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Reverse thrust: American aerospace dominance and the British challenge in jet engines, 1941–58

At the end of the Second World War the United States dominated civil aircraft production and was at least five years ahead of Britain, the only other nation at the time with the capacity to manufacture commercial airliners. The British were aware of their deficiency and were determined to catch up. Government policy aimed to foster a new generation of British civil aircraft in order to provide continued employment in the aircraft industry and save the state-owned airlines (BOAC, BEA and BSAA) from spending precious funds on US types. There was also a view, widely held in government and in the civil service, that Britain needed a major civil-aircraft industry in order to maintain the prestige and technological prowess befitting a great power. The problem was how to go about it. Should Britain simply copy the best airliners coming out of the United States, staying abreast with, but not getting ahead of, proven technology? Or should it attempt to leapfrog the Americans by exploiting its lead in jet engines? It chose the latter path and made the jet engine 'the basis for a bold but flawed challenge' to American postwar domination.[1] Thus turbo-prop and pure jet engines were fitted to conventionally-designed aircraft such as the Vickers Viscount and the de Havilland Comet 1, the world's first jet-propelled passenger aircraft. Then, in 1954, the Comets began crashing and the risks of the leapfrog strategy became painfully clear.

This paper considers the background to the Comet's development in the 1940s and the policies which led Britain to seek economic revival on the basis of the narrow technological advantage represented by leadership in jet engines. It also spotlights the Comet itself, both as a symbol of the new Elizabethan age of the 1950s and as a key artefact of Britain's much-vaunted jet engine programme.

The European jet, 1935–45

The jet engine, as one of the leading researchers in the field has pointed out, is a striking example of the commercialisation of military technology.[2] Like a number of other innovations which changed the lives of ordinary people in the twentieth century, it was born out of the Second World War.[3] However, it was in the 1930s that the principles of its operation were first studied and understood. Until that time no-one conceived of an aircraft power plant as being anything other than a sophisticated internal combustion engine, a technology borrowed from automobile engineering. The two figures credited with first seeing the potential of jets are the Englishman Frank Whittle and the German Hans von Ohain.[4] Whittle's patent for a turbojet engine was registered in 1930, so there is some basis for seeing him as the father of the jet. However, because there was a six-year delay before Whittle's ideas gained acceptance, the Englishman was overtaken by Ohain, who had begun a fruitful collaboration with the Heinkel aircraft company and who ran a static test of his first engine in 1935. From this time onwards, the endeavours of Whittle and Ohain proceeded neck-and-neck, although they worked independently in Britain and Germany and were unaware of the other's progress. In 1937 Whittle ran the first test of his engine, the W1, but two years later Ohain's He-S8B engine powered the world's first jet-propelled flight in the Heinkel He-178 aircraft. Whittle had to wait until 1941 until his W1 engine powered the first British jet aircraft, the Gloster E28/39 (Figure 1), by which stage another Heinkel, the He-280, was flying with two Ohain He-S8A jet engines.[5] By 1944 both the British and the Germans had jet-propelled fighters in operational use: the Gloster Meteor, with a developed version of the Whittle jet, known as the Rolls-Royce Derwent, and the Messerschmitt Me-262, with Junkers Jumo 004 jets.

Figure 1 Gloster E28/39, the first British jet aircraft. (Deutsches Museum)

By the end of the war the Germans had at least three separate full-scale company-based jet engine programmes in progress, as American and British interrogators discovered to their astonishment in the summer of 1945. Ohain's original test engine, the He-S3B, had been built for simplicity with a centrifugal compressor like Whittle's, but Heinkel had then proceeded to more advanced designs like the He-S30 with axial-flow compressors. Meanwhile at Junkers, Germany's leading engine maker, Anselm Franz had led the development of the Jumo 004, a simpler axial-flow turbojet, which went into mass production and powered the Me-262 fighter. A third programme at BMW produced the Bramo 003 engine, which featured a counter-rotating compressor, different from both the Jumo 004 and the Heinkel He-S30. Ultimately it was this Heinkel design, incorporating both rotors *and* stators, which became the standard configuration for commercial jet engines.[6]

On this evidence it is clear that the Germans were decisively ahead in the field by the spring of 1945. And this feat is all the more extraordinary when one considers that they lacked vital raw materials with which to make heat-resistant turbine blades, such as nickel, cobalt and manganese, and that their work was continually disrupted by the Allied bombing campaign.[7] By contrast the British were proceeding on a narrower front, with Whittle's relatively primitive design remaining the main empirical reference point for British engine manufacturers. As in Germany, all the main manufacturers had begun jet programmes, but without the same conceptual range and variety as their opponents. De Havilland, for example, announced the successful trial of its Vampire jet fighter in 1945, powered by the company's own Goblin engine, which used a centrifugal compressor, like the Rolls-Royce Derwent. Frank Whittle himself was to leave the industry, a somewhat disillusioned man, in 1948, while his company, Power Jets Ltd, was nationalised and reduced to the status of a research establishment. The business of mass-producing his creation shifted to the private engine firms, who by the end of the war were beginning to consider peace-time applications for the new technology. Rolls-Royce, the leading company, decided that it would switch entirely from piston engines to turbine-driven power plants and had initiated its own research programme, advancing somewhat beyond the hitherto sacrosanct Whittle design as early as 1944 with the Nene engine.[8]

There is not much doubt that had Germany not been defeated it would have led the world in jet engine development in both the military and civil sectors. As it was, the Allies not only enjoyed a windfall at the end of the war, with both German engines and German engineers falling into their hands, but they also had the satisfaction of seeing the race leader stopped dead in its tracks: German aero-engine production was halted and did not resume to any significant degree before the 1960s. The British were now in front, but for how long? And where had the Americans been?

The American aero-engine industry, 1930–45

The American aircraft industry in the 1930s had been innovative and successful. Civil airframe builders like Douglas, Lockheed and Boeing had produced a new generation of transport aircraft with all-metal, stressed-skin construction and retractable undercarriages. These aircraft were powered by air-cooled, radial piston engines manufactured either by the Wright Aeronautical Company or its rival Pratt & Whitney. Neither company had any inkling of the work being carried out in Europe on the jet engine, or of its potential. Radial piston engines were the bedrock of their commercial success: they were strong and dependable, gave good economic performance to the new airlines springing up in America and were the principal source of the companies' profits.[9]

The fact that American engine manufacturers carried out no work on jet engines before the war is not surprising: British and German companies (with the notable exception of Heinkel) did not do so either. What is more striking is that there was no activity among the scientific communities in universities and government-sponsored research establishments. Why, for instance, did America produce no Ohain or Whittle? The answer may lie with the fact that those American research establishments that did work on aeronautical science tended to confine their activities to solving problems already encountered by the engine companies with *existing* technology.[10] And as for the companies themselves, the high degree of competition between them meant that *fundamental* research was not carried out or was carried out by each company separately, entailing a great duplication of effort.[11]

While jets may have been ignored by the Americans in the 1930s, there was important work being done in the United States on turbines and turbine-driven power plants, for example by Eastman Jacobs at the National Advisory Committee on Aeronautics (NACA). More significantly, knowledge on turbines was acquired from work on piston engine superchargers. Superchargers had been around since the First World War and were especially applicable to aircraft engines because they substantially increased the intake of air at high altitudes. Their power was drawn from a turbine driven by the engine's exhaust gas and applied through gearing to the crankshaft. The technology of supercharger turbines progressed steadily during the interwar years in the United States and a whole range of new nickel alloys were created to build temperature-resistant fan blades: the same technology, with similar theoretical problems, which was required to build jet engine turbines on the other side of the Atlantic. Moreover, the technology was pushed forward not only by the aero-engine builders – Wright and

Pratt & Whitney – but also by companies that previously had been associated with large stationary turbines for power generation. It was Sanford Moss's work with General Electric (GE) which produced the Moss turbocharger, a device that turned the B-17 bomber from an aircraft approaching obsolescence at the time of Pearl Harbor into one of the most effective offensive weapons of the Second World War.

Thus the intellectual climate in the United States at the beginning of the Second World War can be summarised as being *scientifically* conducive towards jet engine development, but *commercially* very much less so. The traditional engine makers were complacent, although they possessed crucial technical know-how from their work with superchargers, and official opinion was doubtful. In 1940, for example, the American Committee of the National Academy of Sciences stated in a report that: 'In its present state, and even considering the improvements possible in adopting the higher temperatures proposed for the immediate future, the gas turbine could hardly be considered a feasible application to airplanes, mainly because of the difficulty in complying with the stringent weight requirements imposed by aeronautics.'[12]

Into this environment was introduced the catalyst of war, which, as so often happens with major technological breakthroughs, accelerated the pace of research and converted sceptical minds. In 1940 news of Whittle's jet was brought to the United States by Sir Henry Tizard, the head of the British Air Ministry's Aeronautical Research Department.[13] Then in March 1941 General 'Hap' Arnold of the US Army Air Corps visited England and learnt of the Whittle engine's forthcoming test in the Gloster E28/39. Arnold was an immediate convert and saw the British engine as the seed corn for a whole new field in the American aeronautical industry. Within months a disassembled Whittle engine was crossing the Atlantic, under a veil of military secrecy, and heading not for Wright or Pratt & Whitney, but for GE. Arnold chose GE partly because of the work the company had done for the Air Force on the Moss turbocharger, partly because of its experience with new heat-resistant alloys like Timkin and Vitallium, and partly, it seems, because it was *not* Wright or Pratt & Whitney and therefore had more to gain from pioneering a new technology.[14]

It is easy to see the British government's decision to hand the Americans the jet engine as an act of extraordinary and misguided generosity, and this is certainly the way some commentators have seen it.[15] The explanation, of course, lies in the war. In the autumn of 1941, when the Whittle engine was sent to America, the news from the Soviet Union was not encouraging and the United States was still neutral. Britain remained vulnerable to Nazi invasion and many people still considered that such an invasion was likely. For the British, sharing the jet engine with its best potential ally made political as well as strategic sense against the background of the war and the hard bargaining which was going on over the Lend-Lease Agreement.[16]

Having obtained the British engine, however, the Americans worked with customary speed. Indeed, the speed with which General Electric, Westinghouse and airframe makers like Bell and Lockheed converted Whittle's invention into prototype engines, and very soon thereafter into jet fighters, should have given the British a lesson, if they needed one, on competition with American industry. The US was able, by virtue of its size, resources and advanced production techniques, to adopt the inventions of others long after the initial research process had been completed and still deliver production models *before* the inventors did.

By the end of 1942 the Bell Airacomet XP59 was flying with the GE I-14 engine, a copy of the Whittle design, and in 1943 de Havilland's Whittle-type engine, the Goblin, was being reproduced by Westinghouse for installation in the Lockheed Shooting Star jet fighter.

Britain's lead, 1945–54

The initial transfer of jet engine technology from Britain to America can be seen as a direct consequence of the Second World War. After 1945, however, the transfer continued in the same direction against the backdrop of the Cold War. American research was catching up, and its progress received a major boost from the assistance of German scientists after the end of the war in Europe. But Britain still retained a clear lead in jet engines, one of the few remaining areas in high technology where she could make this claim.

With the exception of Napier, all the British engine manufacturers had made a somewhat dramatic switch to turbine technology. Indeed, the amount of turbine activity in Britain in 1946 was remarkable: de Havilland was working on turbines, Bristol on heat exchangers, Armstrong-Siddeley on the design of their Sapphire jet engine, and Rolls-Royce on a whole range of engines including the Derwent, the Nene and the highly advanced Avon.[17] British plans included turboprop as well as pure jet engines, but piston engines were definitely seen as obsolete. This is surprising, not only because the manufacturers still had successful piston engines in production – for example Rolls-Royce with its liquid-cooled, in-line units (Merlin, Griffon) and Bristol with its sleeve-valve radial engines (Centaurus) – but also because jet engines were by no means a fully-developed aircraft propulsion system and many important commercial as well as technical questions remained to be answered.

Jet engines consist of compressors, combustion chambers and turbines, and nobody at this stage was entirely sure of the best way to design and build any of them.[18] The choice of compressor, for example, remained a major locus of contention. Should it be of the simpler centrifugal type adopted by Whittle, or should it be of the axial-flow design favoured in the later German engines? In Britain this debate divided the Whittle supporters from the followers of the scientist A A Griffith. Griffith had done important work on axial-flow technology in the 1930s for the Royal Aircraft Establishment, but had preferred the turboprop solution to the pure jet engine and as a result had not garnered the laurels of fame as Whittle had.[19] The axial-flow compressor, which offered a much higher thrust per frontal area, eventually prevailed, but in the late 1940s it was still uncertain which design would become the standard, particularly as the axial-flow compressor required far-reaching scientific skills at the foremost edge of thermodynamic theory.[20] Other problems related to whether jet engines could be mass-produced and how the very high temperatures in the turbine were to be dealt with: by using the new heat-resistant alloys which the Americans had in abundant supply, or with the turbine blade cooling pioneered by the Germans?[21]

Although mechanically far simpler than the reciprocating engine, the jet required a level of engineering sophistication beyond that which was found in the majority of British engine companies in the prewar era. So why did Rolls-Royce, Bristol, Armstrong-Siddeley and de Havilland throw themselves with such abandon into jet and turboprop manufacturing? An explanation lies in the greater degree of cooperation that had been built up between the British companies during the war, manifest in the Gas Turbine Collaboration Committee (GTCC). This committee, which was set up by the government in 1941 and to which all the companies sent experts, met on a regular basis until well into the 1950s. It functioned with a high degree of openness, initially to make Whittle's findings available to all the British manufacturers, later as a general forum for the exchange of information on jet engine development. It represented a degree of collaboration between private companies which would have been quite impossible in the United States, with its strong antitrust tradition. Moreover, in addition to cooperation between the companies, the jet engine received a boost in Britain from active government involvement. We tend to think of Frank Whittle as an inventive genius from humble origins who fought single-handedly against a hostile scientific establishment to gain acceptance for his ideas.[22] In fact he seems to have been a catalyst in a wider government-coordinated programme of technological research. As early as 1943, the premier British engine builder, Rolls-Royce, received a letter from Sir Stafford Cripps, Minister of Aircraft Production, in which he had written that 'nothing, repeat, nothing is to stand in the way of the development of the jet engine'.[23] The historian David Edgerton has written of Britain's technological culture at this time in terms of a contrast between the Americans, who 'were felt to be unimaginative and unsubtle', and the English, who 'had daring and unconventional boffins'.[24] Whether or not this is true, the government, in the shape of the Air Ministry and the Ministry of Supply, seized on their 'boffin' (Whittle) and his invention (the jet engine) to spearhead the advance of an important industrial sector. And as the end of the war approached, British officials saw a new window of opportunity in American 'backwardness', namely the early application of jet engines to *civil* aircraft.

The Comet

'There is no reason whatever', wrote a senior civil servant in a letter to Cripps in early 1946, 'why Britain should not design and produce civil aircraft as good as, if not better than America.'[25] Whether or not this was realistic, there were many senior figures in the postwar Labour government who thought this was true, although the same cannot be said of Britain's newly nationalised international airlines. The United States led the world in transport aircraft at the end of the war with new four-engined types such as the Douglas DC-4 and the Lockheed Constellation. Could Britain catch up? A start had been made with the Brabazon Committee and its list of five new civil types which were to be developed for British airlines. From its beginnings in 1943, this committee had stressed the need to capitalise on Britain's jet engine know-how in the construction of transport aircraft. Not all the Brabazon types succeeded, of course, and at least one was an unmitigated disaster (the Bristol Brabazon). But two path-breaking airliners did emerge from the programme in the early 1950s: the Vickers Viscount and the de Havilland Comet (Figure 2), and both were distinguished by their turbine-driven power plants.

There is no question, however, that the early application of jet engines to commercial aircraft by the British was a risk and a gamble. At the end of the war there was concern on both sides of the Atlantic that jets, while fine for fighters and bombers, would prove too unreliable for commercial aircraft and have too high a fuel consumption for airline operation. Moreover, the airlines themselves could hardly imagine passengers flying at speeds of 500 mph and there were even doubts (reminiscent of the early railways in the nineteenth century!) that the human body could withstand it. The fact that jet engines and cabin pressurisation would actually make flying *more* comfortable at high speeds and altitudes seems to have been little understood.

Of the five Brabazon types, the de Havilland Comet was by far the biggest gamble. The chronology of the Comet's history is well known. Conceived as a four-engined jet mail plane, it quickly evolved into a passenger aircraft and made its first flight in 1949. It entered service with the flag-carrier BOAC to great acclaim in 1952 and in 1953 it enjoyed a year of enormous popularity with passengers and considerable commercial success. Then, eighteen months after their introduction, Comets began breaking up in midair, and in the summer of 1954 they had to be withdrawn. There followed a prolonged period during which a Comet was tested to destruction in a pressure tank

Figure 2 De Havilland Comet 1, the world's first jet airliner. (Deutsches Museum)

before the cause of the crashes was finally revealed as metal fatigue of the pressurised fuselage. Only in 1958 did the aircraft reappear, with a much smaller fanfare, as the Comet 4.

Behind these bare facts is a more subtle picture which focuses on the idea of the Comet as a symbol of Britain's postwar industrial recovery. The aircraft itself was conventional in design, without the swept wings that were being adopted on military jets in the United States and even in the Soviet Union by this stage.[26] It was also quite small, carrying a maximum of 44 first-class passengers at a time when its main piston-engined rivals (the DC-6, the Super Constellation) could carry at least 70. It was very fast, of course, cruising at nearly 500 mph at 35,000 feet. But despite its popularity in the year of Queen Elizabeth II's coronation, it was very much a prestige vehicle in terms of the air transport industry, indeed a throwback to the prewar era of elitist air travel. An instructive way of seeing the Comet is as a showcase for its jet engines, which were, initially at least, the Ghost jets manufactured by de Havilland's own engine company. The Ghost was a development of the wartime Goblin, built during the war by de Havilland to the Whittle formula with a centrifugal compressor. It was a good engine in itself, but it was not the best engine for the Comet, either in terms of thrust or fuel economy. The best engine, and the engine which was planned for the Comet, was the Rolls-Royce Avon – one of Britain's first two commercial jet engines with an axial-flow compressor (the other one was the Armstrong Siddeley Sapphire).[27] The Avon was more powerful and inherently superior to engines with centrifugal compressors such as the Derwent, Nene (Figure 3) and Ghost.[28] Unfortunately, it also took almost seven years to develop and was simply not ready in time to power the first Comets in 1952. De Havilland therefore installed their own Ghost engines in the aircraft until the Avon was available.

It has never been suggested that the de Havilland Ghost engines were in any way responsible for the Comet crashes, or that their replacement with Avons would have made any difference. The cause of the crashes was simply lack of knowledge on the part of the de Havilland airframe company of the dynamics of metal fatigue in pressurised aircraft cabins – an ignorance which it shared with every aircraft manufacturer in the world. The deeper lesson of the Comet story, however, is the penalty which is paid by pioneers and first users: in other words, being first is not always the most economical way of getting into business. While the Americans patiently built up experience with military types like the Boeing B-47 and B-52 bombers before finally launching the Boeing 707 in 1958, the British adopted a policy of jets-at-all-cost and accepted an undistinguished airframe in the Comet to win 'the race' with the Americans. That the British government saw jet engine competition with the Americans in terms of 'a race' is apparent from government records. Indeed, the jet seems to have become as much an obsession for the British as the atom bomb had been for the Americans: it was seen as a key to the maintenance of Britain's economic and strategic power, however narrow a technological basis it represented. It was argued that Britain needed to concentrate on manufacturing products which its economic rivals could not match in engineering sophistication and which yielded a high unit gain. Aircraft were such products and the only way aircraft could be sold in the face of the entrenched power of the American manufacturers was to put jet engines in them. The idea that Britain was engaged in a race with the Americans is evident in the tone and phrasing of an important statement of policy by the Minister of Supply, Duncan Sandys, in 1952 (the year of the Comet's launch):

> During the next few years the UK has an opportunity, which may not recur, of developing aircraft manufacture as one of our major export industries. On whether we grasp this opportunity and so establish firmly an industry of the utmost strategic and economic importance, our future as a great nation may depend. [...] If our aircraft industry is not sustained by export orders, it will not be able, qualitatively, to meet all our own needs, and we shall have to resign ourselves indefinitely to dependence on America.

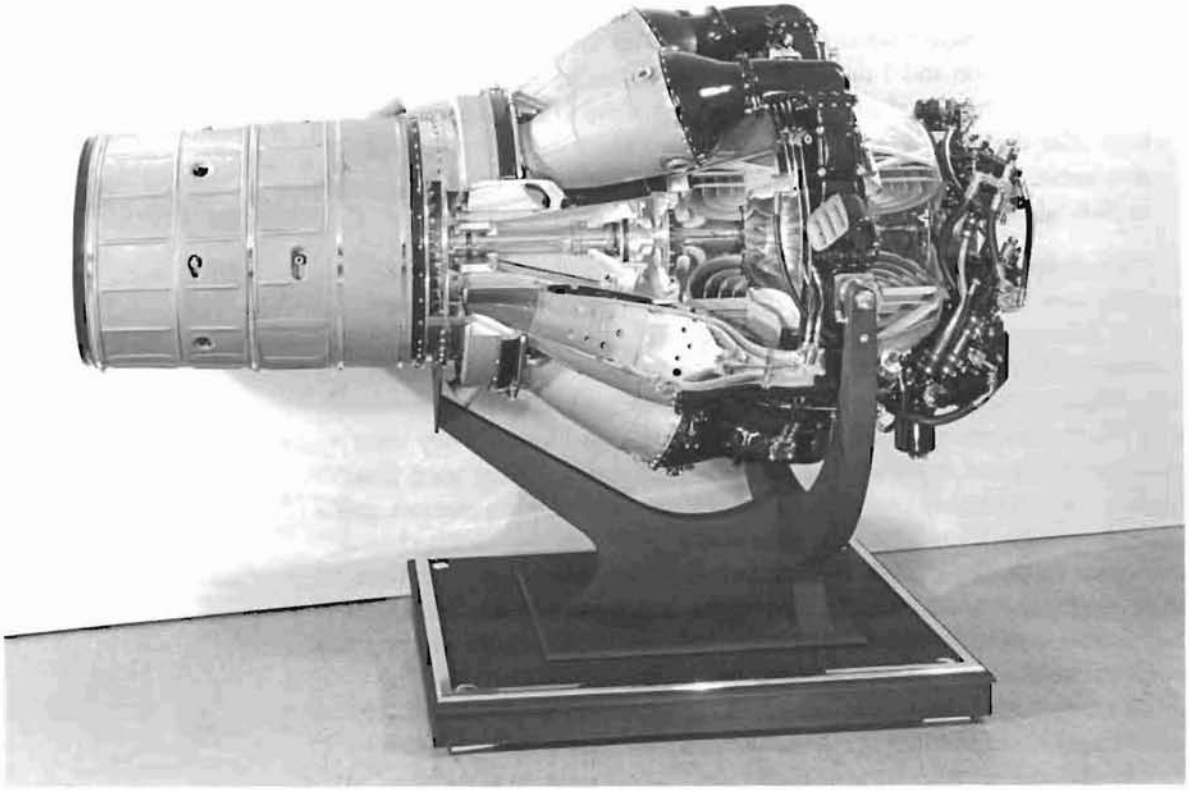

Figure 3 Rolls-Royce Nene engine, 1955. (Deutsches Museum)

Sandys reckoned that Britain's competitive position was strong because British costs were lower than American costs and aircraft did not lend themselves 'to the mass production technique in which the Americans excel, to the same extent as other products such as motor cars. [...] In this particular industry (aircraft and aircraft engines) we are less exposed to the competition to which we are so vulnerable elsewhere.'[29]

Even assuming that Sandys' analysis was correct, which is doubtful given that aircraft production eventually proved itself to be as amenable to 'mass production' as any other technologically advanced product, the idea of the 'race' was misplaced in dealing with the Americans. This is partly because the Americans themselves did not conceive of civil aircraft production in such terms, but more importantly because such a contest could not be won, at least in the long term, against a nation with far greater human and material resources. The best indication of this is in the field of testing. The key to the whole lengthy and complicated process of aero-engine development – indeed aerodynamic progress generally – is the wind tunnel. This piece of equipment is vital in testing the limits in performance of new engines and aircraft shapes, yet Britain was desperately short of them. A senior British scientific advisor to government wrote in 1953:

> The USA now have 5 times as much equipment for the collection of basic information and 3 times as much for the testing of complete aircraft models as we have in the UK. We lost the initiative in aerodynamics soon after the 1939–45 war. At least one high Mach-number tunnel of reasonable size will be required even when the present building programme at National Gas Turbine Establishment has been completed.[30]

The shortage of wind tunnels and altitude chambers for testing engines was symptomatic of the threadbare infrastructure involved in the British approach to jet aircraft and engine development. The British, to use Edgerton's formulation, relied on brilliant individuals – 'boffins' – to make up for the lack of scientific hardware that the Americans possessed in comparative abundance. They were short of resources, both money and raw materials, so they used their brains. Unfortunately this was no longer enough: making aircraft and engines was far more complicated and expensive in the 1950s than it had been in the 1930s. To ensure a decent return on the investment in research and development required to make a jet engine, an even larger investment had to be made in trials and permanent testing equipment. And this is where the more thorough approach of the Americans ('unimaginative and unsubtle' in Edgerton's phrase) paid its eventual dividend: they may have lost the 'race' to get the first passenger jet aircraft into the air in 1952, but they won the competition to dominate the jet age after 1958.

The responsibility for what one might call the 'Comet syndrome' (but which refers equally to other British hi-tech projects which were attempted on a shoestring, for example the high-speed Advanced Passenger Train in the 1970s) lies with the government, the only institution that had the power and resources to provide the basic testing infrastructure needed by the British engine companies. In 1955 engineers from Rolls-Royce visited the American engine testing facilities at NACA in Cleveland, Ohio. They were shocked and delighted at the lavish extent of the installation in comparison with what they had to work with in Britain. As the aviation historian Virginia Dawson has put it, 'they lamented that their company had been "led up the garden path" by the Labour and Conservative governments, that had promised "to provide full-scale test facilities for the British gas turbine industry since 1945"'. The politicians had failed the scientists and 'although in 1955 the British made plans to build a large altitude test facility to test full-scale engines at the National Gas Turbine Establishment at Pyestock, with a second at Bedford, these facilities came too late to recoup the British lead'.[31] The race was lost.

Reverse thrust – the American response

The Comet jet airliner is a perfect example of the characteristic British approach to high technology and a prime artefact of Britain in the 1950s. The crashes of 1954, however, shook the confidence of the whole industry. The fantasy-inducing enthusiasm of 1949, when it was expected that everyone would be flying in jet aircraft by 1954, was replaced by traumatised inaction, so that plans to produce other British jet airliners like the Vickers V-1000 were shelved. The V-1000 was to have been based on the Vickers Valiant bomber, which was already flying with Avon engines. Had this project gone ahead it would have reflected American practice, which allowed for the protracted trial of new designs in military versions before they were adopted for passenger-carrying roles. The best example of this approach was the Boeing 707 airliner, which went through earlier incarnations as the Boeing B-47 and B-52 bombers, and the Boeing KC-135 jet tanker.

After the Comet crashes, the American engine companies moved inexorably to the fore in jet engines. In the late 1940s the two senior companies, Wright and Pratt & Whitney, had pursued research and development into jet engines for *military* aircraft, while continuing with the still-profitable manufacture of radial piston engines for the civil market. Wright engines, which had begun with the famous 575 hp Cyclone in 1931, were raised in power output to around 3850 hp by 1955 – ironically by using the same turbine technology, known as 'compounding', which was used to build pure jet engines.[32] But Wright was to be the major casualty of the shift to jet engines: after collaborating with Armstrong-Siddeley to build the Sapphire engine under licence (the J-65 in US designation), it got into severe difficulties with its successor, the J-67, and was forced to abandon aero-engine production altogether.[33] Pratt & Whitney began its experience with jets by acquiring a licence to the Rolls-Royce Nene (the J-42) and followed this with a further Rolls-Royce design, the Tay, during the Korean war. The latter engine, known as the J-48, was the last and the most powerful American jet based on the original Whittle concept with a centrifugal compressor. In the early 1950s, Pratt & Whitney moved out of the shadow of the British manufacturers with its own axial-flow engine – the famous J-57 – incorporating an innovative twin-spool compressor.[34] This engine enabled the company to shift production entirely to jet engines; the J-57 not only powered numerous American combat aircraft, but it also, in its civil version, powered the Boeing 707 and Douglas DC-8 airliners (Figure 4). Meanwhile, GE, which had begun its jet engine history by assembling the Whittle engine for General Arnold, had since developed its own expertise and in 1947 had brought out the 12-stage axial-flow J-47. This was immensely successful in military application, powering the F-86 Sabre jet and, more significantly for civil transport, the early swept-wing Boeing B-47 bombers.[35] GE followed this in 1954 with

Figure 4 Douglas DC-8 jet airliner in flight. (Deutsches Museum)

the J-79, an engine built in response to Pratt & Whitney's J-57, and incorporating for the first time the innovation of variable stators in its six-stage compressor. By the mid-1950s the two companies were on their own, innovating for themselves, and the only remaining American companies producing jet engines.

It is interesting that while British civil airframe design did not keep pace with British aero-engine development, in the United States the situation was reversed, and more easily corrected. The Americans were cautious and undecided about civil jet aircraft when the Comet was launched, and because of this caution the world's airlines were not easily persuaded that jets could be operated on an economical basis, despite BOAC's single triumphant year with the Comet in 1953. This caution made it more difficult for de Havilland to achieve sales before the crashes, and seemed justified to the airlines afterwards. However, when Boeing and Douglas began building their own jet airliners in the mid-1950s, the airlines (including BOAC) rushed to order them straight from the drawing board. As the economic historian Nathan Rosenberg commented on Anglo-American jet airliner rivalry: 'In retrospect it is apparent that the American delay was salutary rather than costly to them, and that Boeing and Douglas chose the moment to proceed better than did de Havilland.' Because the Americans were slower, more powerful engines (like the Pratt & Whitney J-57) were available to them and they could build their aircraft bigger.[36] Moreover, the Boeing 707 and the Douglas DC-8 were both technically and from an operational viewpoint superior to the Comet, largely thanks to basic research done in wind-tunnel testing. In particular they embodied two features borrowed from American jet bombers, which were to prove paradigmatic in the long-term history of jet airliner development, namely thin swept wings and podded engines.

In the year after the Comet crashes, de Havilland comforted itself with the thought that it had been its pioneering role that had convinced a sceptical industry in America.

> The Americans were taken aback by the success of the *Comet* and the fact that it could be operated in exactly the same way as a conventional piston-engined aircraft; they had nothing of comparable performance even on the drawing board and needed at least 6 years to bring a new turbine-engined aircraft into passenger service.[37]

On this last point, however, the firm was in error. The fact that a major British aircraft manufacturer could seriously underestimate the productive capacity of the American aircraft companies suggests that there was an element of self-delusion about Britain's entire civil aircraft effort in the 1950s. The Americans produced their jet airliners with remarkable speed once the decision had been taken to go ahead: a result of their much larger capacity, and in particular, their higher rates of manufacturing productivity.

By way of a postscript to the story of the Comet it is worth considering the last jet engine which demonstrated a British lead over the Americans – the Rolls-Royce Conway. The Conway began life in the late 1940s at the same time as the Avon, but was a more radical departure from the prevailing design philosophy of the time because it was a *bypass* engine. Bypass jet engines use a front fan to duct colder, slower-moving air past the compressor and turbine, to the exhaust gas jet, thus increasing the mass of the jet and its thrust. Bypass engines have the advantage for airline operations of being both quieter and more economical with fuel. The more air that they divert past the hot compressor and turbine, i.e. the higher their bypass ratio, the more thrust and the greater potential economy that will be achieved. In fact the Conway had a low bypass ratio because it was intended, like the Avon, for a bomber (the Handley Page Victor) and British bombers at this time, like the Comet, had engines 'buried' in the wing roots – a design which did not allow for a wide front fan. Nonetheless, the principle of the Conway represented a significant breakthrough, on a par with the shift from centrifugal to axial-flow compressors.

The Conway's superiority over American civil engines was recognised by Boeing, who recommended the replacement of the launch engine on the Boeing 707 (the Pratt & Whitney JT3C, the civil version of the J-57) with a bypass unit. Thus the large-scale use of bypass engines in commercial aviation began in the 1960s with the Conway's adoption for the Boeing 707 and Douglas DC8. The improvement in fuel consumption and the lower takeoff noise which it offered appealed to the airlines, although it did not significantly outperform the JT3C, and Pratt & Whitney were initially reluctant to follow Rolls-Royce and adopt the bypass system.[38] Eventually, however, the Americans caught up and overtook the British. The Conway stimulated US manufacturers to produce much larger engines with much higher bypass ratios, culminating in the Pratt & Whitney JT9D, the GE CF6 and finally the British response to the American challenge, Rolls-Royce's own RB-211. As with the Whittle engine in the 1940s and the jet airliner in the 1950s, the Americans copied the idea of the bypass engine and improved on it.

Aircraft and aero-engine design and development, as does any other field of advanced technological research, reveals strong national characteristics that can determine the manner and speed at which the work is done. There are different national cultural approaches at play here. In the United States there has been a distinct preference in aerospace for broad-based progress at a steady, but unspectacular tempo, drawing to the maximum extent possible on national resources at the research and development stage before moving into an efficient and commercially-orientated production phase. In Britain high-technology enterprises like the Comet have tended to assume an iconographic value in terms of national culture; they have advanced at a more frenetic pace, on a narrower front, with less clearly identified commercial goals, and more than once have given the impression that winning the race to be first is more important than being the best competitor.

Notes and references

1 Hayward, K, *The British Aircraft Industry* (Manchester: 1989), p29

2 Dawson, V P, 'The American turbojet industry and British competition', in Leary, W M (ed.), *From Airships to Airbus: The History of Civil and Commercial Aviation*, Vol. 1 (Washington DC: Smithsonian Institution Press, 1995), p127

3 Radar is another obvious example.

4 Two more Germans, Herbert Wagner and Helmut Schelp, were responsible for crucial work on turbines and compressors. For the race to get the jet engine operational, see Constant, E W, II, *The Origins of the Turbojet Revolution* (Baltimore, MD: 1980), pp178–207.

5 Golley, J, *Whittle: The True Story* (Shrewsbury: 1987)

6 The progress made by the Germans up to 1945 is outlined in Schlaifer, R, *Development of Aircraft Engines* (Boston, MA: 1950), pp377–428. American gains enabled by interviews with captured German scientists are described in Lasby, C, *Project Paperclip: Germans Scientists and the Cold War* (New York: 1971).

7 Constant, E W, II, note 4, p208

8 Work on the Rolls-Royce Nene began in May 1944 and the engine was ready for testing in October 1944. In the words of its designer, Sir Stanley Hooker, 'In five months the company had built the most powerful aircraft engine in the world.' Although the British never found a use for the Nene, many other countries did, including the United States, where Pratt & Whitney turned it into the excellent J-42. In 1946 the Nene was innocently sold to the Soviet Union, where it was copied and used to power the MiG-15 and MiG-17 fighters. See Hooker, S, *Not Much of an Engineer: An Autobiography* (Shrewsbury: 1984), pp90–8.

9 For the history of American air-cooled engines, see Schlaifer, R, note 6, pp156–98. Also useful is Sherry, M S, *The Rise of American Air Power: The Creation of Armageddon* (Newhaven: 1987).

10 Dawson, V P, *Engines and Innovation: Lewis Laboratory and American Propulsion Technology* (Washington DC: 1991)

11 Dawson, V P, note 10, p14

12 Quoted in Golley, J, note 5, p114.

13 Kevles, D J, *The Physicists* (New York: 1979), p302

14 Schlaifer, R, note 6, pp328–9

15 According to one rueful authority, 'the entire turbojet engine industry of the United States grew directly from the acquisition of two British engines' (the Whittle W.1/GE I-14 and the de Havilland/Westinghouse Goblin). Gibbs-Smith, C H, *Aviation: An Historical Survey from its Origins to the End of World War II* (London: HMSO, 1970), p213.

16 Dawson, V P, note 10, p41

17 Points from the Gas Turbine Collaboration Committee Proceedings, 21 June 1946, Public Record Office, Ref. AIR 62/963

18 In understanding technical matters, the author has found it helpful to consult Smith, G G, *Gas Turbines and Jet Propulsion* (London, New York: 1955). For a more challenging introduction, see Meyer, C A, 'The turbojet engine', in Lancaster, O E (ed.), *Jet Propulsion Engines* (Princeton, NJ: 1959), pp82–198.

19 For Griffith's work on axial-flow turbines in the 1930s, see Constant, E W, II, note 4, pp110–14.

20 Dawson, V P, note 2, pp133, 138

21 The Americans were ahead in high-temperature materials in 1941, and even in the early 1950s had better supplies than the British of vital metals like titanium. See Whittle, F, 'General impressions', development work by GEC, July 1941, liaison with the USA, AIR 62/1009; 'Titanium for engines', 1952–55, Public Record Office Ref. AVIA 65/57.

22 See, for example, his own story: Whittle, F, *Jet – The Story of a Pioneer* (London: 1954).

23 Quoted in Hooker, S, note 8.

24 Edgerton, D, *England and the Aeroplane: An Essay on a Militant and Technological Nation* (Basingstoke: 1991), p90

25 Cribbet, G, letter to Sir Stafford Cripps, 7 February 1946, aircraft production, 1946, Public Record Office Ref. AVIA 9/89

26 De Havilland did consider a swept-wing version of the Comet at an early stage, but did not proceed with it.

27 Sharp, C M, *DH. A History of de Havilland* (Shrewsbury: 1982, first published 1962), p315

28 The Rolls-Royce Avon became a highly successful engine in the 1950s, powering military aircraft such as the Hunter fighter and the Canberra and Valiant bombers, as well the Comet and French Caravelle airliners. The adoption of axial-flow compressors on engines like the Avon and the Sapphire raised the critically important compression ratio before combustion from about 4:1 (for centrifugal engines) to about 7:1.

29 Memorandum by the Minister of Supply (Duncan Sandys) and the Secretary of State for Air, Cabinet Economic Policy Committee, 23 May 1952; 'The aircraft industry as a major exporter – policy', Public Record Office Ref. AVIA 63/25

30 Banks, F R, Ministry of Supply paper, 22 April 1953, Public Record Office Ref. AVIA 65/14

31 Dawson, V P, note 2, pp144–5

32 The Wright turbo-compound engine which used the radial's exhaust gases to drive as many as three separate turbochargers may have been an immensely impressive piece of machinery, but it was the last hurrah of an obsolete technology. See Smith, G G, note 18, pp283–5.

33 Fansel, R W, *What ever happened to Curtiss-Wright?* (Manhattan, KS: 1991)

34 The twin-spool compressor had two axial compressors rotating at different speeds. See Smith, G G, note 18, p252.

35 Smith, G G, note 18, pp248f

36 Rosenberg, N, 'On technological expectations', *The Economic Journal*, 86 (1976), p527

37 'The future of the Comet', De Havilland Public Relations, 11 March 1955, Public Record Office Ref. AVIA 63/26

38 The early engine most used on the Boeing 707 was the P&W JT3C, a civil version of the J-57. Later Pratts introduced the bypass JT3D turbofan version. See Newhouse, J, *The Sporty Game* (New York: 1982) p112.