FARNBOROUGH AND THE BEGINNINGS OF GAS TURBINE PROPULSION

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Abstract

This paper is a revised and slightly expanded version of the 3rd Cody Lecture, originally delivered under the joint auspices of the Farnborough Branch of the RAeS and the RAeS Historical Group, on 6th December 2005. The Cody Lectures are given annually in honour of the memory of S F Cody, who on 16th October 1908 achieved at Farnborough the first powered, controlled flight in the UK, in an aircraft he designed and built himself.

The foundations of UK axial-flow gas turbine technology were laid at RAE, Farnborough. The paper describes and discusses the history of this far-reaching innovative work, from the early ideas and small-scale experiments of the 1920s, to the larger-scale effort in the later 1930s and then through World War II. The contributions and interactions of a number of leading personalities are outlined, together with problems and achievements of the work and the progressive involvement of industry.

The relationship with Whittle's work on centrifugal jet engines at Power Jets is described, and the important role of Farnborough in the hazardous wartime flight testing of the early jet engines, of both axial and centrifugal types, is outlined. A brief account is given of the controversial government decision in 1944 that Whittle's Power Jets company and the RAE Turbine Division should be amalgamated.

Finally, it is argued that it proved greatly to the advantage of the nation that there existed the two innovative and largely complementary initiatives towards gas turbine propulsion, led respectively by RAE and Whittle. The strong benefit of the total of this pioneering work, in providing a broad technical springboard to a successful future for the UK aero-engine industry in the post WWII gas turbine era, is emphasised.

Contents

1. Introduction

Samuel Franklin Cody was an imaginative, energetic and determined pioneer of aviation in this country. He faced, and overcame, many problems in developing his aeroplanes, but he was able to obtain engines that served his immediate purposes quite well. He used spark-ignition, reciprocating piston petrol engines. In the first decade of the 20th century this type of engine was becoming established as very suitable for automotive use generally. It was reasonably compact; as the combustion process took place within the engine cylinders themselves it did not require additional external systems like steam boilers and fireboxes. It also offered quick start-up capability without such preparatory processes as ‘getting steam up’. It was enabling the rapid development of road transport, and was clearly applicable, when built with attention to minimising weight, in the emerging new field of aviation.

When Cody was flying, however, another form of machine for delivering mechanical power was also seeing major development, and expansion of its applications. This was the turbine, at that time driven by steam. A turbine rotor is shown in Figure 1.

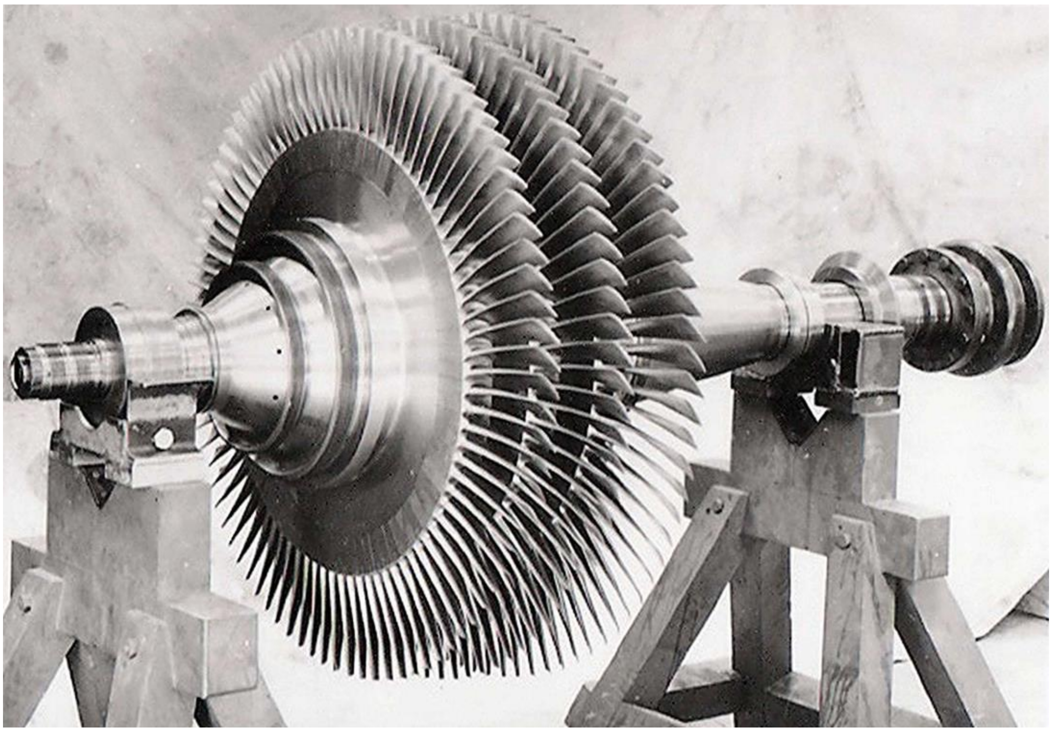


Figure 1. A Turbine Rotor

In a turbine, fluid is directed through blading, giving up energy as it drives the rotor and so delivering power to the rotor shaft. A turbine is an essentially smoothly operating steady-flow unit requiring no reciprocating pistons and cranks which produce out-of-balance vibratory forces, and no valves with their complex actuating gear. A turbine rotor can be designed to run at high rotational speed and can therefore consume working fluid at a high rate, delivering high power in relation to its size.

A turbine is also well-suited to applications where high power is wanted from a single unit, because generally it can be built in as large a size as desired – and, in general, the bigger the better, because working clearances can be better controlled and, due to the fundamental fluid scale effect expressed by Reynolds Number, the fluid-dynamic performance of the blading tends to improve as size is increased.

Piston engines, on the other hand, become more complicated to engineer for higher power. In the aeronautical field, the overarching requirements of low weight and compactness, combined with design factors such as heat transfer rates and inertia forces in reciprocating parts, result in mechanically complex engines having many cylinders. For example, some high power aero-engines used in World War II had 24 cylinders. Alternatively, if fewer but bigger cylinders and thus reduced complexity are considered, the resulting engine designs become constrained to lower rotational speed and are therefore unsuited to aviation because of their size and weight – an extreme example being the modern low-speed diesel as used in large merchant ships.

In the early years of the 20th century, turbines powered by steam were becoming increasingly used for electricity generation and in the maritime world. A major pioneer was the great British engineer, Sir Charles Parsons. Having successfully applied steam turbines in electricity generation, he turned to marine propulsion, proclaiming that the turbine would *"enable much higher speeds to be attained than have hitherto been possible with the fastest vessel"*. He also listed other advantages as including reduction in vibration and in the space occupied by machinery aboard ship, thus increasing the vessel's carrying capacity. He made many experiments with model boats and then built, for experimental and demonstration purposes, the world's first turbine-driven vessel – the Turbinia.

About 100 ft long, Turbinia was launched in 1894. Performance was initially disappointing, largely due to flow problems around the high-speed propellers, but after development and modifications Turbinia made a spectacular appearance at Queen Victoria's Diamond Jubilee Review of the Fleet at Spithead in 1897, demonstrating a speed of more than 34 knots and attracting much attention. Figure 2 shows Turbinia.

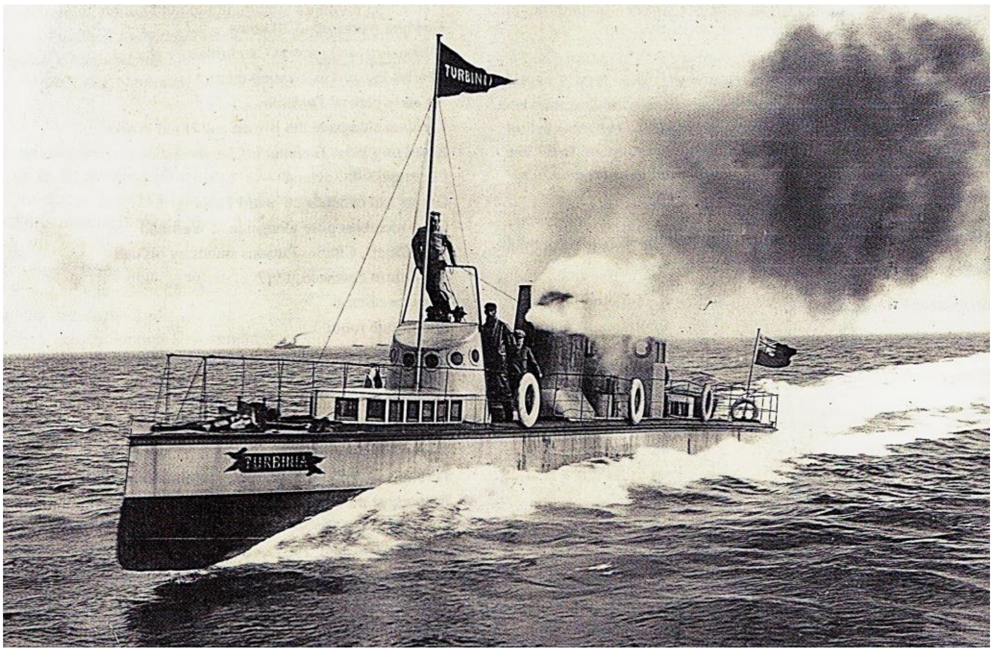


Fig. 2 Turbinia at Speed

Important applications to marine propulsion soon followed. Shortly before Cody flew his first aeroplane, and just 10 years after Turbinia's demonstration at Spithead, two major Cunard liners powered by turbines began service on the North Atlantic. These were Lusitania and Mauretania. Figure 3 shows Mauretania, which for a long period held the coveted 'Blue Riband' for the fastest transatlantic crossing.

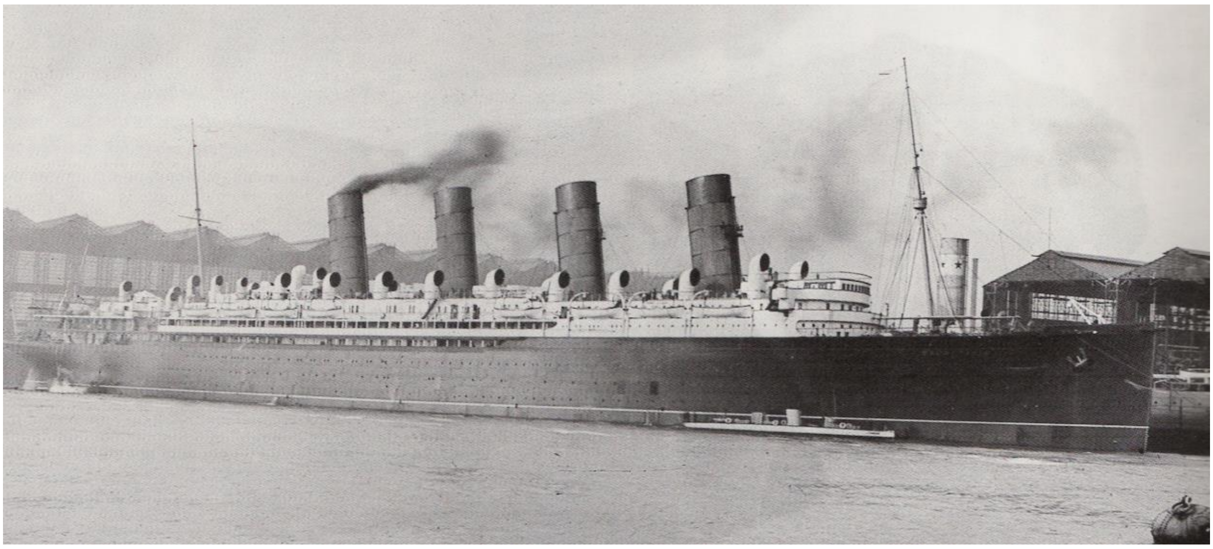


Figure 3. Mauretania with Turbinia

Figure 3 illustrates the rapid progress made in exploiting turbine propulsion, because Turbinia is lying alongside, and looking quite tiny relative to Mauretania! The power in Turbinia was 2,000 horsepower. The turbines in Mauretania produced about 72,000 horsepower!

With this burgeoning of steam turbine applications, it is not surprising that even during the birth pangs of aviation, some forward-looking engineers wondered about the possibility of using some form of turbine engine to propel aircraft. A notable example is recorded in the annals of the Institution of Mechanical Engineers (1), arising from the presentation by Charles Parsons of an important paper describing his design and development of a steam turbine-driven electricity generation system. During the discussion of that paper, a former President of the Institution, Mr Jeremiah Head, followed his congratulatory remarks about Parsons' innovative work on electricity generation by making the far-sighted suggestion that the high-speed, smooth running characteristics of turbine drive might in future ".. render it suitable for aerial navigation .." in which application ".. burning petroleum instead of coal .." would be appropriate, ".. with direct internal combustion to create hot gas from atmospheric air, rather than using steam."

These visionary comments by Head were made in October 1888, fully 15 years before the first flight of any mechanically powered aeroplane! His words show that he had grasped the basic attractiveness for an aircraft of a compact, smooth-running turbine engine, not depending on steam but making use of the surrounding atmosphere as the source of the working fluid, with liquid fuel being burned inside the engine itself. This form of powerplant became termed an *Internal Combustion Turbine* – or in today's language, a *Gas Turbine*.

2. The Gas Turbine and its Inherent Challenges

However, despite the elegance of the gas turbine concept, major technological obstacles stood in the way of its practical realisation as a serious competitor to other kinds of prime mover. To overcome them would require scientific advances in aerodynamics and combustion technology, innovation in temperature-resistant metals, and extensive mechanical engineering development.

The basic layout for a continuous-flow aircraft gas turbine, burning fuel at constant pressure and arranged to provide output power on a shaft to drive a propeller, is shown schematically in Figure 4.

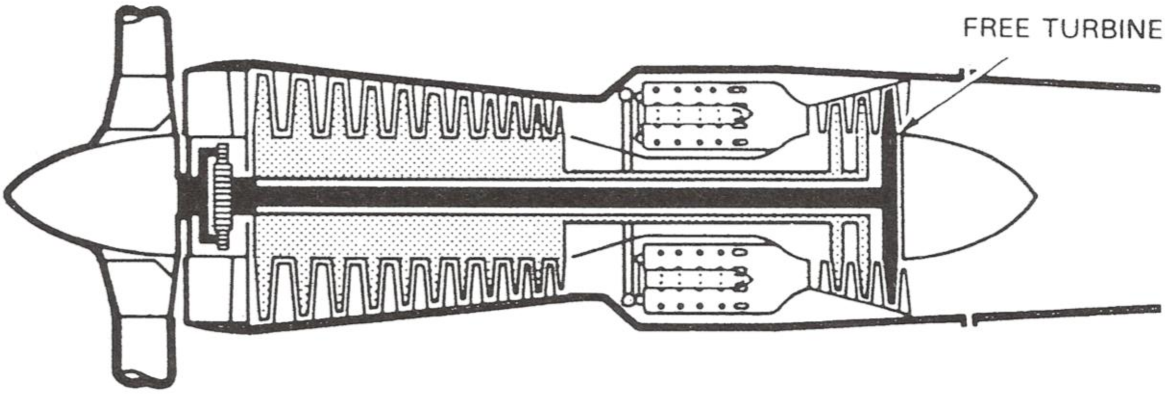


Figure 4 ‘Turboprop’ – schematic

A vitally important component in a gas turbine, not needed in a steam turbine, is the compressor. This takes in air from the atmosphere and raises its pressure. Fuel is then burned in the compressed air and the resultant gases expand through the turbine system, doing work, and finally exhaust to atmosphere. In Figure 4 there are two turbines, the first purely driving the compressor and the other, the aircraft propeller. Sometimes, a single turbine drives both. A very important alternative to the propeller, appropriate for high-speed aircraft, is to use ‘jet propulsion’, by expelling the engine exhaust directly to atmosphere as a high-velocity jet.

It should be noted at this point that to match the compactness and high flow capacity of the turbine to which it is connected, the compressor for a gas turbine engine also needs to be of a continuous-flow, ‘aerodynamic’ type – as opposed to the simpler but relatively bulky reciprocating or ‘positive displacement’ pump.

There are two basic forms of continuous-flow compressor. First the axial-flow type, where the air passes along the machine, parallel to the axis, and gradually builds up pressure as it passes through successive stages of blading. The other form is the centrifugal compressor, where the air is ‘whirled’ outwards, then collected in a casing where its kinetic energy is converted to pressure in diffusing passages. Figure 5 shows the rotor of a gas turbine with a 9-stage axial compressor. Each ‘stage’ consists of a row of rotating blades on the driven rotor and its adjacent row of stationary blades (not shown in Figure 5) mounted in a casing. The compressor is at the left-hand end of the rotor, the turbine at the right-hand end. Figure 6 shows the rotor of a Whittle engine with a centrifugal compressor.

Important differences between the two compressor types are that, with good design, a higher efficiency is potentially achievable with an axial than a centrifugal. Also, for a given airflow, the axial is considerably slimmer than the centrifugal – a significant matter for a high-speed aircraft, because of the reduction in airframe drag. However, the design of high-performance axial compressors requires a high level of scientific understanding and technological experience. The centrifugal is simpler than the axial, though still presenting significant challenges.

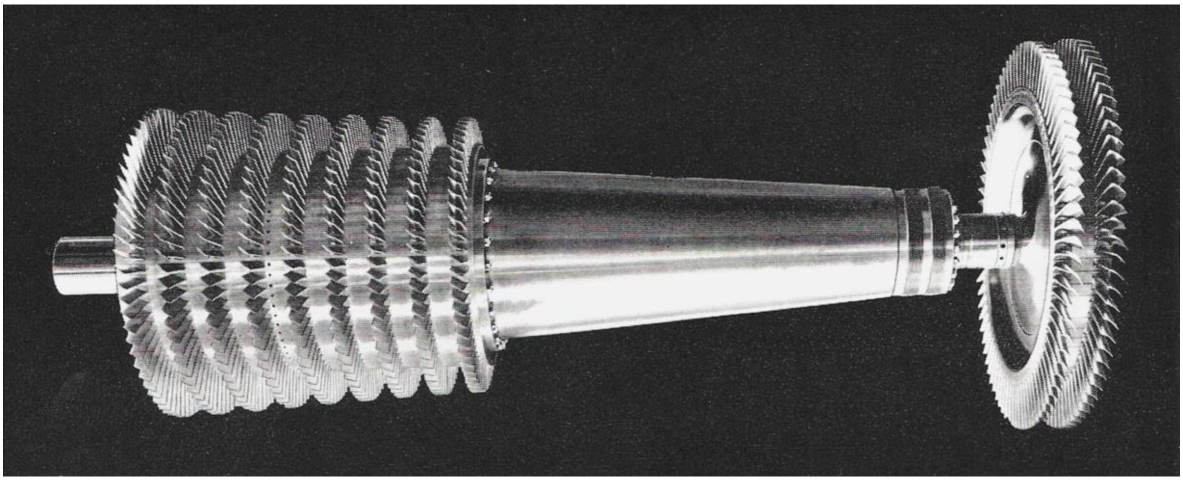


Figure 5 Rotor of an Axial-Flow Engine

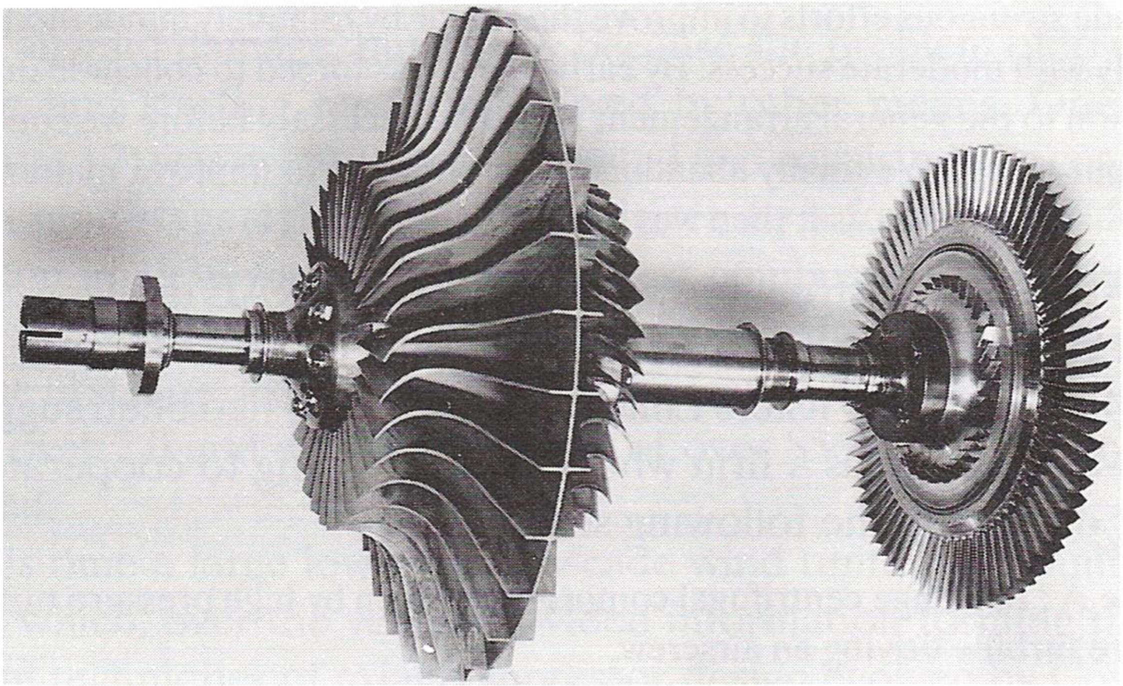


Figure 6 Rotor of a Whittle Engine

Compared with the steam turbine, the need in a gas turbine engine for a compressor carries with it a crucial technical challenge. The air compression process requires a considerable amount of energy, which must be supplied by the turbine system, so reducing the remaining amount of turbine power available for useful work output from the engine. To maximise the output power, it is therefore necessary to minimise the energy needed for compression, but this requires an advanced understanding of compressor aerodynamic design that did not exist in the early years of the 20th century.

Another factor strongly affecting the power available from a gas turbine is the turbine entry temperature (TET), i.e. the temperature to which the compressed air is raised in the combustion chamber. Engine performance is improved by raising TET, but a limit is set by the capability of available materials to withstand the combination of high temperature and the stresses associated with a high rotational turbine speed.

Figure 7 is an illustration showing the major influences on the output power available from a gas turbine of the type shown on Figure 4, for a compressor pressure ratio of five.

This figure shows how the useful power output from the engine varies in relation to turbine entry temperature and component efficiency η for a constant pressure gas turbine cycle. The power is shown as a proportion (termed the ‘work ratio’) of the total power generated by expansion of the working fluid through the turbine system. The higher the temperature that can be tolerated by the turbine blading, the greater will be the useful power output. It is also clear that unless quite high compressor and turbine efficiencies can be achieved, the engine is incapable of driving its own compressor (shown by the shaded part of the diagram), let alone providing any useful output.

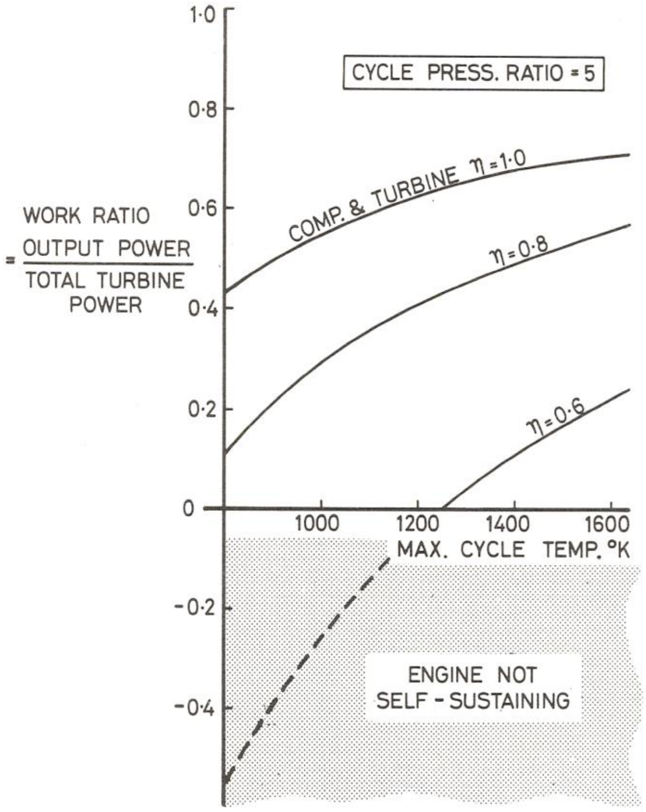


Figure 7 The Power Output Problem

3. Early UK studies and research on aircraft gas turbines

A government-backed study of the prospects of employing the gas turbine for aircraft propulsion was carried out in this country in 1920. At that time there existed an Air Ministry Laboratory, on the site of Imperial College, South Kensington. W J Stern, working at that institution, issued a report entitled “The Internal Combustion Turbine”, dated September 1920 and submitted to the Engine Sub-Committee of the Advisory Committee for Aeronautics (which later became the Aeronautical Research Council).

Stern’s very extensive report (2) compared current achievement and prospects for reciprocating engines with those for gas turbines, including some variations on the basic gas turbine cycle. He identified several potential advantages of the gas turbine, the main ones being summarised in Figure 8.

Overall however, Stern concluded that *"In its present state of development, the internal combustion turbine is unsuitable for aircraft, on account of weight and fuel consumption, the main difficulty in the case of aircraft being the design of a light, compact and efficient compressor".* He also noted that *"There seems to be no prospect of immediate improvement in turbine blading material".*

Simplicity and reliability

Perfect balance – smooth running

High power on one shaft –relatively low weight

Possibility of using heavy fuels

Figure 8 Potential advantages of gas turbine, identified by W J Stern (1920)

By 1920, the experience with the few experimental gas turbines so far built (all for non-aeronautical purposes) was mostly of disappointment. Usable turbine entry temperatures had been greatly limited by the properties of available materials, and although good aerodynamic efficiencies were attainable in the turbine (as demonstrated by considerable and successful steam turbine experience), the efficiency levels of compressors were only about 60%. This difference between turbines and compressors reflected the fact that in a turbine the flow conditions are basically favourable, being from a higher to a lower pressure, but the compressor presents a far more challenging aerodynamic problem. The compressor blading increases the pressure of the air as it flows through the machine, and does this with the least possible waste of energy. Given the disappointing experience so far, and Stern's discouraging view of gas turbine prospects, there the matter lay for the next several years.

In 1926, however, a major move forward was initiated by an RAE man, Dr A A Griffith, Figure 9, who was then in his early 30s and already a highly respected engineering scientist.

Fig. 9 Dr A A Griffith

Before Griffith was 25, he and G I (later Professor Sir Geoffrey) Taylor, working together at RAE, had jointly been awarded a Gold Medal of the Institution of Mechanical Engineers for devising an analogue method of determining the torsional stress distribution in components of complicated shape, such as shafts with keyways cut in them – an important practical problem of the time. This involved using soap films (3) and Griffith's activities in this area had earned him the nickname "Soap Bubble Griffith" at RAE.

Griffith had also done fundamental work on the mechanical strength and rupture properties of materials, and had made a major conceptual advance (4) regarding the criteria for crack propagation – an advance that was important in establishing the foundations for the modern science of 'fracture mechanics'. To the present day, Griffith's fundamental work in the materials field is commemorated by the annual award, by the Institute of Materials, Minerals and Mining, of the Griffith Medal and Prize.

Griffith's entry into the gas turbine field may have had an element of chance about it. He had been working, with Ben (later Sir Ben) Lockspeiser as his assistant, on the strength of fine-drawn fibres, using glass as a model experimental material. One evening, Lockspeiser forgot to turn off the glass-melting torch before going home. There was a fire. This had the unfortunate result, apart from doing a bit of damage, of attracting the attention of senior management – not always a good thing! Their project was reviewed, judged to be no longer worthwhile, and cancelled! Griffith was instructed to interest himself in other things.

Perhaps, therefore, Griffith came to the gas turbine 'on the rebound'. We don't know. However, he was soon addressing fundamental issues. He examined the implications for gas turbine design of recent developments in aerodynamic theory. He argued that the poor performance so far exhibited by axial compressors was because their blades were often stalled, and he predicted that by proper design, with aerodynamic loading kept within limits determined by wind-tunnel aerofoil tests, compressor and turbine stage efficiencies exceeding 90% would be attainable. He worked out an example design for a compressor and estimated that a gas turbine could become competitive with the reciprocating engine for powering an aircraft via a propeller.

Griffith issued a ground-breaking RAE Report in 1926 (5), which was classified Secret and remained so for many years. Lecturing in 1945 about the successful development of the axial-type aircraft gas turbine, Hayne Constant, who later became Director of NGTE, described (6) it as *"The first practical proposal to use a gas turbine as an aeroplane powerplant."*

In his report, Griffith also put forward a scheme for a small, low cost turbo-compressor rig designed to verify his theoretical work. A few months later a conference was held at RAE under the auspices of the Aeronautical Research Committee (ARC), which resulted in a unanimous recommendation to proceed, and detail design and construction of the turbo-compressor rig was put in hand. Fig 10 shows the rig, which is on display in the Science Museum, Kensington.

This apparatus featured a single-stage turbine, driving a single-stage compressor – quite small; the rotor tip diameter was 4 inches. Operation was by simply sucking air through the assembly. Pressures were measured upstream of the turbine, between the turbine and compressor, and downstream of the compressor. Concurrently with the design of this rig, the first wind-tunnel tests on cascades of blades, also under Griffith's direction, were carried out at RAE. Figure 11 shows a cascade tunnel rig.

Tests on the turbo-compressor rig began in early 1929, and the results (7) indicated a maximum value for stage efficiency of about 91%. This very high figure was probably 3 or 4% above a true mean stage efficiency, the measurements probably being taken in the middle of the blade span where the airflow would be least affected by deleterious end wall effects. Nonetheless, the tests confirmed that a high efficiency was reachable in an appropriately designed axial compressor, and demonstrated the basic validity of Griffith's approach. So, these first steps at RAE had been of far-reaching significance!

Griffith's little turbo-compressor rig still exists. It can be viewed in the aeronautical gallery at the Science Museum – together with the first RAE multi-stage compressor, to be described later.

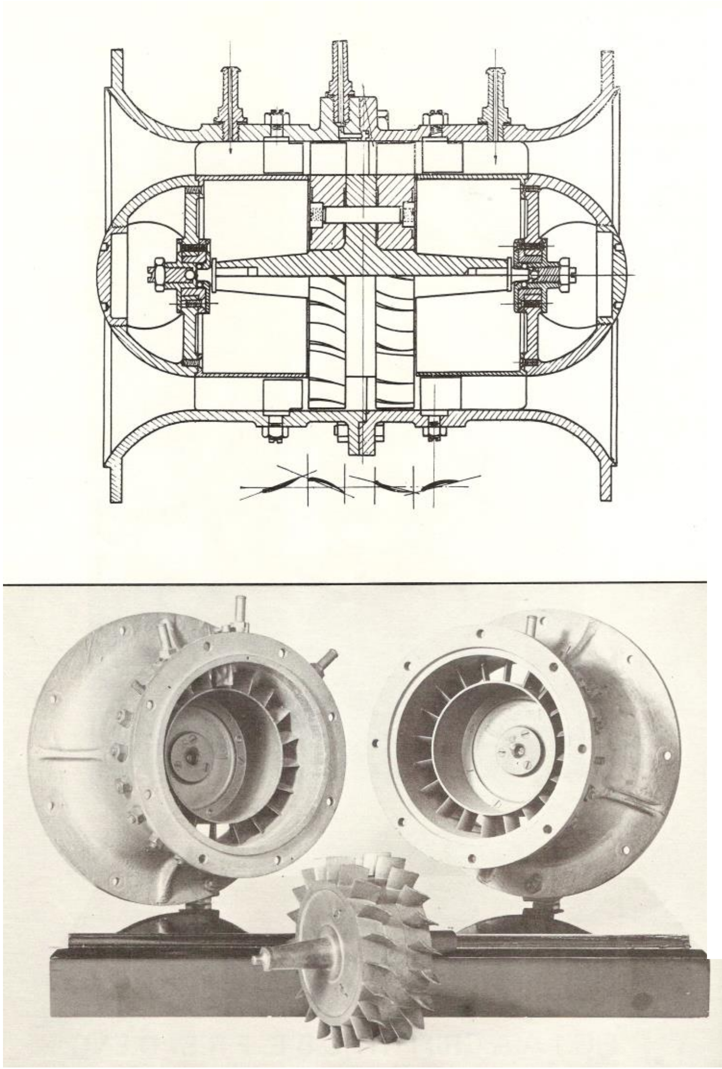


Figure 10 RAE turbo-compressor rig, 1928/29

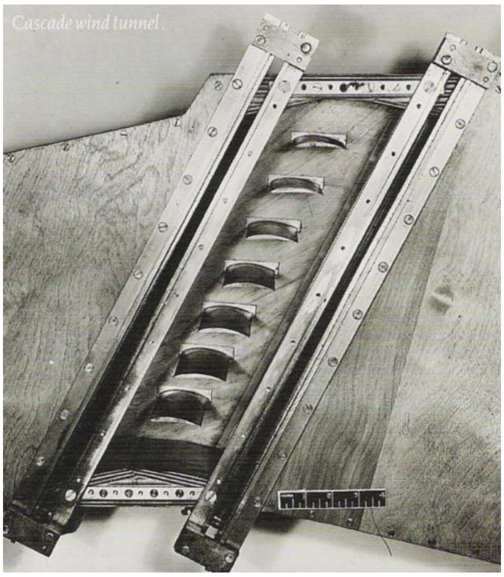


Figure 11 RAE Blade Cascade Rig, 1927/28

In mid-1928 Griffith had been appointed Principal Scientific Officer in charge of the Air Ministry Laboratory at South Kensington – a post he held for 3 years before returning to RAE to take charge of engine research.

In 1929, much encouraged by the test results from the turbo-compressor rig, Griffith carried out a more extensive assessment of the gas turbine as an aircraft engine (8). He had shown that high blade performance could be obtainable at the design operating condition or 'design point' of the machine, where the blade angles and airflow are designed to be mutually matched. He now went on to consider how an engine with a multi-stage axial compressor would behave at conditions away from the design point – as the engine speed was varied, for example.

A characteristic of 'aerodynamic' compressors (in contrast to the 'positive displacement' type), is that they have a boundary of stable operation, beyond which a violent and dangerous instability of the whole flow, termed 'surging', will occur. It is therefore essential, for safe operation of an engine, to ensure that an adequate margin will be maintained between all intended engine operating conditions and this surge boundary. This requirement applies not only for steady running but also for transient conditions - as emphasised by the fact that when an engine is being accelerated, flow processes within the engine cause the compressor operating point to move towards the surge boundary. Other undesirable and potentially dangerous phenomena, such as 'flutter' and other forms of blade vibration, can also arise at various off-design conditions.

Griffith was a man who liked to calculate things wherever possible – in fact, he would usually do a lot of exploratory calculation mentally, rather than on paper. For a compressor working away from its design point, he expressed his concern at what he termed *"the incalculable form"* of the flow, and suggested that *"it is conceivable that the efficient range of conditions would prove to be so narrow as to render the installation useless for any practical purpose"*.

Faced with an uncertainty like this, most research engineers would probably tend to build an experimental compressor and explore its behaviour, hoping that satisfactory operation could be achieved by detailed adjustment to design or control techniques. But this was not enough for Griffith. He bent his mind to inventing a way around the problem. He devised a drastically different engine configuration! This was his "Contra-Flow" arrangement, shown below.

Here, each compressor stage would be driven individually by its own row of turbine blades, the turbine blades being mounted on the ends of the compressor blades outboard of a shroud ring. Thus, the gases driving the turbines would flow along an annulus surrounding the compressor annulus, the airflow having been reversed in direction in the combustion system. All the compressor/turbine wheels would be separate, independently mounted on a common shaft, with adjacent wheels arranged to rotate in opposite directions. Griffith argued that with this scheme, the departure from design blade incidence during off-design operation would be less than in a conventional machine with all stages on a common rotor. Figure 12 shows a machine of contra-flow type which was built much later by Rolls-Royce, to Griffith's design.

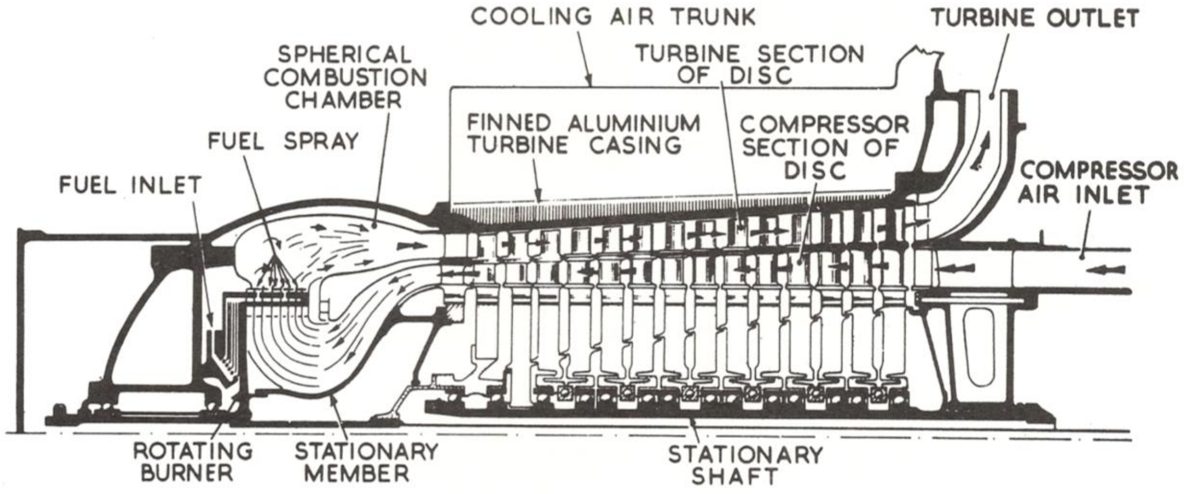


Figure 12 Griffith 'Contra-Flow' engine

Figure 13 shows one wheel for an experimental Griffith contra-flow unit, built in 1939 under RAE contract by Armstrong-Siddeley.

Experimental experience later showed that this ingenious scheme of Griffith's was by no means the right way to go. There were severe difficulties in minimising leakage across the many running seals between the stages, and the contra-flow arrangement awkwardly constrained the engine layout. Overall, Griffith's solution turned out to be worse than the problem! But he did continue to put his faith in it for a long time, as outlined later in Section 8.

Griffith's 1929 appraisal (8) included a study for a 500 horsepower engine, using the contra-flow principle, and he estimated that it would be significantly superior to a corresponding reciprocating engine in fuel economy, weight, and power at altitude. Importantly, he also proposed the construction of an experimental 14-stage contra-flow unit which could later be used as part of a complete engine.

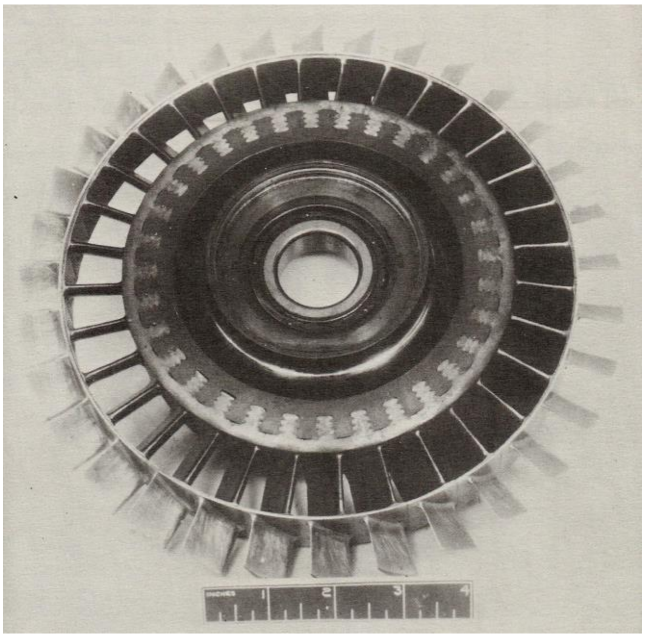


Figure 13 Rotor of a 9-stage contra-flow wheel

Also in late 1929, Griffith had his first contact with another innovative individual who was interested in the use of a gas turbine for aircraft propulsion. This was Flt Lt (later Sir Frank) Whittle, shown in Figure 14.

In 1928 Whittle, then a Cadet at the RAF College, Cranwell, and knowing nothing of Griffith's work, had written a student thesis on future aircraft development that included some discussion of the possibilities of gas turbines driving propellers for achieving very high aircraft performance (9). The following year, after leaving Cranwell, he conceived the visionary idea of using the exhaust of a gas turbine *directly* to produce a high-velocity propulsive jet, thus forming a compact powerplant that became known as a *turbojet*. This differed importantly from Griffith's thinking in that it did not involve the use of a conventional rotating propeller, whose efficiency was known to decline progressively at increasingly high aircraft speeds. Whittle's RAF superiors arranged for him to put his ideas to the Air Ministry, with the result that he was interviewed by W L Tweedie, of the Directorate of Scientific Research, and Griffith in his role of Head of the Air Ministry Laboratory.

Figure 14 Sir Frank Whittle

Unfortunately, this meeting did not go as well as Whittle had hoped. Griffith probably felt this confident young officer's technical assumptions were too optimistic, and that the high fuel consumption of Whittle's turbojet would rule it out for all but very special, short-duration, high-speed flying. He was possibly also aware that the Air Ministry was not, at that time of financial depression, anxious to allocate resources to speculative gas turbine development. Following the meeting, Whittle received a letter from the Air Ministry, signed by Tweedie and dated 5th December 1929. This confirmed the criticisms and cautionary views expressed at the meeting by himself and Griffith and indicated that no support for work on Whittle's scheme would be forthcoming. Furthermore, his patent would be regarded as not being of official interest, meaning that there would be no restriction on open publication, which then followed in due course and became available internationally. Not long afterwards, Whittle also contacted some aero-engine firms, but found no willingness at that time to invest resources in a radical engine scheme for which important technological ingredients had not yet been developed.

Overall, Whittle was very disappointed. He accepted that "at the end of 1929 it [his turbojet] was before its time, but only by very few years" and therefore felt that rather than simply rejecting the scheme, the Ministry should have recognised its potential and "kept the proposal 'on ice' for a later period (10). It seems that he also felt that Griffith, in view of his research experience and scientific standing, could have been more supportive to him in the meeting. Whatever the detailed reasons, the tone of this first contact between Whittle and Griffith appeared to persist in the future. They never generated a close rapport, and cooperation in future years between Whittle's 'Power Jets' team and RAE Turbine Division was mainly due to Hayne Constant.

Not long after his encounter with Whittle, Griffith's own gas turbine activities became the subject of an examination by the ARC. Early in 1930 the ARC Engine Sub-Committee set up a special panel, chaired by H T (later Sir Henry) Tizard, to consider Griffith's proposals in his 1929 paper. Its deliberations were extensive, involving four meetings, during which the panel reviewed Griffith's studies and the associated experimental work at RAE, and discussed the limited experience and knowledge currently available on gas turbines generally. By invitation, a senior engineer from the steam turbine industry participated in one meeting. In addition, two supplementary papers were provided by Griffith for the final panel meeting.

The panel's formal report was issued in April 1930 (11). This stated that *"The panel consider that, at the present state of knowledge, the superiority of the turbine with respect to the reciprocating engine cannot be predicted, and they have no intention of advocating the large expenditure that would probably be involved in any attempted development of a turbine power plant by the Air Ministry."* But importantly, the report did encourage further work at a research level, recommending that *"the multi-stage test rig proposed by Dr Griffith should be built and the necessary analysis made of the flow, pressure and temperature distribution in order to determine the conditions under which high efficiency of compression can be obtained and – providing a high efficiency is realised – the efficiency of the unit when used as a high-pressure component of a turbine compressor of 500 bhp installation."* The panel also recommended *that "if possible, some experiments on the rapid combustion of fuel at constant pressure should be carried out since experimental data of this nature will be required when further developments are considered."* These recommendations were endorsed by the Engine Sub-Committee, and by the ARC itself in May 1930.

Thus, although the panel had judged that it was premature to recommend the major commitment of embarking on an engine development programme, they by no means rejected Griffith’s ideas entirely but made positive recommendations for experimental research at RAE in two significant areas. And it could have been expected that these recommendations, coming as they did from this influential and independent body, would be helpful in gaining the allocation of the resources needed for their implementation. It is therefore surprising that although Griffith returned to RAE in 1931 and became responsible for engine research, these recommendations were not acted upon and no further RAE experimental research on gas turbine powerplants was done for more than six years!

The reasons for this hiatus are not firmly known, as no relevant documentation has yet come to light. It has been said (12, 13) that some who had close contact with Griffith knew that he was very disappointed that his proposals had not received the level of support he hoped for. But it remains uncertain as to whether Griffith’s personal disappointment was the decisive reason for the lack of action, or whether other factors were also involved – for example, management decisions on programme expenditure related to the early-thirties depression. Griffith himself was an experienced and versatile researcher, and he soon became much involved in other things. For example, the improvement of fuel control for conventional piston aero engines was important, and in 1931 he put forward proposals for a new form of carburettor. This led to development during the 1930s of the RAE pressure injection and metering carburettor, which saw service use in WWII.

Thus, in the early 1930s both the Whittle and RAE initiatives towards gas turbine propulsion came largely to a standstill for several years. The effect on subsequent history will always remain a matter for speculation. If the work had gone ahead without delay, would British jet aircraft have entered service earlier in World War II, and to what effect? Would an earlier start have resulted in the work progressing as well as it did later under the spur of likely approaching war and with benefit from advances made meantime in high-temperature materials and other areas? We shall never know.

Although the RAE research recommended by the ARC did not proceed, we have evidence that gas turbine propulsion did not entirely disappear from Griffith’s mind, because early in 1935 he proposed that a simple turbojet engine of Whittle concept (i.e. not using a conventional propeller) would be a suitable powerplant for an unmanned, automatically controlled small aircraft carrying an explosive warhead and acting as an aerial bombardment weapon over ranges up to several hundred miles. This early ‘cruise missile’ project stemmed from RAE research in the 1920s with flight trials in 1927/29 using small specially designed pilotless aircraft known as ‘Larynx’, powered by a conventional ‘Lynx’ radial aeroengine driving a propeller.

Figure 15 shows one of these aircraft, mounted for catapult launch from a warship. The programme provided confidence that a weapon for service use could be developed, and over the next few years the possibilities for raising performance and/or reducing production cost were further reviewed. This process gave rise to Griffith’s turbojet proposal (14). His engine scheme featured a four-stage axial compressor, driven by a two-stage turbine with an entry temperature of about 600 °C. Diameters of the compressor and turbine blading would not exceed 8 inches. It was estimated that with such an engine, an aircraft of total weight 1,000 lb could have a

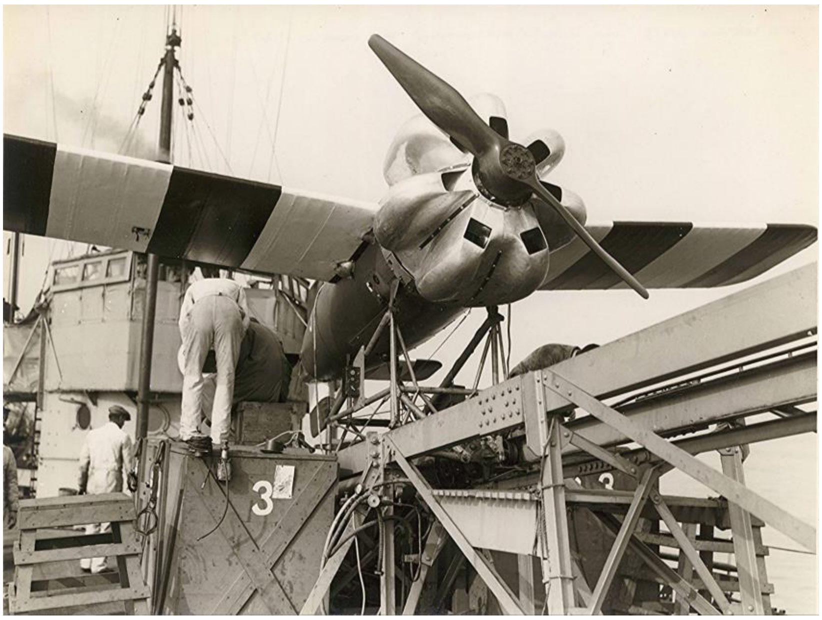


Figure 15 RAE 'Larynx' experimental pilotless aircraft

maximum speed of about 500 mph and cruise at 15,000 ft.

Although this small turbojet was not built – because for other reasons this weapon system was not selected for service use – check calculations done in recent years (15) have confirmed that Griffith's design scheme was feasible and could have led to a successful engine.

Two comments seem appropriate regarding this Griffith turbojet proposal. First, its date of early 1935 probably means that it can be accorded the historic position of being the first specific gas turbine engine scheme put forward in the UK for a particular aircraft project. Secondly, the fact that it came from Griffith shows that he was not basically prejudiced against Whittle's 'pure jet' or 'turbojet' type of engine, as some have implied in commenting on the cool relationship between the two men. Although at that time Griffith favoured the use of the open propeller for many aircraft applications to avoid the longer take-off runs needed by jet aircraft, and the higher fuel consumption caused by the high-velocity propulsive jet, he recognised that for some applications the turbojet could be very appropriate – an example being the high-speed guided missile with its accent on simplicity, low cost and short flight time.

4. Re-awakenings

In 1936 movement restarted on both fronts. Whittle and some friends formed a small company, Power Jets Ltd, with limited funds raised commercially, and embarked on developing a turbojet engine, contracting British Thomson-Houston Co (BTH), Rugby, for manufacture. At first it was intended to develop the main components one by one, and then combine them in an engine, but Whittle *"... soon realised that this was likely to be a long and costly process and we decided to go for a complete engine right away"*. The history of that bold pioneering venture is set out in Whittle's James Clayton Lecture to the Institution of Mechanical Engineers (16). Constructive relations between the Farnborough and Power Jets research and development efforts stemmed from the collaborative atmosphere that developed between Whittle and Constant, after the latter returned to RAE as indicated below. The flight testing of Whittle-engined aircraft at Farnborough, from late 1942 onward, is outlined later, in Section 7.

At RAE, 1936 was marked by the return of Hayne Constant, who was to become a central figure in the Farnborough gas turbine story (Figure 16).

Constant had originally joined the Establishment from Cambridge in 1928 and had been influenced by Griffith and his thinking. He had moved to Imperial College in 1934, but re-joined RAE to become Head of the Supercharger Division of Engine Department, under Griffith. Tizard, who was Rector of Imperial College as well as Chairman of the ARC and a key figure in the defence science world, had indicated to Constant that he felt that the future of aircraft propulsion might well lie with the gas turbine, and Constant quickly gained approval to design and construct at RAE an experimental axial-flow supercharger. This was the first RAE multi-stage compressor. Called "Anne", and depicted in Figure 17, it was the first of a series of research machines bearing girls' names. With a diameter of about 6 inches, it had 8 stages and was of conventional layout - i.e. not a Griffith contra-flow design. It is on display in the Aeronautical Gallery, Science Museum, South Kensington.

Fig. 16 Hayne Constant

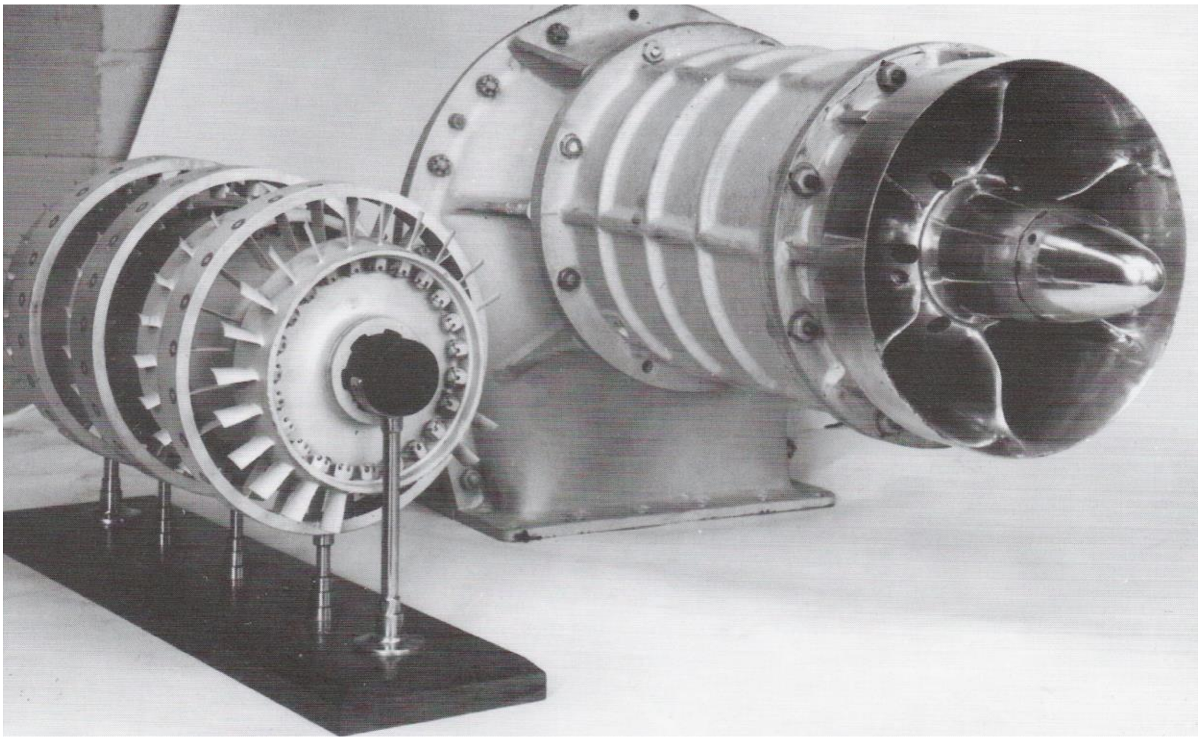


Figure 17 RAE 8-stage compressor, 'Anne'

At the request of the ARC, another general assessment of the prospects of the gas turbine was written, this time by Constant, and issued in March 1937 (17). Constant, though regarded by some as rather aloof, even a somewhat arrogant figure, had a sense of humour which he was prepared to use in writing as well as verbally. In his report, which concluded strongly that there was now a prospect of constructing a turbine engine well competitive with reciprocating engines, he also wrote *"The magnitude of the advantage it has to offer, associated with the repeated* *failures to achieve a practical design, have given the impression that the Internal Combustion Turbine is merely a convenient medium on which to work off the surplus energy of imaginative inventors".*

In April 1937 Whittle achieved the first testbench run of his engine – an event of significance both technically and in terms of demonstrating to sceptical minds the practicability of his turbojet concept. Following an assessment of the current technical situation, and the increasing importance for fighter aircraft of higher speed, the ARC formally recommended that the Air Ministry should now press ahead urgently with the development of the gas turbine for aircraft propulsion. Importantly, they also wrote *"this will probably require the cooperation of turbine builders and recommend that possibilities in this direction should be explored without delay".* The firm of Metropolitan Vickers Ltd was suggested for possible involvement.

Compressor "Anne" was run early in 1938 and provided a foretaste of the tribulations characteristic of compressor development by immediately stripping all her blading due to a bearing failure! As Constant wrote later *"Thus over 18 months work was lost in 30 seconds".* But after rebuilding, and some design modification, "Anne" achieved a very encouraging performance. Despite being damaged in a German bombing raid on Farnborough in 1940, "Anne" still exists and is displayed with the small Griffith turbo-compressor rig (Figure 10) in the Science Museum, London.

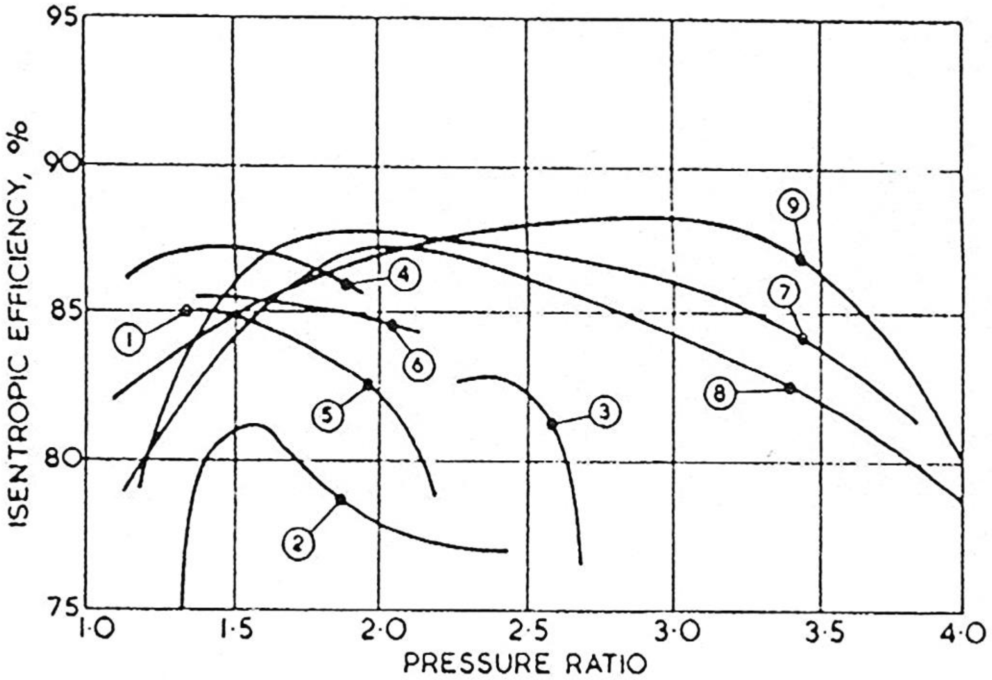
The work that was to lead to the axial-flow engine now gathered momentum. A number of experimental axial compressors were designed by RAE and mostly built under contract in industry over the next few years. Figure 18 provides a summary picture of the results (12).

It is not necessary to discuss these compressor results in detail here. Essentially the diagram shows that machines having various numbers of stages and design pressure ratios were made and tested, delivering a range of pressure ratios with their best efficiency levels generally exceeding 85%. The machines are listed, together with manufacturers and when they were tested.

In addition to these, there was the 9-stage Griffith contra-flow unit, (one stage of which is shown in Figure 13, built as previously mentioned by Armstrong-Siddeley). This was tested at RAE in 1940 but didn't achieve high performance.

Griffith himself had been promoted in 1938 to Head of Engine Department, but he left to join Rolls-Royce in early 1939, and all the RAE gas turbine work was then led by Constant. It may well be that Griffith's promotion at RAE in 1938 was an important factor in his decision to leave. He was not keen on administrative duties, much preferring to work on scientific problems alone or with one or two colleagues. Rolls-Royce gave him such an environment, with a very free rein to explore his own ideas. Griffith's activities at Rolls-Royce are outlined later, in Section 8.

As a diagrammatic summary of the early UK work, Figure 19 shows the two parallel timelines – on the left, the axial-flow work starting at RAE, and on the right, Whittle's jet engines using centrifugal compressors. The dotted parts of the timelines are the fallow periods. After these, various events, and phases of activity, are indicated.



Curve	Name	No of stages	Manufacturer	Tested
1	Alice	8	Parsons	1939
2	Anne	8	RAE	1939
3	Ruth	6	Fraser & Chalmers	1940
4	B10 (Betty)	9	Metro Vick	1940
5	E5 (Edith)	8	Metro Vick	1941
6	E5 (Edith)	8	Metro Vick	1941
7	F2 (Freda)	9	Metro Vick	1941
8	D11 (Doris)	17	Metro Vick	1941
9	F2 (Freda)	9	Metro Vick	1942

Figure 18. Early RAE axial compressor results

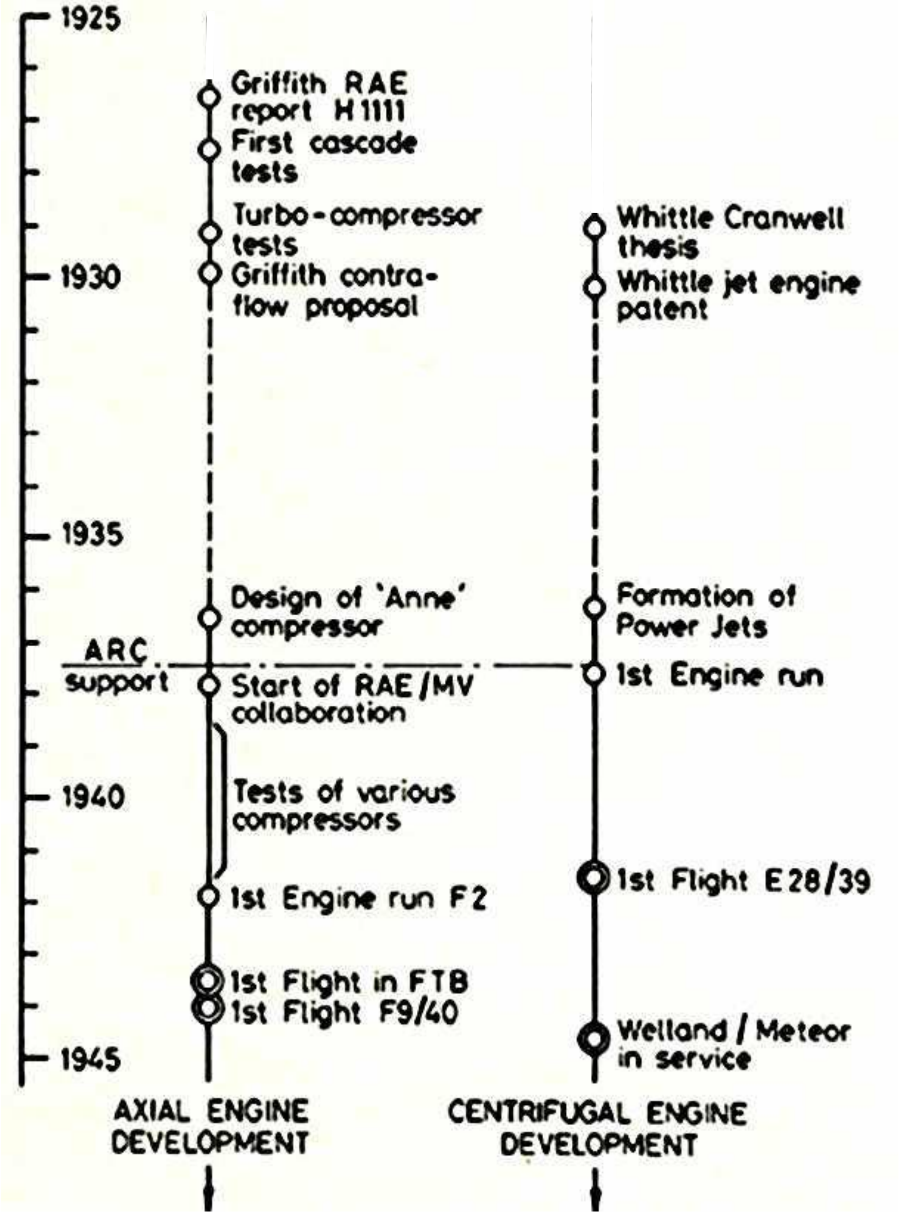


Figure 19 Beginnings of UK aero gas turbines

5. RAE involves industry

Following the ARC recommendation, referred to in Section 4, that the possibility of involving the "turbine builders" be explored, RAE opened discussions with the Metropolitan-Vickers Electrical Company, Manchester, a leading manufacturer of electricity generating equipment including steam turbines. 'Metro-Vicks' (as it was widely known) was an excellent choice – a firm with a very high reputation for innovation in its field, and great strength in its technical staff. The firm placed responsibility for the gas turbine work with a distinguished engineer, Dr D M Smith (Figure 20).

Several RAE schemes for possible large-scale experimental units were examined jointly, and the first to be built was the so-called B 10 scheme, involving a turbo-compressor unit that might become a candidate for the high-pressure turbomachinery of a future compound engine which was envisaged as eventually including two compressor units in series to obtain good fuel economy.

Figure 20 Dr D M Smith

Figure 21 shows the B10 layout, with turbo-compressor and ducting to a combustion chamber mounted to the side. The plant could be 'loaded' by blowing off air from the compressor outlet. The main components were rig-tested individually and then assembled and run as a gas turbine in October 1940. It provided experience that Metro-Vick stated (18) as being *".... of the utmost value for all subsequent gas turbine work"*. An idea of the excitement surrounding the testing can also be gathered from Dr Smith's description that "*the running was most impressive with the turbine at a bright red heat at the high-pressure end and a dull red heat at the low-pressure end*". It must have been an awe-inspiring sight! The B10 compressor, "Betty", still exists and can be seen, along with other Metro-Vick memorabilia, at the Museum of Science and Industry, Manchester.

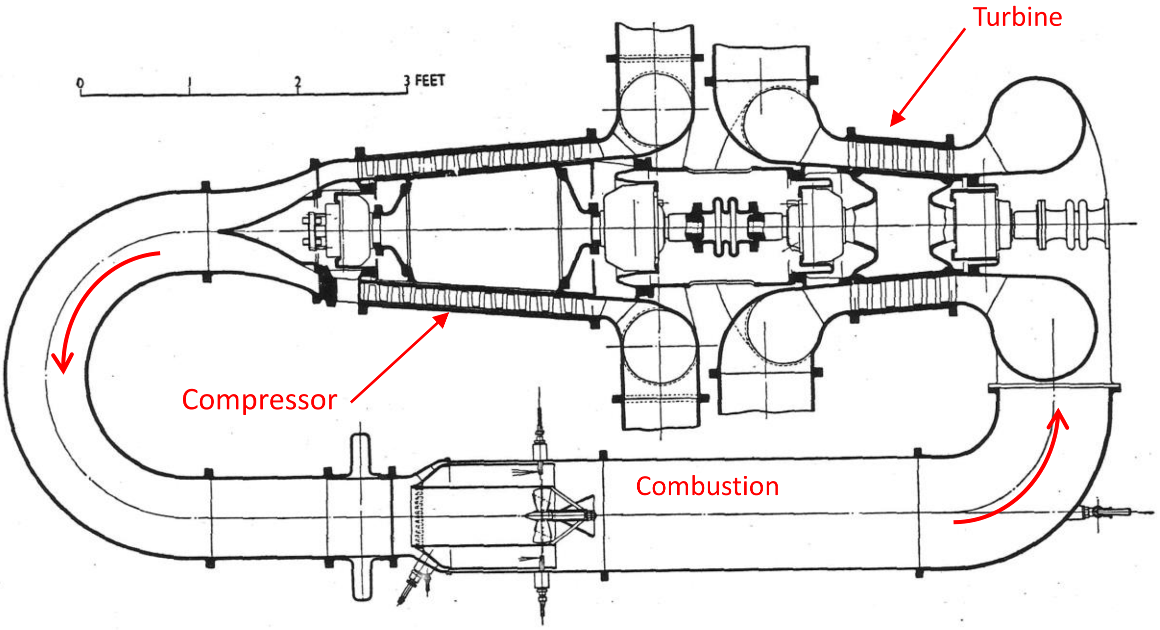


Figure 21 RAE / Metro -Vick B10 turbo-compressor unit

The next system planned to be built at Metro-Vick was a 'straight-through' axial engine with a free power turbine – all on a common axis. In other words, the general configuration of later turbo-prop engines, though it was regarded as an experimental machine rather than a flight prototype. However, after the components had been rig-tested individually, there was a major change of priorities and this project was discontinued.

The change of priority was the decision, in view of the outbreak of war, that RAE would concentrate its effort first on an axial-flow jet engine, which would be less complex and therefore simpler and quicker to develop than a turboprop. Constant, unlike Griffith, got on well with Whittle and had already suggested to Whittle that Power Jets should build a jet engine with an axial compressor for which RAE would provide the design. This was agreed but Power Jets withdrew in mid-1940 due to pressure of other work, so RAE then turned again to Metro-Vicks. Thus began a very fruitful collaboration which led to the first British axial-flow jet engines.

RAE put to Metro-Vick a design for a jet engine with a 9-stage axial compressor, aiming at a pressure ratio of 4 and a thrust of 2,150 lb. With continued studies, the design evolved further and the engine as built had 10 compressor stages and was designated the F2. It first ran in December 1941. Development proceeded, and Figure 22 shows in cross-section the first flight-build standard (18).

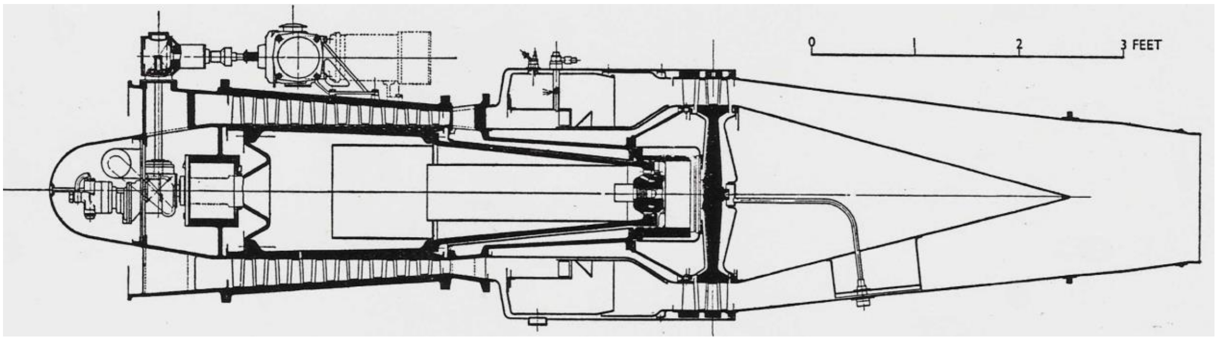


Figure 22 F2 engine – first flight build standard

The F2 engine had a ‘straight-through’ arrangement of compressor, combustion chamber and turbine. The combustion chamber was fully annular – not the ‘cannular’ type used in many early turbine engines. So, its main components were basically of the form used in jet engines today.

The very promising results of F2 testing led to a later, definitive version, designated the F2/4, which had a higher airflow compressor and take-off thrust of 3,500 lb. It was decided that Metro-Vick engines would bear the names of precious stones, and the F2/4 was named the ‘Beryl’. Although not many Beryls were built, one of them had a historic role as the basis for the first ever application of a gas turbine for marine propulsion – in a modified Royal Navy Motor Gunboat, MGB 2009, in 1947 (19) (Figure 23). In its standard form this boat had three conventional petrol engines, each driving a propeller. One of these engines was removed and replaced with a Beryl with a power turbine added, as shown in the cross-section of Figure 24. This exercise produced a very successful demonstration of the potential of the gas turbine for high-performance naval vessels. It was another British marine turbine ‘first’, echoing Parsons’ demonstration with “Turbinia”, just 50 years earlier!

Gas turbines are of course now widely used in warships, most of them being ‘aero-derivative’, i.e. adaptations of established aircraft engines, taking advantage of the development effort devoted to the original aero-engine. As well as powering Royal Navy vessels, UK engines have gained a substantial share of the world market.

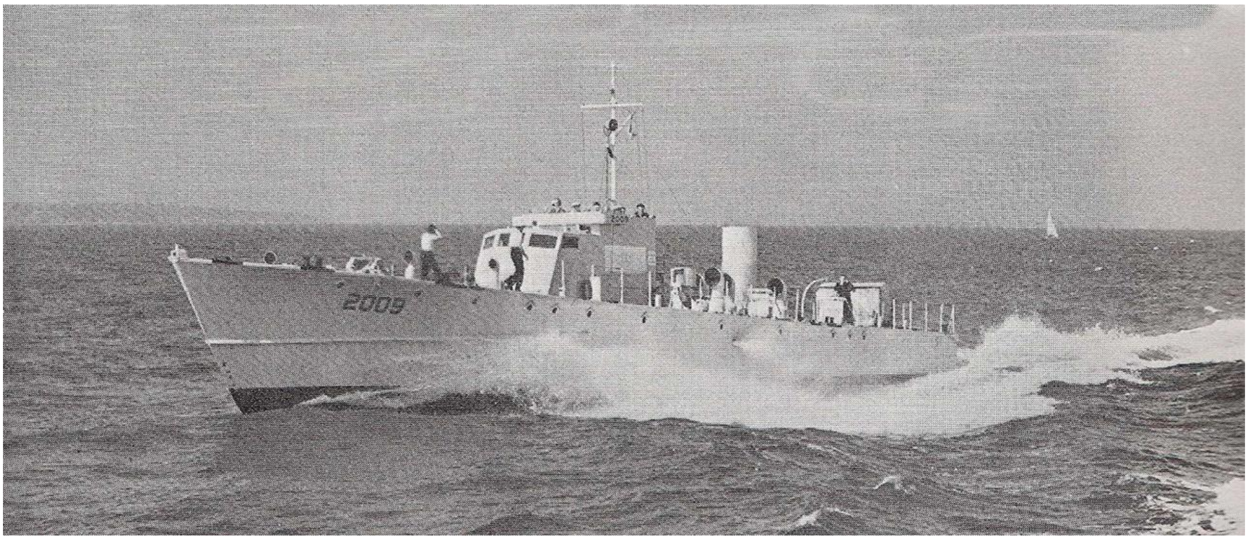


Figure 23 First marine gas turbine, MGB 2009, 1947

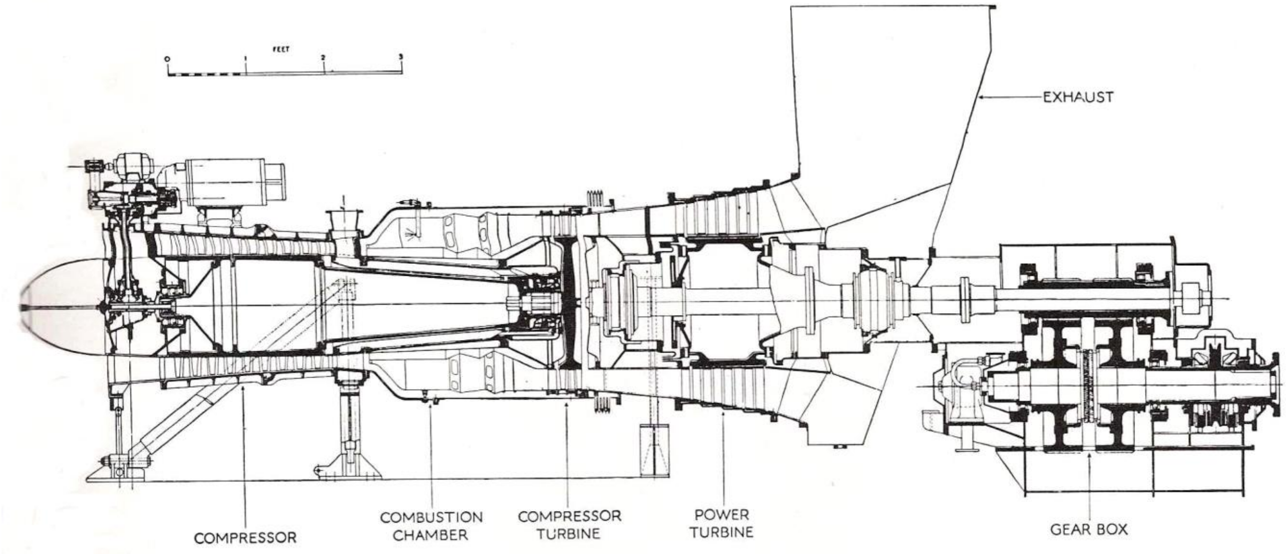


Figure 24 Layout of Metro-Vick G1 engine in MGB 2009

Following some further exploratory engine projects (which included a ‘ducted fan’ thrust augmentor mounted on an F2), the last in the line of Metro-Vick aero-engines that stemmed from the RAE association was a major new design, the F9. During the 1940s the firm had built its own cascade wind-tunnel and other facilities, enabling it to become progressively less dependent on RAE. The F9, designed to an ambitious Ministry requirement for a 7,000 lb thrust engine, was named the ‘Sapphire’ and turned out to be an extremely good machine. It is shown in Figure 25 (19).

The Sapphire compressor had higher pressure ratio than the F2 - about 6.5 in 13 stages (blades mounted on discs, not a drum). A major, and very welcome, feature of the engine was its very good off-design behaviour, allowing rapid accelerations without danger of stalling. The Sapphire

was probably the world's best axial engine of its era, and it is ironic that by the time it first ran, in 1948, Metro-Vicks had arranged to leave the aeronautical field, not being equipped for quantity production to the extent needed for front-line aero-engines. However, the company did continue to work on gas turbines for other purposes, supplying a successful series of engines for British naval use and some exploratory land-based power generation machines, alongside their established business of providing major power generation and electric traction equipment.
The Sapphire was handed over to Armstrong-Siddeley, who continued development, and the Sapphire became the first British jet engine to pass an official Type Test at over 10,000 lb thrust. It served in various British aircraft and its quality is demonstrated by the fact that over 12,000 were built under licence by the Wright Corporation in America for US military aircraft.

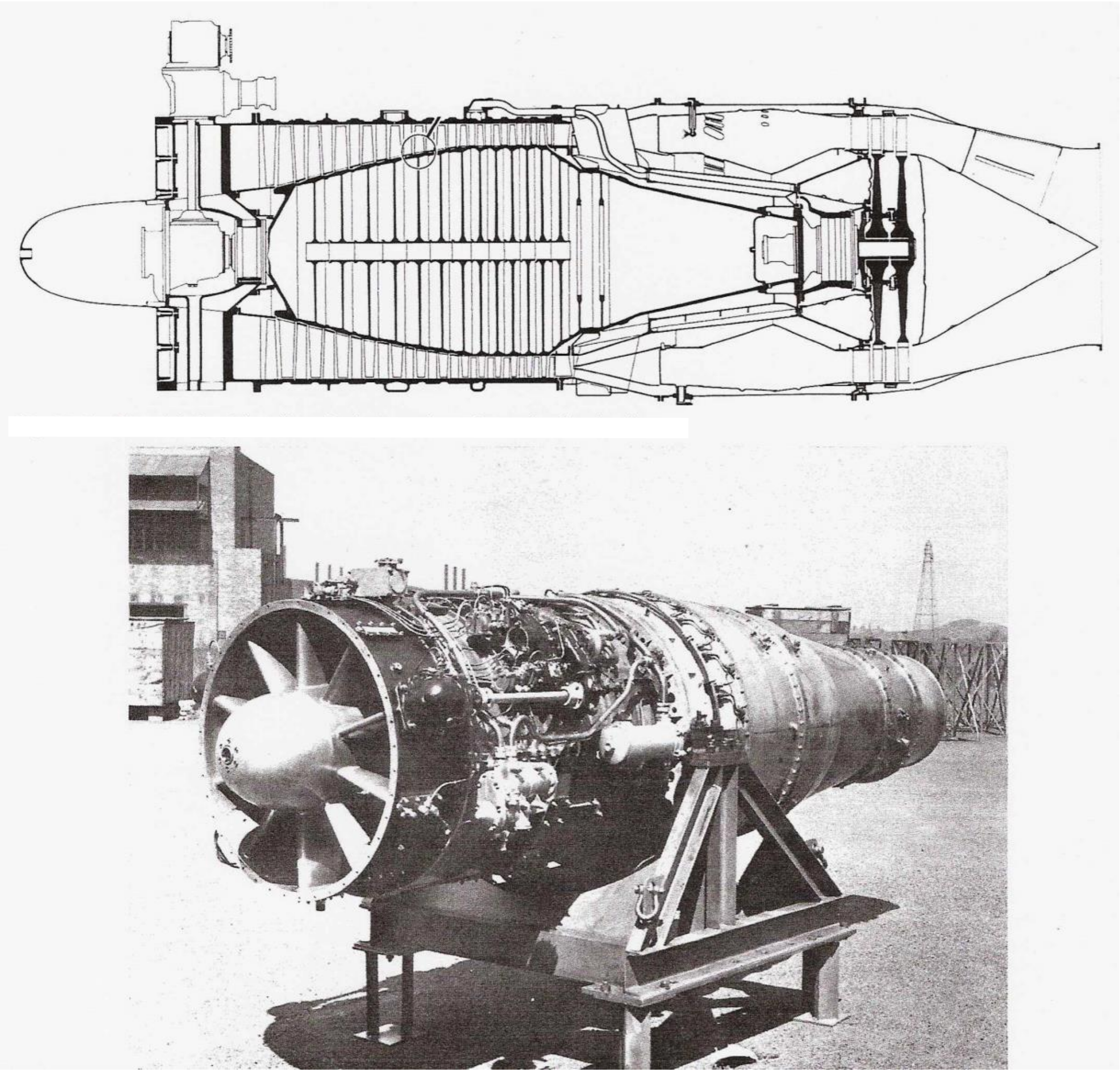


Figure 25 Metro-Vick F9 Sapphire turbojet

By the time the Sapphire arrived at Armstrong-Siddeley, the firm was already well involved in gas turbines. Following their early work for RAE when they manufactured the first Griffith contra-flow compressor / turbine wheel shown in Figure 13, they continued an association with the Establishment and used RAE compressor designs as the basis for axial-flow engines – first the ASX jet, later adapted to be the Python turboprop, used in the Westland Wyvern naval fighter, and then another turboprop, the Mamba. The latter saw very effective service, mainly as a 'twinned' version, the Double Mamba, comprising two Mambas driving separate co-axial propellers through a common gearbox to provide the capability of single or two-engined operation in the widely-used Fairey Gannet anti-submarine patrol and attack aircraft.

5. Development of RAE research

We now turn to the growth of research and assessment within the Turbine Division of Engine Department at RAE. Section 7 will deal with Farnborough's gas turbine flight test work.

The research work under Constant built up steadily after the 1937 go-ahead, with the small team gradually expanding. In addition to axial compressors, the research included work on duct and nozzle flows, turbines, mechanical aspects, materials, engine performance studies and combustion.

Combustion presented serious challenges because to achieve the compactness necessary in an aeroengine, a very high intensity of heat release was needed; furthermore, the combustion system had to operate reliably over a very wide range of flight conditions. Both the RAE and the Whittle teams had plenty of difficulties. Reflecting the good relations between Constant and Whittle, several RAE people, headed by Dr William Hawthorne (later Professor Sir William), were seconded for a year to assist Power Jets on combustion.

Constant, in a lecture in 1957 (20) deployed his humour again when discussing combustion, saying *"My only contribution to gas turbine combustion is confined to a brief period at RAE when I did my first combustion test. I arranged for a flow of air to emerge from a bit of 6-inch piping at a few hundred feet per second. I then contrived a jet of diesel fuel from a small pipe. My fitter threw a piece of burning waste into the jet, thus lighting it. I then poked the burning jet into the 6-inch pipe, and the flame went out. This created a precedent. The object of the past two decades of work at Pyestock has been to improve on this state of affairs"*

And in an internal paper (21) he commented on the issue of how compressor blades should be attached to the rotor; "*By June 1937 we were at the peak of a wave of welding optimism, and a contract was awarded to British Insulated Cables to make electric welding experiments to study the possibility of butt-welding blades to drums. These welding waves apparently occur at regular intervals and may be connected with sunspots".*

As the effort grew, and more experimental facilities became necessary, a new site for the RAE work on gas turbines was established. This was at Pyestock, which was eventually to become the main site of the National Gas Turbine Establishment (NGTE). The Turbine Division set out to become the government's 'back room' for the new kind of aeroengine. In reference 10, Hawthorne records that in the 3 years between 1941 and 1944, the Division produced over 250 reports or technical notes. It also provided the aerodynamic design for the turbine of the de Havilland H1 engine (the Goblin) and the layout of its combustion chambers, and the compressor of the first Armstrong-Siddeley engine. The Division also became responsible for technical assessment of all industry projects tendered to the government. This important specialist advisory role continued throughout the lifetime of NGTE and RAE.

Regarding that crucial and challenging component, the axial compressor, the accumulation of test data from cascade rigs and multi-stage compressors, coupled with scientific analysis, enabled a major advance to be made in establishing aerodynamic design rules. The name of Raymond Howell will always be associated with this achievement.

Howell, shown in Figure 26, had joined RAE directly after graduating from Cambridge in 1938. Under Constant he evolved a practical design framework which was reported first in 1942 (22) and published more widely after the war (23).

The value of this major contribution was generously endorsed later by Gordon Lewis, who eventually became Technical Director at Rolls-Royce. In the late 1940s Lewis (at the age of 22!) had found himself faced at Bristol with the challenge of designing the compressors for the engine that became the famous Olympus, used first for the Vulcan bomber, and in later versions for TSR 2, Concorde, naval ships and electrical power generation.

Figure 26 A R Howell

The Olympus, shown in cross-section in Figure 27, has two compressors in series, each driven by a separate turbine, to achieve the high cycle pressure ratio needed for good fuel economy. In a lecture in the 1990s outlining his career, Lewis described (24) how his compressors had immediately performed very close to the design aim, and said *"In fact, the success was basically due to Howell, and the foundation was laid for decades of steady progress in the field of axial compressors"*.

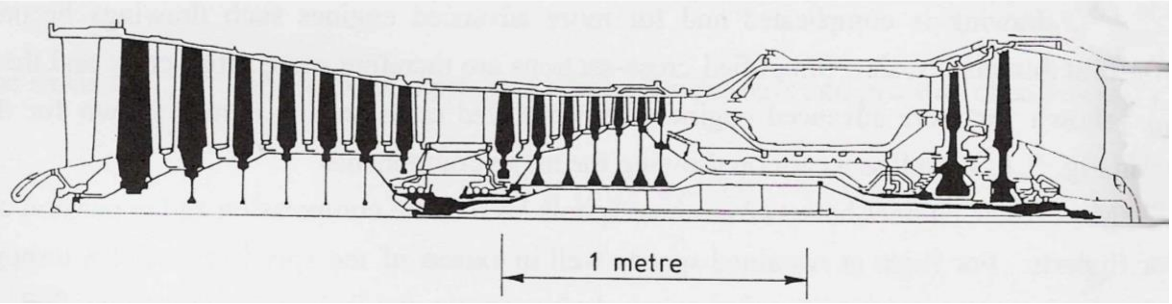


Figure 27 Olympus 593: Concorde engine

Howell subsequently led the NGTE research work on turbomachinery for many years. He was awarded the Royal Aeronautical Society Silver Medal in 1964, and the Wetherill Gold Medal of the Franklin Institute in 1973. His distinguished career was later described in a special paper (25) to an international conference by Dunham.

RAE's compressor work continued strongly. Further research machines were designed and built to explore particular problems and opportunities. An important example was the 109 compressor, aimed at reducing the number of stages necessary to achieve a given pressure ratio, by designing for higher airflow velocities through the machine. It was designed to give a pressure ratio of nearly 5 in 6 stages – about half the number normally required at that time. Here is the 109, which still exists and is in the FAST Museum, Farnborough (Figure 28).

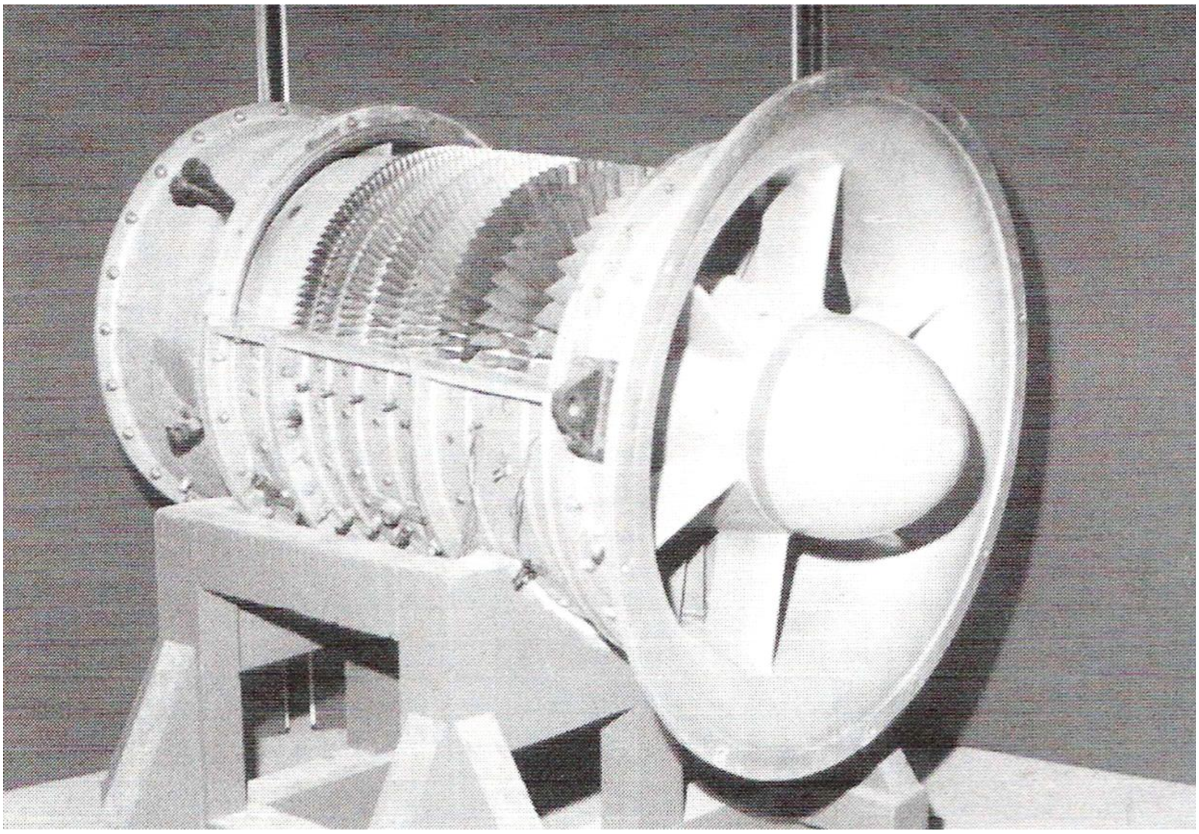


Figure 28 C109 research compressor

This machine produced its high design performance and was a milestone in compressor achievement. Figure 29 illustrates how its stage temperature rise (which is a measure of pressure ratio) stood out above the general trend, as a pointer to future potential. The 109 research compressor went through a number of rebuilds with different blading designs and numbers of stages. In a modified form, it was later adopted by de Havilland as the basis for their Gyron and Gyron Junior jet engines.

The general aim of raising the amount of work done in each stage, while keeping efficiency high, has been a central objective of turbomachinery R&D through the years, and still remains so. Two RAeS papers by Dunham (26, 27) summarise respectively the history of NGTE's aerodynamics research on compressors and turbines.

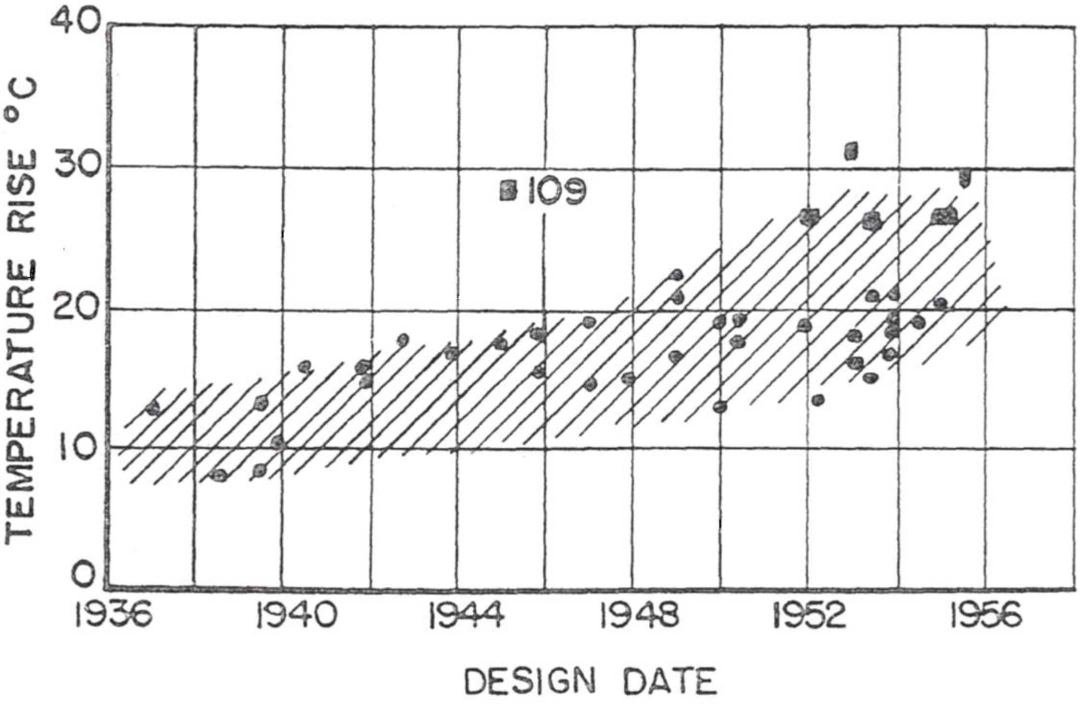


Figure 29 Axial compressors: work per stage

7. Early Jet Flight Testing at Farnborough

Now to the flight work at RAE. One of the great strengths of the Establishment was the way laboratory research could readily be paralleled by test flying. Jet propulsion was no exception to this, and its hazards are illustrated by the fact that two experimental aircraft, and a test pilot, were lost in the process.

The first flight test of a gas turbine aircraft at RAE was late in 1942, by the first of the two Gloster E28/39 aircraft that had been designed for flight testing of the early Whittle engines. Figure 30 shows an E28/39.

A more extensive series of flight tests were made on the second E28/39 fitted with a higher thrust engine, starting in May 1943, to measure performance over the whole flight envelope. Unfortunately this aircraft was lost on 30th July due to irreversible jamming of the aileron controls at an altitude of about 37,000 ft – a problem unrelated to the engine. The pilot, Sqn Ldr Davie, baled out and successfully made the longest deliberate free-fall recorded to that date before opening his parachute. A further programme of flight tests at Farnborough using the first E28/39 took place in 1944.

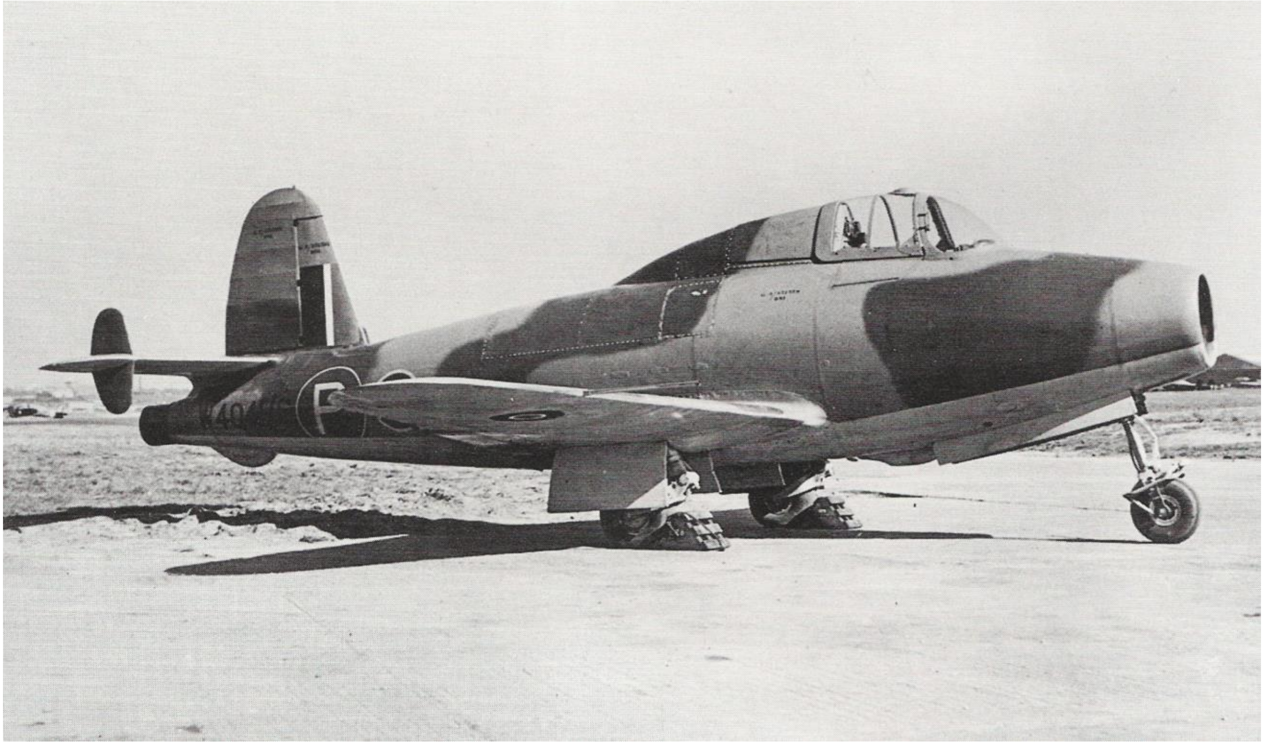


Figure 30 Gloster E28/39, Whittle engine

By the beginning of 1944, four different turbine-driven aircraft were being tested (11) at the Establishment, plus a Lancaster flying test bed with a Metro-Vick F2 engine mounted in the tail, shown in Figure 31. A similar modified Lancaster aircraft was used for flight testing an Armstrong-Siddeley ASX engine.

Figure 31 Metro-Vick F2 installation in Lancaster flying test bed

The four aircraft entirely powered by turbines were the first Gloster E28/39; two early versions of the Gloster F9/40, which later became the Meteor fighter; and an American Bell XP-59A Airacomet, powered by two General Electric Whittle-type engines. The latter, shown in Figure 32, came to

RAE for test as part of the inter-government agreement in 1941 whereby an early Whittle engine was sent to the USA to form a basis for initiating American jet engine development.

Figure 32 Bell XP-59A, two Whittle/GE engines

Of the two Gloster F9/40s, basically intended for Whittle engines, one was modified to mount Metro-Vick F2 engines. It had first flown on 13 November 1943, and this was the first flight in this country of a jet aircraft powered with axial-flow engines. Because of their slimness, the F2s could be neatly mounted under the wings (Figure 33).

In contrast, the larger-diameter centrifugal engines had to be mounted behind the main wing spar, with the incoming air divided to flow above and below the spar. The Whittle engines were not initially ready, so the other F9/40 was fitted with de Havilland H1 centrifugal engines (this engine was later produced in large numbers as the Goblin, used in the de Havilland Vampire fighter). This is shown in Figure 34.

The importance and urgency attached to the jet flying programme at RAE is illustrated by the fact that on Christmas Day 1943, four test flights from Farnborough were carried out on the aircraft with the Metro-Vick engines (28). Tragically, however, disaster struck soon afterwards. On the second flight of the day on 4 January 1944, during a climb to high altitude, the compressor drum of one of the F2 engines burst and caused the aircraft to break up. Sqn Ldr Davie, who had survived the accident to the E28/39 a few months earlier, was fatally injured when he was struck by part of the aircraft's tail after baling out. He was the first man in this country to lose his life in a jet aircraft accident.

Figure 33 Gloster F9/40 with F2 engines

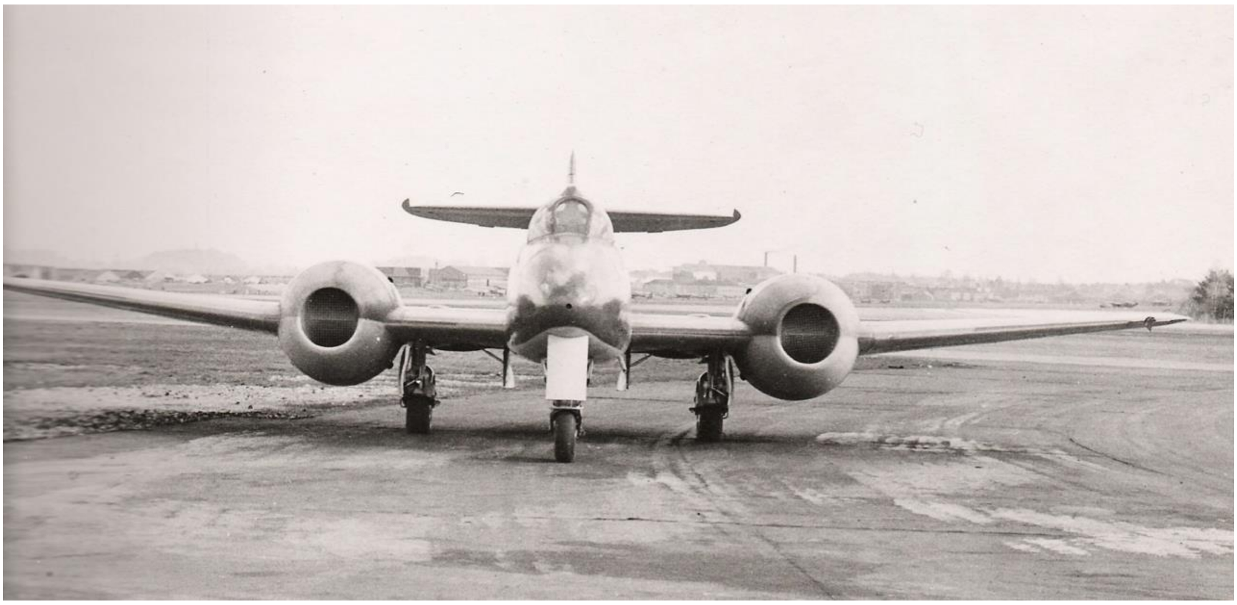


Figure 34 Gloster F9/40 with de Havilland H1 engines

The engine failure was traced to a metallurgical defect in the forged compressor drum. Despite this setback, work on the F2 engine development progressed strongly. As mentioned in Section 5, the definitive version of the engine was the F2/4, named ‘Beryl’. Beryl engines later powered a remarkable project – a jet-propelled flying boat fighter, the Saunders-Roe SR.A/1, designed with possible application in the Pacific war with Japan in mind (Figure 35).

This had two Beryl engines, which were readily accommodated side-by-side in the fuselage because of their small diameter. Flying began in 1947, and there were three prototypes. The aircraft was not ordered into production, but some might remember spectacular displays by this unusual machine at Farnborough Air Shows. The surviving example is on show, with one of its engines, at the Solent Sky Museum, Southampton.

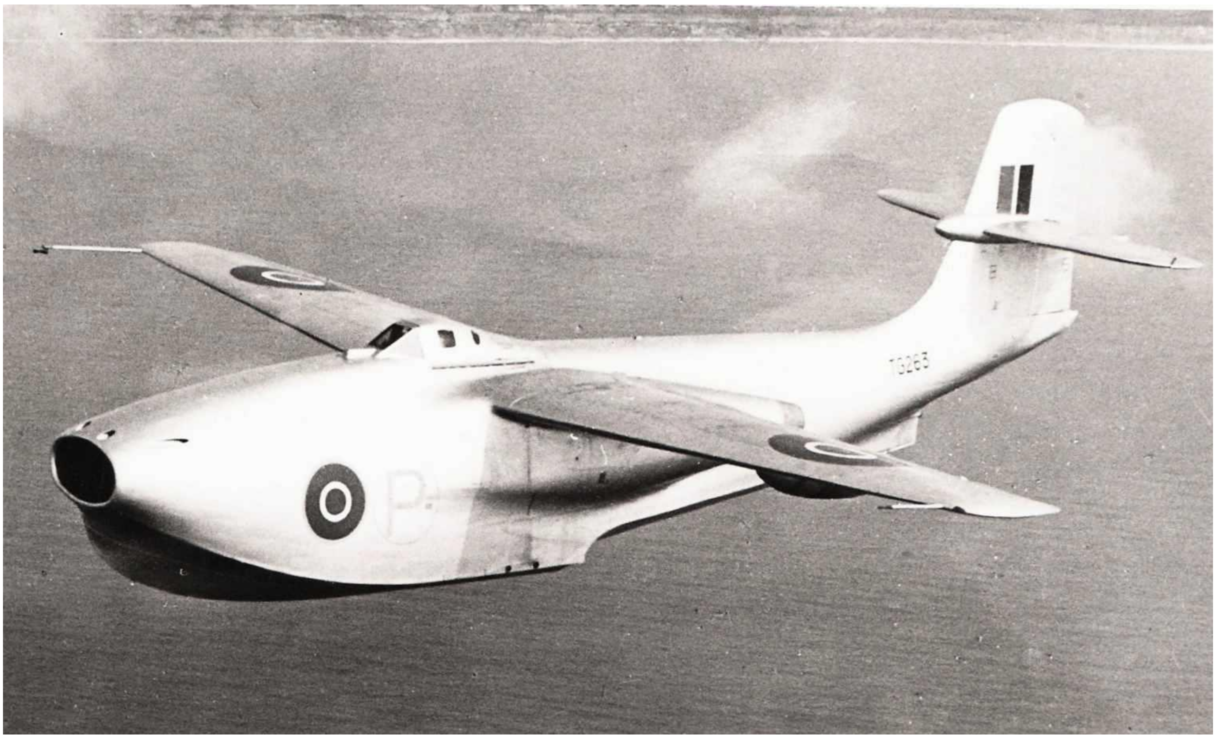


Figure 35 Saro SR.A/1, two Metro-Vick Beryl engines

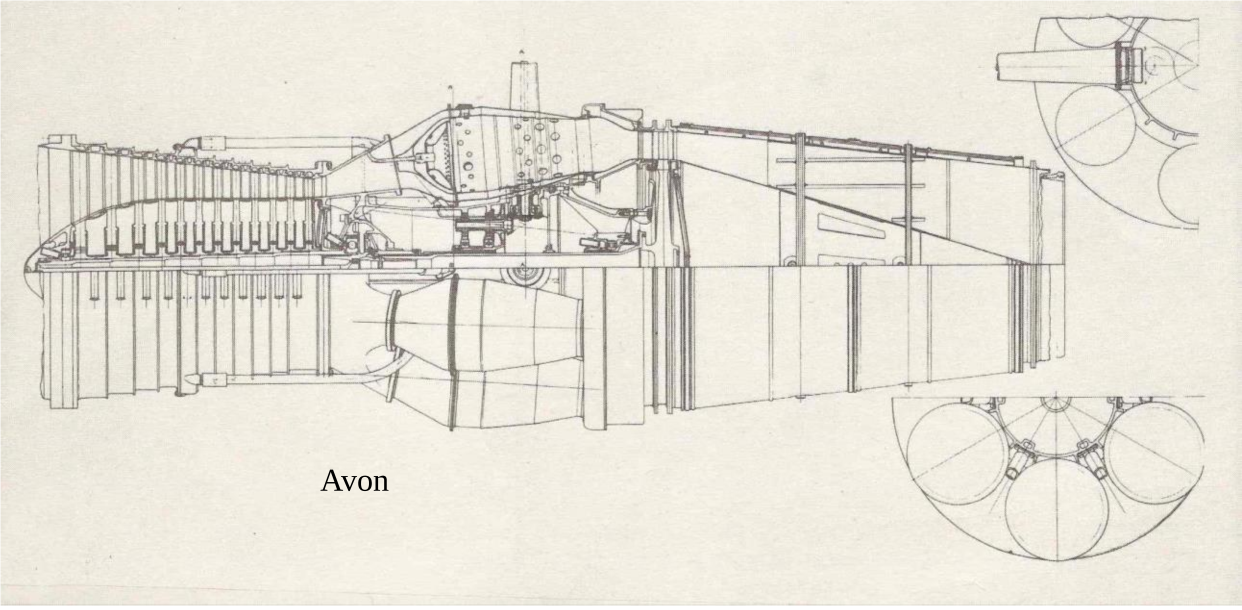
Beryl engines from the batch built for the SR.A/1 were later used by Donald Campbell for some of his world water speed record boats.

8. Griffith at Rolls-Royce

We now look briefly at Griffith's activities following his move from RAE to Rolls-Royce. As mentioned earlier, he was given a great deal of freedom. At first he devoted himself to further studies of his contra-flow schemes, and persuaded Rolls-Royce to build a contra-flow machine of the kind shown in Figure 12. Unfortunately it proved difficult to start, and test running showed that a very great deal of development would be needed to approach the design performance. Work was continued for a while, but eventually the success being achieved elsewhere with axial-flow compressors of conventional layout caused it to be abandoned.

Although Griffith had stuck to his contra-flow concept until about 1944, reviews within RR led to a change of approach. In mid-1945 he produced a proposal that was to lead to the first Rolls-Royce axial-flow jet engine - the Avon. In 1946 he came forward with a scheme for a larger and more sophisticated jet engine incorporating the 'bypass' principle whereby, after passing through the early compressor stages, a portion of the air entering the engine was bypassed around the high-pressure central 'core', re-joining the core flow downstream of the turbine to produce a propulsive jet of lower velocity but higher total flow than in the simple type of engine – thus improving fuel economy by reducing the wastage of kinetic energy in the jet exhaust. This is the principle that has since been exploited increasingly and now forms the predominant feature of today's 'high bypass ratio turbofan' engines.

Figure 36 shows these two schemes. The quality of this picture is not very good, but it has the merit, from the viewpoint of a historical paper, of having been reproduced from the original drawings made in Griffith's office. The details were of course modified as the designs were refined, but the form of the final engines is recognisable.


Avon

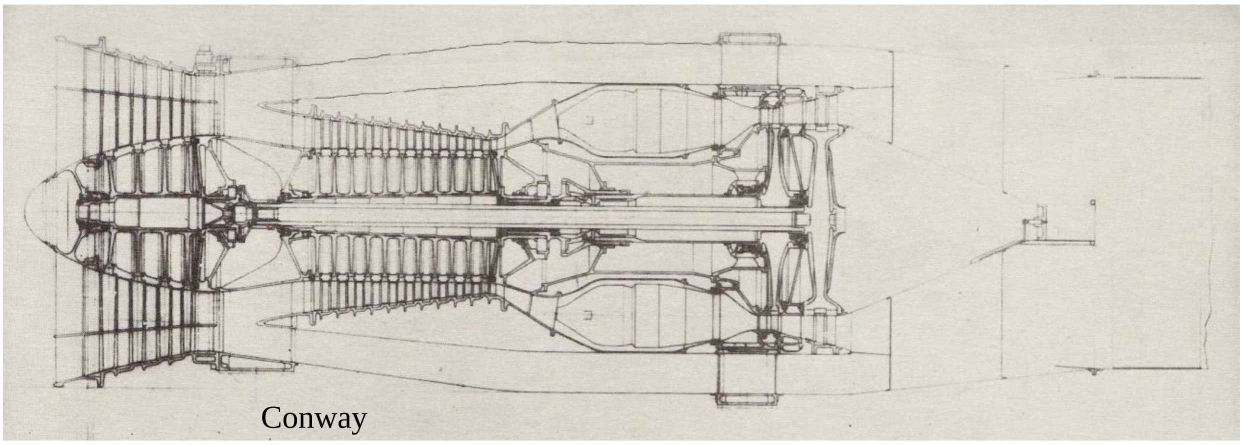

Conway

Figure 36 Early schemes for Avon and Conway

The Avon had a 12-stage compressor, with a number of tubular combustion chambers around the annulus – the so-called 'cannular' configuration The Avon was very widely used, and developed through many versions – but early on it gave its development engineers many headaches due to problems with its compressor. A significant step forward in this respect was the redesign of the front stages, in the early 1950s, to use blading more similar to the Sapphire design. The larger Conway was also developed through several versions and was used in large 'V bomber' aircraft and some airliners.

9. The undesired amalgamation

The story of Farnborough's part in the beginnings of gas turbine propulsion cannot be complete without mention of the controversial government decision in spring 1944 to combine the two UK mainsprings of such work into a single organisation that would conduct research and development, while the production of engines for service would be the province of the established aeroengine industry. Thus the Turbine Division was taken out of the RAE and combined with Whittle's Power Jets Ltd. to form a new nationalised company, Power Jets (R & D) Ltd. This move was not welcomed by any of the principal players.

Over many months previously Whittle, concerned about the future status of Power Jets Ltd, had pursued negotiations with the Ministry of Aircraft Production. He had advocated nationalisation of the whole UK aero-engine industry (10) to exploit the new form of aircraft propulsion – not the nationalisation of Power Jets alone. Furthermore, he was totally opposed to limiting the new joint company to research and development. He, and his team, wanted to design and manufacture engines, and had aspired to an industry leadership status in the coming gas turbine era.

At RAE, both Constant and Hawthorne felt (11) that the aspirations of Whittle's team towards engine design and production would not be entirely compatible with the ethos of the Turbine Division which, like that of the RAE as a whole, was to conduct scientific investigations, to give advice to industry and government, and to provide technical data for use by industry in designing its products. This view was shared by Sir William Farren, Director of RAE.

The new, combined company came into being in late April 1944. Soon, however, it became clear that its activities would actually be more limited than envisaged in the directive (29) from the Minister of Aircraft Production, which included the wording "design, construct and develop prototype engines .." and "manufacture small batches of such engines so as to carry development up to the production stage ...". Strong objections were raised by some established industry firms, to the effect that such development to the engine prototype stage would constitute an unacceptable degree of competition from a state-owned company. Given this situation, the new company's operations had to be limited to research and associated activities, which further accentuated the frustration felt by the Whittle team. A particular example of this was the impact on their advanced engine project launched as a step towards future, more economical, longer range jet flight. This engine (30), known as the 'LR1', embodied both the bypass configuration and a higher compressor pressure ratio. Work on this project had to be abandoned when construction of a prototype was already well in progress.

Power Jets (R&D) operated under some strain through 1945, but early in 1946 Whittle, closely followed by many of his key staff, resigned. Most of them did not join the aeroengine industry, though some became involved in exploiting the gas turbine for non-aeronautical purposes.

In spring 1946 the organisation was re-constituted within the Civil Service as the National Gas Turbine Establishment (NGTE), a sister establishment to RAE under the Ministry of Aircraft Production. Although the role of NGTE regarding the gas turbine then became similar to that of RAE regarding aircraft, an additional responsibility laid upon NGTE was to study and advise government and industry on the exploitation of the gas turbine more widely than in aeronautics alone. This far-sighted extra remit paved the way for later significant contributions by the establishment to naval and land-based applications. NGTE operated as a separate establishment until again becoming part of RAE in 1983.

10. Outcomes

Overall then, what were the fruits of all these gas turbine beginnings? Jet engines did not play any major part in World War II. They saw some use, but not soon enough or in large enough numbers to affect matters critically. The great impact of gas turbines came later, as a revolution in aircraft propulsion – first for military and then for civil purposes. That story is well-known and does not need rehearsing here.

The main conclusion, I think, that we can draw from the part of history outlined in this paper is that the efforts of all those involved placed this country in a very strong position to exploit the hard-won new technology, after World War II. The two thrusts of R&D activity, springing from RAE and Whittle, operated in largely complementary ways. The effect of Power Jets' highly focussed effort was to enable rapid UK exploitation of the first generation turbojet engines of centrifugal type. RAE, concentrating on axial-flow technology, was laying essential foundations for the subsequent far-reaching exploitation of gas turbine propulsion. If either had been absent, the UK would have been much less well-placed for the post-war race into the gas turbine era.

Collaboration was also important in bringing about this robust position. As industrial companies began to engage with the new challenges and opportunities posed by the gas turbine, an imaginative arrangement was set up to stimulate collaboration and information exchange across the industry on technical issues of common interest. This was the Gas Turbine Collaboration Committee (GTCC), formed in late 1941 with a membership of leading personnel from industry, RAE, Power Jets and appropriate government officials. Its first chairman was the MAP director responsible for administration of gas turbine work, Dr Roxbee Cox, who in 1946 was appointed the first Director of NGTE and later became Lord Kings Norton. Although initially there were some doubts about the degree of information exchange that would be practicable among competing industry firms, confidence grew with experience and the GTCC became a well-used forum for detailed technical discussion of many topics of general concern, such as bearing design, blade and disc vibration, temperature-resistant materials, testing techniques and numerous other matters. Its effectiveness in assisting the adaptation of the industry to the new and radically different kind of aero-engine was widely recognised and publicly commented upon following the war, including by senior American officials (31), and the GTCC remained a valued feature of the UK gas turbine scene for over twenty years.

A great deal has happened since the events recounted in this paper. The ideas and possibilities that inspired the pioneers have been fully exploited. Gas turbine powerplants are now used in a variety of forms to suit the wide range of modern propulsion requirements. The engine industry, like the rest of aerospace, has consolidated and at the same time grown more international. There are few major UK areas of industry that are today in the global top rank. Gas turbine aeroengine design and manufacture is. Long may this continue.

REFERENCES

1. Head, J Comments during discussion of a paper by C A, Parsons *Description of the Compound Steam Turbine and Turbo-Electric Generator* Proc Inst of Mechanical Engineers, 1888, Vol 39, p 509-511

2. Stern, W J The internal combustion turbine. Technical Report of Advisory Committee for Aeronautics 1920-21, Vol 2, p 690 (Engine Sub-Committee Report No 54, September 1920) Note: ACA became Aeronautical Research Committee

3 Griffith, A A and Taylor, G I The use of soap films in solving torsion problems. Proc Inst of Mechanical Engineers 1917, Vol 93, p 755

4. Griffith, A A The phenomena of rupture and flow in solids Phil Trans Roy Soc A221, p 163

5. Griffith, A A An aerodynamic theory of turbine design RAE Report H1111, 7 July 1926 (unpublished)

6. Constant, H The early history of the axial type of gas turbine engine. Proc Inst of Mechanical Engineers. WEP 1945, Vol 153, p 411

7. Clothier, W C Test of aerofoil section turbine blading. RAE Report E2868, December 1929 (unpublished)

8. Griffith, A A The present position of the internal combustion turbine as a powerplant for aircraft. Air Ministry Laboratory Report 1050A, November 1929 (unpublished)

9. Starr, F A Commentary by Dr F Starr on *Future developments in aircraft design* A Thesis by Officer Cadet Frank Whittle, Cranwell 1928, Journal of Aeronautical History Vol 9, pp 1-89, 2019

10. Whittle, Sir Frank Jet – the story of a pioneer Frederick Mueller Ltd, London, 1953

11. Hawthorne, Sir William Aircraft propulsion from the back room Aeronautical Journal, Royal Aeronautical Soc., Vol 82, March 1978, p 93

12. Hawthorne, Sir William The early history of the aircraft gas turbine in Britain. Notes Rec Roy Soc London, 1991, Vol 45, p 79

13. Gandy, R W (former Secretary of the ARC) Personal discussion, 1976 (unpublished)

14. Gardner, G W H Automatic Flight – the British Story Journal of Royal Aeronautical Soc., July 1958, Vol 62, p 476-496

15. Collins, A G (formerly Rolls-Royce Ltd) Personal communication, April 2013 (unpublished)

16. Whittle, F The early history of the Whittle jet propulsion gas turbine. Proc Inst of Mechanical Engineers, WEP 1945, Vol 152, p 419

17. Constant, H The internal combustion turbine as a powerplant for aircraft. RAE Note E3546, March 1937 (unpublished)

18. Smith, D M The development of an axial flow gas turbine for jet propulsion. Proc Inst of Mechanical Engineers 1947, Vol 157, p 471

19. Whyte, R R Engineering Progress Through Development Mechanical Engineering Publications Ltd (I Mech E), London, 1978, p 8 et seq

20. Constant, H Pyestock's contribution to propulsion Journal of Royal Aeronautical Soc., 1958, Vol 62, p 257

21. Constant, H Influence of the RAE on the Early History of the Gas Turbine Internal RAE Engine Dept Paper, Eng/2038.R/HC/21, Sept 1942 (unpublished)

22. Howell, A R The present basis of axial flow compressor design: Part I – cascade theory and performance ARC R&M No 2095, 1942

23. Howell, A R (a) Design of axial compressors; (b) Fluid dynamics of axial compressors. Proc Inst of Mechanical Engineers, WEP 1945, Vol 153, p 441

24. Lewis, G M 50 years of gas turbine engineering. The International Society for Air Breathing Engines (ISABE) conference, 1995

25. Dunham, J A R Howell – Father of the British Axial Compressor Paper No 2000-GT-0008, ASME Turbo Expo 2000, Munich, May 2000

26. Dunham, J 50 Years of Turbomachinery Research at Pyestock – Part 1: Compressors Aeronautical Journal, Royal Aeronautical Soc., March 2000, Vol 104

27. Dunham, J 50 Years of Turbomachinery Research at Pyestock – Part 2: Turbines Aeronautical Journal, Royal Aeronautical Soc, April 2000, Vol 104

28. Dennis, R Farnborough's Jets Footmark Publications, Fleet, Hants. 1999

29. Notes on the Organisation, Duties and Facilities of Power Jets (Research and Development) Ltd, with Two Appendices Prepared for the DSIR Advisory Council Committee on Mechanical Engineering, April 1944

30. Feilden, G B R The Contributions of Power Jets Ltd to Jet Propulsion Aeronautical Journal, Royal Aeronautical Soc., Feb 1993, Vol 97

31. Roxbee Cox, H British Aircraft Gas Turbines Ninth Wright Brothers Lecture, and published discussion Journal of the Aeronautical Sciences, Vol 13, February 1946

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Tyne & Wear Museums	Figs 2 and 3
Pratt & Whitney, via ‘Development of Jet and Turbine Aero engines’, by W Gunston, 4th Edn., PSL 2006	Fig 4
Institution of Mechanical Engineers	Figs 5, 6 ,23, 24, 25, 33
Rolls-Royce plc	Figs 12, 27, 36
Royal Aeronautical Society	Figs 8, 28, 29, 34, 35
Royal Aircraft Establishment / Farnborough Air Sciences Trust (FAST)	Figs 9, 10, 11, 13, 15, 17, 18, 19, 30, 31, 32,
Personal photograph; Mrs D Howell	Fig 26

The author

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