The Royal Aircraft Establishment Farnborough

100 years of Innovative Research, Development and Application

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ABSTRACT

Aviation research and development has been carried out in Great Britain for well over a century. Starting with balloons in the army at Woolwich Arsenal in 1878, progressing through kites and dirigibles in 1907, through to the first practical aeroplanes, the B.E.1 and B.E.2, designed and built by the Royal Aircraft Factory in April 1911. At this time Mervyn O'Gorman was installed as the Superintendent of the Army Aircraft Factory and began to gather the best scientists and engineers and bring scientific methods to the design and testing of aeroplanes. Renamed the Royal Aircraft Factory (RAF) in April 1912, it designed, built and tested aircraft, engines and aircraft systems throughout WW1. In 1918 its title was changed to the Royal Aircraft Establishment (RAE) to avoid confusion with the newly formed Royal Air Force. From then on RAE Farnborough and its outstations, including Bedford and Pyestock, developed into the biggest aviation research and development establishment in Europe and one of the best known names in aviation, working in all the disciplines necessary to build and test aircraft in their entirety. On the 1st April 1991 the RAE ceased to exist. The Establishment was renamed the Aerospace Division of the Defence Research Agency (DRA) and remained an executive agency of the UK Ministry of Defence (MOD). It was the start of changing its emphasis from research to gain and extend knowledge to more commercially focussed concerns.

1. INTRODUCTION

The problem of compressing 100 years of the Royal Aircraft Establishment (RAE)'s research, development and innovation into a short article risks understating the breadth and depth of the advances made in aviation science and technology by the RAE. At the risk of alienating many of those who worked at RAE and whose speciality and expertise cannot be included I have tried to summarise many of those things that RAE did well and tried to bring out the innovations of some of the less 'glamorous' departments. It is inevitable that this paper highlights a sequence of interesting and significant projects, rather than providing a comprehensive account of the full scope of the Establishment over the past hundred years. The RAE was not only Farnborough but also outstations such as Bedford and (at times) Pyestock and ranges such as Aberporth.

The Royal Aircraft Establishment was formed in 1918 when the Royal Aircraft Factory (RAF) and the newly formed Royal Air Force (RAF) ended up with the same initials. To avoid confusion 'Factory' was changed to 'Establishment' - thus, the Royal Aircraft Establishment was named.

However, to give a more complete historical context it is necessary to start earlier, when the Royal Engineers' Balloon School first moved to its Farnborough site on the Swan Plateau (Figure 1). The move was from Balloon Square in Aldershot at the end of 1905, bringing a single balloon shed and constructing on the site an airship shed, some workshops and a hydrogen generation station. At the time the main interest of the army was in using balloons for reconnaissance and the move to Farnborough was to allow the necessary space to start work on the bigger powered dirigibles which, they surmised, would be the future of aerial operations.(1)

Because balloons could only be used when there was little or no wind, man-carrying kites were developed for use in windy conditions, led by Samuel Cody, and this was followed by heavier-than-air machines by the Wright brothers in the USA in 1903/5, by Samuel Cody in Britain in 1908 and by Louis Bleriot, amongst other French pioneer aviators. When Bleriot spanned the English Channel in 1909 the War Office, perhaps realising that Great Britain was no longer a secure island, began to view aviation and its military potential in a more advantageous light.

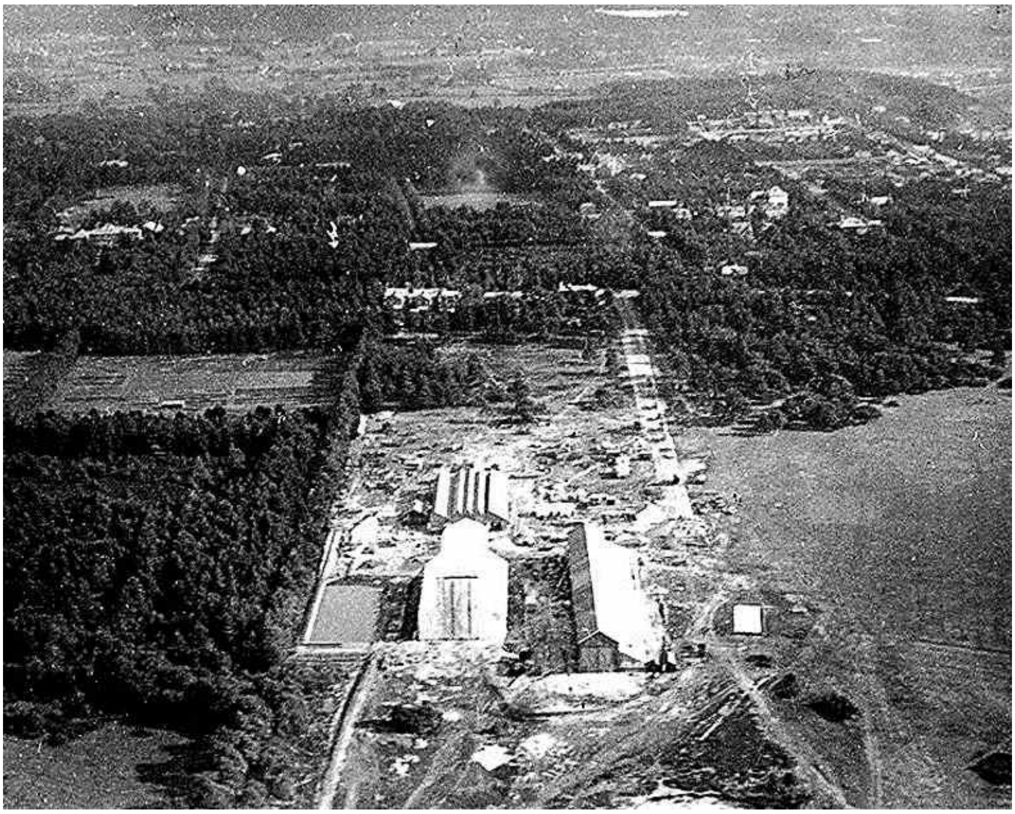


Figure 1 The Balloon Factory in 1906 on the Swan Plateau
just after its move from Balloon Square, Aldershot

1.1 The start of scientific development of aeronautics

The real basis for scientific advance in aviation was started when Mervyn O'Gorman was appointed the civilian Superintendent of the newly formed Royal Aircraft Factory in December 1909. He brought the beginning of a coherent structure to aviation research, introduced scientific method to the development of aeronautics and recruited the first true aeronautical scientists and engineers. The work of the Factory included airships, aircraft and engines.

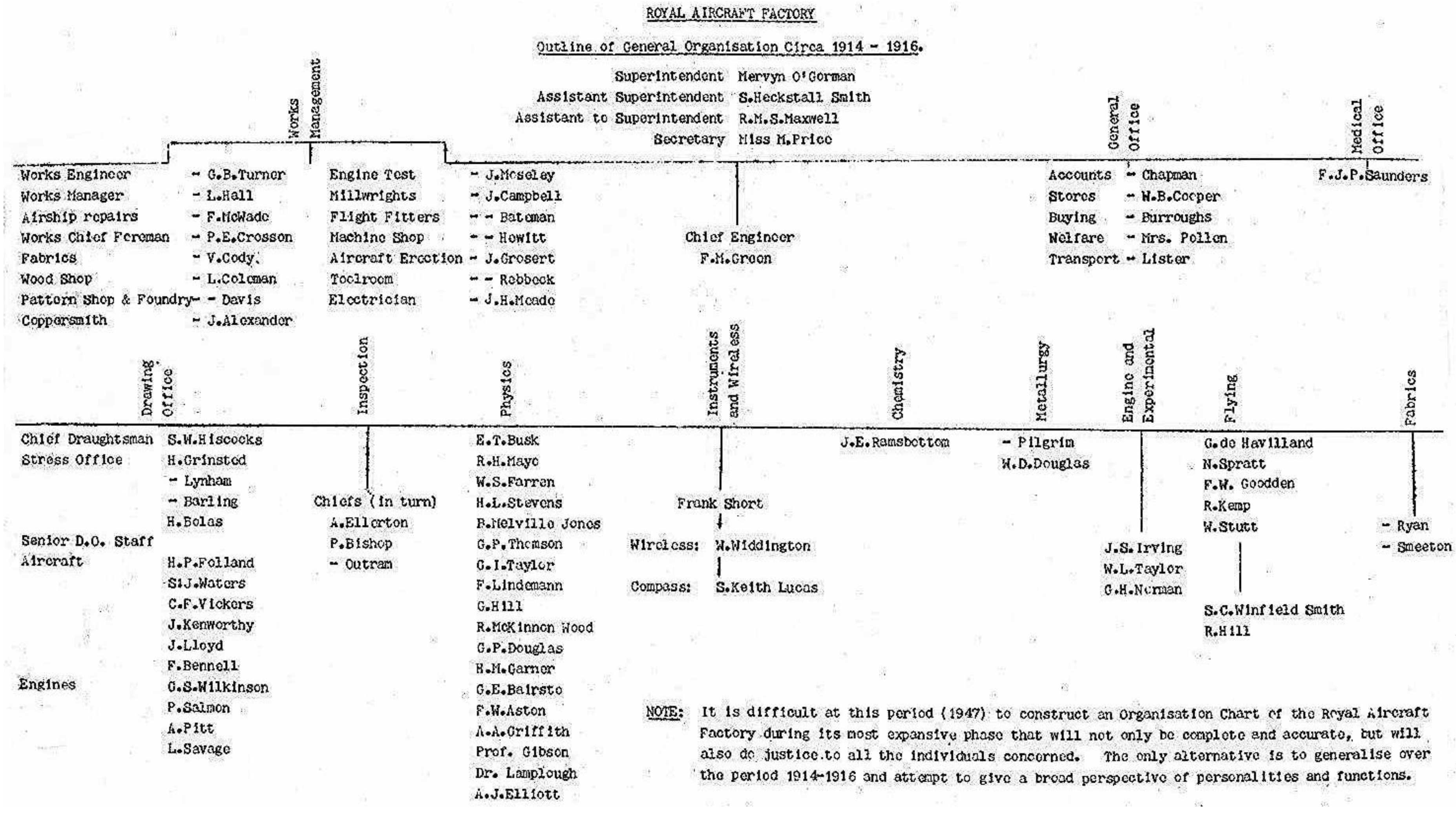
In January 1910 F M Green, one of O'Gorman's early acquisitions from the Daimler Company, on the recommendation of Dr F W Lanchester, joined the Factory as 'Engineer in Charge of Design' (E.D.). He was directly responsible for the design of the Beta, Gamma and Delta airships, most of the aeroplanes from the S.E.1 to the B.E.1 and all the engines from the RAF 1A in 1913 up to 1916. Later, in 1945, he described the 1910 beginnings of scientific method:

> *'...rational methods of stress calculations were developed and introduced into the technique of design, and strength testing of complete structures was started. Calculation of stability and control began to take the place of inspired guesses, and design ceased to be purely an art and became more of a science'* (2).

Through use of these methods the Factory began to develop more efficient aeroplanes and better understand and control many of their irregularities. By the beginning of the Great War it had ready for production two effective machines - the B.E.2 and its derivatives (Figure 2), and the pusher F.E.2.

Figure 2. Geoffrey de Havilland in a B.E.2/2a with the RFC/Inspection 'Black' Sheds in the background in May 1912

Considerable advances in all areas of military aviation were made in WW1 which were not, theoretically, part of the later RAE's R&D but which strongly influenced the future of the Royal Aircraft Establishment. At the end of the war the Factory had developed significantly and had formed some eleven scientific departments researching into full scale flight and all the other scientific and engineering processes that are needed to support safe and effective flight (Figure 3a). This was the structure that RAE inherited in April 1918 (or June if you read other histories), but by 1922 it had developed into the organisation shown in Figure 3b.



ROYAL AIRCRAFT FACTORY

Outline of General Organisation Circa 1914 - 1916.

Superintendent Mervyn O'Gorman
Assistant Superintendent S.Heckstall Smith
Assistant to Superintendent R.M.S.Maxwell
Secretary Miss M.Price

Works Management

Works Engineer - G.B.Turner
Works Manager - L.Hall
Airship repairs - F.McWade
Works Chief Foreman - P.E.Crosson
Fabrics - V.Cody.
Wood Shop - L.Coleman
Pattern Shop & Foundry - - Davis
Coppersmith - J.Alexander

Engine Test - J.Moseley
Millwrights - J.Campbell
Flight Fitters - - Bateman
Machine Shop - - Hewitt
Aircraft Erection - J.Grosert
Toolroom - - Rebbeck
Electrician - J.H.Meade

Chief Engineer
F.M.Green

General Office

Accounts - Chapman
Stores - W.B.Cooper
Buying - Burroughs
Welfare - Mrs. Pollen
Transport - Lister

Medical Office

F.J.P.Saunders

Drawing Office

Chief Draughtsman S.W.Hiscocks
Stress Office H.Grinsted
- Lynham
- Barling
H.Bolas
Senior D.O. Staff
Aircraft H.P.Folland
S.J.Waters
C.F.Vickers
J.Kenworthy
J.Lloyd
F.Bennell
Engines G.S.Wilkinson
P.Salmon
A.Pitt
L.Savage

Inspection

Chiefs (in turn)
A.Ellerton
P.Bishop
- Outram

Physics

E.T.Busk
R.H.Mayo
W.S.Farren
H.L.Stevens
B.Melville Jones
G.P.Thomson
G.I.Taylor
F.Lindemann
G.Hill
R.McKinnon Wood
G.P.Douglas
H.M.Garner
G.E.Bairsto
F.W.Aston
A.A.Griffith
Prof. Gibson
Dr. Lamplough
A.J.Elliott

Instruments and Wireless

Frank Short
Wireless: W.Widdington
Compass: S.Keith Lucas

Chemistry

J.E.Ramsbottom

Metallurgy

- Pilgrim
W.D.Douglas

Engine and Experimental

J.S.Irving
W.L.Taylor
G.H.Norman

Flying

G.de Havilland
N.Spratt
F.W. Goodden
R.Kemp
W.Stutt
S.C.Winfield Smith
R.Hill

Fabrics

- Ryan
- Smeeton

NOTE: It is difficult at this period (1947) to construct an Organisation Chart of the Royal Aircraft Factory during its most expansive phase that will not only be complete and accurate, but will also do justice to all the individuals concerned. The only alternative is to generalise over the period 1914-1916 and attempt to give a broad perspective of personalities and functions.

Figure 3a. This 1914-16 organisational chart is the closest available to the RAE structure in 1918, apart from the change of Superintendent of the Factory to Henry Fowler in September 1916, replacing Mervyn O'Gorman, and then by W. Sydney Smith in March 1918. It is indicative but considered to be accurate in the number, type and size of departments.

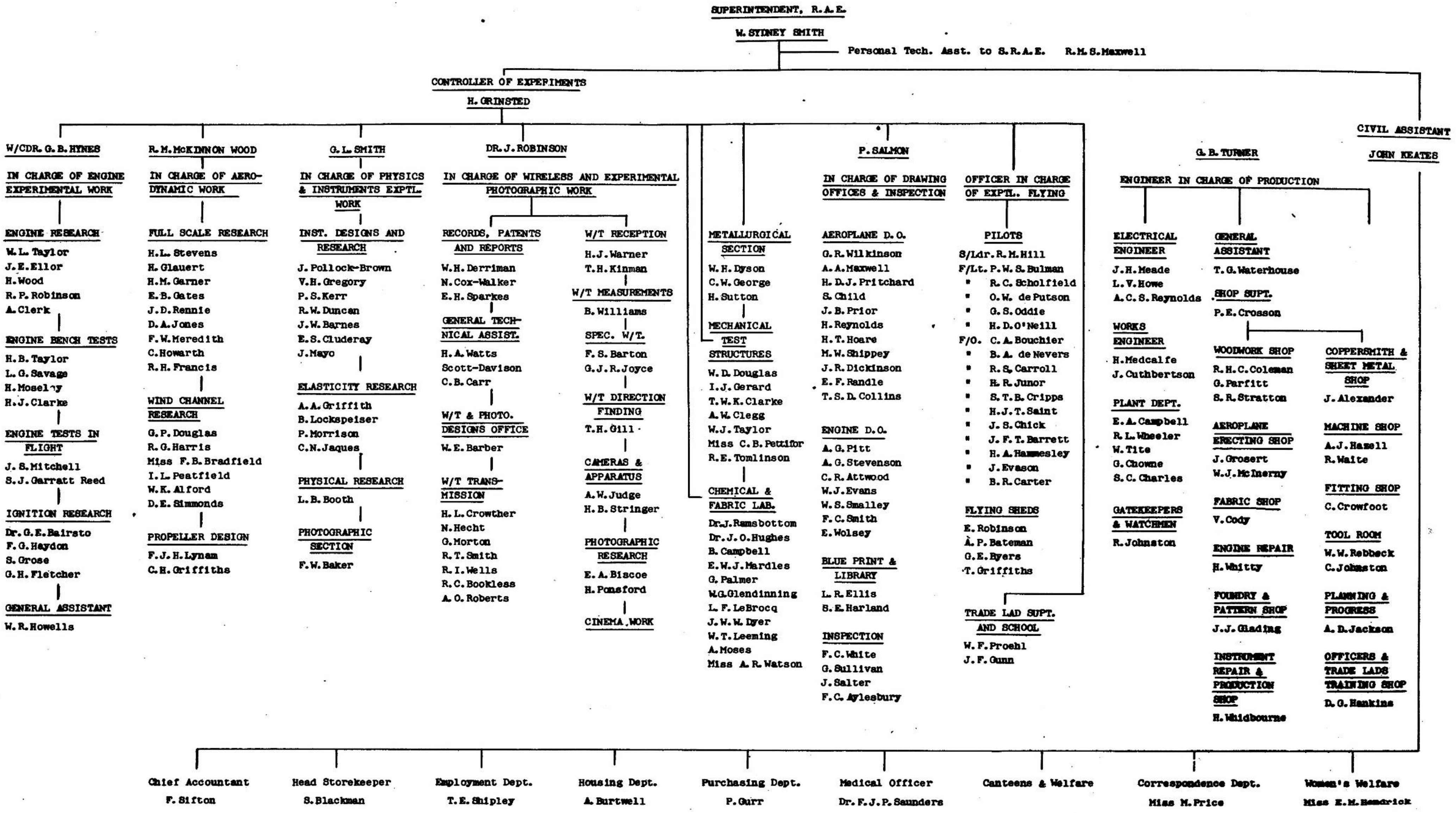


Figure 3b The organisational chart for RAE in 1922

Figure 3b shows the organisation in 1922 by which time the transition from the WW1 footing had been completed and the organisational structure was set – with a few modifications and additions over the years – until well past WW2. In the Production section, running the Fabrics Shop, is Vivian Cody, son of Samuel Cody, who remained Head of Fabrics Division right through to his retirement in 1950 and was, in due course, succeeded by his son Leslie. The Fabric Shop was always known just as "Cody's".

1.2 Post-war financial cut-backs

As with the cessation of all conflicts, certainly in Great Britain, the end of WW1 was followed by large reductions in Treasury funding and thus resources and staff available to support research. The Establishment funding reduced to about 20% of its 1918 figures. In 1917/8 the total number of employees was 5,052 which, by 1920, had fallen to 1,380 - a reduction of some 73%.

However, there remained a few positives with the Trade Lads School (Apprentice training) being established in 1918. In 1922 the Wireless and Photographic Departments arrived from Biggin Hill and Airworthiness and Contracts Supervisions from the Air Ministry.

The financial stringencies hit the work at Farnborough and over the next few years research and development continued but at a considerably reduced level. RAF/RAE had been developing variable pitch propellers and had carried out ground trials on the whirling arm and flight trials with an S.E.5a and a B.E.2. Hermann Glauert – one of Aerodynamics Department's distinguished scientists - had developed "*The Elements of Aerofoil and Airscrew Theory*" (R&M 786) in 1922, published as a text book in 1926, which contributed significantly to the world's understanding of the design of wings and propellers (3, 4). Louis Brennan had begun the construction of a helicopter at Farnborough in 1919, the development of which stretched through six years to 1926 with some 300 flights before being abandoned with the advent of the Autogiro which did much of the same job in a simpler form (Figure 4).

By 1922 the total number of staff stood at 1,316, comprising 250 Scientific and Technical including RAF officers, 85 clerical, 626 skilled including apprentices and 335 labourers and general workers (Figure 5 shows the extent of the establishment in the 1920s).

In 1924 further savings in funding were proposed and the Halahan Committee was formed and tasked to

> "*examine the present organisation of the Royal Aircraft Establishment and to report what steps, if any, should be taken to reduce the cost without impairing its value as an experimental establishment in peacetime or its capacity to expand in an emergency*". (5)

The findings concluded that "The primary function of the Establishment is that it should provide a full-scale aeronautical laboratory for the Air Ministry with its main activities being:

1. Development work on experimental aeroplanes and engines
2. Testing of experimental instruments and accessories
3. Development of special flying instruments for which there is little commercial demand
4. Investigation of failures

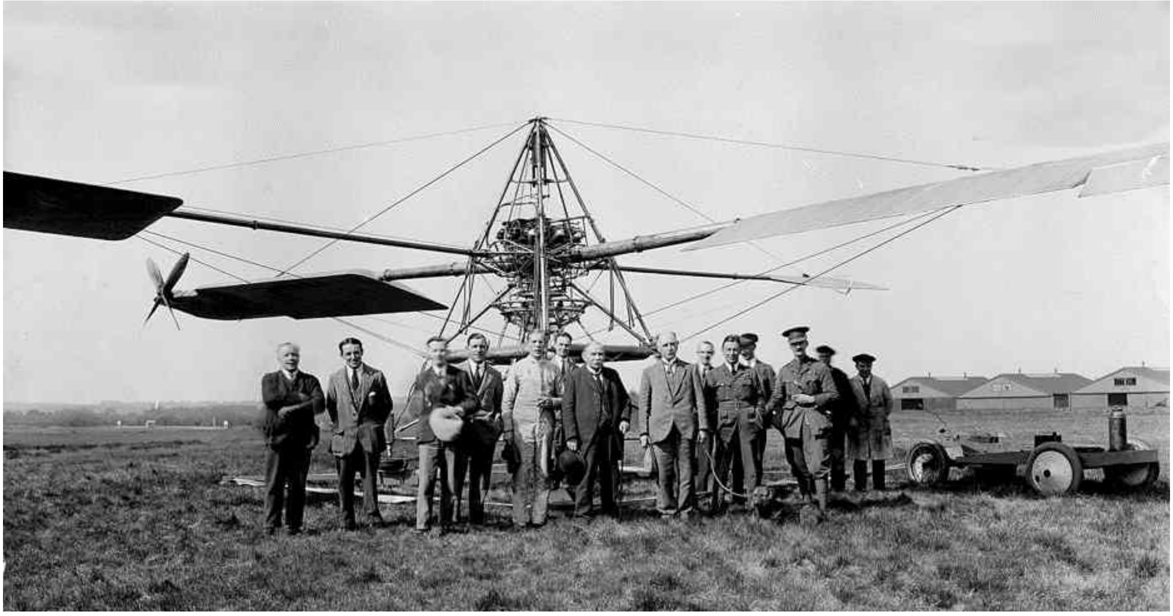


Figure 4. Louis Brennan poses in front of his helicopter on the airfield with the Black Sheds in the far background

In addition, there were subsidiary functions for the support of HQ and RAF

5. Liaison with contractor’s research
6. Technical supervision of the construction of experimental aircraft
7. Stressing of new types of aircraft, approvals of designs for these and recommendations for the issue of airworthiness certificates
8. The issue of certain technical publications

This resulted in the Establishment progressing in much the same way but with a close eye on expenditure and finding innovative ways of getting round financial inconveniences - a process in which they excelled into the future.

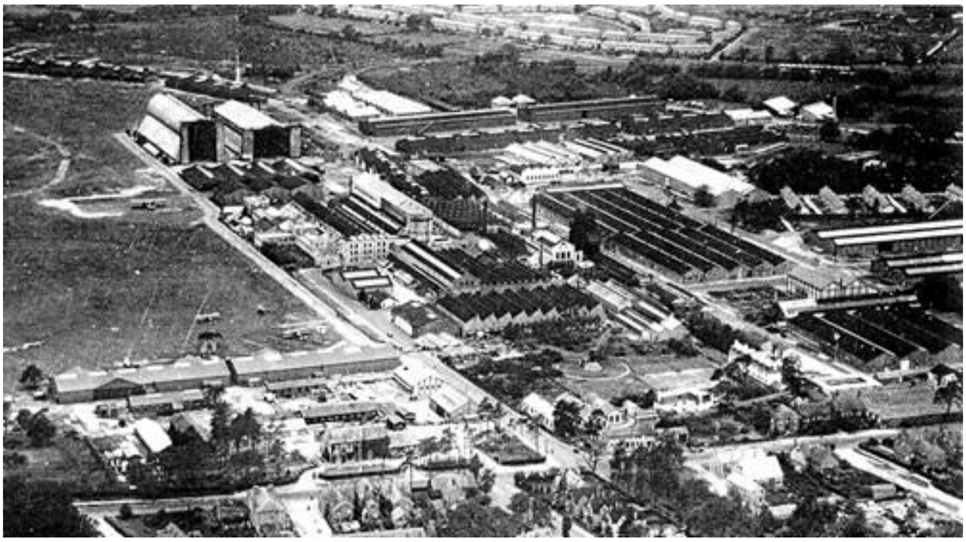


Figure 5. An aerial view of RAE in the 1920s showing the extent of the research facilities and supporting workshops. The airfield extends to the left of the picture in front of the Black Sheds (originally the Inspection and RFC sheds, and not yet painted black)

2. UNMANNED AIRCRAFT

The RAE has always had an involvement in unmanned aircraft (UMA), starting in 1914 when they worked on the development of a radio-controlled UMA to attack Zeppelins which were, for security purposes, called the Aerial Target (AT). Not used during the Great War, development went on at a low level but with flight trials undertaken. In 1927 a better-developed machine – the Larynx – was completed and was designed to carry a 250 lb bomb a distance of 300 miles (Figure 6). This proved successful but it did not spark interest in the Air Ministry who presumably were having trouble finding funding for conventional squadron aircraft and were probably not keen to hasten the demise of the human pilot. In brief, this direction of research included the provision of proper Aerial Targets using conventional bi-planes under radio control as targets for gunnery (the Fairy Queen and developments) to the post WW2 X-RAE Unmanned Aircraft to the current Zephyr solar-powered long-duration very-high-altitude surveillance machines.

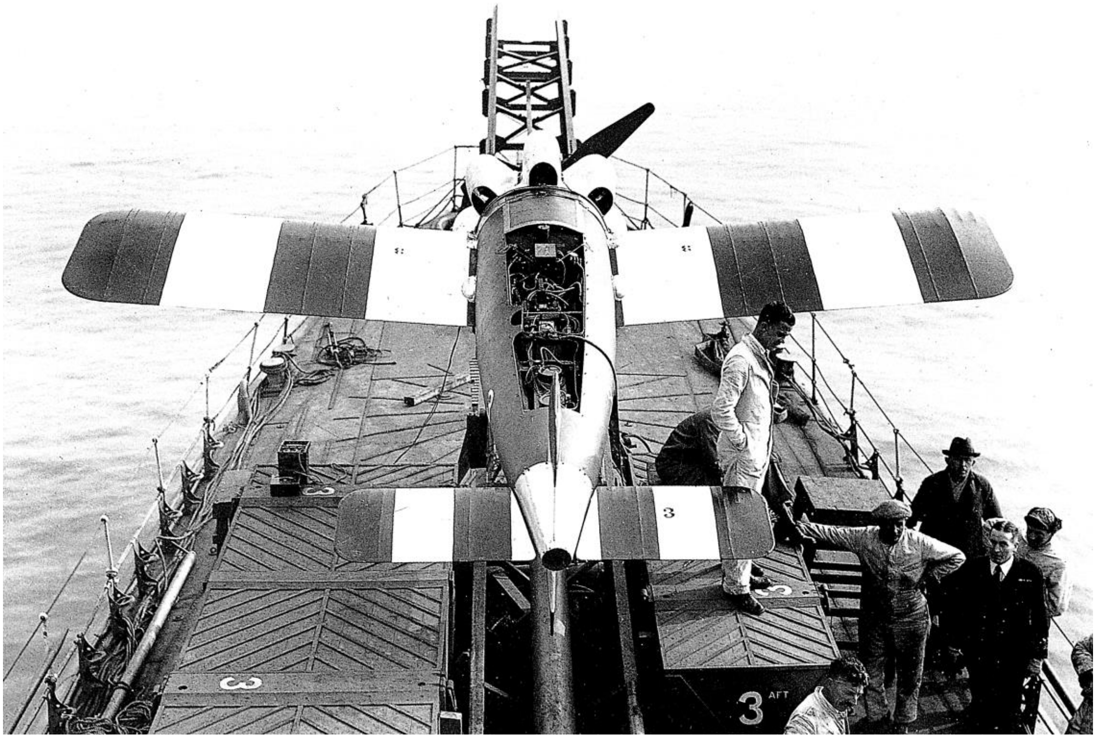


Figure 6. RAE Larynx No.3 prepares for flight from HMS Stronghold on the 19th October 1927 with a future Director of RAE, George Gardner, standing between the wing and tail unit.

3. WIND TUNNELS

A competent aviation research establishment needs to have a comprehensive range of facilities that allow ground testing of aircraft designs and systems prior to flight testing. One of the foremost is the use of wind tunnels to develop and refine the aerodynamic performance of a future aircraft - which is considerably less costly than modifying aircraft once fully constructed. The other significant advantage is that scientific and engineering measurements and changes can be made in a controlled, consistent and repeatable environment. In the early part of the 20th Century the National Physical Laboratory had led much of the aeronautical research and had several wind-tunnels. By 1907 the Factory had a small tunnel and by 1917, R52 building had been constructed as the 'Small wind tunnels' building and contained two seven-foot working section tunnels (Figure 7).

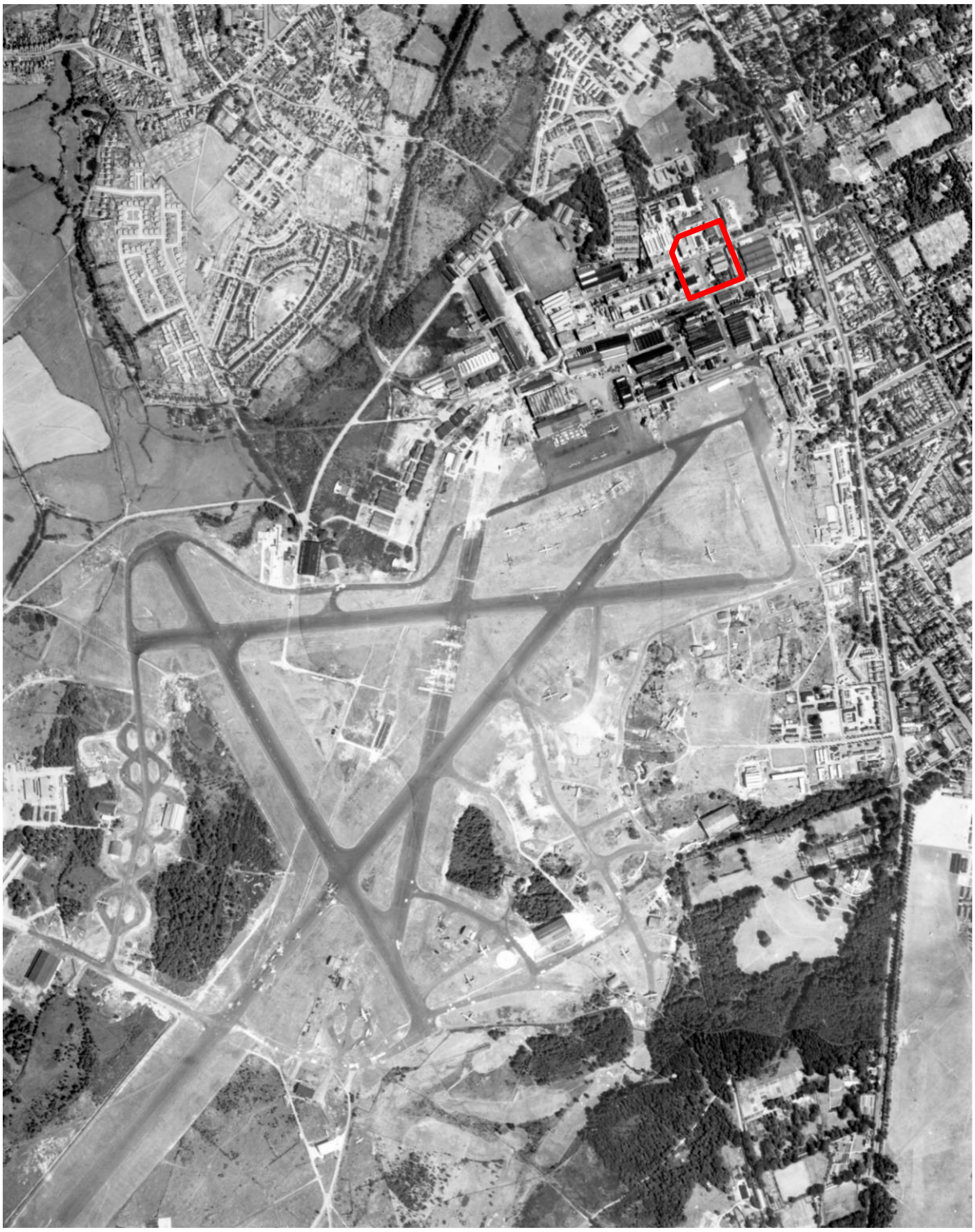


Figure 7 An aerial view of RAE taken in 1950 with the wind tunnels area shown marked in red in the top right-hand of the image. Also shown in the top left-hand corner are the crescent of RAF accommodation buildings built in WW1 and called the RAFBOROUGH estate

3.1 The 24 ft tunnel and engine cooling

In the early 1930s it was realised that larger tunnels were needed and in 1930 recommendations were made for a tunnel which could be used for the current and predicted problems of future aircraft designs. These included the cooling of air- and liquid-cooled engines, the reduction of drag on aircraft and engine cowlings, the development of full scale airscrews and experiments on large aircraft and component parts of aeroplanes such as gun turrets, cockpit canopies, etc.

The tunnel was specifically designed to be able to run engines with a fresh-air intake and exhaust extraction system either side of the working section. In April 1932 work commenced and on April 4th 1935 the 24 ft tunnel was opened by the Secretary of State for Air, the Marquis of Londonderry. It was an open-working-section closed-return tunnel with a 24 ft working section, the airflow being generated by a 30ft mahogany fan with airspeeds of up to 120 mph. Until it was closed in the 1990s the tunnel was used for testing full scale aircraft (Hurricane, Whirlwind, Pou de Ciel, etc., Figure 8), air-cooled and fluid-cooled engines, fir trees for the Forestry Commission, motor cars for Jaguar, Austin and Vanwall, advanced helicopter rotor blades, jet engines for the Meteor nacelle design and finally, amongst many other experiments, the high incidence research models – for post- or near-stall manoeuvring, in the early 1990s.

For the aerodynamicists at Farnborough (and anywhere else) the last thing they needed were protuberances extending into the airstream and interfering with aerodynamic efficiency whilst for the engine researchers at Farnborough there was a need to fit ducts that were large enough to provide the cooling necessary for the engine. This balance between the drag caused by the necessary cooling ducts and the aerodynamic efficiency (for high speed with the available power) becomes more important the higher the speed and had been a constant problem for aircraft designers, much exercised in the 24 ft wind-tunnel, particularly as WW2 approached and lower drag monoplanes became more prevalent

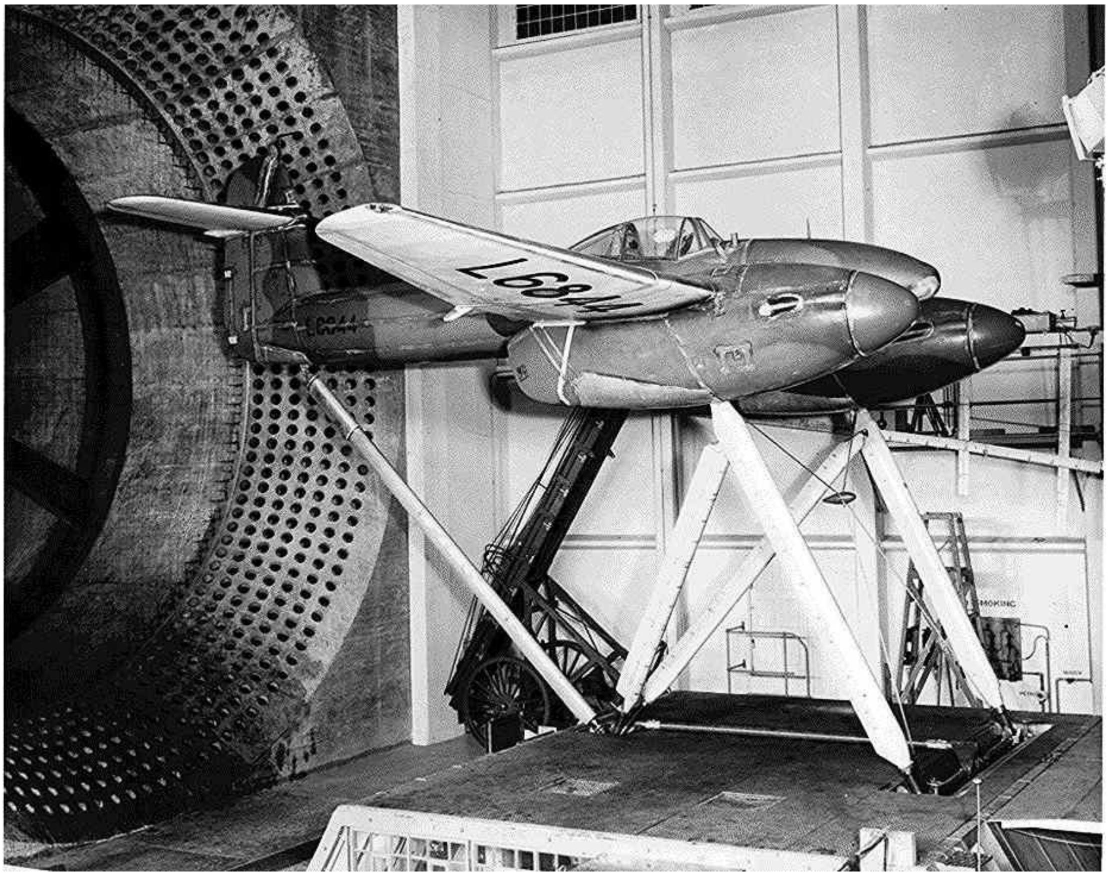


Figure 8 A full-scale WW2 Westland Whirlwind undergoes drag confirmation and reduction tests in the 24 ft tunnel. The radially positioned holes are for exhaust extraction.

In 1936 one of these perpetual problems of balancing drag and performance was largely solved in one area by the innovative research of F W Meredith. The modern high power engines such as the Rolls Royce Merlin used ethylene glycol as an engine coolant and he realised that the energy of the waste heat transferred to the cooling air in a hot radiator need not be lost and, with careful design, this could be used to generate thrust, thus negating much of the drag of the radiator duct protuberance. His seminal work was published in 1936 (BA.1348) (6) and the purpose of the report was to show that, by correct design of low velocity cooling systems, in which the cooling surface (generally in the form of honeycomb radiator) is exposed in an internal duct, the power expended on cooling does not increase with the speed of flight, but that, on the contrary, it should diminish to vanishing point at a practicable speed beyond which the cooling system contributes to the propulsion.

The phenomenon became known as the "Meredith effect" and was quickly adopted by the designers of prototype fighter aircraft then under way, including the Supermarine Spitfire and Hawker Hurricane. An early example of a Meredith effect radiator was designed into the prototype Supermarine Spitfire which first flew on 5th March 1936. Later the system was used to even greater advantage in the P-51 Mustang.

RAE, through its new form in QinetiQ, still runs a 5-metre pressurised low-speed tunnel for low speed studies (up to M = 0.34) where dynamic modelling of airflow remains at a lower level of confidence. The fact that it is pressurised allows direct measurements of the effect of Reynolds Number, improving predictions of full-scale aerodynamic quantities.

3.2 The high-speed tunnel

The 24ft tunnel was a low speed tunnel – up to 120 mph – and by 1937 the aerodynamicists of Aerodynamics Department realised that over the next few years, particularly if a conflict intervened, the speed of aircraft would rise significantly and RAE had no way of testing at high speeds. Thus was borne the idea of the High Speed Tunnel. The tunnel was designed with a working section 10 ft by 7 ft, reaching speeds of 600 mph with a fan driven by a 4,000 hp motor. (7)

Permission to start was given in July 1938 and building commenced in early 1939. The tunnel was completed August 1942 and opened on 6th November 1942. The tunnel was a closed pressurised tunnel, to allow a range of Reynolds Number to be achieved, needing a large cooling system due to the kinetic heating of the high-speed airflow.

Used almost full time during the war, it tested almost all of the aviation industry’s new projects, particularly towards the end of the war when the jet engine allowed high subsonic speeds and high-altitude flight. It was this increase in speed and the necessity to understand the complex aerodynamics of the approaching “Sound Barrier” that caused the original High Speed Tunnel to be closed in October 1954 and the tunnel modified to increase the airflow speed from 600mph (Mach 0.8) through Mach 1 to Mach 1.15 – the so-called transonic region. The tunnel structure was used with modifications to the walls of the working section to reduce shock wave formation in the tunnel (the dark slots in the tunnel floor in Figure 9 allow air to flow in and out of the working section) and needed a new 12,000 hp motor. The original working section would have choked above M = 0.8 because of reflected shocks affecting the air flow.

Opened on the 1st April 1956, it remained a significant tool in the understanding of the difficulties of transonic flight until June 1993 (Figure 9). The tunnel provided assistance to industry in testing most of the high-speed designs; the three V bombers, TSR-2, Tornado and interaction between fuselage aerodynamics and weapon during high speed weapon release of bombs and missiles (Figure 10).

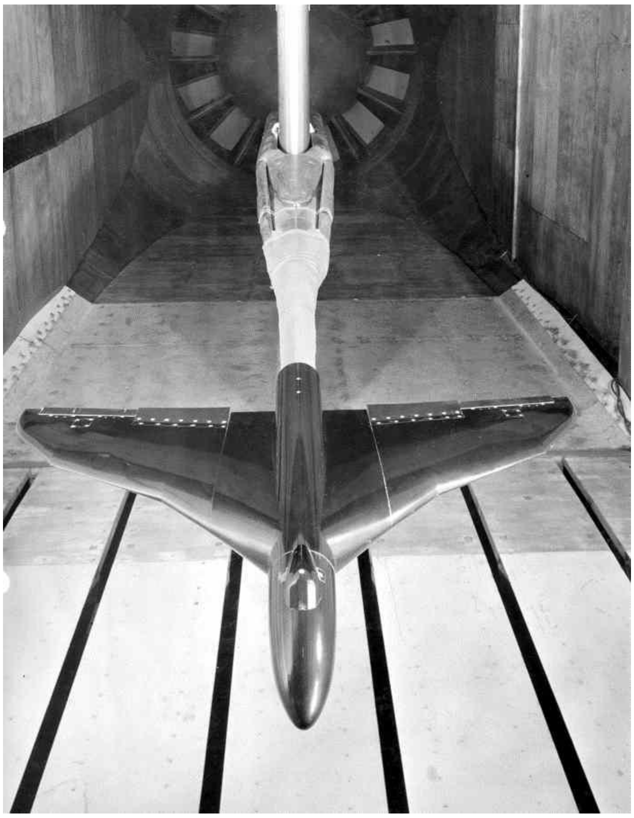


Figure 9. An Avro Vulcan with the modified leading edge tested in the Transonic Tunnel (M < 1.15) which was a Cold War facility developed from the earlier M < 0.8 WW2 High Speed Tunnel. Note the slots in the floor of the tunnel to reduce shock wave reflection

Figure 10. The Transonic tunnel facilities were developed such that any aerodynamic interferences during weapon release at high-speed could be studied prior to flight trials

As well as testing aircraft models the tunnel was used to develop mathematical and computer models of wing aerodynamics and the RAE method became one of the standards for civil aircraft high speed-wing design.

3.3 Hypersonic tunnels

At the higher end of the speed scale RAE had several other tunnels which included, in the Ball Hill wind tunnel complex, tunnels with a hypersonic capability.(8) Design of the first hypersonic facility started in 1954 and comprised a 7” x 7” working section running at between Mach 5 and Mach 9. It was a conventional intermittent supersonic tunnel operating with heat addition upstream of the settling chamber but with stream conditions in the working section near to liquefaction (a so-called cold tunnel). In 1956 a decision was made to construct a large shock tube where Mach numbers of above 10 could be generated along with the corresponding enthalpies. Initially built in the open air, the tube was constructed of old gun barrels of 6-inch internal diameter and suitably bored, smoothed and chromium plated. The high-pressure chamber was 30 ft long and stressed for a working pressure of 1,000 atmospheres.

On the Ball Hill site were a number of smaller tunnels. A 2-inch diameter shock tube was used to study relaxation effects, a 3” x 1½ ” shock tube used to calibrate specialist pressure gauges and a square section 4” x 4” tunnel with large side windows to investigate the interaction of the reflected shock wave in a tube with the wall boundary layer at high Reynolds numbers. Thus RAE had covered the range of speeds liable to be used in conventional aircraft plus the speeds that were needed for most of the re-entry conditions for space vehicles.

4. SEAPLANES AND DITCHING

In the 1930s there arose an interest in the wider civil commercial use of seaplanes to extend operations to areas which were short on runways but large on rivers, lakes and coastal areas. To carry out the necessary research into the hydrodynamics of new forms of seaplane hulls and floats the RAE constructed a seaplane tank. This comprised a water trough nine feet wide by four and a half feet deep which extended for some 650 ft in length, through which the test hulls could be driven at a speed of up to 40 ft/sec (9). Built alongside Fowler Avenue, it carried a carriage on rails above the trough which contained the lift and drag balance and two intrepid operators who journeyed the 650 ft length, taking measurements and filming the seaplane dynamics for later analysis. Used from the mid-1930s, it was in use right up to trials on the Saunders Roe Princess and included some interesting experiments on a Spitfire fitted with floats in May 1941 to prepare for operations from lakes in the Middle East in 1943.

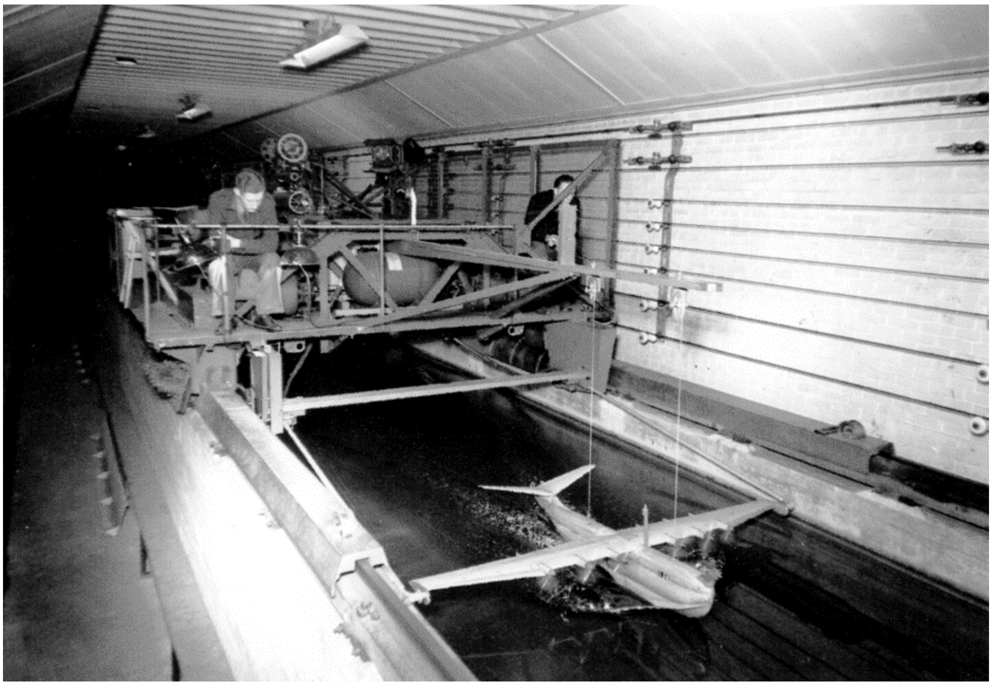


Figure 11. The water-borne characteristics of the Saunders Roe Princess are studied in detail in the seaplane tank. The moving carriage and balance are controlled by the two riding operators.

Prior to WW2 very little research had been carried out on the behaviour of aircraft during an emergency landing on water (ditching). Information on how a landplane behaves on water had been obtained before the war from dynamic model tests made on three aircraft in the seaplane towing tank at the RAE Farnborough. But in these trials no attempt was made to represent the strength of parts of the aircraft's structure that would probably fail under water loads, and no attempt was made to represent the alighting contact which, in subsequent tests, was shown to have a direct bearing on ditching behaviour. The general information obtained was, therefore, of limited usefulness.

Early in 1941 the Royal Aircraft Establishment was asked to advise how best to put landplanes down on water; in other words, how best to ditch. The inconclusive results from the pre-war RAE seaplane tank trials, using a towing technique, led to the use of a catapult to project dynamic models on to water in free flight – a technique that was adopted early in the war to investigate, in the first instance, the ditching characteristics of the Hudson, Spitfire, Hurricane and Fulmar.

Free launching model tests were started in an outdoor tank at RAE Farnborough (10) where scale dynamic models were catapulted on to the water and the alightings were observed and photographed with a high-speed Vinten camera. Owing to the complete freedom of the model once it had left the catapult, these tests were considered to be dynamically considerably more realistic; also, the failure of parts of the structure thought to be important were represented. It was possible to explore the ditching behaviour of an aircraft over a wide range of touch-down conditions, and information was obtained both on the best method of handling the aircraft before impact and on the hydrodynamic and structural design features that made aircraft good or bad ditchers.

The outdoor tank was the spray pond of the high-speed wind tunnel, then under construction. The models were attached to a carriage which would be catapulted down an inclined track and the model released to fly on to the water. The catapult was powered by the fall of a heavy weight attached to the carriage by a rope and pulley system. By relying on gravity, the trials did not suffer from power cuts as the wind tunnels often did! From the results of tests and from the experience of pilots who ditched successfully, it was possible to assess the qualitative effect of the various parameters that may be considered as primarily affecting ditching behaviour.

During, and after, the war RAE tested in excess of 50 aircraft, both military (e.g. Stirling, Tempest, Vampire, Sea Hawk, Javelin….) and civil (e.g. Viking, Viscount, Britannia, Tudor, York …) and many more (10).

From these series of experiments the primary parameters affecting the ditching behaviour could be determined (e.g. effects of size and wing loading, fuselage shape, wing position, wing height and setting, tailplane position, nacelles, air intakes, underslung radiators, undercarriages, bomb doors and other weak parts of the under-fuselage structure). From these data a series of design parameters were set for both military and civil aircraft to minimise the risk to aircraft and passengers in ditching – all of which carries through to the present generation of aircraft.

5. STRUCTURAL INTEGRITY

In another significant area of aviation safety, RAE had been responsible for aircraft structural integrity since the 1924 Halahan Committee recommended it undertake "Stressing of new types of aircraft, approvals of designs for these and recommendations for the issue of airworthiness certificates". Structural testing had gone on at Farnborough since the Cody flying days, initially with dead-weight testing using loose sand and lead bags on an inverted airframe – which was carried through to structural failure. The load factor could then be assessed and in addition could be compared with the theoretical calculations.

To assist the structural design of the pre and early WW1 aeroplanes, the Factory, under the name of the Superintendent – Mervyn O'Gorman – published in the open literature an article in *Flight* on October 13th 1913 (11) entitled 'Stresses in wings – The RAF method of estimating'. This article set out the method of stressing the wings for the flight loads of the time and was intended to assist the British Industry in its design of new aeroplanes. Farnborough followed up this article by the issue, in November 1916, of a six-page pamphlet on the "Design Requirements for Airplanes" – essentially the first Av.P 970 and predecessor of the current Def Stan 00-970 'Design and airworthiness requirements for service aircraft'. Indeed, the first certificate of airworthiness awarded on 14th March 1912 for a Factory B.E.1 aircraft partially stated "*the machine has been inverted and suspended from the centre and the wings loaded to three times the normal loading. On examination after this test the aeroplane showed no signs of defect*". The Airworthiness Division of Structures Department provided structural airworthiness approvals for the aircraft and airborne weapons of all three service right through to 1990 and beyond.

As aeroplanes developed from wood and fabric to metal structures, dead-load testing was superseded by a structural frame test allowing loadings to be more precisely applied. In 1927 the RAE applied for Treasury funding for the new test rig but permission was refused. However, the Treasury would support a rig going to industry under a Treasury Economy Scheme. RAE devised a solution where Bristol Aircraft accepted the rig for a short period of testing before it was re-assigned to Farnborough (a fine example of lateral thinking by RAE and Industry!). This 'Temple' rig could accommodate half wings up to 25 ft in length and used dial-reading extensometers sensitive to 0.0001 inch for the recording deflection. Apart from ultimate strength testing, it and other structural rigs were used for strength analysis and improvement. As an example, the Short Singapore II fuselage frames were designed to take a load of 16,000 lb but failed at 3,000 lb. Testing and iterative re-design resulted in the Singapore III frames which, when tested, failed at 20,600 lb with a bonus reduction in weight of some 16%, contributing to savings of some 10% in the bare hull weight.(12) Thus the rigs could be used in trade-offs between weight and strength (and presumably cost). Used extensively by RAE for research, by industry for confirming the strength of new aircraft types (Figure 12) and RAE for airworthiness clearances, the rig was also in use when new structural materials were introduced with new construction techniques. When the Bristol 188 experimental aircraft with a stainless steel airframe was tested, the rig was used to review the use of spot-welding and other structural developments as a reliable and safe construction technique.

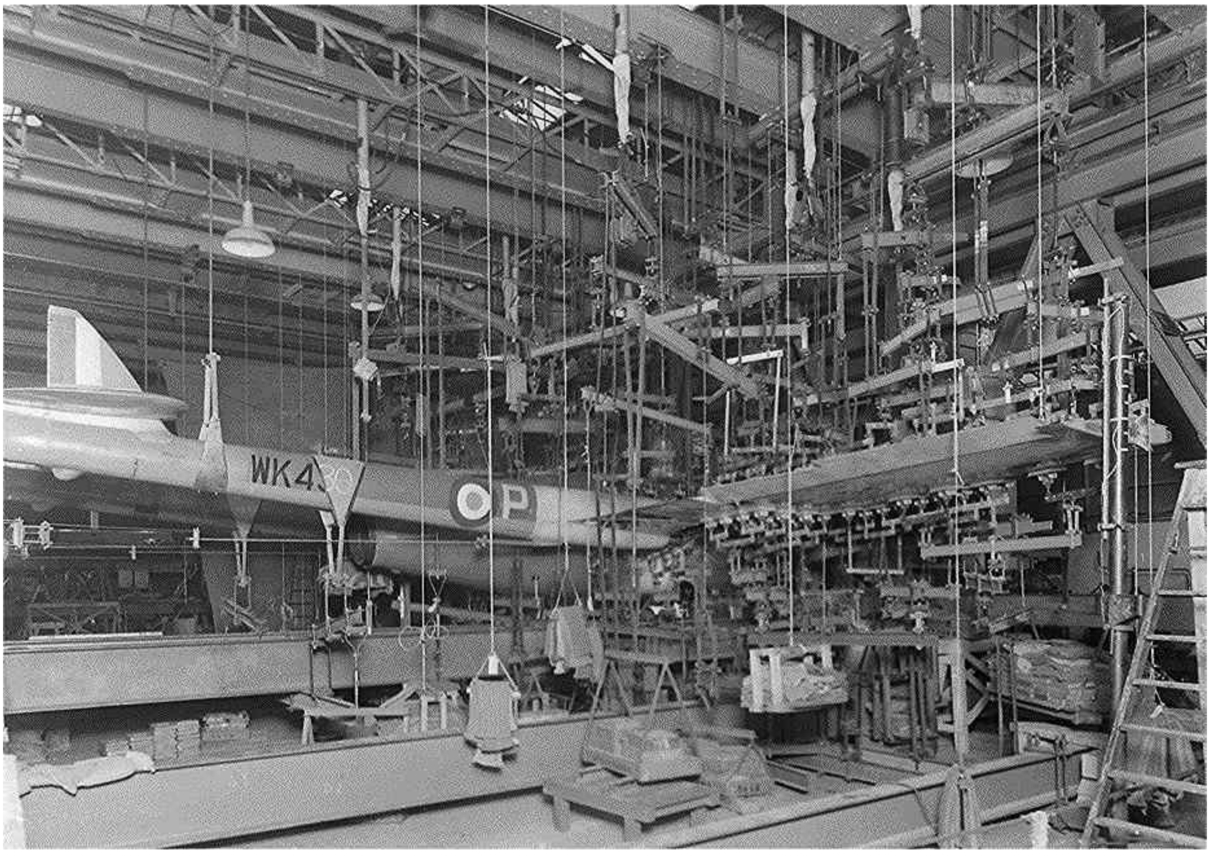


Figure 12 A prototype de Havilland Venom undergoes structural strength testing in the SME Department 'Cathedral' test rig in Q153 Building

6. THE AIRFIELD

The airfield was, obviously, an integral part of RAE. At the start of the Balloon School and the Factory, the large grassed area south of the balloon and airship sheds – Farnborough Common – was used as the launching and landing grounds. Throughout the First World War and up to the beginning of WW2, the area—although slightly enlarged—was still a grass airfield (Figure 13), but with public access restricted. In 1940, with the advent of the heavier bombers, the 07/25 concrete runway was constructed with runway 00/18 added in 1942, which involved filling in of a local landmark, Cove reservoir. The post war extension of runway 07/25 took it across Laffan's Plain. An aerial photo, taken in 1958 (Figure 14), shows the airfield essentially as it remains today with its main and two auxiliary runways – which, incidentally, are no longer used in its current role as a commercial airfield for business jets.

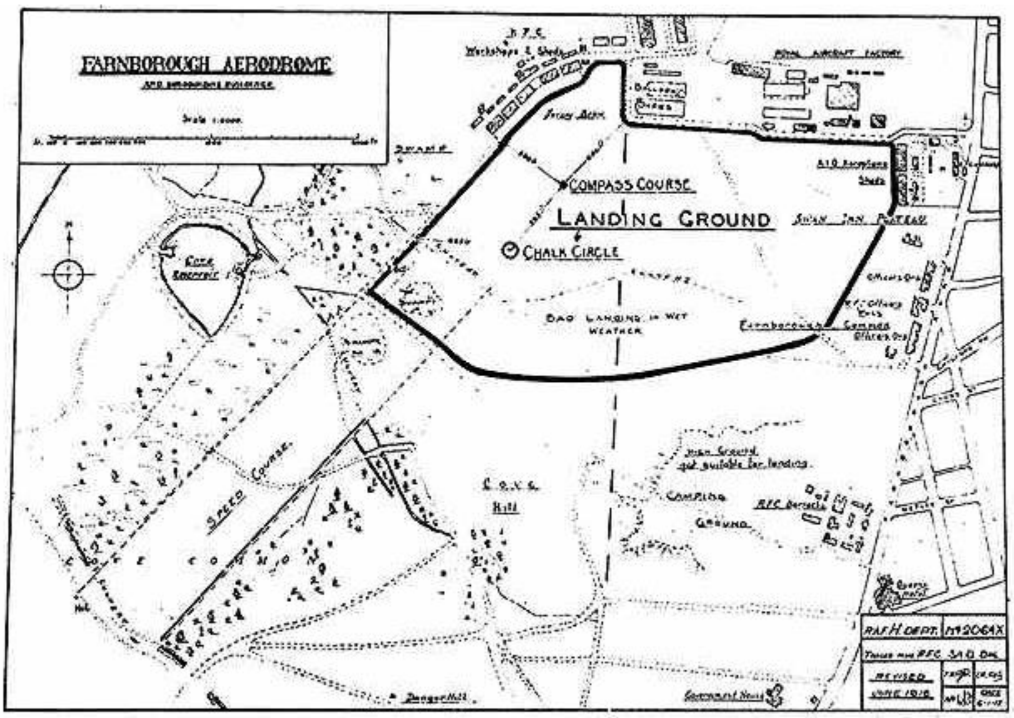


Figure 13. A plan of the Factory airfield in 1916

Figure 14. An aerial view of the Farnborough runways and research facilities in 1958. The bottom right hand corner shows the display tents for that year’s SBAC Airshow

6.1 Landing in poor weather conditions

Of the many problems in aviation, landing an aircraft in bad weather, particularly fog, rates fairly highly in the pilot’s scale of difficulty. During WW2 bombers based in Britain would sometimes return to their home bases in the early morning hours to find all their landing sites completely fogged in, which resulted in the senseless loss of airframes and aircrews. Providing a capability for landing safely in adverse conditions would be of significant benefit to both military and civilian flyers, as military missions would be made possible in all conditions and airlines could avoid the wasteful and expensive practice of diverting away from fogged-in airports.

Initially a system of local fog dispersal called FIDO was tested, some simple dispersal experiments being carried out at Farnborough and then larger scale trials at Hartford Bridge Flats (Blackbushe), Farnborough's 'satellite' airfield. This involved burning copious amounts of fuel along both sides of the runway, the resulting hot air clearing enough fog to enable a landing to be accomplished. This was used successfully on a number of dispersal airfields in WW2 and saved many aircraft and lives but was only viewed as a short-term palliative solution.

The more permanent solution was to ensure that an aircraft could blind-land in any conditions. The RAE Blind Landing Experimental Unit (BLEU) was formed at RAF Woodbridge and Martlesham Heath during 1945 and 1946. It was a multi-disciplinary unit, drawing staff from the RAE Farnborough and the Telecommunications Research Establishment (TRE) Malvern. The terms of reference were that the unit "will operate as a satellite of the RAE and will be responsible for the development of blind approach and landing of RAF, Naval and Civil aircraft". An alternative system had been briefly used early in 1945 by TRE at RAF Defford using the American SCS 51 radio guidance system in a Boeing 247D aircraft. The initial research at BLEU led to the conclusion that a promising approach to blind landing would be a fully automatic system, later to be called Autoland. (13)

The systems would use developments of the Instrument Landing System (ILS) which had been developed from wartime technology, but with accuracy increased sufficiently to provide guidance during landing. Lateral guidance was enhanced using magnetic leader cables extending from each end of the runway for a length of one mile. In elevation, an improved FM radio altimeter developed by BLEU and capable of resolving height differences to 2 feet at low altitude was employed. Thousands of test landings were carried out using this system. It was later modified to work with a radio-based solution for lateral guidance rather than the leader cable system, since for most airports installing the cables parallel with extended runway centrelines for a mile beyond landing thresholds was simply not practicable. Working in collaboration with UK industry and the civil aviation authorities, most of the trials flight work was undertaken from the RAE Bedford airfield.

Several types of aircraft were tested, including the Lancaster, Viking, Devon and Albemarle, and a demonstration of the techniques used was given to military and government representatives in May 1949. By 1950 the entire system had been installed on a DH Devon and the first demonstration of Autoland was given on that aircraft on 3 July 1950. Over the next 20 years, BLEU, in conjunction with UK industry and the UK airworthiness authorities, was responsible for almost all the pioneering work needed to convert the concept of those experimental demonstrations into safe accurate blind landings by civil and military aircraft. In particular, the system was fitted to the RAF V-Bomber fleet, extending their operational capability in all weathers.

6.2 Approach lighting

Prior to this blind landing capability entering service there was a long period where the problems of final approach to land in conditions of limited visibility still existed. Civil airfields in the early to mid-1940s were starting to be equipped with high intensity approach lighting patterns on what were termed their 'precision approach runways' to assist pilots make the transition from 'blind' approaches, using instruments or automatics, to a manual visual landing. In 1946 the RAE was requested by a UK Ministry of Civil Aviation Airfield Lighting Committee to investigate the problem of approach lighting and establish the general principles involved. RAE's Electrical Engineering Department took up the request and an outstanding and elegant analysis by E S Calvert and J W Sparke, backed by simple practical simulations (on the CYCLOAMA, a panoramic image on the inside of a cylindrical platform designed to give viewers standing in the middle of the cylinder a 360° view) demonstrated conclusively the mental processes by which visual judgements on the present position of the aircraft, aiming point and rate of change of position were extracted from the changing perspective of lighting patterns.(14)

As a result of this exhaustive analysis, Calvert concluded that in the absence of the real horizon, all existing systems might give ambiguous indications when the aircraft banked. He then demonstrated that illuminated bars running transversely across the direction of approach would appear in perspective to be parallel to the real horizon for lateral and heading errors, however large. He also pointed out that if the width of the bars decreased progressively as they approached the runway, a rough indication of whether the aircraft was overshooting or undershooting could be given, even if only a limited portion of the whole approach pattern were seen. The superiority of the cross-bar pattern was almost unanimously agreed by some hundreds of pilots who compared the RAE system with others on the CYCLOAMA.

In 1948 a temporary cross-bar approach lighting system was installed on the Farnborough airfield as a preliminary to its adoption for London Airport Heathrow. The successful trials of the system, both at Farnborough and on the Berlin Air Lift, led to its general adoption for British Civil airfields and to a permanent installation at Farnborough in 1949.

7. AERIAL PHOTOGRAPHY

Aerial photography was an area in which Farnborough was involved from its earliest days. The B.E.2c was designed as a stable aeroplane for reconnaissance purposes but that stability made it an excellent vehicle for camera work. The Balloon School building has the first dark room for developing and printing of aerial photographs, contained in a small cupboard under the stairs in the entrance to G1 Trenchard House. The Air Photography Section had produced the first report on Air Photography in 1915 and concentrated upon the development of aerial cameras and their specialized technique. In 1919 RAE were involved with the Air Ministry Directorate of Scientific Research in the design and testing of the new F8 camera which used 7” x 7” roll film in place of the glass plates and which could be fitted with lenses of varying focal lengths. However, the Ministry considered it too heavy for the aircraft in service at the time and too expensive at £200, although it continued to be used in less demanding installations.

In 1924 the Wireless and Photographic Department designed the F24 camera, intended to be lighter and smaller than the F8 with a 5” x 5” image and which was in production in 1925 and used by the Royal Air Force for day and night aerial photography until 1955. However, it lacked the high definition of the earlier F8 camera with its 7” x 7” negative and was therefore of limited use for military mapping. In 1942, with the need for more detailed images for bombing assessments etc, the F24 was developed into the F52 that used an image format of 8.5" x 7", magazines up to 500 exposures, and was better suited for 36” and 40” lenses in larger installations. The F.52 camera was so called as it took RAE just 52 days from design to completion.

Farnborough also had a decisive part in the first significant attempts at aerial photography in WW2. Sidney Cotton, the civilian and controversial champion of aerial photography in WW2, had visited Farnborough and asked advice on fitting cameras to a Mk1 Spitfire. When two Spitfires were set aside for this photographic work they were equipped at Farnborough, and these aircraft became the first Spitfire PR(1)s. In November 1939 they were used by 212 Squadron, flying from airfields at Coulommiers and Senlis in France to take the first aerial images inside the German border, of Aachen from 34,000 ft. To support this type of dispersal Farnborough designed and constructed the first fully independent Mobile Photographic Printing Unit, consisting of trailers which contained all the components needed to process and print the film. Taken to France in December 1939 it was set up near Arras. RAE was also carrying out many high-altitude experiments to stop cameras lens misting and camera control systems freezing at these heights and temperatures, as well as the physiological protection of pilots at these high altitudes with the Bazett flying suit.

8. BOMB AIMING AND NAVIGATION

From the earliest days of aviation, bombs were dropped by hand from airships and aeroplanes. As the use of aircraft increased during WW1, the need for better accuracy became pressing. Farnborough had been involved peripherally in testing and developing bombsights from the beginning of WW1, but prior to 1930 bomb-sighting problems had been the responsibility of the Air Ministry Laboratory (AML). After this date, the design, development, the technical aspects of production and the introduction into service use of this equipment became the direct responsibility RAE’s Instrument and Photographic Department (I&P). In particular, all the fundamental design work and the majority of the detail design and development was carried out by the Department. In 1935, as part of this responsibility, a modern version of the original Bombing Teacher was designed and built to simulate bombing with bombsights of the existing course setting bombsight type (CSBS), which made use of four vectors: height, airspeed, wind speed and direction,

By 1939 the Farnborough-designed Mk. IIA automatic bombsight was being introduced into service; later it was used with considerable success against small important targets such as the *Tirpitz*. However, as WW2 started, revised versions of the CSBS, the Mk. VII and Mk. IX, remained universal, and the Mk. X, a more extensive improvement, was in mass production and being readied for service entry.

The downside to the CSBS was that the settings, made through four main input dials, were for a given altitude and heading. If the aircraft manoeuvred, the entire system had to be reset. The CSBS generally required the bomber to fly straight and level for up to a minute before releasing the bombs, and the predictability of this track made it very vulnerable to anti-aircraft fire and fighter attack.

On 28 March 1939 the Head of RAF Bomber Command hosted a conference on the state of Bomber Command and, noting many problems with operational readiness, he stated that not only were RAF bombs much too small but that bombsight technology was obsolete. Bomber Command pressed for a new bombsight that featured stabilization to allow the aircraft to manoeuvre while it approached the target. What was needed was a new bombsight that could be very quickly set up, had useful illumination of the crosshairs for night use, and was stabilized so the bomb aimer could watch the approach as the bomber was manoeuvring.
The request for a new bombsight was quickly passed on to RAE and Patrick Blackett, a founder member of the Tizard Committee, volunteered to lead the new design and was given facilities and a small team of engineers at Farnborough. The resulting Mk. XIV, comprising a control cabinet mounted on the left of the bomb aimer and a separate stabilised sighting head with an illuminated optical graticule, was first tested in June 1941. It was the first modern bombsight that allowed for accurate bombing immediately after radical manoeuvring, with a settling time as little as 10 seconds. The fast settling time was invaluable during night bombing missions, as it allowed the bomber, in order to evade an enemy night-fighter, to fly a corkscrew (a helical path), climbing and turning, and then level out immediately before the drop. Even slow turns made it difficult for night fighters to track the bombers within the limited view of their radar systems and continually changing altitude was an effective way to avoid anti-aircraft fire.

Although the Mk. XIV was not as accurate as the US-developed Norden bombsight at altitudes over 20,000 ft, for typical night bombing altitudes of 12,000 to 16,000 ft any differences in accuracy were minor. When the need for more accuracy with the Tallboy bombs arose in 1943 and for Pathfinder operations, the Stabilized Automatic Bomb Sight (SABS), a development of the earlier Automatic Bomb Sight, was introduced in limited numbers.

8.1 Ground Position Indicator

A further significant navigation aid from I&P Department was the Ground Position Indicator (GPI) which combined the earlier RAE designed Air Mileage Unit and Air Position Indicator into a single unit showing the position and heading of the aircraft optically on a map pinned onto the navigators table. This provided essentially fully automatic navigation, leaving the navigator with the remaining job of determining the wind speed and direction and inserting the values into the GPI. Accurate to within 1 to 2% in any type of flying, including evasive action, it was of great value for navigation to important targets and, usefully, was not vulnerable to enemy counter-measures. The Establishment helped to fit this equipment to 617 Squadron Lancasters for the Mohne and Eder Dams raid and also to USAAF Liberators for the Operation Tidal Wave attack on the Ploiesti oilfields on 1st August 1943.

9. POWERPLANTS

A further major area of concern for Farnborough was in the area of aircraft power plants. Research on aircraft engines had been carried out since the very early days of WW1, and throughout WW1 Farnborough produced at least four types of engine based on a modified Renault design. These were V-8 and V-12 air- and water-cooled designs. Much research was also carried out, particularly on air cooled engines, and detailed and definitive design rules on air-cooling were promulgated by Griffith, Heron and Gibson.(15) Also in the period from 1913 to 1918 some 23 research engines were built and tested. Supercharging flight trials were carried out using the Factory RAF 1a engine in a B.E.2c (Figure 15). The climb performance improved from 8,500 ft in a time of 35 minutes with normal aspiration to 11,500 ft in 35 minutes while supercharged. Similar trials were carried out in 1918 with turbo-charging using the Factory RAF4D engine with a Rateau turbine in an R.E.8, improving the attainable altitude from 11,000 ft to 15,300 ft in the same time (23 minutes).

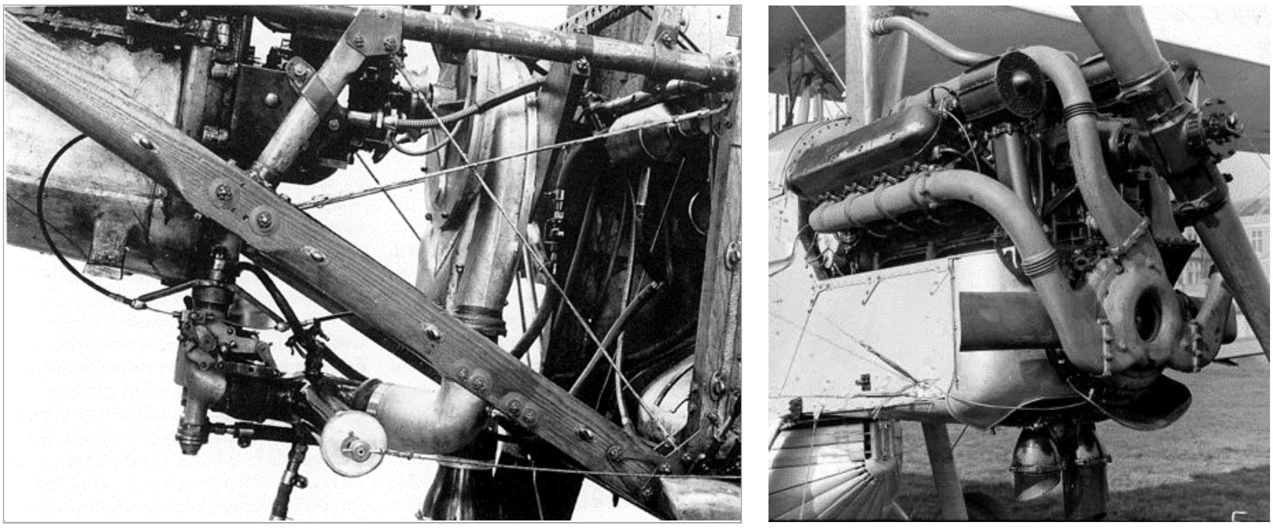


Figure 15. Two early examples of engine development at Farnborough. On the left is a supercharger fitted to a RAF 1a engine in a B.E.2c for trials in 1915. Another method of forced induction, on the right, in this case a Turbocharger in 1918.

In September 1916 the Factory designed the RAF 8 engine, an air-cooled fourteen-cylinder two-row radial, with aluminium overhead cylinders, lined and with valve seat inserts, that was engineered to use a gear driven supercharger. In January 1917 a number of staff left the Factory for Industry, one of whom was F M Green, one of O'Gorman's first hires, who went to the Siddeley Deasy Motor Car Company and later developed an engine at Armstrong Siddeley based on the experimental RAF8 engine which, with some changes, became the highly successful Jaguar engine. The Factory also carried out a design study for the RAF 10 engine, a 12-cylinder water-cooled 'W' format which later formed the inspiration for the Napier Lion engine, which was widely used in the 1920s and early 1930s.

9.1 Piston engine fuel systems

In the early days of WW2, particularly during the Battle of Britain period, Spitfires and Hurricanes fitted with a SU carburettor on their Merlin engines were having problems with a hesitating engine during negative 'g' manoeuvres. Farnborough was asked to provide a simple and hopefully immediate answer which would not delay aircraft production. This problem was referred to the RAE engine section and taken up by a prominent lady scientist - Beatrice Shilling (Figure 16). Her innovative and elegant solution was to control the flow of fuel into the carburettor, which was starved then flooded under negative 'g', to a level that did not exceed the engine's requirements. The solution was simple, cheap and immediately effective; by inserting a calibrated restrictor into the feed from the fuel pump to the carburettor fuel chamber

– restricting the maximum fuel flow normally controlled by the carburettor float. Although the official title was the RAE Restrictor it was more widely known a 'Tilly Shilling's Orifice' (16). During the Battle of Britain Miss Shilling could be found delivering the restrictors to the operational squadrons on her motorbike and helping to supervise the fitting. Later her Department and H M Hobson Ltd produced the RAE pressure injection metering carburettor in which the fuel flow was determined by charge density and the engine speed, and which solved this particular problem**.**

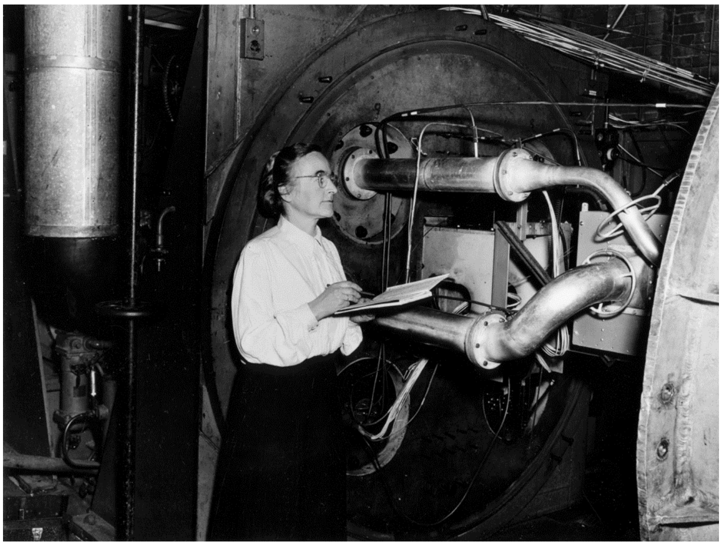


Figure 16. Beatrice "Tilly" Shilling of RAE's Engine Department, originator in 1940 of the RAE Restrictor for fitting to the RR Merlin engine in Spitfires and Hurricanes to ameliorate the negative 'g' problems

9.2 Gas turbine engines

Work on gas turbine engines by Dr A A Griffith, of the Experimental Engine Department, started in July 1926 when he produced RAE Report H1111 'An Aerodynamic theory of turbine design'.(17, 18) He showed that the comparatively low efficiency of existing turbines was due to the blades being stalled, and proposed treating the blades as aerofoils to improve their performance. The paper went on to describe an engine using an axial compressor and two-stage turbine, the first stage driving the compressor, the second a power-take-off shaft that would be used to power a propeller.

In 1927 the ARC recommended tests on a single stage compressor and turbine to confirm this theory, and this was built under Griffith's supervision (Figure 17). The results from the test rig were published in 1929 by Griffith, who had by then joined the Air Ministry Laboratory in Kensington, in AML Report No 1050A 'The present position of the internal combustion engine as a power plant for aircraft'.(19) He outlined the design of an axial flow gas turbine engine - a completely new approach to aircraft propulsion design. He summarized:

> *"The turbine is superior to existing Service engines and to projected compression ignition engines in every respect examined. The efficiency is higher and the weight and bulk less. No external cooling is required at high altitudes, there is an inherent supercharger effect, coupled with a substantial decrease in specific consumption. The use of a variable pitch airscrew is unnecessary. Starting presents no difficulty and control is simpler than in the case of existing engines. Any liquid fuel of suitable composition may be used, without reference to anti-knock value or volatility".*

Griffith returned to RAE in 1931, and Hayne Constant returned from Imperial College in 1936, when work at RAE on gas turbines restarted. In parallel, at Power Jets, Whittle was developing gas turbines with centrifugal compressors, and achieved a first engine run in April 1937.

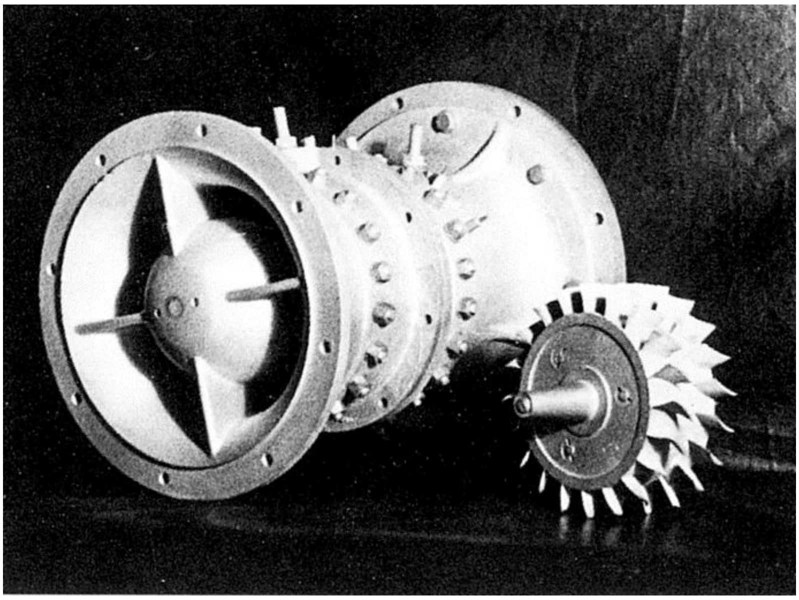


Figure 17. Dr A A Griffith's experimental axial turbo-compressor rig
(AML Report No.1050 entitled 'The present position of the internal combustion engine as a power plant for aircraft', March 1929)

In the two-year period from 1939 to 1941, RAE tested seven experimental axial-flow compressors. Flight trials of the Metro-Vickers built F2 axial flow engine in the tail of a Lancaster started in 1943 (Figure 18).(20)

Figure 18. A Metro-Vickers built F2 axial flow engine fitted in the tail of a Lancaster for flight testing

9.3 The National Gas Turbine Establishment

With the growing importance of RAE's gas turbine work, the Turbine Division of Engine Department moved across the road to the Pyestock site and thus was later born the National Gas Turbine Establishment (NGTE). Construction of the test facilities started during the 1950's, and in 1951 the Battle Test House was commissioned as a boiler house to provide steam for the turbines that drove compressors and for general use on site. The boilers were from a *Battle*-class destroyer, giving the building its name. In 1953, the Compressor Test Facility was added, comprising two test beds at either end of a 14,000 hp double ended steam turbine. A further extension in 1956 added a Turbine Test Facility, fitted with a 25,000 hp dynamometer to absorb the power from a turbine under test. With its boiler house and two testing cells, the Battle Test House became an important turbomachinery research facility.

Also commissioned in 1951, the Admiralty Test House allowed turbines for warships to be run using marine grade fuel, salt water and air containing sea salt. Successive generations of gas turbines used in RN ships were tested in the ATH throughout the life of NGTE.

New research facilities were constructed – Test Cells 1 and 2 – which were to be the first high altitude jet engine test beds in the country. The construction took 3 years to complete and the cells were commissioned in 1957. In 1961 the largest testing facility in Europe, Cell 3, was commissioned (Figure 19). This chamber provided a much more enhanced high-altitude

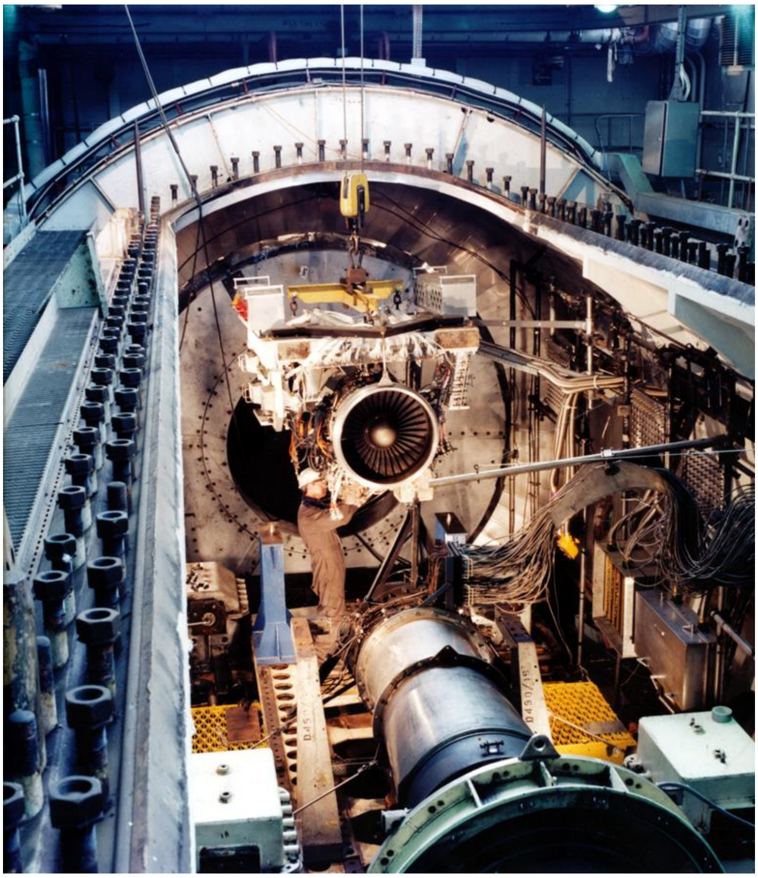


Figure 19. Pyestock Test Cell 3, setting up for an RB199 test. In 1961 it was the largest altitude chamber in Europe, capable of simulating Mach 2.2 at 70,000 ft.

testing facility and, to provide the enormous volumes of air needed to the cell, the Air House was built. This contained four large air compressors and exhausters, the number soon being increased to eight.

To address the complex propulsion problems associated with supersonic flight, Test Cell 4 was constructed in 1965.(21) This cell was unique (and the most advanced) in the world and was an integral part of the massive supersonic-testing expansion at Pyestock, as the need to test engines in close association with their air intake systems was an urgent requirement for the new generation of supersonic aircraft. This could only be achieved by full-scale free-jet testing and Cell 4 was designed to provide that capability. It was most famously used to simulate Concorde's flying conditions – Mach 2 (1,324 mph) at 61,000 feet – but could test Concorde's engines at a maximum air speed of 1,520 mph – M 2.3. The unique combination of the complex intake system and Olympus engine could not be tested in the safety of a ground test facility in any other way.

The final test cell to be built, Cell 3 West, was the largest altitude chamber on site and was used to test 50,000 lb thrust class turbofan engines. It also allowed engines to be tested in icing conditions. It was also used to test the icing characteristics of complete helicopter engine installations for Sea King and EH101 Merlin as well as early development of the rotor blade de-icing system for Merlin, in collaboration with Westlands. The construction of Cell 3 West and Cell 4 required the construction of two new exhausters.

Pyestock was not solely a test establishment but carried out much research work on compressors, combustion and exhaust emissions, high temperature materials and unidirectional solidification of turbine blades, turbine blade cooling, high temperature research turbines, digital engine control, ramjets and much more.

As engine powers increased, with commensurate increases in jet velocities and temperatures, the environmental problems of noise pollution – particularly around large and busy airports – became important and Pyestock set up the early noise reduction test facilities; the first anechoic chamber was built in the early 1960s. The increasing demand for quieter aircraft stimulated more research work, and as a result a larger test facility capable of undertaking large scale noise tests on a variety of gas turbine components opened in the 1970s.

The new facility consisted of two main laboratories, fully independent of each other – the Absorber Rig (1972) and the Anechoic Chamber (1974). The Anechoic Facility had a 10,000 cubic metre chamber for noise testing which reproduced environmental conditions comparable to those in flight and permitted work to separately identify the source and direction of noise wave phenomena. The building was principally intended for noise testing jets, turbines and certain configurations of acoustically lined ducts (Figure 20).

Working with UK industry, significant advances were achieved in the understanding and the reduction of engine noise which led to the Queen's Award for Technological Achievement being jointly awarded in 1990 to Propulsion Department RAE and the Design Engineering Group, Rolls-Royce.

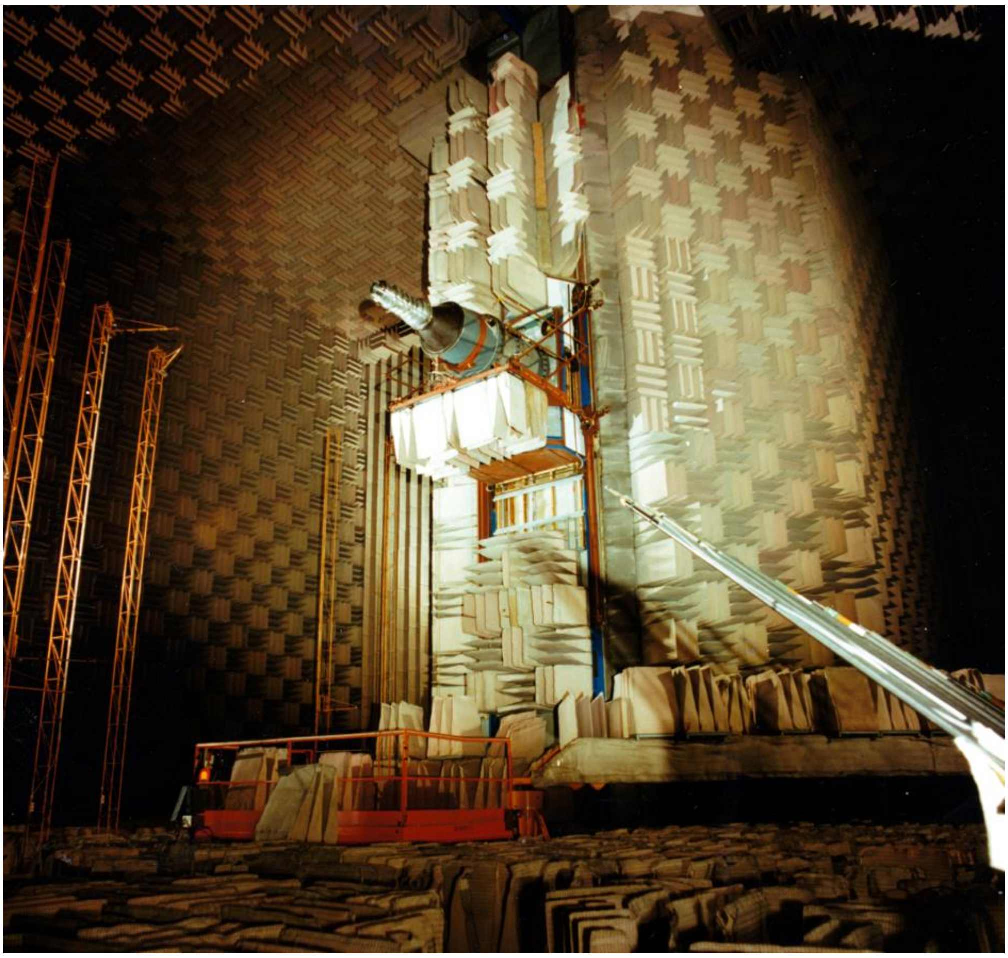


Figure 19. The anechoic facility comprised an acoustically lined main test chamber 85ft wide and 46ft high with an overall length of 88ft, of which 52ft formed the working section. The jet flow from the main noise source was projected towards an acoustically lined, flared duct 28ft diameter at inlet with a 20ft diameter throat, which acted as an exhaust inducer.

10. NAVAL AVIATION AND ASSISTED TAKE-OFF

In the 1930s the Royal Navy had continued to develop aircraft launching for capital ships and aircraft carriers, but the increased weight and launching speeds of the new generation of ship-borne aircraft needed a solution. In the 1930s RAE had built a series of catapults to test the accelerated launching of aircraft suitable for use at sea. In 1930 a Vickers Virginia was launched from a catapult reaching a speed of 60 mph in 100 yards at a weight of 18,000 lb. Both steam and cordite catapults were developed and tested, and systems developed for launching aircraft on their own undercarriage by catapult from, say, aircraft carriers, or by rocket assisted take-off or by launching from a rocket powered trolley - the P (Projectile / Pyrotechnic) catapult. This last technique was developed by Farnborough in 1941 to launch Hurricanes off CAM (Catapult Aircraft Merchantmen) ships in the Atlantic convoys to counter the attacks by German bombers or the surveillance of the Focke-Wulf Condors which directed the U-boat wolf-packs towards the convoys (Figure 21). The whole development programme took only 25 days from start to completion.

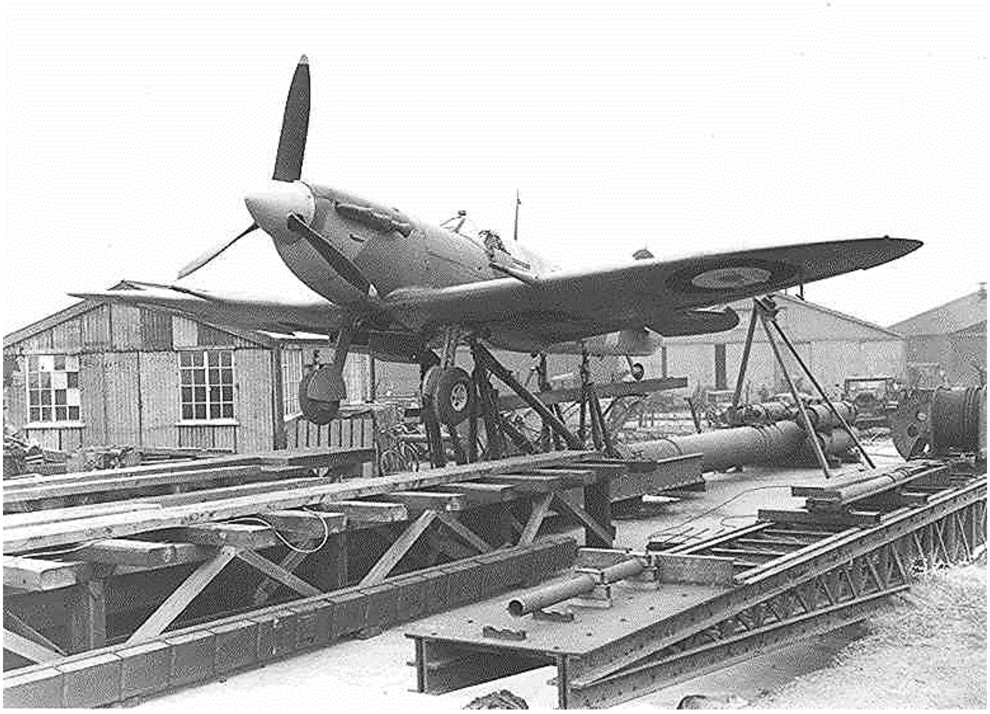


Figure 21. A Seafire fitted on a catapult built at the beginning of WW2. Accelerated across the airfield on a short runway it was sited on Jersey Brow on the northern edge of the airfield

In 1939 calculations were made on the application of auxiliary rockets to reduce the take-off run of overloaded bombers and 1941 saw the initiation of flight test with cordite rockets. RAE based aircraft were used to test a concept now called Rocket Assisted Take-Off (RATO) where solid fuel rockets were attached to the aircraft structure to provide the additional thrust for take-off at high weights or short distances (22).

Figure 22. The trials installation in June 1946 of a rocket pack on one side of a Blackburn Firebrand III prior to rocket assisted take-off (RATO) experiments using three 5 inch cordite rockets on either side.

11. SPACE

Black Knight was a successful rocket programme to investigate the properties of a re-entry vehicle. First launched on 7th September 1958, the programme carried out 22 launches without a single failure. Black Arrow followed and was used in its final flight to launch the UK satellite Prospero – the only full UK effort to build a launch vehicle for a UK satellite. Later the Government found it cheaper to launch UK satellites using American rockets.

Another success story for Space Department was the development – from the RAE Control Test Vehicle (CTV) programme – of Skylark, a rocket used for high altitude research and space astronomy, with a unique pointing system using a star tracking system.

The RAE Space Department was a significant contributor to the UK Space Programme in its formative years. The UK Blue Streak ICBM was designed and developed in the early 1960s with industry. The missile was successfully tested at the Woomera ranges in Australia. With the operational disadvantages of a liquid fuelled rocket being vulnerable to pre-emptive strike, the project was cancelled in 1960. There was a possibility of using the rocket as the first stage for the Europa satellite launch vehicle, but this came to nothing, despite several launches during which Blue Streak performed well (23).

The Department was also involved with new ideas in propulsion for space vehicles, starting a programme in 1962/63 on the T4 Ion Thruster engine – an engine that is still being developed and will be able to deliver manned or un-manned space craft to Mars or other planets.

12. NUCLEAR WEAPONS

From the early days of post-war nuclear devices, RAE has been involved with the aircraft related aspects, particularly in the release of the weapon from an aircraft, ensuring that it leaves cleanly from the bomb bay or weapon station and that the subsequent trajectory is accurate and stable. The first British atomic bomb, Blue Danube, was a large bomb; 24 ft long, 62 inches in diameter, and weighing close on 10,000 lb, it was RAE’s introduction to the nuclear era. The new generation of V-bombers, then in design, were intended to carry this weapon and needed a bomb bay that would take this bomb and carry it the distance required by the Staff Requirement. FAST Archive holdings (24) include drawings showing a Blue Danube in each of the Valiant, Vulcan and Victor and important parameters such as ground clearances which, apart from ensuring that take-off can be accomplished without ground contact by the extremities of the fuselage, ensures that the bomb can be loaded into the bomb-bay easily.

With the development of smaller but more powerful bombs, Yellow Sun models were tested in a Victor bomb bay in the RAE high speed / transonic wind-tunnel to help understand the aerodynamic interactions when the bomb bay is first opened as well as when the weapon was released (Figure 23). Similar trials, including flight trials, were carried out to look at the release of an externally carried WE177 free-fall atomic/fusion weapon.

Flight trials to ensure a clean clearance from the aircraft, in this case a Valiant flown by RAE test pilot Roly Falk, were carried out over a number of ranges including Orfordness.

Figure 23. A model of the Handley Page Victor carrying a ‘Yellow Sun’ atomic weapon runs in the Transonic Tunnel to measure the potential aerodynamic interactions experienced during weapon release.

Further RAE involvement, working with AWE Aldermaston and British Industry, was on aspects of the design and development of the re-entry vehicle – Chevaline – carried on the submarine launched upgraded Polaris A3T missile, in service from 1982 to 1996.

13. HUMAN FACTOR ISSUES

13.1 Clothing and equipment for high-altitude flight

In the later years of the Great War the altitudes to which aircraft were reaching required the pilots and observers to use breathing oxygen to prevent hypoxia. Farnborough, along with industry, developed oxygen breathing apparatus using either liquid oxygen as a source (which was a lighter system) or pressurised oxygen bottles (heavier). Post-war development was slow but by 1936, with WW2 in sight, the RAF had a growing interest in high altitude flight. Farnborough, in conjunction with Siebe-Gorman, developed one of the first full pressure (space) suits which provided an individual pressurised environment for the pilot, allowing the pilot to survive at the heights reached. In the next two years, flying from Farnborough, Sqn Ldr Swain reached 49,967 ft on 28 September 1936 and F/Lt Adam followed in June 1937 by reaching 53,963 ft – both World Records for altitude (Figure 24).

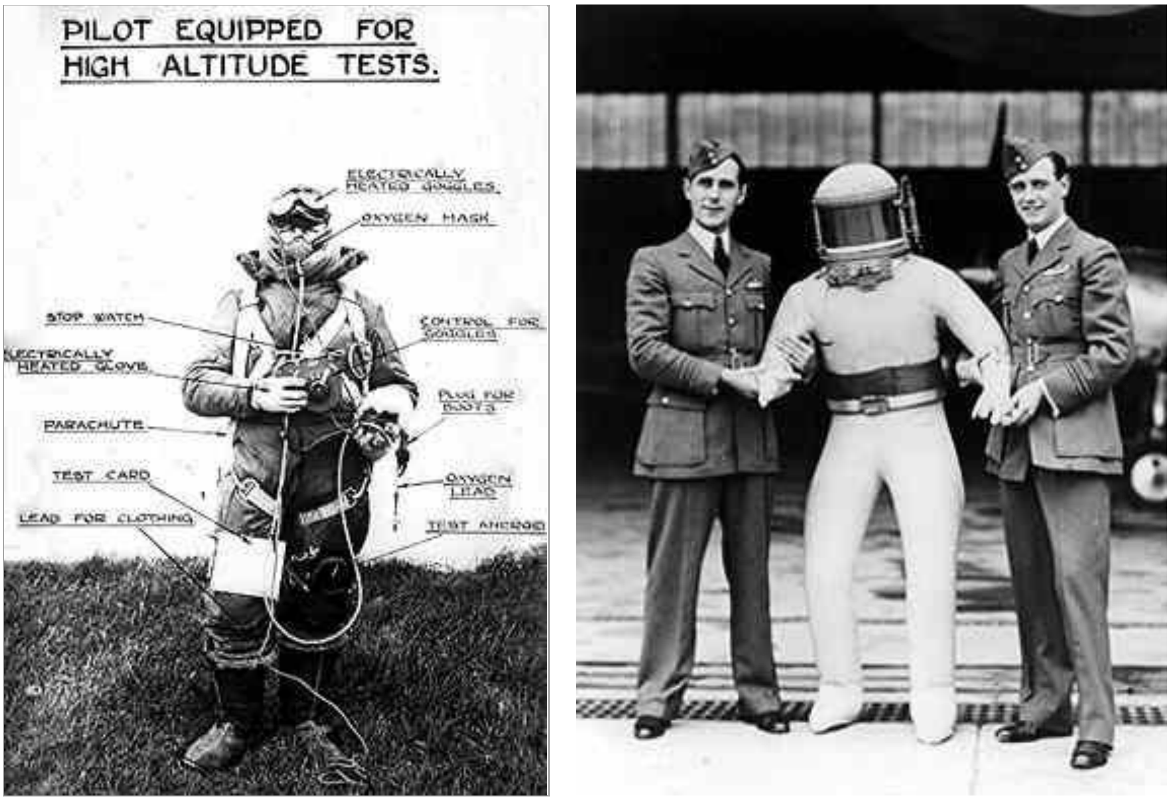


Figure 24. Two images of high and higher altitude dress. On the left a RAE test pilot dressed for altitudes up to 30,000 ft in an open cockpit. On the right Swain and Adams, both World Altitude record holders, Swain at 49,967 ft in 1936 and Adams at 53,936 ft in 1937, with the inflated RAE/Siebe Gorman full pressure suit needed for altitudes above 40,000 ft

To carry on research into high altitude physiology, the RAE Physiology Laboratory (PL) was set up in mid-1939 using laboratory-based high-altitude chambers. This facility was heavily used during WW2 to develop oxygen systems and to condition pilots to high altitude flight in the RAF Boeing B-17s as well as more general aircrew high altitude training. This facility was also used during the development of more efficient and useable full-pressure suits right through to their potential application in the V-bomber fleet in the Cold War period, when the fleet was used at high altitude.

The Human Engineering Division of Structures and Mechanical Engineering (SME) Department was formed to ensure that the human aspects involved with aircraft design (e.g. ergonomics, cockpit layout, flying clothing, environmental protection, escape from aircraft, etc.) were fully taken into account in the early stages of aircraft design and development. One of the critical areas was protection against the life-threatening risks of high-altitude flight, should a malfunction or combat damage breach the pressure cabin on the V-bombers. Proposals were put forward for the use, by the aircrew, of full-pressure suits, which were simplified versions of space suits. Over the years the many problems of integration of all the conflicting requirements were gradually resolved (including protection during ejection at over 600 knots!) with RAE providing the design and prototype construction and various parts of Industry involved in the post-prototype build. The mechanical aspects were tested by RAE Human Engineering and the medical issues by the RAF Institute of Aviation Medicine (IAM). A practical solution was developed but, whilst resolving the technical and medical issues, could not meet the operational requirements for RAF use. A simpler solution was then proposed by RAF IAM which involved the use of pressure breathing of oxygen and a developed G-suit which would allow survival whilst the aircraft was brought down to lower altitudes. This approach is still used, essentially, in today's RAF high-altitude operations (25).

The RAF Institute of Aviation Medicine (IAM) started its life at Farnborough by the formation in 1939 of the RAF Physiological Laboratory (PL) set up as RAE17 Department. Nestled beside the original 1906 Beta airship shed, it had high-altitude chambers which were used extensively during WW2 to study the problems of high-altitude (up to 30,000 ft) and long duration flight, particularly when the RAF started to use the Boeing B-17 on operational sorties. Experiments on the effects of hypoxia and the training of aircrew to recognise the effects of hypoxia on flying were extensively researched. In 1945 the PL moved to the south side of the Farnborough site and formed the new IAM.

When operational requirements resulted in the need to cease flying bombers at high altitude (mainly due to Russian ground-to-air missiles becoming effective above 60,000 ft) the move to high-speed low-level flight brought alternative problems. There arose the problem of cockpit temperatures becoming too high and, as the RAF continued to have a role in the Near East, in-flight and stand-by in high ground temperatures exacerbated the cockpit temperatures. RAF IAM had been involved in developing an air-cooled undergarment as part of the flying clothing which worked well but had some disadvantages. RAE Human Engineering, in the form of ex-RAE apprentice Des Burton, put forward an idea to use water cooling as a substitute for air-cooling (26).

The physics made sense and the liquid-cooled suit (LCS) was developed over several years and tested in a number of aircraft, including the Vulcan. By the time it was ready for production, the RAF had moved out of the Near East and that particular type of suit never reached operational use. However, the idea and approach were sound and later aircraft in RAF service (Tornado, Typhoon) have use this approach to aircrew cooling. Prototype suits had been produced by RAE in 1962 and reported in 1964 and the results were effective enough for NASA to request a demonstration of the RAE suit, which was shown in Houston late in 1963. The effectiveness of the suit was apparent and the Americans undertook a development programme of their own, culminating in the late 1960s with the liquid-cooled suit used in the Apollo space programme (27).

13.2 Protection against Nuclear, Biological and Chemical attack

A further highly successful programme was providing aircrew with protection against Nuclear, Biological and Chemical (NBC) attack. The risk of such NBC attack became greater in the latter part of the Cold War and whilst ground crews and the below neck areas of aircrew could be suitably protected by carbon impregnated coveralls, the above neck protection was often incompatible with the pilots vision devices – weapon sights, Night Vision Goggles etc. – in both fixed and rotary wing applications. After a number of inconclusive solutions RAE came up with a workable solution which involved a rubber hood worn by the aircrew with the helmet fitted over the top – simple but highly effective. This could be used with all the current and future aircrew vision devices and was compatible with the NBC operational procedures that the RAF had in use on its airfields. Much work went on at an accelerated pace with RAE, IAM and Chemical Defence Establishment Porton Down all contributing and the programme from inception to operational use was completed in an amazingly short period. This system, called the Aircrew Respirator No.5 (AR5), was probably the most effective solution for NBC protection and was taken up by the US forces and others around the World (Figure 25).(28)

13.3 Protection against acceleration

Figure 25. Flight testing of the AR5 NBC Respirator was carried out in the RAF IAM Hunter shown here with the pilot holding its ground ventilator (the 'Whistling Handbag'). The AR5 on the right is worn with Night Vision Goggles

In the 1950s the construction of the man-rated centrifuge brought another string to the aviation medicine bow and allowed many years of fruitful research and development into high 'g' protection and the benefits of breathing high pressure oxygen. The development of aircraft performance resulted in higher 'g' levels being attained and the ability to sustain these higher acceleration levels was tested and developed in the centrifuge through human experimentation. This has carried through to today when RAF Typhoon pilots are protected against manoeuvres up to 9 'g'. The centrifuge continued to train pilots before being closed down in 2019 after some 63 years, when this training was moved to a new centrifuge at RAF Cranwell which can meet the 'g' onset times of current airframes. Flight testing of the protection systems was carried out over the years by several specially fitted aircraft. Amongst many other areas of aircrew protection, the safe restraint of aircrew under violent decelerations was another area of research using a linear catapult as well as impact protection by the use of flying helmets.

13.4 Night vision

'Cloak of night' operations were generally effective prior to WW2, but this protection was gradually eroded by the use of airborne interception radar (AI). Farnborough was involved in the aircraft installation and testing aspects of AI as well as supervising the production of the Coastal Command based ASV (air-to-surface vessel) Mk II. As the Cold War developed it became essential to be able to fly safely at night and in adverse weather conditions either by manual flight (controlled by the pilot) or by automatic flight control of the aircraft. The normal RAE process of theoretical work followed by extensive laboratory trials and simulation was followed by extensive flight trials.

One major programme was involved in flying by low-light TV and later an infra-red (forward looking infra-red – FLIR) camera. These cameras fed to a flat panel display by which the pilot could operate down to 250 ft (sometimes lower) at high speed. This was carried out on a two-seat Hunter T.7 named *Hecate – Lady of the Night* (WV383). These trials also involved experimenting with the thermal imaging and laser designator (TIALD) which was used to gain operational advantages during combat in the Gulf and later wars. A refinement of such experimentation came with the incorporation of a terrain database which fed the ground mapping conditions to the pilot to assist in the difficult conditions of low-level flight. This research further fed into the automatic flight over difficult terrain using radars and predictions of forward terrain to combine with radar and allow timely manoeuvring. Along with similar work in helicopters for the Army Air Corps, the RAE carried out work with a Buccaneer – *Nightbird* (XV344). This programme was essentially a follow-on to the Hecate Flight Trials. The flight programme utilised the FLIR for forward looking flight and NVGs for looking out laterally for manoeuvring flight. However, the use of NVGs in cockpits with standard cockpit and instrument lighting, in either fixed or rotary wing aircraft, overloaded the goggles and prevented their intended use. RAE devised a pragmatic and simple solution whereby cockpit lights and displays were filtered to remove red and infra-red emissions and the goggle lenses were fitted with complementary blocking filters that only passed deep red and infra-red light. This approach was soon standardised and used by most operators.

FLIR was later used for thermal cueing trials (not targeting) for auto-cueing of targets for the pilot's attention. This later expanded to target acquisition and weapon aiming at night. This notable flight trial programme was run in a close partnership with the UK avionics industry.

As with the RAE fixed wing programme, a similar programme was evolved for day / night all-weather flying of helicopters using the technologies of FLIR, NVGs and new cockpit flat-panel displays. The advantages of the lower speed flight regime in helicopters was that the visual cameras could be fitted on a steerable external pod allowing a much greater sphere of vision fed to either the head down or head-up displays or direct to the pilot helmet mounted display (Figure 26). This allowed the system, and thus the pilot, to effectively look through the floor of the cockpit and behind him. Later technologies allow the pod to be slaved to the pilot's helmet so that where the pilot looked the camera pod followed.

Figure 26. Early helicopter trials with enhanced vision devices led to further developments, as technologies improved and advanced, in later Sea Kings and Pumas as part of the RAE day / night all-weather (DNAW) research programmes. Other programmes covering all aspects of helicopter technology and operational use were run at Farnborough and Bedford.

14. ROTARY WING AIRCRAFT

In 1946 the earliest practical helicopters, in the form of the Sikorsky Hoverfly, arrived at Farnborough and began a new series of challenges in the detailed understanding of rotor-borne flight and the use of helicopters for military purposes (Figure 27).

Figure 27. Early experiments in visualising the airflow through and around the rotor disc

Whilst much R&D went on in the next few years, one of the significant later advances was the RAE invention of carbon fibre in the early 1960s which, for helicopters, raised the possibility of designing and manufacturing more complex, and efficient, rotor and rotor tip shapes. An example of such a tip shape is the BERP rotor created during the British Experimental Rotor Programme, led by the Helicopter Division of Structures Department in the late 1970s to mid-1980s and run as a joint venture programme between the RAE and Westland Helicopters Ltd. BERP included the application of a series of RAE aerofoils specifically tailored to the varying conditions between the root and tip of the blade, together with highly refined structural dynamics to control vibratory forces.(29) The design was adopted very successfully for Lynx and EH101 Merlin helicopters, and in the case of the latter resulted in a rotor of reduced diameter which enabled the aircraft to fit on the flight deck of a frigate. Hover power could be reduced by approximately 5%, cruise power reduced with an approximately 10-15% saving under typical hot and high conditions, and the blade stall envelope extended by at least 10 knots. In addition, vibration levels were significantly reduced and levels were halved in transitions from forward flight to the hover. In 1986 a specially modified Westland Lynx, using BERP rotor-blades, set an absolute speed record for helicopters over a 15 and 25 km course of 400.87 km/h (249.09 mph), a fitting finale to a combined research RAE/industry programme. The BERP programme gained a Queen’s Award for Industry, awarded jointly to RAE and Westland Helicopters.

Carbon fibre went on to be used extensively in aircraft, the automobile and motor racing industries, the leisure industry - fishing rods, tennis racquets, sports - Olympic bicycles, and for general industrial use.

15. CONCORDE

If a country needs to have a thriving aviation industry, the necessity of investing in aviation research – expensive though it may sometimes be – is no better illustrated than in the Concorde programme. Long-term aerodynamic and other research programmes at Farnborough and Bedford had accumulated the knowledge to be able to focus quickly on the basic structural and aerodynamic needs for a supersonic transport aircraft, Thus, less than 50 years after Cody made the first manned, powered and controlled flight in Great Britain in 1908 from Farnborough Common, in 1956, the RAE set up the Supersonic Transport Aircraft Committee (STAC) which resulted in the world-beating Concorde programme. Led by Aerodynamics Department, the STAC was staffed by government, aviation industry and airline personnel (30).

A number of wing planform options for a range of supersonic speeds were considered and there needed to be decisions by the airline operators as to which route the supersonic transport would be used on. This in turn would define fuel and passenger loads and using the Breguet equation for range the options could be defined more closely. After much discussion the ogee wing shape was decided upon, favoured by RAE’s Head of Aerodynamics Dietrich Küchemann, and the airline industry had decided on the North Atlantic Transatlantic route to New York and beyond (Figure 28). As supersonic aerodynamics was still very much in its infancy, considerable wind tunnel work was undertaken both at Bedford and Farnborough. Hundreds of tunnel models were tested to refine the designs which would allow the optimum aerodynamic performance whilst carrying a commercially viable number of passengers.

Paul Drane RAE

Figure 28. Concorde on final approach to runway 07/25 over the 1946 control tower and with the 1906 Balloon School grade 2* listed building in the background.

One of the problems was the range of speed – supersonic at altitude and conventional landing speeds to fit in with normal air traffic flows at major airports. Clever aerodynamic design provided a solution and a number of experimental aircraft were built to ensure the modelling met real life performance. The HP.115 was built to investigate low speed handling, with over 1000 flights being carried out (Figure 29). The Fairey FD2 was turned into the BAC Type 223 with a Concorde wing for high speed verification and the Bristol 188 was built using stainless steel construction to test sustained supersonic flight to investigate any potential kinetic heating problems. Also, at Farnborough, a full-size Concorde fatigue test rig was built to simulate the in-flight heating and loading cycles and kept ahead of commercial Concorde flight operations. As well as structural stress testing, the facility utilised a heating and cooling system for the airframe to test sustained supersonic flight and investigate any potential effect of the kinetic heating cycles of real flights but on a shorter time-scale (Concorde airframe temperatures reached 125^{o} C on the nose and 100^{o} C on the wing leading edges).

Beyond the 'big picture' work on Concorde, RAE made many smaller but important contributions in support of Industry. For instance, within Engineering Physics Department work on the fuel system and air conditioning systems was done in a major RAE test facility called the High Altitude Test Plant. EP Department also did work on hail strike (a gas gun capable of firing 2-inch diameter balls of ice at Mach 2 at windscreen specimens) and on the fire hazards of a proposed hydrazine powered Emergency Power Unit. Structures Department worked with the Dynamics Group of British Aircraft Corporation Ltd. to overcome a problem with vibration in the cockpit during takeoff. This led to the fitting of modified undercarriage oleos in 1976, after the aircraft had been granted permission to use New York JFK Airport.(31)

Figure 29. The simple Handley Page HP.115 was built and flown to confirm the basic design and wind-tunnel tests of the aerodynamics of the proposed high-angle approach to landing for Concorde. Over 1000 flights from RAE Bedford were performed with this unique aircraft.

16. RADIO AND COMPUTING

A department that carried out an enormous amount of research and development over the 100 years but is often hidden, to some extent, from view was Wireless and Radio Department. From the earliest days of airship flying the most effective means of air to ground communication was radio, originally by wireless telegraphy (Morse code) and then by radio telephony (speech). During the 1930s the Department pioneered many techniques for both airborne and ground stations – including the radio installations in the R100 and R101 airships – and developed the equipment to utilise these systems effectively.

One of the most significant was in 1938 when Radio Department on its own volition (i.e. no Staff Requirements or immediate operational needs) decided to develop a VHF radio system for RAF use. At the time HF radio was fitted to the RAFs fleet and problems in the ranges of air-to-air and air-to-ground voice communications (and vice-versa) were apparent but the services had made no requests to provide better solutions. Radio Department considered that VHF was the answer and decided to go ahead alone on their internal research funding (32).

Between 1936 and 1938 RAE had developed the 2-channel TR9 (HF) with a ‘Pipsqueak’ system – a radio location system using the voice radio to send out a signal periodically which Direction Finding could use to locate the aircraft using triangulation. It was in 1938/39 that the

RAE decided to develop a complete air and ground VHF system. The experimental TX/RX radio was developed in a form suitable for production and in September 1939 the TR1133 was produced in small numbers.

On the 30th October 1939 a trial was carried out at Duxford operational airfield with six Spitfires of 66 Squadron. The existing ranges with the TR9 (HF) were 35 miles air-ground and 5 miles air-to-air whilst the TR1133 (VHF) achieved 140 miles at 10,000 ft air-to-ground and 100 miles air-to-air. These significant improvements, helped by increases in power, allowed adequate communication between each other and with the ground control stations and enough sets were produced for fighters to use operationally in the Battle of Britain (Figure 30). Radio Department then designed and constructed the prototype TR1143 – a development of the 1133 – and it was taken to USA and used as the basis for US VHF production as the SCR522.

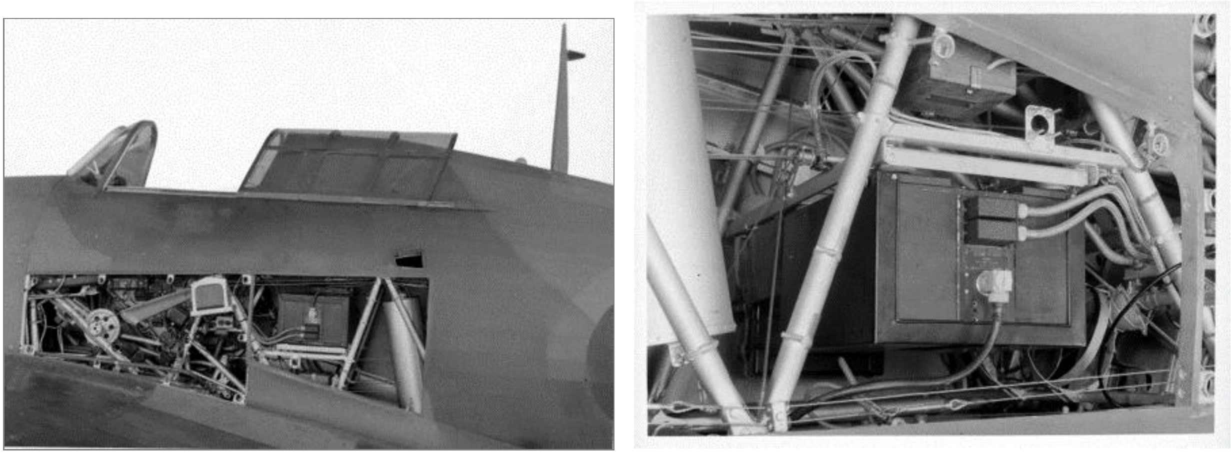


Figure 30. The fitting to the experimental TR1133 VHF radio system to the RAE Hurricane (L1788) photographed on the 18th September 1939

The Department also had a significant input to the 617 Sqn. Dambusters raid – Operation Chastise. In early May 1943 training for the attack over two reservoirs had resulted in the comment “Air to ground reception during day and night was satisfactory, but air to air was not and became worse at night”. On May 4th the final trial was declared as completely unsatisfactory and the Radio Department RAF liaison officer, F/L Bone, advised use of the TR1143 VHF. By Sunday May 9th, after many transmission tests and trials of the siting of aerials and the ancillary equipment in the Lancaster, all sets had been fitted and air-tested and all were working by 1730 hours.

On the 16 -17th May Operation ‘Chastise’ was successfully flown and Guy Gibson *“considered that VHF had provided “perfect” method of control. A lot of voice on VHF during bombing runs*”. A programme completed in an incredibly short period - less than 12 days. This use of VHF in Bomber Command was adopted by the Pathfinder Force, both in the Lancaster and Mosquito, to control the bombing patterns during the late 1943 and 1944 bomber offensive when the main stream of bombers approached the target.

16.1 Computing and simulation

As the complexity of aircraft increased after WW2 and experimental research and flight trials expanded, the process of analysing data took longer and longer, with hold-ups between tests waiting for the analysed results to be completed. The advent of analysis by computer held the promise of shortening this analysing process considerably and allowing much shorter intervals between tests, particularly flight trials where large amounts of data needed processing - typically aerodynamic experimental data. In May 1955 Maths Department, in R14 building, purchased a DEUCE computer (digital electronic universal computing engine) which was used as a central computer for the use of all departments.(33) Later a second DEUCE was acquired at the end of 1956 and these were named 'Gert and Daisy' (Figure 31). In 1957 Pegasus was acquired followed in 1959 by Mercury, both being used by Maths Department.

Figure 31. A pair of DEUCE computers acquired for Maths Department in 1955/56 - named Gert and Daisey after the two characters of a British WW2 female comedy act on the BBC radio variety programme Workers' Playtime

Simulators built to represent complete aircraft in flight were often constructed at Farnborough but one of the earliest and most ambitious was the design and build of TRIDAC (three-dimensional analogue computer) which was designed to solve problems of flight in three dimensions for use by Guided Weapons Department (GW). It enabled two independent 3-axis vehicles to be simulated which, in the GW case, were the missile and the target aircraft. Work started in 1950 with Elliott Brothers supplying the computers from a RAE design. Installed by 1954, it was fully operational by 1956. A large and complex computer, needing its own building and power supplies, it consisted mainly of 2,000 high-gain d.c. amplifiers, 8,000 thermionic valves and nine hydraulic servo mechanisms. Other aspects of GW work included some ballistic missile simulations where it could be used to verify the design of the control and guidance systems throughout flight, from moving up out of the silo to engine shutdown.

A further area that benefitted from computers to solve complex equations was in the aeroelastic problems of flutter – a dynamic instability of an elastic structure in a fluid flow caused by positive feedback. First recognised in 1916 on tail-plane instabilities on the Handley Page 0/400 bomber (34) it became more serious as speeds increased and the structural build of aircraft became more complex. The theoretical flutter equations developed were complex and their manual solution involved large teams of female ‘computors’ using manual calculators. Analogue computers provided a quicker solution to the increasingly complex calculations and the ability to change parameters in the equations to more rapidly explore alternative methods for the control of flutter (Figure 32).

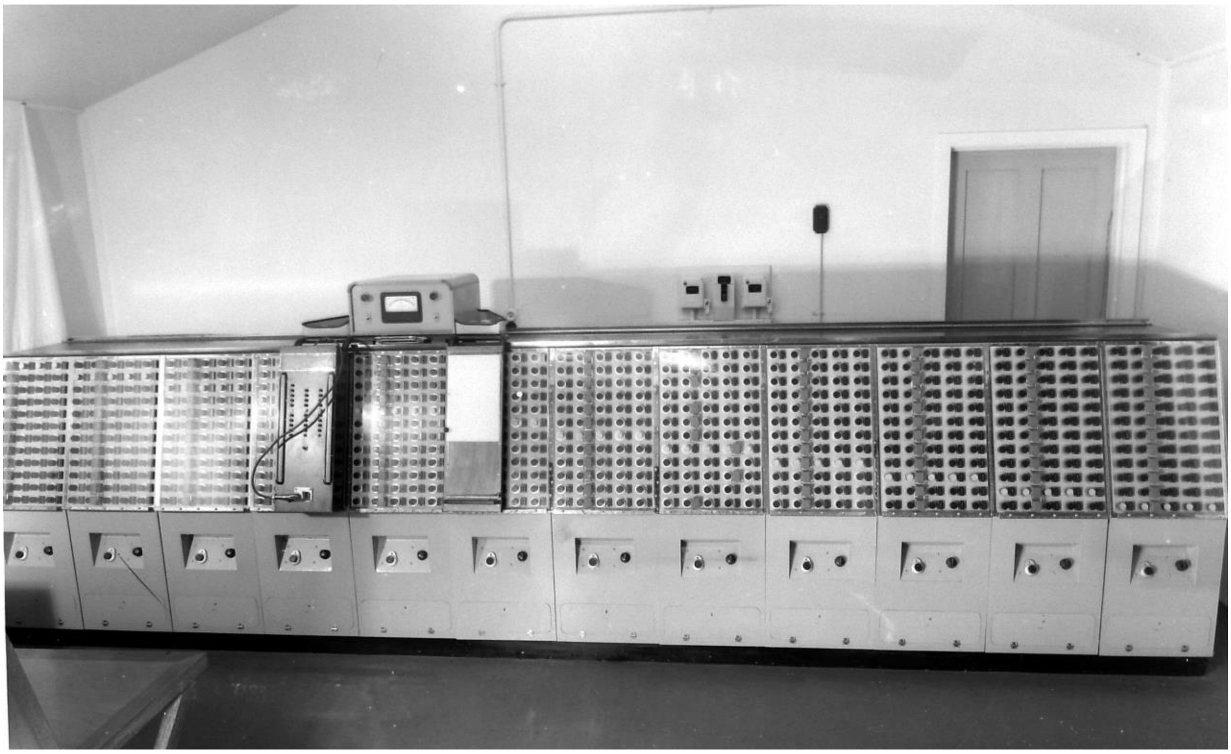


Figure 32 The RAE 12 degree-of-freedom flutter simulator which replaced a myriad of female ‘computors’.

More general-purpose computers followed – the ICT/ICL1907 (1967/8), another in 1974, and finally the powerful Cray 1A computers in 1984.

17. COCKPIT SYSTEMS

Cockpit Systems were a significant part of Flight Systems Department and Man-Machine Integration Department research programmes. Much of this research was into ensuring that the interface between the cockpit systems and the wide range of tasks the pilot had to perform were well matched. As the necessity to fly low and fast increased, the pilot had very little time to look down into the cockpit at his instruments and displays. In 1959 RAE produced, in conjunction with Rank Cintel, a head-up steering display for the TSR-2 programme and flew the system in their Meteor T7 with the display in the front cockpit and the electronics controlling the display in the rear cockpit (Figure 33) (35). This R&D continued to develop the optics, illumination systems and increasing symbology needs, particularly to increase the field-of-view, all of which was carried out with UK industry collaboration.

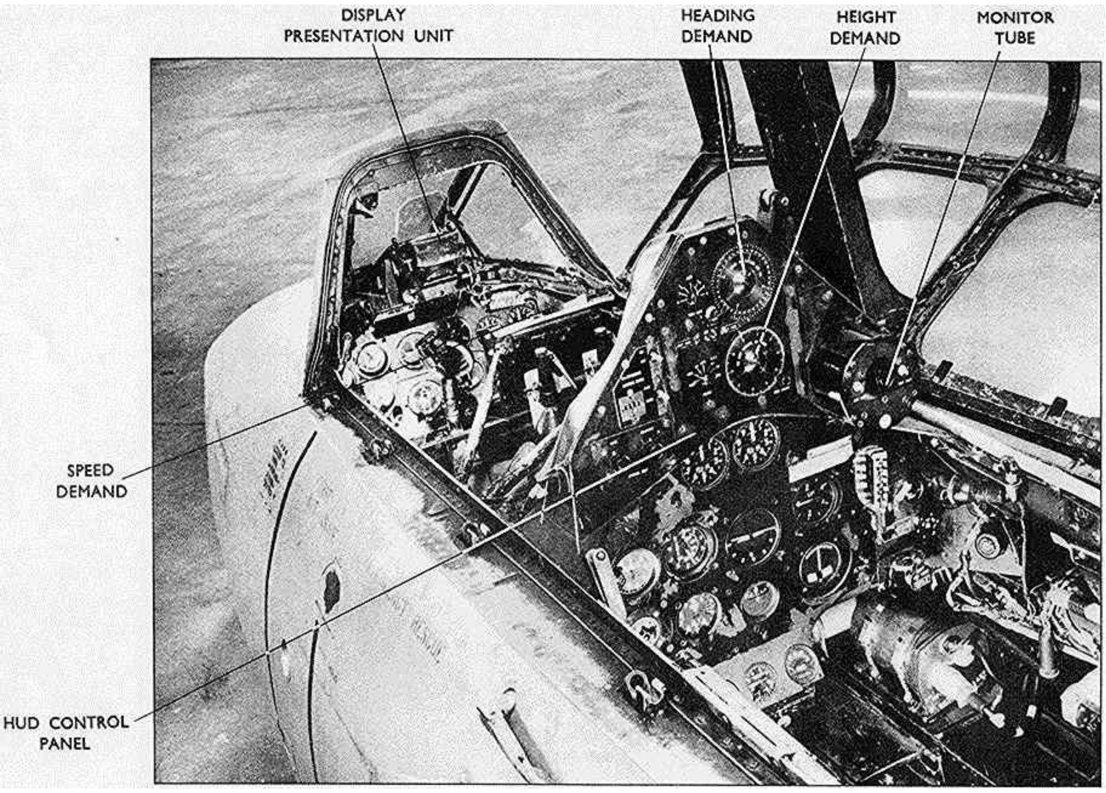


Figure 33. The head-up steering display for the TSR2 programme in the Meteor T7 with the display in the front cockpit and the electronics controlling the display in the rear cockpit

Over the years a proportion of the displays - initially flight and weapons information - migrated onto the flying helmet. One of the earlier RAE programmes was to fit a weapon sight in the helmet, linked to the weapon sensor which, with a head tracking system, allowed the pilot just to look at the target off-boresight (i.e. either side of the line of flight of the aircraft) and fire the weapon without changing the direction of flight. This programme followed the classical RAE approach – theory – laboratory – simulation – flight testing and all the time talking to industry. The helmet mounted sight (HMS) morphed into the helmet mounted display (HMD) which, with its monocular or binocular display, allowed not only aircraft related data to be displayed but also outside world data (e.g. FLIR images) (Figure 34). It seemed possible that it would replace the HUD (if all the integrations, including the pilot, could be satisfied) and this appears to have been achieved to a large extent on the Lockheed Martin F-35. Some work on fully synthetic vision was developed on a simulator in the laboratory and later flight tested but still awaits an operational need.

The R&D programmes at RAE also contributed towards other developments on the F-35, one of which was in the control of the Harrier in the hover and transition to and from wing-borne flight. In spite of what RAE and Hawker Harrier test pilot John Farley used to say, for the squadron pilot it was an exacting aircraft to fly, particularly in VTOL mode where the pilot needed to control the throttle and the thrust nozzle angles together (two separate controls) with one hand while controlling and balancing the attitude of the aircraft with the other. Landing on a static airfield was relatively straight-forward but landing on an aircraft-carrier in poor visibility with a pitching and heaving deck exacerbated the difficulties.

Figure 34. An experimental helmet mounted sight (left) which completed laboratory, simulator and extensive flight trials in RAEs Jaguar aircraft before going into production and operational use for Jaguar, Harrier and Tornado. The experimental binocular helmet mounted display (HMD) on the right was tested in flight in Lynx and in the Bedford helicopter simulator

In the early 1970’s RAE was tasked to enable Sea Harriers to recover to a vertical landing on a ship at night in poor visibility and the work was to be carried out at RAE Bedford. Two-seat Harrier XW175 was allocated as the trials aircraft. During 1977/78 two sea trials were completed with HMS Hermes. The research programmes included recovery to the ship using MADGE guidance (microwave aircraft digital guidance equipment), head up display (HUD) symbology, ski-jump launch, auto-stabiliser and autopilot development and, later, forward looking infra-red (FLIR) visual enhancement, while conducting pilot work-load assessments using heart rate measurements.

In the early 1980’s, studies into future advanced STOVL aircraft concepts, as a planned Harrier replacement, indicated that flight control at low speed and hover would be more complex. This started a research programme into novel pilot control. To test the design principles the aircraft was converted to fly-by-wire control such that digital techniques could be implemented. Control of the aircraft was to be as similar as possible to conventional aircraft, thus significantly reducing the time and the training costs for pilot type conversion. The installation provided a full authority fly-by-wire system with links to the aerodynamic surface actuators and the engine thrust and thrust vector control actuation. It retained the basic mechanical control system in the second seat to provide flight safety and meet airworthiness requirements.

The aircraft became known as the Vectored thrust Aircraft Advanced Control (VAAC). Over the period 1986-2004 several different control and safety concepts were developed with UK universities and industry. The most important task was the ability to land vertically on a rolling, pitching and heaving ship deck and flight trials led, in September 1989, to the first ever deck landing with what became known as the ‘Unified’ control technique. The implementation allowed an untrained Harrier pilot to fly the aircraft like a conventional aircraft with the addition that there were no restrictions due to the conventional wing stall speed. It made possible the continued control of the aircraft down to zero airspeed with the wing lift blending from aerodynamic control seamlessly to direct lift control without any additional effort required from the pilot, unlike the conventional Harrier. In 2002 this Unified Control concept was selected for the JSF STOVL variant (Figure 35).

Figure 35. In 2002 the Bedford Unified Control concept was selected for the JSF STOVL variant. The VAAC Harrier (left) and JSF BF-01 (right) hovering under the flight control of the Unified Control method

With the established STOVL flight control standard, XW175 (in its new Raspberry Ripple livery) continued to support JSF recovery requirements to ships with a 60 knot approach and landing method referred to as 'Ship Rolling Vertical Landing' (SRVL). This approach speed provided JSF with ship recovery flexibility as wing lift at this airspeed would offset some engine direct lift and enhance safety margins. In conjunction with this programme, ship deck lighting was developed for poor visibility and night recovery to ships. This programme produced the new 'Bedford Array' of deck lights to provide an unambiguous touch down point irrespective of the ship deck motion. The 'Bedford Array' with SRVL provided an effective and alternative solution to ship recovery at night in poor visibility and considerably enhanced operational flexibility,

Using a SRVL on a carrier allowed an effective landing without the use of an arrestor-wire and tail-hook. A further, predominantly operational, advantage of this technique is that it can increase the landing payload of a V/STOL aircraft, which can be restricted when it lands vertically. It can also reduce the level of wear on the lift engines and extend their operational life. Similarly, it can reduce the amount of wear upon the deck surface of a carrier caused by the downward jet exhaust from vertical landings – important as jet velocities and temperatures increase with engine developments.

18. GUIDED WEAPONS

During the First World War rockets fired from aircraft were briefly used. Towards the end of WW2 the use of unguided rockets was encouraged by Armaments Department, who spent much time designing and refining their performance; rockets became an effective weapon particularly in Normandy after the invasion of Europe in June 1944. Some ground-to-air guided weapons had been being developed by Britain (Brakemine, Stooge, Lopgap, etc.) but not to the same extent of the German war industry.

In 1945 RAE formed a Controlled Weapons Department; in 1946/47 it became Guided Weapons Department (GW), and in 1962 Space Department. GW Department decided that the best approach was to acquire basic information and practical experience in GW by building and firing test vehicles, and to gain knowledge through wind tunnel assessment, simulator studies and weapons assessment using test vehicles. Two categories of test vehicle were decided upon - CTV and RTV (component/control test vehicle and rocket test vehicle). CTV.1 was a 5" diameter rocket used for guidance experiments (e.g. Beam Riding) and the CTV.2 class were for control and stability research into aileron power, roll stabilisation and telemetry (36).

The RTV series were larger and more related to actual weapons with RTV.1 being a 9" diameter rocket, 16 ft long and weighing 500 lb whilst RTV.2 was a large surface-to-air test vehicle. The smaller CTVs were fired from a new land-based range at Larkhill on Salisbury Plain whilst the bigger RTV series were launched from RAE Aberporth into the sea ranges on the Welsh coast.

The knowledge gained from these experiments assisted considerably to the development and production of Bloodhound, Thunderbird and air-to-air missiles such as Firestreak, Red Top and Fireflash, as well as setting ground-rules for future generations of guided weapons. The CTV-5 Series 3 developed into the highly successful Skylark rocket with the Raven rocket motor. As well as carrying out much research and developing the air-to-ground TV guided weapon Blue Boar (which was cancelled), the knowledge gained fed into Space Department's work on ballistic missiles and satellite launchers

19. GUNSIGHTS

A project on which RAE provided an outstanding service to the RAF and Allied air-forces during WW2 was in the design and construction of the gyro gunsight (GGS).

In 1938 RAE Instruments and Photographic Department (IAP) joined the Air Fighting Development Unit at Northolt looking into the accuracy of gun aiming in fighter aircraft and were somewhat taken aback by the poor results, particularly in deflection shooting. It was decided that a gyro gunsight would provide an effective and a practical solution to achieve improvement and by May 1940 the Instrument Department at RAE had formed a team for the development of the gyro gunsight. The problem was to be given priority over all other work, no expense was to be spared and the utmost secrecy was to be observed. When the Government utters the words that 'no expense was to be spared' it must be important!

The first working sight, the Mk 1 gyro gunsight, utilised an existing prismatic sight system which, when tested by operational squadrons in mid-1941, was given approval for the results but not for the type of sight (prismatic) which had been produced by Elliott Brothers of London. The sight was returned to Farnborough for redesign. Two quotations set the scene: "The new sight had had the attention of some of the most able brains in the country, some of those taking part under Sir Melville Jones being A A Hale, B Sykes and G/Cpt Ford. Ferranti played a central role in the design and development of the complex gyro and electrical components." And, for the Mk II series sights, "Farnborough devised a solution which was one of the simplest yet most effective solutions of the war" (37).

From this re-design exercise emerged the Mk II gyro gunsight which was successfully used in fighters and bombers and went into full production by Ferranti in 1944 (Figure 36). The sight worked by the gyro holding back the image of the target to allow the correct deflection and this point of aim also allowed for range and bullet drop as well as deflection. Demonstrated to the USAAF early in its inception, it was soon in full production for their fighters under a K-14 gunsight badge.

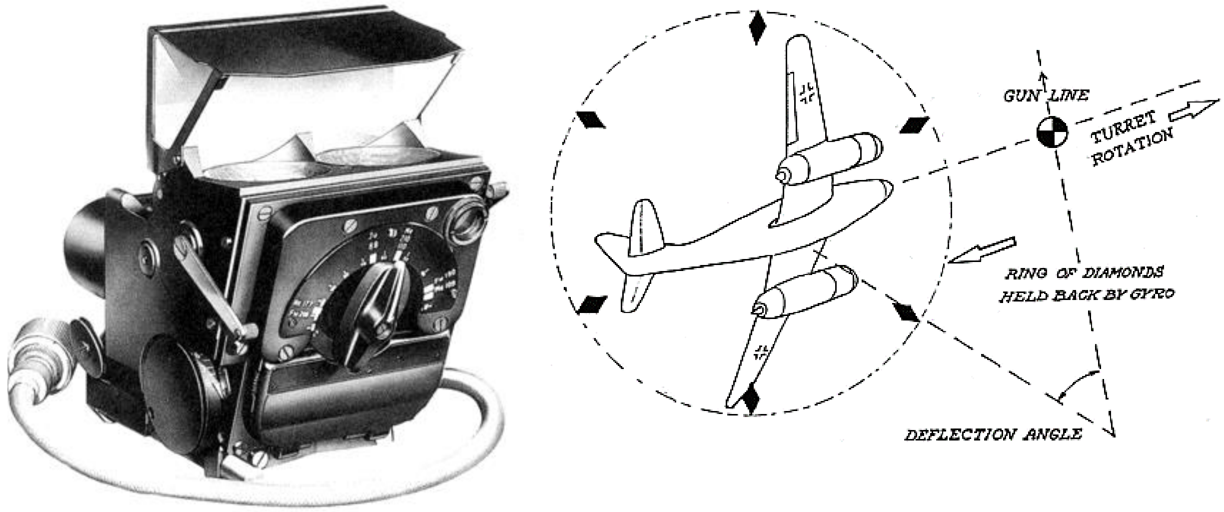


Figure 36. The Mk. IIc gyro gunsight was designed by RAE and produced by Ferranti in 1944. The point of aim, depicted on the right, allowed for range, bullet drop as well as the primary purpose of correction for deflection.

20. THE ENEMY AIRCRAFT DEPARTMENT

During WW2 RAE set up an Enemy Aircraft Department which scrutinised those enemy aircraft – German initially and then Italian and Japanese – which had been captured and transported to Farnborough. Equipment from enemy aircraft that crashed in Britain was also analysed by the Department. Some aircraft came from the North African battlefields, and all were sent to the specialist Departments to test and analyse the enemy equipment, engines and radio/radar systems and, if possible, to refurbish or rebuild and fly against British fighters. One interesting result was when a BMW engine from a Focke-Wulf 190 fighter was encouraged to run far more smoothly using British sparking plugs! Another area of interest was in the use of ejection seats in the Dornier 335 and the Heinkel 162, something that was long coming in post-war British jets (Figure 37).

Along with Martin-Baker, RAE's Mechanical Engineering Department carried out much work on ejection seat systems and in conjunction with the RAF IAM minimised the physiological risks to pilots from ground level ejections to high altitude escape. The rocket sled track at RAE

Pendine on the Welsh coast was used widely for dynamic testing of escape systems allowing ground based ejections in speeds of up to 600 mph – testing not only the effectiveness of the ejection seat mechanisms but also the protection afforded to the pilot by his protective flying clothing and the mechanical integrity of both seat and clothing to air-blast.

Figure 37. The Enemy Aircraft Dept. flew this Dornier 335 which was fitted with a production ejection seat

21. FLIGHT TEST, ACCIDENT INVESTIGATION AND WORKSHOPS

21.1 Experimental Flight Department

With all aviation experiments there has to be a time when they are tested in flight and the Experimental Flight Department (EFD) carried out these tasks with their pool of test pilots. Test pilots were allocated to each Department but, of course, there was cross fertilisation when necessary. Aerodynamics Department had one of the largest programmes of flight trials, particularly during the investigations into the transonic flight regime. From the earliest of days, flight trials were used to understand the correlations between theoretical calculations of lift etc., measurements in the simple wind tunnels of that period and in-flight pressure distribution measurements from the actual lifting wing (e.g. on a B.E.2 wing).

As aircraft speeds increased, particularly at the beginning of the 1940s, the understanding of the higher speed aerodynamics became increasingly important and how these higher speeds - approaching the speed of sound - affected aircraft performance and handling. Wind-tunnel experiments were fed into the flight trials and correlations between scale tests in the tunnel and full-scale flight tests established. Flight tests at RAE at high Mach numbers were made on seven different types of aircraft, including two jet powered aircraft, the Gloster E28/39 and the Meteor 1. The highest speeds were reached by the Spitfire XI which was dived to a Mach number of 0.9. Over the period 1942 to 1945 some 100 technical reports on compressibility and its effects on aircraft performance were issued by RAE.(38)

Post WW2 the principles remained the same and similar correlations between theory, wind tunnel and full scale flight allowed the mathematical models – later called computer models – to be refined until calculation and real-life became better correlated and understood to a level that could be reliably used for aircraft design.

EFD was always a busy department and in 1945 the year's total flying carried out by the test pilots amounted to 8,593 hours (an average of some 24 hours per day flying) (Figure 38).

Figure 38. Part of the Experimental Flight Department (EFD). Pilots of Aero Flight: S/L Tony Martindale, S/L Jimmy Nelson, Lt Eric Brown and S/L Doug Weightman.

Test pilots took many high-risk flights to push forward science and although the risk was always assessed - based on current knowledge - many test pilots paid the ultimate price. This is clearly illustrated in the FAST / Aeroplane Test Pilots Memorial Book which commemorates those aircrew and scientific flight observers who died in the service of advancing aviation science.

21.2 Accident analysis

Farnborough also carried out specific tests in relation to aircraft accidents, working closely with the Air Accident Investigation Branch (AAIB) situated on the other side of the airfield in the Berkshire Copse area. Probably the most well-known was the investigation into the cause of the early de Havilland Comet accidents. A water tank was set up in Dingley Dell and the Comet exposed to the flight aerodynamic wing loads and the changes in cabin pressure experienced on normal commercial flights (39). With the ability to represent flight loads in a much shortened timescale the cause of the accidents was rapidly established and though the significant lead that the Comet had gained by being the world's first jetliner was lost, the later redesigned Comet 4 was a commercial success.

21.3 Workshops

It would not be right to finish without noting the significant contribution of the RAE Workshops. Highly skilled and able to accommodate the many changes to an initial design by RAEs scientists and engineers – mostly without rancour – the workshops turned out exquisite wind-tunnel models of all scales from the miniature models used in the hypersonic tunnels to the larger types used in the 24 ft low speed tunnel. Working in wood and composites for the slower speeds, and metal for the high-speed tunnels, they were works of art.

22. OVERTAKEN BY TIME (OR PROOF-OF-CONCEPT?)

Research, particularly investigation into good ideas ahead of their time, can take a long time to develop into fruition even when funding and manpower is consistently available and even longer when not. Areas of research that are considered 'essential' for military or political reasons often fall foul of rapid changes in military or political direction. Often technology advances are quicker than predicted, particularly when there is a strong commercial 'push' (e.g. computing memory and speed) and others (materials, energy storage systems) that are needed to make such research successful, tend to lag – for many reasons – behind the curve. RAE had its share of such programmes where knowledge is generated but changing practice made the research (almost) redundant. A few examples follow:

22.1 The Flexible Deck

In 1943 a project was put forward to allow aircraft to land on aircraft carriers without the use of an undercarriage. The reason behind this approach was that the undercarriage and systems were taking some 6% of the total aircraft mass and that this might be better used for fuel or weapons. War priorities slowed the work but in 1946 trials were carried out on an airfield-based flexible landing deck with a Horsa glider. Development, construction, testing and trials proceeded and by March 1948 flight trials were in progress with a Sea Vampire on a flexible deck sited on the cross runway near Jersey Brow (40). Apart from the odd glitch, results were positive and in late 1948 a landing was made on the aircraft carrier HMS Warrior by test pilot Lt Cdr Eric 'Winkle' Brown (Figure 39). This technique was never used operationally, mainly due to improvements in the power and fuel consumption of jet engines overtaking and outweighing the

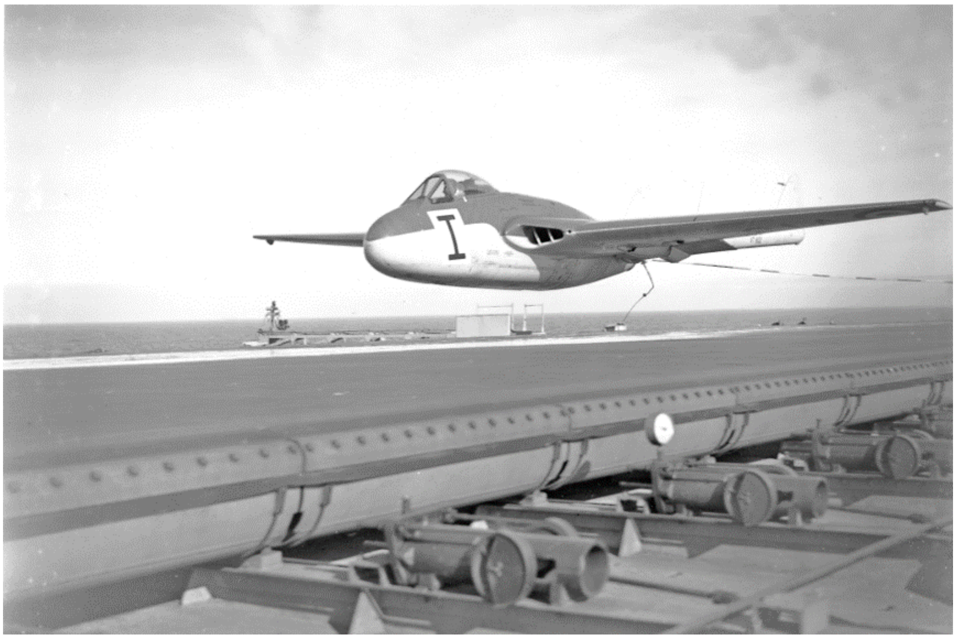


Figure 39 Landing the experimental Sea Vampire on HMS Warrior by Lt Cdr 'Winkle' Brown

disadvantages of the weight of the undercarriage. Later in the life of naval aircraft, after much research and development into improvements in carrier catapults as aircraft weights and launching speeds rose, the take-off performance of the VSTOL Harrier was enhanced by the use of the ski-jump. This was developed at RAE Bedford and is now being used by virtually all the navies operating with VSTOL or vectored-thrust aircraft.

22.2 Prone piloting

One of the limitations in pilot performance is the body's inability to operate efficiently under increased 'g' levels. At high 'g levels the blood supply is forced by the centrifugal forces away from the brain and to the lower levels of the body. As the brain, then the eyes and the heart get starved of blood the pilot's systems slowly shut down and pilot performance is significantly reduced before unconsciousness ensues with the obvious risks to the pilot and the aircraft. For aircrew the average onset of deterioration (grey-out) is around 4.1 g with complete 'black-out' at around 4.7g. Anti-g suits raise these thresholds by some 25%. An alternative to the discomforts of the 'g'suit - at least theoretically - is for the pilot to adopt a more horizontal position within the aircraft so converting the downward accelerations to transverse (across the body) and significantly reduce the vertical distance between the brain and the heart.

Future designs for very high-performance aircraft were contemplated with limited cockpit areas and it was decided to test the theories. Building on the German WW2 ideas, a Reid and Sigrist RS3 Desford was acquired and modified for normal and prone pilot operation, later designated the RS4 Bobsleigh. However the gentle performance of the aircraft, both in turning power and altitude, would not allow the supposed benefits of prone piloting to be established. A fast-jet was needed and a suitably modified Meteor would suffice. On the 31st August 1954 the Prone-Meteor arrived at Farnborough for the Institute of Aviation Medicine's Flight Section. The nose had been modified to take a prone pilot, with a normally seated pilot behind. All controls were power-assisted to reduce the physical loads on the pilot, the couch was foam rubber covered with leather on a tubular steel frame. At the head end was a V-shaped chin-rest and on either side of the couch was moulded to the pilot's shoulders. Adjustments to the couch could be made to vary eye-level, thigh and leg angle and position, and foot position (Figure 40).

Figure 40 The prone piloting position in the experimental Meteor

Installation of the pilot into the cockpit was not too difficult, although assistance was often needed to place the feet on the organ-type rudder pedals. After 55 flying hours in 99 sorties the trials finished in July 1955 and the conclusions drawn were that flying in such positions was perfectly feasible - with limitations - but the overall conclusion was that it should be adopted only if the aerodynamic advantages were over-riding.

Thus ended the UK dalliance with prone-position flying.

However, the major experimental parameter – the enhanced 'g' tolerance – was proved to be considerable, to a point which exceeded the 6.5g structural limitation on the aircraft. Subsequent developments in high-speed and supersonic flight, the gradual reclining of the conventional ejection seats and IAM research which allowed operationally effective personal protection for aircrew up to 9g, showed that prone position has not been the way forward to date but, like a lot of research, had pointed the way forward if ever needed.

22.3 WW2 DCTO – Direction Controlled Take Off (catapults for launching bombers)

In 1940/41, when grass airfields were still in operational use and the RAF's bombers of the time were generally underpowered and overweight when loaded with full bomb and fuel loads, a scheme was devised where a bomber - in this case an Avro Manchester - was mounted on an airfield catapult on a turntable. The catapult was then turned into wind and the fully loaded Manchester accelerated to take-off speed (Figure 41). This scheme was successful with the aircraft being launched - at a weight of 31,000 lb - at 6.45am on the 8th September 1942 for a 5-minute flight terminated by a conventional landing. Two flights had been carried out earlier in late 1935 launching a Handley Page Heyford III. However the technique never came to fruition as concrete runways of sufficient length were constructed at RAF Bomber Command

Figure 41. The underpowered Avro Manchester prototype mounted on the catapult prior to being turned into wind for experiments into accelerated take-off.

airfields. As an alternative to catapult assisted take-off, the use of rockets attached to the aircraft allowed assisted take-off on runways with considerably shorter take-off distances (or increased payloads) (40).

22.4 Jet Deflection Meteor

The concept of using engine power directly to provide or supplement the lift required for sustained flight has recurred frequently in the history of aviation. Helicopters are an example but changing the line of propulsive thrust in a conventional aircraft is an alternative solution. However, until the jet engine arrived the bulk and excessive weight of a power plant prevented practical solutions. The jet engine with its low specific weight and compactness gave the possibility of a solution.

An early proof-of-concept experiment at RAE/NGTE (41) involved a Gloster Meteor with vectored thrust to enable the aircraft to fly at slow speeds with the diminishing lift from the wings supplemented by vectored thrust from the two engines. The Meteor was modified by Westlands in Yeovil and the RAE/NGTE programme was formulated as it was considered that it would have an obvious application to deck landing on aircraft carriers or any situation where lower landing speeds were needed. The aircraft – Meteor RA490 – started life as a Mk III which had specially modified centre sections to adapt them to carry out flight trials on the Metrovick Beryl (F2/4) turbojet in preparation for flying in the Saunders Roe SR-A1 flying boat fighter.

The modifications needed were significant with more powerful Rolls-Royce Nene engines, rather than the production RR Derwents, and these had to be mounted well forward of the wing to ensure that the reaction of the deflected jets acted through the aircraft's centre of gravity to avoid pitch changes during selection. The position of the centre of gravity was maintained by removing the armaments, armour and ballast from the nose and adding some ballast to the tail. To improve the lateral control and to cater for an engine failure with the jets deflected, wings of a larger span – taken from a Meteor PR10 – were fitted. The nose and main undercarriage units were from an NF11 and F4 respectively.

The design, construction and development of the jet deflector ducts lay with NGTE Pyestock whilst the flight test programme was the responsibility of RAE. The maximum jet deflection angle was 63˚ from the horizontal and at full deflected power the aircraft was flown under full power at speeds below 70 knots, substantially below the normal stalling speed of around 100 knots. The minimum speed of 75 knots indicated showed that over 40% of the weight of the aircraft was being supported by jet thrust. The conclusions drawn were that the stability and control of the Meteor were adequate for test flying at 70% of the normal (power off) stalling speed but that new techniques concerning throttle control were needed in piloting. The flight and ground test programme provided valuable experience in the control and handling of a class of aircraft that was expected, at the time, to be encountered more frequently in the future. First flown in May 1954 at the constructors, Westlands, it arrived at RAE in August 1954 and it was the first aircraft in the world to be flown with jet assisted lift.

23. CONCLUDING DISCUSSION

23.1 The RAE approach

As a finale, there were two different areas that typify RAE's approach to scientific and engineering R&D.

In March 1927 R W Hardisty and the Staff of Wireless Department issued a report (H1160) entitled 'Report on the Investigation of the possibility of remote control of aircraft by the means of Light'. The conclusions were that 'With the potassium gas filled cell the sensitivity was such that the relay could be operated by the illumination of the fifth of a candle meter given by an eleven inch projector with a one kilowatt arc at a range of 3,000 yards. This range was obtained under good conditions at night. In daylight no useful conditions were obtained. A considerable increase in sensitivity could be obtained with more complicated apparatus'. Science somewhat ahead of its time.

On the engineering side and in the closing years of WW2, Winston Churchill was to use an Avro York – 'Ascalon' – with an unpressurised cabin for long distance journeys and RAE Mechanical Engineering Department were asked to design, test and construct a pressurised module, which could be carried in this aircraft and in which Churchill could reside during the long flights at higher altitudes. A clamshell module was designed and built with British industry and trials, including emergency escape, carried out in ME (Mechanical Engineering) Department (Figure 42). This was, of course, later superseded by transport aircraft with cabin pressurisation and, sadly, never used by Churchill.

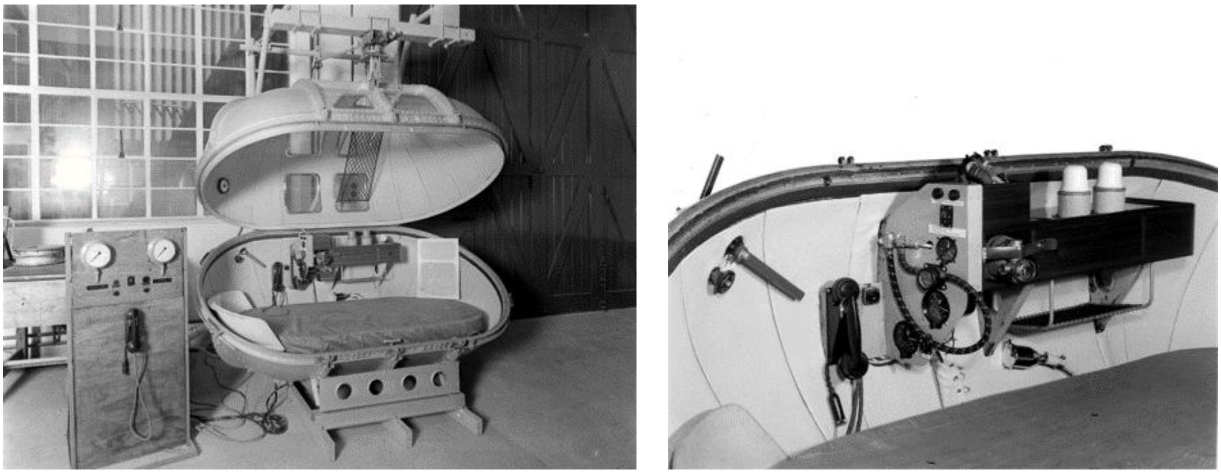


Figure 42. Churchill's Pressure Capsule with the details of the controls on the right

Like many – perhaps most – research centres, Farnborough had, necessarily, its complement of scientists and engineers with unconventional ideas for research, and generally strongly and stubbornly expressed. Frank Trevail, the RAE Secretary, summarised the situation with his assessment "Some of our geniuses have been awkward buggers, but not all our awkward buggers have been geniuses". Perhaps the mark of a good research establishment is the ability to accommodate and support the wide range of innovative ideas often necessary for 'cutting edge' research and development. An example of an individual who made a significant contribution to Concorde was W E Gray, an ex-RNAS pilot who had joined Aerodynamics Department in 1938. American research had predicted that at the 'Dutch roll', a roll-yaw motion, would be unstable at the incidence needed for landing. To show that the aircraft's 'Dutch roll' would be stable to high angles of incidence, he built a series of free-flight models which he launched from the roof of the balloon shed and across the jet of the 24 foot wind tunnel. A page from the Technical Memorandum on these tests is shown in Annex A.

In general, Arnold Hall (Director 1951-55) approached the implementation of research with three simple rules:

1. See what we know;
2. See what we think can be done with what we know;
3. See what we do not know, and what we have to do to find out.

and noted "Laboratories must not live in isolation. They must know what great men are doing elsewhere". This was, of course, a reference to industry and universities with whom RAE had significant collaboration in its research and development programmes. Words which stood the passage of time for research at RAE Farnborough.

In 1988 the Royal Aircraft Establishment changed its name to the Royal Aerospace Establishment to reflect the increased breadth of the research and development that it was undertaking.

Through its lifetime, the RAE brought benefit to the UK aerospace community, to academia, industry, regulatory authorities both military and civil, MoD Procurement Agencies, and operators. RAE knowledge and reputation bought the Establishment places in international collaboration for both research studies and development projects. RAE specialists were hugely involved in the drafting of standards for military aircraft such as AvP970 (later to become Def Stan 00-970) which are fundamental to the safe design and effective operation of military air systems. They also provided detailed technical inputs to MoD project staffs, including an independent Aircraft Performance modelling capability used for all MoD projects and also in support of Defence Intelligence. Major development programmes such as Tornado, Typhoon and Merlin all benefitted greatly from the availability of the supporting technical expertise of RAE.

23.2 The present situation

On the 1st April 1991 the RAE ceased to exist and became the Aerospace Division of the Defence Research Agency, an executive agency of the UK Ministry of Defence (MOD), which was formed by merging four defence establishments:

- Admiralty Research Establishment (ARE) comprising the major sites of Portsdown in Hampshire and Southwell in Dorset. This became the Maritime Division DRA;
- Royal Aerospace/Aircraft Establishment (RAE) – major site Farnborough, Hampshire – the Aerospace Division;
- Royal Armament Research and Development Establishment (RARDE) – Fort Halstead, Kent – the Military Division;

- Royal Signals and Radar Establishment (RSRE) – the site at Malvern in Worcestershire – the Electronics Division.

The HQ of DRA was based at Farnborough, but the other sites retained much of their former independence. The DRA lasted until 1st April 1995 when it was re-arranged into DERA (Defence Evaluation and Research Agency) by amalgamating DRA with:

- CBDE Porton Down (Chemical and Biological Defence Establishment – later changed to PLSD Protection and Life Sciences Division);
- The Centre for Defence Analysis (CDA – the former DOAE at West Byfleet); and
- The Aeroplane and Armament Experimental Establishment (A&AEE) Boscombe Down, now amalgamated with the DTEO (Defence Test and Evaluation Organisation), which also covered the MOD's ranges for weapons and armaments testing.

The DERA staffing level was around 9,000 scientists, technologists and supporting staff, making it, at the time, the UK's largest science and technology organisation.

On the 2nd July 2001 DERA was split into a private and commercial company – QinetiQ – and the retained state-owned DSTL (Defence Science and Technology Laboratory), which continued with the more sensitive aspects of the MOD R&D (Porton Down, Fort Halstead, weapons research, etc.). QinetiQ retained the Ball Hill site of the old RAE, sharing it with DSTL until 2010 when DSTL finally decamped to the old Admiralty Research Establishment site at Portsdown near Portsmouth.

23.3 A Comparison

Since RAE ceased to exist in its own right in 1991 as the central UK aviation research facility – a victim of a Government change of direction away from central funding of national aviation research and development – it is perhaps instructive to take a brief historical look at how RAE stood against similar establishments of the time in the world. Probably the establishments that were of similar status were, in the USA, NACA/NASA for science and Wright Patterson AFRL (Air Force Research Laboratory) for engineering development, and in Russia the TsAGI (Central Aerohydrodynamic Institute). The author had a number of collaborative R&D links both with NASA and WPAFB/AFRL under various UK/US Memoranda of Understanding (MOUs) and longer-term research programmes, but unfortunately none with TsAGI.

All establishments had technical and research departments that dealt with the science and basics of aeroplane design – aerodynamics, structures, materials, mechanical and electrical engineering, as well as the systems departments - armament, guided weapons, radio, chemistry, instruments and photography, etc., and differences were primarily in the scales of the facilities and the number and depth of research programmes that could be run simultaneously.

Generally, the technical quality of the scientists and engineers seemed to be very much on a par but one of the more significant differences which affected the way in which RAE approached its research was in the levels and consistency of Government / Central funding available for the necessary generation of knowledge. Certainly at Farnborough there were limitations on funding and staff such that the scientifically necessary levels of research to provide a reliable solution were not always available. In some ways this forced the initial analysis of the way forward to be considered in more depth than if the full programme cost was available and whilst it perhaps saved up-front costs there remained a higher risk of a dead-end. Collaborative programmes with the USA indicated that the American establishments were provided with both greater R&D funding and the funds to research a greater number of approaches in parallel with, consequently, a final higher probability of finding the 'right' solution. This is probably still true with the levels of long-term research funding emanating from organisations such as DARPA and perhaps reflects the USA's philosophical and more commercial approach to the importance and use by US Government and US Industry of science and technology. It is, of course, further helped by the considerably bigger national military and civil marketplace and this is generally also true for TsAGI.

Perhaps a unique strength at Farnborough was its ability to tolerate and encourage individualists. Innovation – producing something new out of what is already there – is often driven by limited funding and if RAE ever had the edge over overseas establishments it was at its strongest in these areas. This, perhaps, was supported by the higher educational system in the UK which turned out many original (and often idiosyncratic) thinkers which, when combined with limited financial resources, focussed the mind and allowed the UK to maintain its place in world class innovation (jet engines, carbon fibre, thermal imaging technology and application, WW2 gyro-gunsight, helicopter BERP blades as just a few) with the RAE Establishments (and RRE Malvern on thermal imaging and radar research) being centres of excellence which had the management and technical ability to host and foster such original ideas.

At Farnborough there was always a knowledgeable specialist scientist or engineer hidden away somewhere who could provide a way forward to a fellow researcher from another Department. This was essentially a function of the robust structure built up over the years in the RAE and which allowed the Establishment to quickly turn its abilities to a wide range of contingencies – military and civil.

It is probably also true that TsAGI – the Central Aerohydrodynamic Institute – was well funded with the need to maintain national pride and military technical superiority and with their various design bureaus (OKBs) reflecting the way that both RAE and WP/AFRL worked. OKBs did not possess the means to mass produce aircraft nor were they intended to. Almost all Soviet planes were tested at TsAGI and its many wind tunnels were extensive and covered a wide speed range.

Thus, to sum up, there were few differences between the individual quality of the scientists and engineers – probably Farnborough had the edge in scientific innovation – and wider differences between the number of facilities, primarily related to cost, which often affected the number and depth of similar research programmes that could be run in parallel. The funding available from Government was probably the major factor which influenced the direction of research and development programmes. Without the data on research budgets of the establishments – perhaps normalising the estimating to the budget per scientist/engineer – it is probably realistic to conclude that both the Russian and US work was more focussed on providing a definite and more immediate commercial output, whilst the RAE (certainly in the 1950s to 1970s) much like NASA concentrated on the generation of knowledge which would be of longer term benefit, and could be used commercially later if UK industry considered it profitable (with its much smaller marketplace). Working closely with industry, this left industry to handle the commercial development of systems and full-scale production, where there was a potential market.

RAE generally looked further ahead, either through the ‘Blue Sky’ long term research (around 15 years), the intermediate strategic research programmes or shorter-term R&D. However, many collaborative programmes were carried out with scientists and engineers in industry, as was happening in the USA (Boeing, Lockheed, etc.) and most likely in the USSR. During a war the UK Government/Treasury view is that R&D is important to maintain an edge over the enemy e.g. WW2, Falklands, Gulf War etc. and spending is acceptable but during peace it may be considered an expensive luxury.

The hypothesis that the Treasury had a different approach and view to the mechanism of research as well as the funding aviation research – short and long term – is well supported by this particular view the Treasury took during the twilight years of RAE when the Government was looking at changing the status of RAE and other establishments to an Agency charging industry and MOD for its research programmes.

This particular view in 1988/89 may be summarised from a content in a letter (42) stating

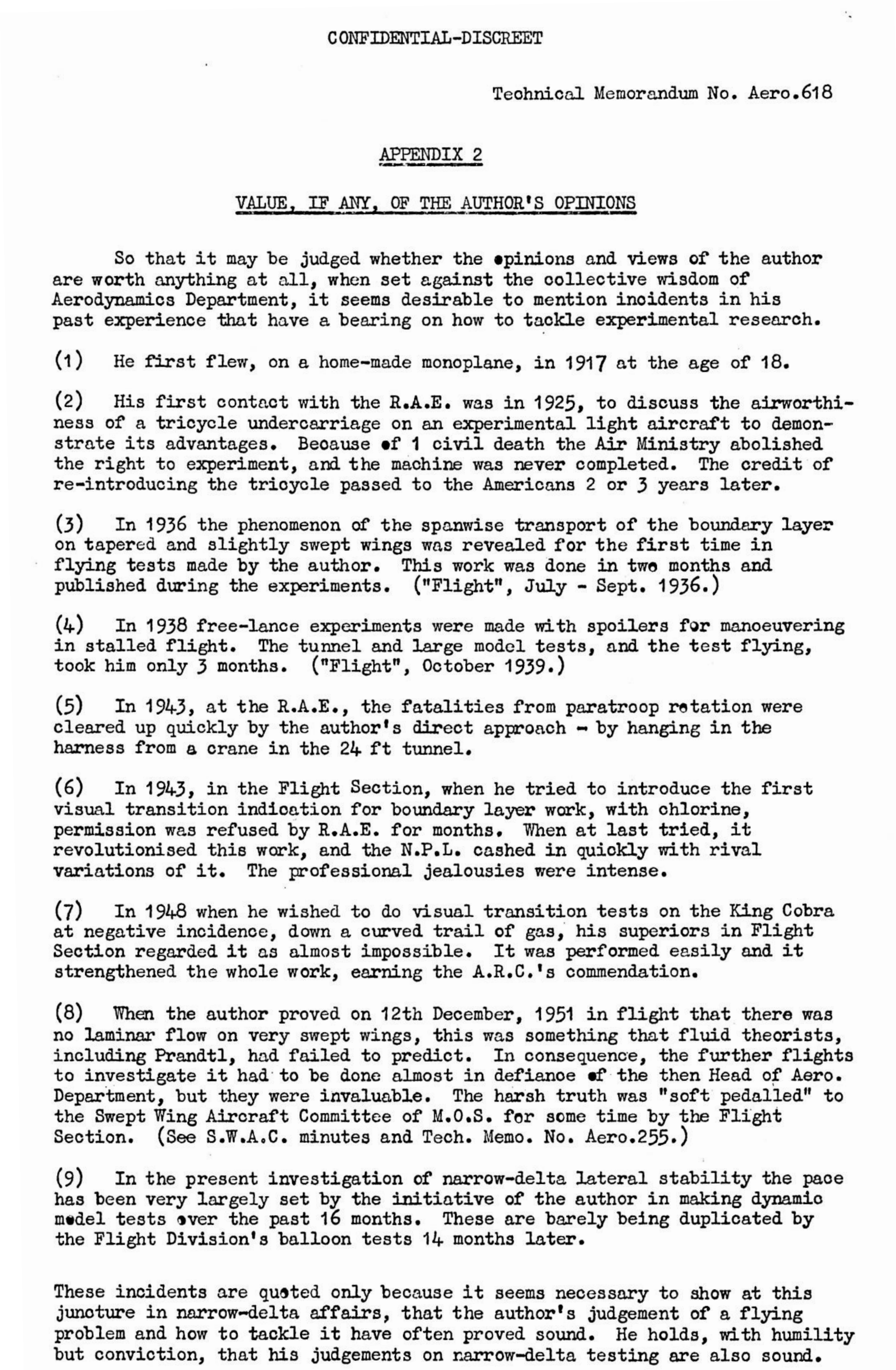
> “*The fundamental problem with the Establishments is that they live in a cosy little world. To a considerable degree they are self-tasking - they advise the rest of MOD on the areas they themselves should research. There is little in the way of cutting edge such as requirements to achieve certain things at a certain cost by a certain date. Internal senior management are simply old scientists with no financial background. The idea of deploying resources in order to balance the benefits and cost is foreign to them and their knowledge of the costs is usually non-existent. In short, the Establishments can be fairly described as an adventure playground run by scientists for scientists.”*

No comment possible or needed – an alternative view, perhaps, of the process of research and the quality of British scientists and engineers – but perhaps more an indication of why RAE’s research and development funding was sometimes difficult to maintain. I wonder where the future of lasers, carbon fibre, Al-Li alloys, thermal imaging, future radars, efficient wing design and modelling, guided weapons, flutter, night vision and much more might have been if the Treasury had been fully in charge of aviation research.

In conclusion, it needs to be finally emphasised that, in this 100-year view, only a limited number of RAE’s research and development programmes can be covered and apologies are made to those RAE staff who worked hard and long with significant contributions to aviation science and technology but whose work is not mentioned here and perhaps later articles may be able to make amends.

For greater detail and depth of the science and engineering research carried out at Farnborough, the RAE records are to be found in the many aviation and national archives in the UK including the comprehensive RAE archive at FAST (Farnborough Air Sciences Trust).

ANNEX A



CONFIDENTIAL-DISCREET

Technical Memorandum No. Aero.618

APPENDIX 2

VALUE, IF ANY, OF THE AUTHOR'S OPINIONS

So that it may be judged whether the opinions and views of the author are worth anything at all, when set against the collective wisdom of Aerodynamics Department, it seems desirable to mention incidents in his past experience that have a bearing on how to tackle experimental research.

(1) He first flew, on a home-made monoplane, in 1917 at the age of 18.

(2) His first contact with the R.A.E. was in 1925, to discuss the airworthiness of a tricycle undercarriage on an experimental light aircraft to demonstrate its advantages. Because of 1 civil death the Air Ministry abolished the right to experiment, and the machine was never completed. The credit of re-introducing the tricycle passed to the Americans 2 or 3 years later.

(3) In 1936 the phenomenon of the spanwise transport of the boundary layer on tapered and slightly swept wings was revealed for the first time in flying tests made by the author. This work was done in two months and published during the experiments. ("Flight", July - Sept. 1936.)

(4) In 1938 free-lance experiments were made with spoilers for manoeuvering in stalled flight. The tunnel and large model tests, and the test flying, took him only 3 months. ("Flight", October 1939.)

(5) In 1943, at the R.A.E., the fatalities from paratroop rotation were cleared up quickly by the author's direct approach - by hanging in the harness from a crane in the 24 ft tunnel.

(6) In 1943, in the Flight Section, when he tried to introduce the first visual transition indication for boundary layer work, with chlorine, permission was refused by R.A.E. for months. When at last tried, it revolutionised this work, and the N.P.L. cashed in quickly with rival variations of it. The professional jealousies were intense.

(7) In 1948 when he wished to do visual transition tests on the King Cobra at negative incidence, down a curved trail of gas, his superiors in Flight Section regarded it as almost impossible. It was performed easily and it strengthened the whole work, earning the A.R.C.'s commendation.

(8) When the author proved on 12th December, 1951 in flight that there was no laminar flow on very swept wings, this was something that fluid theorists, including Prandtl, had failed to predict. In consequence, the further flights to investigate it had to be done almost in defiance of the then Head of Aero. Department, but they were invaluable. The harsh truth was "soft pedalled" to the Swept Wing Aircraft Committee of M.O.S. for some time by the Flight Section. (See S.W.A.C. minutes and Tech. Memo. No. Aero.255.)

(9) In the present investigation of narrow-delta lateral stability the pace has been very largely set by the initiative of the author in making dynamic model tests over the past 16 months. These are barely being duplicated by the Flight Division's balloon tests 14 months later.

These incidents are quoted only because it seems necessary to show at this juncture in narrow-delta affairs, that the author's judgement of a flying problem and how to tackle it have often proved sound. He holds, with humility but conviction, that his judgements on narrow-delta testing are also sound.

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Graham Rood joined the RAE in 1957 as a Student Apprentice, completing in 1962 before working at AID, SRDE Christchurch and AAEE Boscombe Down. He then completed an MSc and then a PhD at Southampton University’s Institute for Sound and Vibration Research (ISVR) on Concorde Sonic Boom. He subsequently re-joined the RAE in Human Engineering Division of Engineering Physics Department working on aircraft cockpit noise problems and solutions. After carrying out early research on Active Noise Reduction systems for aircrew flight helmets (amongst other things) he was appointed Superintendent of Man Machine Integration (MMI) Department and later took on the post of Assistant Director MMI across the QinetiQ organisation at Farnborough. On retirement he joined the volunteers at FAST as a Trustee and Curator of FAST’s large RAE Historic Archive and Collection.