in computer capacity [to 8K] was on the cards, first consideration had been given to a 'poor man's' way of dropping 1,000 lb [conventional] bombs but there had been little confidence in that. It had been regarded as a way of making the aircraft more acceptable to the Labour government!

John Goodwin spoke of the problems posed by the Government-provided reconnaissance radar produced by EMI. This [Q Band] radar involved a large metal mass rotating at 24,000 rpm and there had been a fear that a bearing failure could have resulted in its flying through the wing and its fuel tanks. The solution, approved by the airframe manufacturer, had involved introducing a piece of submarine netting (*sic*) between the pod and the wing.

John Burke said that the OR staff had published a paper at about the time of TSR2, concerning the use of digital computers for the F-111 which concluded that such use was premature. That indicated how far ahead the TSR2 programme had been. **Dennis Reader** had gone on to work on the F-111 programme where huge amounts of time and money had been consumed by the productions of interface units which proved to be both costly and highly unreliable. He suggested that this experience put the reliability standards of the day in some sort of perspective.

George Black questioned the input made by RAE Farnborough to the systems work of the TSR2 project. It was suggested that the work done by RAE and RRE had been critical in the early stages in underpinning and supporting the development of the whole system. Industry had accepted much advice from both Establishments which had originated some of the concepts involved. For example, the idea of using a digital computer combined with a digital differential analyser had come from RAE and was then developed by Elliotts, using American equipment, in the absence of similarly advanced British technology. RRE had made a substantial contribution to the development of the sideways looking radar.

Dr Jim Drury said that another part played by RAE had been in the initial design work on the inertial platform which had been by Geoffrey Barnes of RAE. Although the physical work of building it had been carried out by Ferranti in Bracknell, the basic design had been by RAE.

Air Cdre Bill Tyack claimed no direct knowledge of the programme but said that it appeared to him that cancellation had been inevitable, given the escalation of cost. It had been suggested to him that airframe and engine costs had not been growing nearly as fast as the cost estimates for the rest of the systems. He asked if that was an accurate view. **Peter Hearne** said that on some of the basic hardware costs had not changed much. What had changed, and was continuing to increase, was the amount of additional hardware made necessary by the additional tasks demanded of the aircraft. He cited as an example of unnecessary waste the £0.25M cost incurred by altering the dimensions of the computer by a matter of inches, so as to fit in with a Vickers back plug connection system. Generally, although there had been some bad estimating in the first instance, it had been new hardware in response to additional requirements that pushed up costs. **Denis Harris** agreed with that view.

Greg Stewart referred to the expense incurred by what had then been a new approach to the assessment of equipment reliability. A great deal of time and money had been devoted to work on the reliability of the forward looking radar, as a pilot programme. It had been an expensive new aspect which may not have been taken into account when predicting costs.

Jim Cole, formerly of Vickers Armstrong and now of EASAMS, said that he believed that the 'real killer for TSR2' would have been the problem of MTBF. He recalled that the overall MTBF of the system had been measured in minutes. The technology of the time had been that of discrete transistorised components and integrated circuits had not yet materialised. That was not to say that a successful mission could not have been flown, given that not all failures are mission crucial. However, great maintenance problems would have ensued and he concluded that the concept had been technologically ahead of its time. It may be considered that, by bowing out and then re-entering with more up to date technology at a later stage, much money was saved.

David Ince suggested that there was a big pay-off in backing away from the very frontiers of technology and wondered if that approach might have saved TSR2. He acknowledged that his thesis was idealistic in the extreme.

George Black agreed and argued that this dilemma was still very evident today. He suggested that the pursuit of technological excellence might be a very British trait but the conundrum persisted of how to decide between what Industry might offer and what the customer might wish to achieve – and what could be afforded. In his experience, neither Industry nor the customer was anxious to back away from what technology could offer. Affordable or not, there would always be an instinctive wish to operate at the frontiers!

SECTION FIVE

FLYING TSR2

DISCUSSION

Flying TSR2

Wing Commander J L Dell OBE

Wing Commander Jimmy Dell saw service in the Royal Air Force as a QFI and later as a fighter pilot in the early days of the jet age. He is a graduate of the Day Fighter Leaders Course at the Central Fighter Establishment where he later served on the staff and as OC Air Fighting Development Squadron. An exchange tour with the USAF and an appointment as RAF Lightning Project Pilot at Warton prepared him to join English Electric where he became Chief Test Pilot in succession to Bee Beamont in 1961. He undertook more than half the limited test flying of TSR2. Later, he test flew the Jaguar and became Director of Flight Operations of BAe.

At the start of the TSR2 programme I was understudy to Bee Beamont who was the designated Senior Pilot for the initial test flying. I considered I was extremely lucky and fortunate to be in the position and was looking forward to many years of flying the very advanced weapons system during its development programme – as we all know this was not to be!

When I was asked if I would talk on 'Flying the TSR2' I immediately said – yes. However, when I started researching to stir the memory cells after 32 years I realised that those of you who have read Bee's books *Fighter Test Pilot*, *Testing Early Jets* and *Flying to the Limit* plus his inputs to Frank Barnett-Jones book *TSR2 Phoenix or Folly* will know all about operating the aircraft in great detail and described in Bee's inimitable style. The best I can do is to relate some of my own views and thoughts although they will to a large degree echo Bee's assessments as those of us who shared the TSR2 experience were unanimous in our conclusions that as a flying machine we had a potential world-beater.

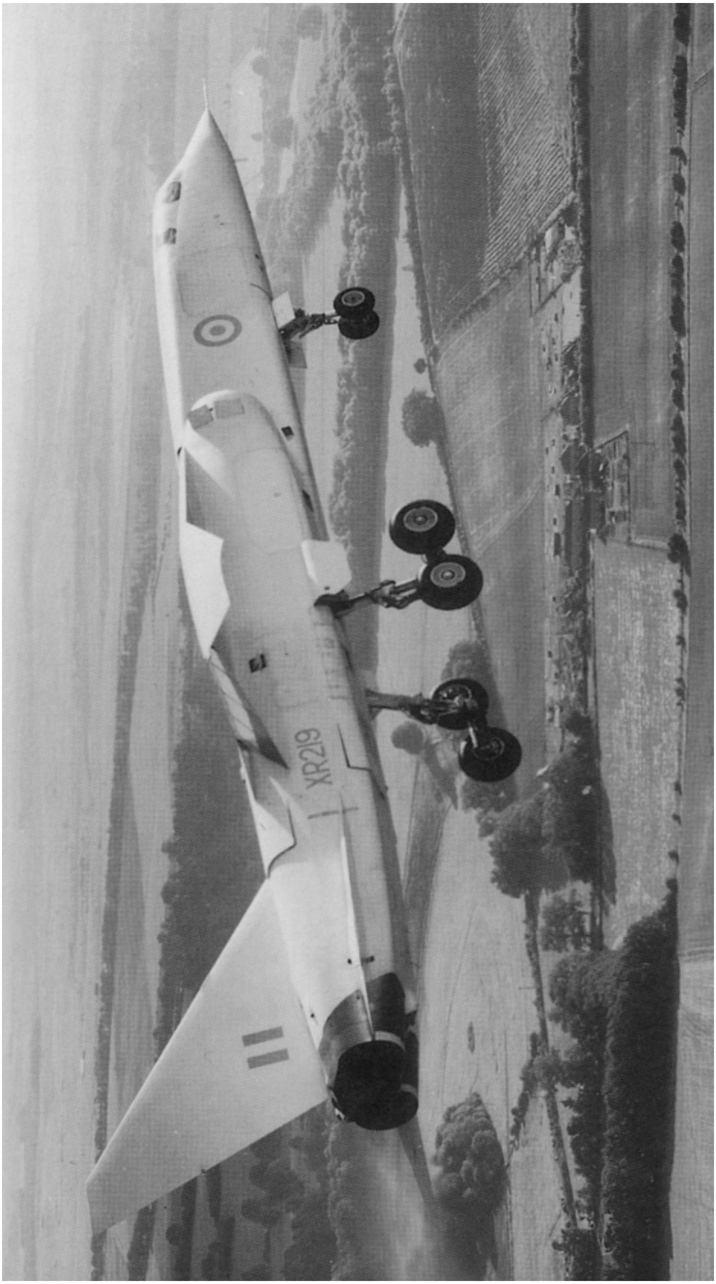
At this juncture those of you who might have been in my role as understudy could understandably have wished for Bee to break a leg before the flight trials started, but I reckon would have had a rapid change of heart when realising the decisions and problems Bee faced during the initial taxy tests and flights.

The flight development programme deserves a brief mention. It involved nine aircraft of which of course only the first flew. The second was scheduled to fly the day the cancellation was announced. The rest were in various stages of build although it is worth mentioning that the third aircraft XR221 had completed an initial ground run of the avionic fit with unexpected success.

The pre-flight preparation was standard in so much as we had the inevitable meetings, cockpit conferences, rig test experience, systems briefings and many hours in the Warton flight simulator which incidentally, proved very close to the in-flight experience. This had been helped by a feed-back from a flight programme run by Cornell University in the States on a variable stability T-33 jet. Don Knight, our number three project pilot, took part in that programme. The simulator at Weybridge represented the aircraft in respect of the crew stations and also the avionics fit and was used to look at terrain following and other avionic aspects. It had a motion system and the usual limited freedom in roll, pitch and yaw but also two additional motions referred to as heave and sway. These latter I considered particularly sick-making and more suited to a funfair device.

Having been briefed on the various systems, operating procedures and emergencies there comes a time when in order to get the programme 'off the ground', a reduced equipment and build standard is accepted which results in a re-brief on systems and equipment 'as is'! The aircraft design/built standard full flight envelope of 800kts IAS/2.25M/56,000ft/6⅔g was reduced to take account of the actual aircraft standard for each flight.

The aircraft I consider to be an impressive sight and every time I visit Cosford XR220 appears to get larger. I think the overall white finish helps. Entry to the cockpit is straightforward and the spaciousness immediately apparent. The Mk 8VA rocket assisted ejection seat was designed to provide safe ejection at all speeds up to 650kts IAS or Mach 2.0 from sea-level to 56,000ft. and, as a result of moulded seat and back panels, was unanimously considered to be the most comfortable of ejection seats by all the aircrew. The escape system provided for the usual leg restraint and also arm and head



TSR2 in flight at last, showing the undecarriage configuration and the partially open airbrakes restraint. Our first experience of a torso harness was generally accepted as a step in the right direction and significantly reduced the usual clutter of parachute and seat harness and oxygen tubes.

The comfort of the ejection seat in my opinion contributed significantly to the general feeling of being ‘at home’ with the aircraft. There was also a feeling of being ‘out in front’ due to not being able to see the wing tips or the nose except with the seat raised.

I remember on the first briefing on the escape system to be told of the 13 cartridges required (my memory) on re-checking in fact there were 17! On pilot initiation of ejection the sequence was:-

Immediately – Navigators’ canopy jettisoned

0.2 seconds – Pilot canopy jettisoned

0.7 seconds – Navigators’ seat gun fired

1.2 seconds – Pilots’ seat gun fired

2.0 seconds – Crash Recorder charge fired

On entering the cockpit the gold leaf de-misting and de-icing transparencies gave the outside world a faint golden hue which was soon forgotten until raising the canopies after flight to an often grey-day. Incidentally this triplex system is installed in Concorde.

The cockpit layout was commendably good considering the number of personnel involved on the cockpit committee (60!). However diligent the individuals involved, it is only in the aircraft operating environment that any deficiencies come to light. A good example was the engine throttle system which incorporated a number of latches – from engine off to idle, max dry power to reheat and also in a reverse sense but with an extra operation. In a dynamic situation, which required rapid reduction in power, this could, and did, result in an inadvertent shut-down of the engines with consequent loss of some services, eg cooling fan operation for the wheel brakes. Obviously a modification would have been required for service clearance. An interim mod was in fact incorporated.

Another deficiency was the miniaturised reheat nozzle and intake cone position indicators positioned at the bottom of the starboard quarter panel. An improvement in readability would have been required.

The optical qualities of the transparencies was less than optimum, particularly the front windscreen onto which the Head-Up Display was to have been projected. An early decision was expected to revert to a separate reflector to ensure accurate presentation of navigation and weapon aiming information. It is understood that the Grumman F-14 Tomcat went through a similar process.

Engine starting from the pilots point of view was straightforward using the ganged rapid start bar. The actual starting required a number of complex switching actions which were controlled automatically.

The cockpits were relatively quiet and apart from some initial minor problems involving the heating system which afforded the pilot a warm environment but left the navigator in the cold!

XR219 was not fitted with a Head-Up Display therefore the head-down standby instruments were the primary flight instruments in this case. The lay-out was not ideal being on two separate planes and the VSI being outside what would be considered a good scan pattern.

Taxying was straightforward using nosewheel steering in its fine or coarse mode. An initial feeling of over-sensitivity and a slight phase lag was quickly overcome with experience. After line-up for take-off the procedure was to hold the aircraft on the brakes, engage minimum reheat, check engine readings, release brakes on increasing reheat to maximum. Acceleration was impressive if not quite up to Lightning standard. Rotation initiated at 120kts resulted in a smooth unstick at 170-180kts. It is worth mentioning that during acceleration/stop tests nosewheel lift had occurred at 105kts IAS using only 10 degree tailplane angle, compared to a predicted speed of 130kts IAS using 18 degree of tailplane angle. This unexpected tailplane power would possibly have resulted in achieving the OR requirement of 650yd take-off distance from a semi-prepared field without resorting to the nose leg extension facility.

Initial climb after unstick was quite steep in order to remain below the undercarriage speed limit whilst the gear went through the necessary machinations before tucking away. During the initial flights, Bee experienced just about all the possible parameters of undercarriage malfunction but fortunately without the possible disastrous consequences. It was Flight 10 before we achieved normal retraction and extension.

Once cleaned up, the immediate impression was of an exceptionally good handling aircraft and one was not conscious of the lack of autostabilisation. A criticism of control 'lumpiness' found on the control test rig and also on the aircraft during ground tests was not evident in flight. It handled and felt like a heavy Lightning (due to higher stick forces) and it was a great temptation to treat it like a fighter and throw it around. As Bee had discovered earlier, the high speed low level ride qualities in the primary operational zone were outstanding due to the good gust response characteristics.

Mild buffet was experienced in the expected areas (low speed, undercarriage and flap configurations, airbrakes) but otherwise flight remained smooth. A lasting impression was formed of the small trim changes required during flight when making configuration changes and even during simulated engine failure. In fact it was possible to fly a sortie without the use of the trimmers unless hands-off flight was required.

At one point it became necessary to disregard the normal flight test progression and jump to designated, so called, 'guarantee points'. I can't remember them all but one was M=0.9 at 30,000 and another at 500kts, 2,000ft. These were carried out and confirmed predictions, so satisfying those that called for these tests. The flight envelope was also extended to 600kts at low level and Mach=1.12 at approximately 30,000ft. Handling throughout remained impressive in terms of stability and control.

An early look at single-engine flying, culminating in approaches, overshoot and landing proved successful, even with the low standard engines.

The roll control by variable tailplane did result in a slight proverse yaw when rolling into a turn then changing to a slight adverse yaw. This was looked at on the last flight to establish the fine tuning necessary when the autostabilisation was fitted.

Handling in the circuit and on the approach was eminently satisfactory with no problem achieving an accurate and stable speed on approach of 165kts. Judging the flare from an elevated position due to the nose high attitude posed no problem and I have recollections of a pronounced ground cushion effect which eased the aircraft onto the runway. In fact on some flights I was supposed to achieve something close to a no-flare landing but failed – I wouldn't have qualified for carrier landings.

The brake parachute deployment was designed to be initiated by pulling the chute handle on the approach which released a primary drogue (6' diameter). If the system was selected to manual a second pull of the handle would release the main chute. If selected to automatic the deployment of the main chute was operated by undercarriage switches on touch-down. The chute was 28' in diameter but could be streamed reefed with a diameter of 16' by a peripheral cord. The reefing facility was designed for use in strong crosswind conditions. The two-pull facility was not cleared for the initial programme, so we used the single pull operation. During early acceleration/stop runs the brake chute system failed twice, which completely vindicated Bee's insistence on a runway longer than Wisley for initial flights.

A problem we had with us for the first 22 flights was that on touchdown an oscillation of the main undercarriage triggered off a violent motion of the front fuselage which threw the crew from side to side. This was for only 2-3 cycles but was sufficient to cause disorientation and momentary confusion on first encounter. In order to understand the dynamics of the problem, landings at varying rates of descent, and including landing on a foamed runway (reduced coefficient of friction), didn't provide the answer. It was concluded that the frequency of the undercarriage oscillation matched that of the natural frequency of the long front fuselage and so a fixed 'de-tuning' strut was fitted to the undercarriage structure and this was assessed as successful on the last flight (with undercarriage down). The next step was to incorporate a strut as an integral part of the undercarriage to allow for retraction, but the project was cancelled before this could be achieved.

I do hope I have not spent too much time on the few warts of the limited flight test programme and have left you with the impression that, as a flying machine, we did indeed have a world beater in our stable.

The TSR2 pilots at the Filton seminar standing in front of the Olympus 22R engine. (l-r) Jummy Dell, Bee Beamont; Don Knight

Discussion

The discussion group chaired by Air Commodore Graham Pitchfork had the benefit of the presence of four of the TSR2 flight test aircrew in considering aspects of its flying and handling. Interesting views were expressed about TSR2's potential for later up-grading.

On the question of the short field performance called for by the OR, **Wg Cdr Beamont** had always thought it very questionable whether an aircraft of TSR2's weight, complexity and performance would ever have been called upon to operate off grass strips: short prepared strips, including motorways, would have been a different matter. That said, in a short flying programme of only 23 flights in which it was scarcely possible to scratch the surface of the aircraft, there was evidence nevertheless that with full-span blown flaps and the thrust available, very impressive take off and landing performance was to be achieved. On the one occasion (around the 14th flight) when optimised approach conditions were attempted, a touchdown speed of 165kts was used and with brake chute the aircraft was stopped in 700yds at a weight of 70,000 lbs.

Roger Dickson was at Westland at the time of Duncan Sandys and remembered the in-fighting that was evident in the industry then on where and how things were done. This was seen in the decisions about where the test flying would be carried out. Weybridge was clearly out; Wisley was short; there was a good runway at Warton. Against the background of the different cultures of the two companies, it seemed inevitable that this would be a matter that would be keenly debated.

Wg Cdr Beamont agreed! This was an excellent example of the confusion that arose in attempting to get a major programme on the road while, at the same time, coping with the amalgamation of the total administration and technical process of two large companies which had hitherto been totally independent and had intended to remain so into the future. The position had been reached in the year before the first flight when no decision had been taken. If it had been the product of only one company, there would never have been any question over what would have been done: the aircraft would have come out of the factory and into the flight test area where all the necessary support would have been available. The prototype was assembled at Weybridge and there was a suggestion that it should make its first flight out of Brooklands! With a year to go, there were no answers forthcoming about where the flight testing would be carried out and Wg Cdr Beamont went, at the suggestion of Freddie Page, to see Sir George Edwards who suggested that Brooklands was a possible venue for the first flight, citing the fact that the VC10 had made its maiden flight there. Wg Cdr Beamont argued that the consequences of an aborted take off or brake parachute failure were totally unacceptable and his arguments prevailed. Despite his strong recommendation that Warton be used, where an existing flight test facility already existed alongside the other English Electric design and engineering facilities, Boscombe Down was selected.

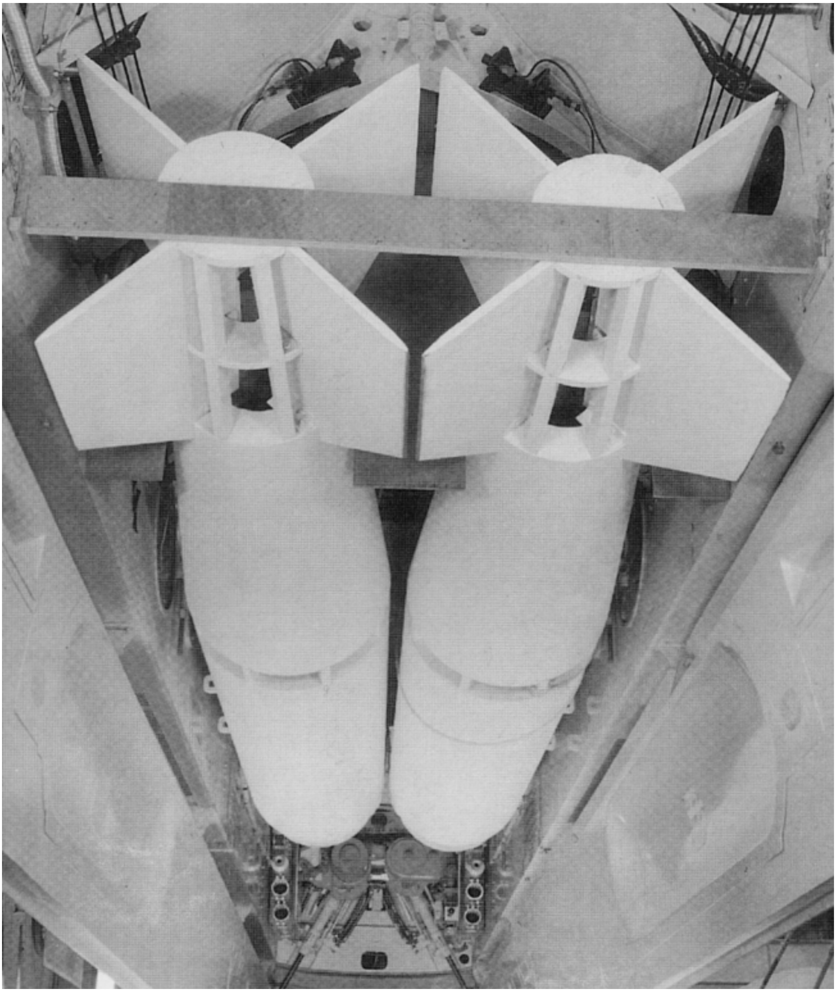
Wg Cdr Beamont returned to the question of low level gust response. In the very short test programme, both he and Jimmy Dell had sampled the quality of the ride at low level, the latter up to 600kts. He himself had taken the aircraft to 500kts at 100ft on the first flight when the undercarriage was successfully retracted. The aircraft handled precisely and probably better than any aircraft he had ever flown. He cited the case of a flight at 500kts and 2,000ft over the Pennines when TSR2 was ‘rock solid’ – and the Lightning chase aircraft had had to break off because of the roughness of the ride.

Brian McCann, who was one of the back-seaters, said that the ride was extremely comfortably and ‘calm’. The stability of the aircraft meant that the navigator’s task, at that stage one of recording and noting, had been easily performed. Although it would ultimately have been equipped with the latest of avionics, allowing precise navigation, day or night and in all weathers, the view from the rear cockpit was outstandingly good – especially for someone like him with a great deal of Canberra experience. The team of navigators, of Don Bowen, senior navigator and flight test observer, Peter Moneypenny and Brian McCann had been involved in rear cockpit design and **Wg Cdr Beamont** noted that Don Bowen had played an especially important part in the ergonomics of the systems. The management of such matters had been very complex and unwieldy and included ‘vast committees’ which sat on cockpit design. At times, it had been almost impossible to pin down by whose authority an endless stream of design changes had been made. This had been one of the major factors in delaying progress.

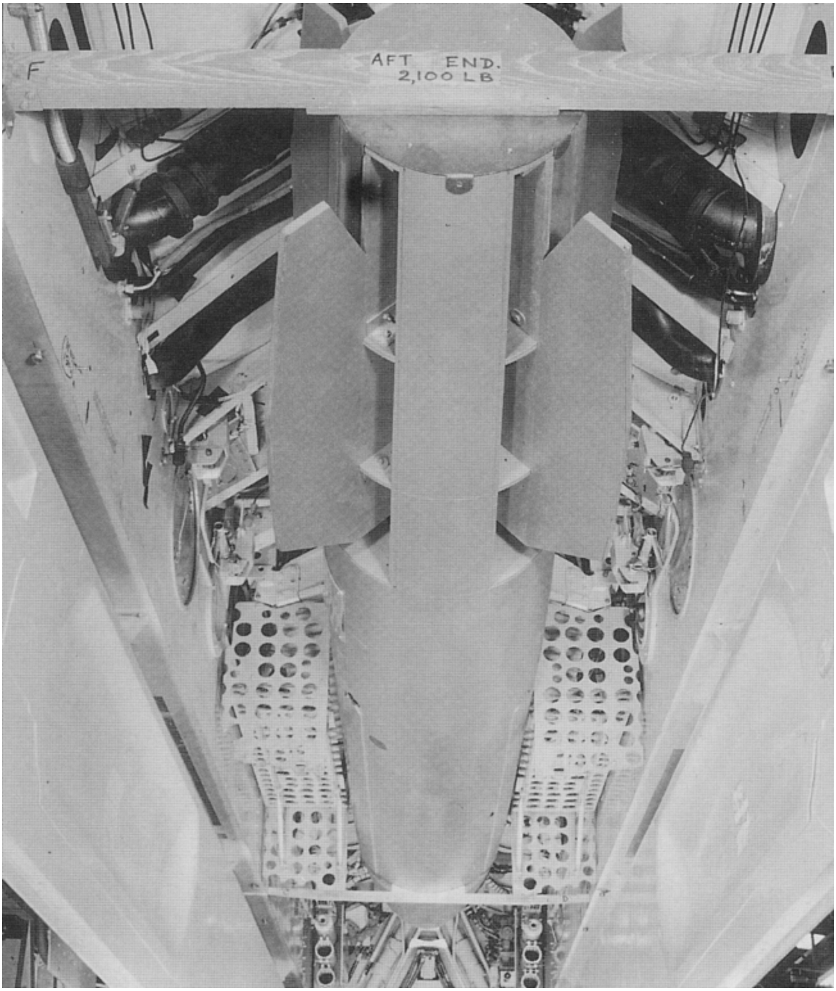
Gp Capt Mears admitted to having been one of the 60 people who turned up to cockpit conferences and he said that these conferences typified part of the control problem. Even in the MoD, there had been no centralised control of the project. There had been four staff officers in the OR office but many other disciplines had conflicting opinions about cockpit layout. The consequence was a constant battle. In the end, despite the process, the cockpits had turned out to be reasonably well designed. The sideways looking radar with its complex processing units created particular problems of cockpit ergonomics. The nav/attack system, as planned, would have required a major upgrading for lack of computer capacity and because of the clumsiness of the sideways looking radar, itself dictated by the use of the nose cone for the terrain following equipment.

Wg Cdr Dell said that he agreed with views expressed by those who argued that the aircraft would have demanded, and been provided with, greatly upgraded computer capacity, as had happened over the years with Tornado. Additionally, it had a huge electronics bay behind the rear cockpit, designed for, then sate of the art, avionics. The potential for mid-life updating was enormous.

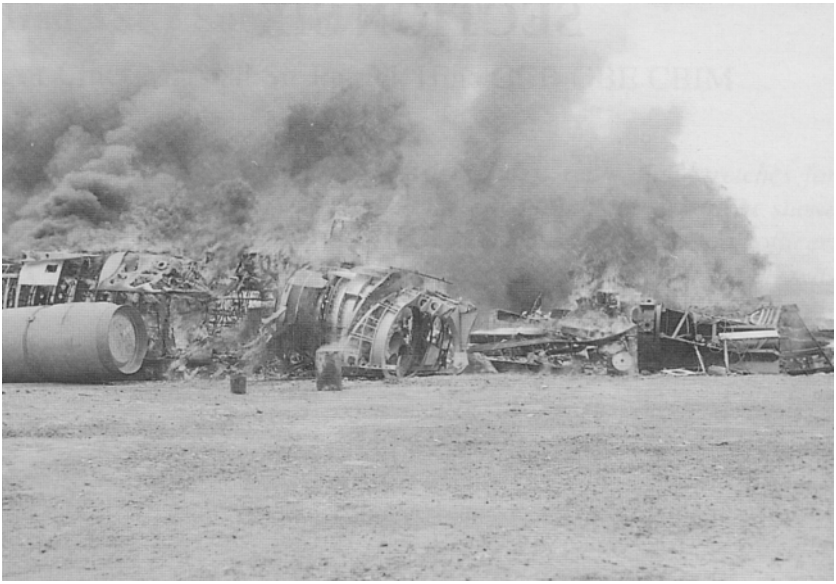
Wg Cdr Beamont's final opinion was that the airframe itself was 'right' and well capable of taking TSR2 forward. It had started flying in 1964 and with micro-technology, systems upgrading and modern weapons, it would today have had performance, without modification, exceeding that of Tornado.



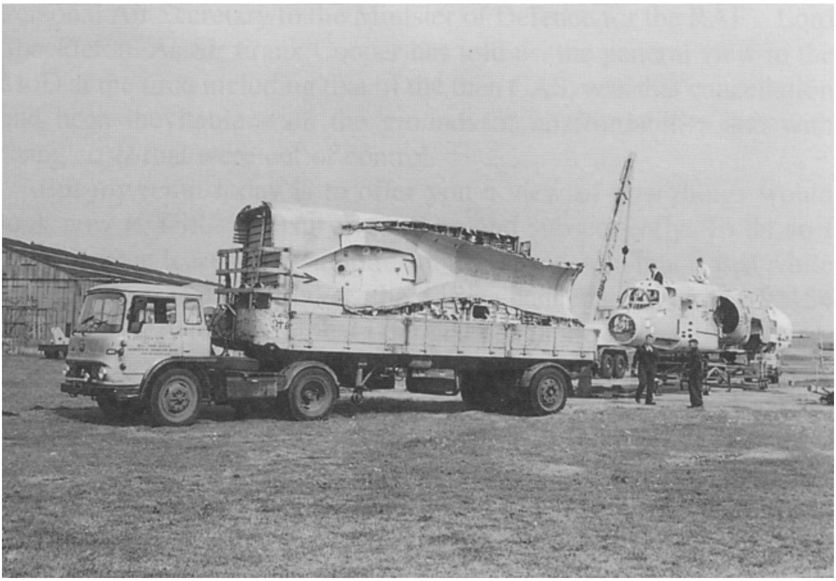
TSR2's weapons bay showing mock-up 1,000 lb bombs



TSR2's weapons bay showing a mock-up 2,100 lb weapon



A sad ending – TSR2 fuselages are burned following cancellation



Expensive scrap! TSR2 remains are towed away for disposal

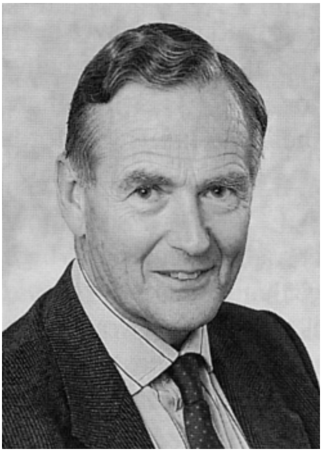
SECTION SIX

HAD TSR2 SURVIVED

ENVOI

Had TSR2 Survived

Air Chief Marshal Sir Patrick Hine GCB GBE CBIM FRAeS



Sir Patrick Hine's reputation stretches far beyond the Royal Air Force where he shone as fighter pilot, commander and staff officer. His ability to inspire others by example was unparalleled in his generation and he is acknowledged as a military thinker of considerable clarity. Since his retirement, after command of all British Forces in the Gulf War, he has become Military Advisor to British Aerospace plc and is a much respected figure in international aviation circles. He is well suited to consider the likely effects 'Had TSR2 Survived'.

I was at the Staff College when the cancellation of TSR2 was announced in 1965, and at the end of that year I was posted as Personal Air Secretary to the Minister of Defence for the RAF – Lord Shackleton. As Sir Frank Cooper has told us, the general view in the MoD at the time, including that of the then CAS, was that cancellation had been inevitable – on the grounds of unaffordability and with rising costs that were out of control.

But my remit today is to offer you a view of how things would look now if TSR2 had survived, then and subsequently. To do so I must make at least one assumption at the outset. And that is that, while the TSR2 project proceeded, the earlier cancellation of the P1154 stood. It is very important that I put that peg in the ground. In passing, I should say that I believe it was right to cancel the P1154. The highly effective off-base operating capability developed by the RAF on the Harrier could not have been achieved on the P1154 with its plenum-chamber burning reheat system which would have caused very severe ground erosion problems. In short, we would have been trying to run before we could walk, and that could have had a most adverse, if not fatal, impact on VSTOL in the RAF.

Here then is my scenario.

First, the RAF would, I believe, have got about a decade earlier the kind of capability it eventually enjoyed with the Tornado GR1. The avionics may not have been quite so well advanced, nor would the TSR2 have been so manoeuvrable, but it would have had longer legs, and in this respect have met the range capability called for in the FOAS Staff Target. But TSR2 would not, of course, have been stealthy. The bottom line is that TSR2 showed all the signs of being a better aircraft than its nearest competitor, the F-111, but there remains a big question mark over cost and therefore ultimate affordability and cost-effectiveness.

Next, let us have a look at force structure.

The TSR2 would have replaced the Canberra but, because of high costs, not on a 1 for 1 basis. Probably no more than 100 aircraft would have been procured. The RAF's strike/attack/recce force would thus have become smaller, unless a second aircraft had been procured, for which money would almost certainly not have been available.

You will recall that by 1965 the days of the V-bomber force were numbered as a result of the Polaris decision of 1963 and which the new Labour Government had endorsed. The Air Staff would probably have argued for more TSR2s to replace some of the V-bombers – but only once the programme was secure – and they may not have been successful.

The TSR2 would have been used for nuclear strike/deeper recce, OCA and interdiction, but not, except in extremes, for OAS (BAI+CAS). It was not tailored for those missions and it would not have been cost-effective in the OAS role. Therefore, another aircraft would have been needed to replace the Hunters in the UK, Germany, Gulf and Far East.

Would this second aircraft have been the Harrier or Jaguar, or something else, perhaps a multi-role fighter like the STOL F-16? I suspect it would have been the Harrier (HSA needed an order), and that the Jaguar would not have been procured – it was always the wrong (or certainly over-elaborate) aircraft for an advanced jet trainer (the original intention) and with its relatively high wing loading, was not optimised for CAS. In any event, the UK became involved in Jaguar as part of a collaborative package agreed with the French, where our real interest lay in the AFVG which was killed of by de Gaulle in 1967.

The Lightning was planned to be run-on in the AD/Interceptor role into the late 1970s and, if TSR2 had survived, I very much doubt that the RAF could have afforded before then a new fighter as well as TSR2 and Harrier.

By the mid-'70s the need for a highly agile fighter like the F-15 or a multi-role FGA aircraft like F-16 or F-18 had been widely recognised throughout NATO. There was also the requirement to replace the F-104 and, in France, the Mirage III; thus an opportunity existed for a collaborative programme in Europe, as an alternative to procurement of an American fighter. Industry here in the UK would have pushed hard for a European programme for an agile fighter – as would the RAF. *But* that option was effectively ruled out following the cancellation of TSR2 and AFVG, and with the Tornado programme launched instead, because industrial, economic and political arguments *de facto* forced the RAF down the Tornado ADV path. In passing, I would comment that the Tornado was never a real MRCA, and the ADV certainly was not an air superiority fighter. It was a long endurance interceptor and has given good service in that role.

So, if TSR2 had survived, it is likely that the UK or Europe would have developed an EFA-type fighter ten years earlier than was the case. The lessons learnt on the Jaguar and Tornado collaborative programmes would then instead have been learnt on the EFA programme, but nonetheless a good product would probably have resulted. Moreover, it is less likely perhaps that the French would have gone their own way on the new agile fighter, as they did in the late '80s with Rafale.

Under this plot, there would almost certainly not have been a Buccaneer in service with the RAF, unless money had been available to fill out the force structure. I doubt it: I believe the RAF would have had only TSR2 and Harrier in the offensive roles.

In the longer term, therefore, the RAF's combat aircraft front line would have been: TSR2, Harrier and the Lightning replacement.

As it was, in 1982 we had the Lightning, Phantom, Harrier, Jaguar and Buccaneer in service. We also still had some Canberras operating in the recce role – and still do. We thus had six types instead of three, moreover, without TSR2, the V-bombers had to be run on for longer than necessary – awaiting the entry into service of the Tornado GR1.

Overall, therefore, in logic there should have been considerable savings in the logistics support area if proper fleet rationalisation around TSR2 had been effected.

The big unknown, of course, is how costly TSR2 would have been, both in capital and life-cycle cost terms; and what impact that would have had on the affordability of Harrier to replace Hunter and a new fighter to replace the Lightning. Also, of course, on the size of the RAF's front line. A TSR2, Hunter, Lightning fleet into the 1980s would have been feasible but is not one that would have appealed to me.

Another question that comes to mind is, 'Who would have designed and produced the new agile fighter to replace the Lighting?' With BAC as prime contractor on the TSR2 and HSA on the Harrier, it could have gone either way, or it could have been an issue that brought forward the formation of the nationalised BAe. We shall never know but there are people here today who will have a view. My own is that the design lead would have gone to Warton given their experience by then on supersonic aircraft.

For me the seeds of destruction of the TSR2 programme were sown back in 1959/60 when inadequate attention was paid to cost/performance trade-offs before endorsement of the operational requirement on which the contract was finally based. That costs then rose so dramatically, particularly at a time when industry was being forced to rationalise across different cultures, is not too surprising, and by 1964 when the first prototype flew, the die was probably cast and the balance of arguments that the MoD and HMG had to address *at that time* inexorably led to a cancellation decision. In this respect, I agree with Sir Frank Cooper.

But that was a great shame, for an affordable TSR2 to the right specification would have given the RAF the world's most capable TSR aircraft and one with at least some potential in the export market (whereas TSR2 had virtually none when it was cancelled).

For the reasons I have given, the RAF's front-line inventory would (or should) have been more coherent than it is today and the Service would probably have had an air superiority fighter at least ten years earlier.

I doubt that, structurally, industry would have looked much different than it does today, except perhaps the process of consolidation in Europe might have been accelerated. Frankly, I doubt it: the real driving force there has been the pace of rationalisation in the US since the ending of the Cold War and the formation (or prospective formation) of mega-giants like Lockheed Martin, Boeing McDonnell Douglas and Raytheon/Hughes.

Finally, I should like to say a word or two on technology demonstration programmes (TDP) which have already been mentioned today, notably by John Wragg. I have been a great believer in their value, and I should like to tell you a true story from my days as Assistant Chief of Air Staff for Policy when I was working for Sir Michael Beetham.

In 1982, MoD were facing a particularly difficult long term costing and I and my Civil Service colleague, the Assistant Under Secretary for Air, John Peters, were having to find major savings in the RAF budget. Amongst many other things we cut £10M out of engine TDPs. We immediately got a request from the then Director General Engines in the Procurement Executive – Mike Neal, I think – for a meeting, to which we agreed. Neal told us we were making a big mistake by economising on TDPs, that the same thing had been done previously on the RB199 for Tornado and that MoD had subsequently spent more than £100M cleaning the engine up. He implored us not to perpetuate this kind of false economy on the engine for Eurofighter – the EJ200.

Neal was so convincing and passionate in advancing his cause, that Peters and I later agreed to re-instate the £10M. It was, I now believe, one of my better decisions as ACAS(Pol)!

Thank you for this opportunity to gaze into the crystal ball with 20/20 hindsight. I have enjoyed it, as I have the whole day. It has been a fascinating experience.

Envoi

Sir George Edwards OM CBE FRS FEng DL

and

Dr Norman Barfield MSc PhD CEng FRAeS FIMechE FRSA AFAIAA

The figure of Sir George Edwards dominates any study of TSR2, just as many regard him as arguably the UK's most outstanding designer and industrial leader. He may be seen as both reason and pretext for the award of the TSR2 contract to what was to become the British Aircraft Corporation. He was certainly the architect of the survival and recovery of BAC after cancellation.

George Edwards joined Vickers (Aviation) at Weybridge in 1935 and by 1945 was Chief Designer of the company. He led BAC as Executive Director (Aircraft), Managing Director and Chairman until his retirement in 1975. Besides TSR2, he was responsible for such aircraft programmes as the BAC 111, Concorde, Jaguar and Tornado. He is now in his 89th year and has contributed his reflections on the industrial and military consequences of TSR2 and its cancellation. It is fitting that he should have the last word on the subject.

Sir George's paper was read at Filton by one of his associates, Dr Norman Barfield, with whom he worked closely, particularly during the TSR2 period. Dr Barfield joined Vickers-Armstrong in 1947 as an apprentice and in his 42-year career at Weybridge was involved in the design, engineering development, promotion and management of Vickers, BAC and BAe civil and military aircraft. He is Chairman of the Collection Trust of the Brooklands Museum and Heritage Advisor to BAe. The Society is very greatly indebted to him for encouraging Sir George to prepare this paper for the seminar.

Dr Norman Barfield

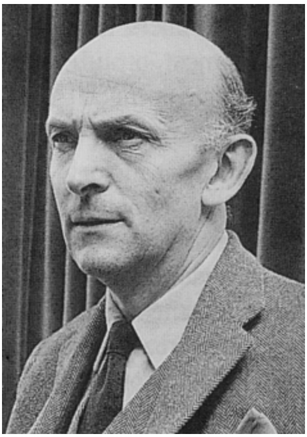
It is a great privilege for me to represent Sir George Edwards here today because not only was he the industrial mentor of the TSR2 programme but also the architect of the enormously difficult survival and recovery of the newly-formed British Aircraft Corporation after the cancellation.

My credentials for doing so are that I have worked for and with Sir George at Weybridge nearly all my working life, including the TSR2 period, and am also proud to count him as a personal friend and continue to be in touch with him every few days.

We are both glad that he is able to make the concluding contribution to this Seminar. I am also glad to bring you his warmest greetings and good wishes, especially to those here who fought so hard and supported him so staunchly throughout the TSR2 saga. I will also reciprocate on your behalf.

At the same time, we are both sorry that he cannot be here in person. Now approaching 89, although not in the best of health, he still puts his head down and gets on with it.

Because what I have before me are Sir George's own words, and not mine, I will read them in the first person – so here goes . . .



Sir George Edwards

That the Royal Air Force Historical Society should have chosen to make this objective and uninhibited recollection of the whole of the TSR2 saga – all these years on and through the eyes of some of those who held the quite awesome direct responsibilities at the material time or were otherwise deeply involved – will have at least provided a definitive record of what actually happened and at best painted a much clearer picture of the consequences at what was a particularly critical time for the whole of the British aircraft industry and for the Royal Air Force. It might even be of some help to some of the younger generation now trying to make their way in the Industry, Government Service or the Royal Air Force.

My views on the TSR2 programme have long been on the record and what I have to say here is largely taken from my Hinton Lecture of 1982 (to what was then the Fellowship of Engineering and is now the Royal Academy of Engineering).

As doubtless you have well explored today, the TSR2 story was unique inasmuch that it was not only intended as a wholly new and very advanced weapon system for the Royal Air Force but was also a politically-charged instrument of the major rationalisation of the British aircraft industry. This meant that it was inextricably bound up with both national and international politics and put us in a situation that was like nothing else that any of us had ever had to tackle before.

On the industrial front, most of the proud Company names that had produced the many thousands of aeroplanes with which the nation had fought – and won – a long and exhausting war were still extant in the early post-war years: twenty-two airframe, six engine and four helicopter. During the early 1950s, we had our hands pretty full in introducing swept wings and jet propulsion and a lot of sophistication in systems – simultaneously in airliners to meet the rapidly-growing civil market and in the V-bombers and fighters to enable the RAF to protect us against the continuing widespread threat of conflict.

At Vickers, within the first ten years from the end of the war, we had flown the Viking only six weeks after VE-Day; pioneered the benefits of turbine-powered air travel throughout the world with the Viscount; realised the Valiant, the first of the V-bombers in record time (the aeroplane of which I was personally most proud); and brought the prototype V1000 strategic military jet transport and trans-Atlantic jet airliner to within only a few months of its first flight.

Although English Electric had a long prior aviation history, and had produced a lot of other company's aircraft during the war, it was effectively restarted from scratch at Preston soon afterwards to go forward again in its own right. The team that Sir Frederick Page built up there, and produced the Canberra and then the supersonic Lightning in much the same timescale, is one of the great highlights of British military aviation achievement. And let us not forget that it was the Lightning which became the foundation of the Saudi Arabian alliance that continues to be so important to British Aerospace, much of the British aircraft industry, and hence the UK economy, today.

After the many British manufacturing companies had themselves reduced their numbers by a fair amount of absorption, pressure came from the Government at the end of the 1950s to rationalise the industry still further. In the first instance, Aubrey Jones was given the task and he prepared the ground, but it was left to Duncan Sandys who came on the scene with some ‘golden welding flux’ in the form of TSR2 as a Canberra replacement and other military orders – the Hawker Siddeley P1154, a supersonic Harrier (which would have been useful in recent times in the Falklands and Gulf wars) and the HS681, a short take-off tactical jet transport. There was also the promise of aid for civil projects.

This was clearly a good way for the Government to get its way about further rationalising. Vickers were given the contract for the TSR2, provided that English Electric did half the work, and together we put a lot of effort into it.

That was also a good way to start a new Company, and the rationalisation duly took place. From 1960 virtually all the remaining smaller companies converged effectively into British Aircraft Corporation, Hawker Siddeley Aviation, Rolls-Royce and Westland. I suppose we were sad about our individual identities being submerged in these new companies but we were adult enough to realise the wisdom, and got on with it, big a job as it was.

The really important qualifying factor was that the TSR2 was a very significant part of the BAC workload. Representing about half of that for the military side of the Company, it was expected to have continued as such well into the 1970s.

It was hard in the early years of a new company to have to fight the battle for survival that we had to fight over TSR2. It suffered from some significant problems. It was a ‘Weapons System Concept’, a new piece of Government book-keeping which meant that the cost of developing its sophisticated equipment and the production investment were all loaded solely onto the bill. There was also at that time a fatal fascination in certain quarters, including with some fairly senior Royal Air Force officers, with anything American. The F-111 was clearly full of problems, but there was a touching belief that the Americans would always get the job right, regardless of how much trouble it was in. I must say that over the years they have given themselves plenty of practice.

After we had flown the TSR2 enough to show that it did the job we had been given to do, it was duly cancelled and in two months the Royal Air Force was therefore deprived of its three main forward aeroplanes – the BAC TSR2, the HS1154 and the HS681. The F-111 was ordered in its place and that in its turn was cancelled because of the cost.

It was no joke pulling BAC together after the sudden loss of such a large part of the forward workload. The production and development teams at Warton and Preston were both very badly hit. Amongst the documents circulating at that time was a Ministry of Aviation official paper saying that there was no way that these two plants could be kept in business and they should both be shut. Even when one considers that those two teams under Sir Frederick Page have since played the absolutely dominant part in the design and manufacture of the Jaguar and Tornado, and are today the most able and experienced partner in the Eurofighter 2000, the idea that this could, even for a short space of time, become official policy was at its lowest unreal. In the end, we had to close a factory, and in the way that these things go, we closed the ex-Hunting plant at Luton. This was a highly-efficient, low-cost, little factory that had nothing to do with TSR2, but the work had to go North in order to preserve the capability of the factories there and their exceptional military expertise.

That was a very difficult stage in the formation of these big new company groupings but a new industrial policy was also beginning to emerge – international collaboration – and let's not forget that at the same time as we were grappling with TSR2 and trying to put together BAC we were getting the Anglo-French Concorde launched as well.

The success of the Concorde as an industrial collaboration is too well known for me to elaborate on it further here. It provided a solid foundation with which to build from the UK domestic collaboration between Vickers and English Electric on the TSR2 within the unified BAC and to go forward with the Jaguar and Tornado programmes in international collaboration. Together with the Anglo-American Harrier, they have since provided the backbone of the British frontline military aircraft programme and given it a degree of stability that it had not had before – and now a commanding position in Eurofighter.

I have often been asked what I thought was the biggest setback that the industry has suffered. Certainly on the civil scene I am sure that it was the cancellation of the Vickers V1000 transport six months before it was due to fly, the prototype of which, as I have said, was in a very advanced state. Now if we had become involved in another major war, I would have said that the cancellation of the TSR2 was the most serious thing that happened. But a military cancellation does not show if you do not have a war, whereas the battle with the enemy never stops on the civil front. If you miss one stage by a cancellation then you are lost – and with the VC10 so it proved.

Whatever the arguments, which I am sure you will have debated long and hard today, the TSR2 saga provided for me one of the clearest possible vindications of an axiom that I have so often expressed about the British aviation industry: the truth always comes out but so often when it is too late to rectify the situation.

Nevertheless, the extraordinary resolution that we had to summon – simultaneously to overcome the TSR2 cancellation, to cement the BAC organisation and to launch the international dimension (notwithstanding the hiccup of the infamous and similarly-moribund Anglo-French Variable Geometry (AFVG) aeroplane) – did ensure that the Royal Air Force eventually received the right and the best home-grown aircraft, which have certainly proved their worth in live combat on the winning side.

This is, I believe, the most satisfying conclusion that we can all come to today – because we must never forget that the Royal Air Force is, and always will be, our most important customer.

A dramatic shot, showing TSR2's typical complex wingtip vortices

ROYAL AIR FORCE HISTORICAL SOCIETY

The Royal Air Force has been in existence for 80 years; the study of its history is deepening, and continues to be the subject of published works of consequence. Fresh attention is being given to the strategic assumptions under which military air power was first created and which largely determined policy and operations in both World Wars, the inter-war period, and in the era of Cold War tension. Material dealing with post-war history is now becoming available under the 30-year rule. These studies are important to academic historians and to the present and future members of the RAF.

The RAF Historical Society was formed in 1986 to provide a focus for interest in the history of the RAF. It does so by providing a setting for lectures and seminars in which those interested in the history of the Service have the opportunity to meet those who participated in the evolution and implementation of policy. The Society believes that these events make an important contribution to the permanent record.

The Society normally holds three lectures or seminars a year in London, with occasional events in other parts of the country. Transcripts of lectures and seminars are published in the Journal of the RAF Historical Society, which is distributed free of charge to members. Individual membership is open to all with an interest in RAF history, whether or not they were in the Service. Although the Society has the approval of the Air Force Board, it is entirely self-financing.

Membership of the Society costs £15 per annum and further details may be obtained from the Membership Secretary, Dr Jack Dunham, Silverhill House, Coombe, Wotton-under-Edge, Gloucestershire. GLI2 7ND. (Tel 01453-843362)