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The Green Airliner that Never Was: Aerodynamic Theory, Fuel-Efficiency, and the Role of the British State in Aviation Technology in the mid-Twentieth Century

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Abstract

Two aerodynamic concepts theorised in the early twentieth century – laminar flow control and flying wings - offer the potential for more efficient aircraft. However, despite compelling advantages on paper and optimistic predictions, the fuel-saving benefits of these technologies have not yet been fully realised. This paper documents British work on these concepts, with a particular focus on laminar flow control. Faced with an increasingly difficult funding context and a lack of a clear military rationale, these potentially significant advances in aircraft efficiency were stymied by a Catch-22 situation: the government was only prepared to provide financial support for the development of an operational prototype if operational performance had already been demonstrated. This case also highlights the challenges faced in the commercial uptake of radical aviation technologies, even when they appear to offer greater efficiency and environmental benefits.

Introduction

In 2003 an authoritative study of the technological options for reducing the environmental impacts of air travel, carried out under the auspices of the Royal Aeronautical Society, set out potential technical advances that could result in substantially greener airliners.[1] Amongst the options described in this *Greener by Design* report was a technique known as Laminar Flow Control (LFC), which when used with a 'flying wing' aircraft design, was said to offer 'the greatest aerodynamic potential for reducing the contribution of air travel to climate change.'[2]

What was notable about this claim was that this approach – a flying wing with LFC – did not involve novel concepts that had recently been invented. As the *Greener by Design* report notes, a LFC flying wing airliner had been proposed over half a century earlier. The British aircraft manufacturer Handley Page sought to pioneer the use of LFC technology during the 1950s, and its 1960 design study of a LFC flying wing airliner (the HP 117) predicted efficiency improvements compared to conventional transatlantic airliners that were expected to 'result in the direct operating costs being reduced by at least 50%!'[3]

Both the flying wing and laminar flow control concepts stemmed from the burgeoning of aerodynamics theory in the early twentieth century. Simply put, a flying wing seeks to eliminate all aircraft structures (particularly the fuselage) that do not provide lift, thus increasing the lift-to-drag ratio of the airframe. The idea of LFC built on the understanding of how air flowing over a wing quickly becomes turbulent, adding greatly to friction and thus drag. The most popular approach to LFC used suction through the wing surface to keep the boundary layer thin enough not to become turbulent.[4] According to a 1999 NASA survey, written before climate change became a mainstream concern: 'Laminar-flow control is a technology that offers the potential for improvements in aircraft fuel usage, range or endurance that far exceed any single known aeronautical technology. For transport-type airplanes, e.g., the fuel burned might be decreased a phenomenal 30 percent. Fuel reduction will not only help conserve the earth's limited supply of petroleum but will also reduce engine emissions and, therefore, air pollution.'[5]

To clarify definitions, there is some overlap between the use of the terms Laminar Flow Control and Boundary Layer Control (BLC). LFC or 'laminarisation' refers to attempts to maintain laminar flow in order to reduce drag and is one possible use of BLC, which can also be used to increase lift (e.g. to enable take off for carrier-based aircraft) or to control stalling effects. Moreover, LFC can encompass passive approaches involving only the shape of the wing or, as documented here, active techniques involving either sucking or blowing.

Given that both flying wing and LFC concepts have long been known (in principle) to offer fuel-efficiency benefits, why is it that their practical implementation in airliner design continues to remain a potential, rather than actual, solution? The airliner of today differs little from those of sixty years ago in its aerodynamic fundamentals. In this regard, the current Boeing 787 airliner, although innovative in its use of structural carbon fibre, is a direct descendent of the Boeing 707, first introduced into service in 1958. Since the 1960s (when the original turbojet engines were replaced by the more efficient turbofan) airliner technology has evolved so that the 'dominant configuration in the world fleet is the classic swept-winged turbofan powered aircraft.'[6] In the meantime, other approaches to airliner design have either proved commercially unsuccessful (the supersonic airliner), have found niche markets only (turboprop-powered straight-winged airliners for short-haul operations), or in the case of LFC and flying wings, have not been used at all.

Within this broader issue, there is also a more specific question of whether the failure of these airliner technologies to become mainstream can be seen as typical of much post-war UK innovation. An extensive UK research base, with many specialised research establishments, some of which were supported and orientated by Cold War concerns, provided a rich source of invention that government and industry appeared unable to nurture to commercial fruition.[7] Civil aviation in particular benefitted greatly from direct government support, as well as from the potential synergies that stemmed from facilities, staff, and a shared knowledge base that had substantive military funding.[8]

This paper addresses these issues with a particular focus on a detailed account of the British experience with LFC. Official NASA histories describe US work on LFC, and several (mainly popular) books and papers have described flying wing developments, but British LFC developments remain almost entirely undocumented.[9] This story is significant because it involves the earliest detailed plans for a LFC flying wing airliner, and more broadly because it sheds light on the obstacles to the development of greener airliners based on these principles, as well as on broader issues of technological innovation. What follows begins with an account of the early development of these two key aerodynamic innovations – laminar flow control and flying wings. The core of this paper then draws on documents in the UK National Archives to describe the period when Britain was at the forefront of LFC research, and when the anticipated advantages of this new technology failed to materialise in operational aircraft.

Early Days

The decades after the first successful powered flight of the Wright brothers' Flyer in December 1903 were characterised by fecund and varied invention. Theoretical understanding of aerodynamics developed rapidly, and almost every conceivable type of aircraft was built and tested.[10] Aircraft structures were made of either wood or metal, or a combination, and both biplanes and triplanes were common, along with more exotic airframes.[11] However, by the end of the 1930s (with some exceptions) what it meant to be an aircraft had stabilised. Thereafter the most common design would be a monoplane with all-metal construction (with both frame and skin made from metal), based on a fuselage with a tail-plane at the rear (for stability) and main wing forward of the midpoint (for lift).

From this rich mixture of theorising and experiment, two aerodynamic concepts emerged that would have enduring conceptual credibility stymied by hard-to-resolve practical challenges: the flying wing and laminar flow control. The idea of a flying wing – in which the whole of the structure provides lift, with no distinct fuselage or separate tail – is almost as old as that of aviation itself. Hugo Junkers patented a wing-only aircraft concept in 1910, though he was not optimistic about its practical realisation, noting in 1920 (in this clumsy translation) that: 'Probably such an ideal aircraft will never entirely become reality, but in my opinion will the further development of aircraft engineering move into that direction so that we will, in the foreseeable future, come very close to this ideal.'[12]

The closest Junkers came to realising this ideal was the 1930 G-38 airliner whose all-metal structure involved a huge 148 feet wide and six foot deep wing (with space for passengers to sit in the wing space next to the fuselage looking forward). However, the G-38 was not a pure flying wing, with a long fuselage after the wing leading to a biplane tail, and a stub of a fuselage at the front. *Flight* magazine noted at the time that the aircraft 'does not realize the ideal of the "flying wing," although it goes some way towards it.'[13]

Others, notably Jack Northrop in the USA, sought to push the flying wing concept to its fullest expression. Work on prototypes led to Northrop being awarded a contract in 1941 to build a large flying wing bomber, the XB-35, with the British noting that the 'predicted performance of this aircraft is outstanding.'[14] A Northrop press release claimed that: 'The savings in cost of construction of such an airplane as compared with conventional types is also extensive, as the Northrop aircraft consists essentially of a thick wing in which there are virtually no structural complications.'[15]

However, Northrop's optimism was misplaced. The XB-35 was plagued by production and technical problems (many unconnected with the flying wing design). Delivery was intended to be two years after the contract was signed, but the first XB-35 did not fly until June 1946, three years late and 400% over budget.[16] The aircraft also suffered from instability in pitch and yaw (the latter of which was fixable but the former not) making bombing much more inaccurate than with conventional aircraft.

Even worse, a test flight on June 5, 1948 of what was now designated the YB-49 (with the propeller piston engines replaced by turbojets) provided fatal evidence of the aircraft's propensity to stall.[17] Although the Air Force still ordered 30 aircraft for surveillance purposes, budgetary constraints, along with a preference for more proven technology, meant that these were cancelled at the start of 1949.[18]

British aircraft designers also sought to exploit the theoretical advantages of the flying wing concept.[19] Aircraft designer Captain G. T. R. Hill developed a series of Pterodactyl aircraft. Ironically, given the problems with stability that would be an enduring issue for flying wing aircraft, Hill's initial motivation was to reduce the large number of fatal accidents suffered due to loss of control.[20] Although the Pterodactyl did achieve good stalling performance, and a subsequent fighter version, the V5, was built, the project was cancelled because it appeared to offer no clear advantage as handling improved for conventional designs.[21] Another 'tailless' design, the HP-75 Manx developed by Handley Page in the 1930s, was neither a pure flying wing (it had both a stubby nose and more vestigial tail than its namesake feline), nor a great success. Its development was interrupted when Handley Page's chief designer, the German Gustav Lachmann, was interned, but revived in 1942 when it became clear that Northrop in the US was seriously pursuing its flying wing design.[22]

Interest in flying wing designs also led the Ministry of Aircraft Production to establish a Tailless Aircraft Advisory Committee in 1943. Projects initiated then – the Armstrong Whitworth AW52 and the de Havilland DH108 (the first British aircraft to exceed the speed of sound) - came to fruition after the war. Of these the AW52 was particularly significant. Not only did it integrate turbojet engines into an almost pure flying wing design (the nose protruded slightly from the front of the wing), but the AW52 also marked the world's first attempt to design an aircraft using boundary layer control with suction through the wing. Two prototype aircraft (half the size of the planned aircraft) were built, and the first flew on 13 November 1947 (see below).

Laminar Flow Control Takes Off

Flying wing aircraft fell out of favour after the Second World War (although before he died Jack Northrop saw designs of the US B2 stealth bomber that would first fly in 1989), but interest in laminar flow control (LFC) was on the up. Airplane development had initially focused on achieving the necessary lift, but the importance of drag in undermining performance soon became a concern. Ludwig Prandtl had set out his boundary-layer theory in 1904, but wider understanding of this took until the 1920s with publication of what became known as the 'Lanchester-Prandtl wing theory' (Prandtl's work built on ideas developed by the British scientist/engineer Frederick Lanchester).[23]

British appreciation of the importance of drag was pioneered by Professor Melvill Jones at the University of Cambridge, whose paper on 'The Streamline Aeroplane' was presented to the Royal Aeronautical Society in 1929.[24] Jones highlighted a number of techniques that could be used to reduce aircraft drag (for example, using retractable wheels) by reducing the friction caused by turbulence on aircraft surfaces. Because the friction for a laminar boundary layer is significantly lower than that for a turbulent boundary layer, a key challenge was how to maintain laminar airflow over surfaces, especially over the wings.

One possibility was to delay the onset of turbulence by clever wing design (moving the point of maximum thickness further back), with the North American Aviation Mustang fighter being the first operational example in 1940.[25] However, even with such passive laminar flow control, the boundary layer will eventually become turbulent and add to drag. Another approach to reducing drag was discussed in a 1936 paper by A. A. Griffith and F. W. Meredith of the Royal Aircraft Establishment (RAE). They noted that:

> Jones showed how great an improvement in the aeroplanes of the time was possible by proper streamlining. About the same time it occurred to the present authors that still better results could be obtained by using perforated surfaces and sucking the boundary layer into the machine by an exhausting fan, the air being finally ejected with its total head restored by the fan. In this way the formation of a wake by skin friction could be avoided and power could be saved.[26]

The potential benefits were reckoned to be considerable, with Griffith and Meredith calculating that it 'appears that the combined saving possible by boundary suction … may amount ideally to five-sixths of the power at present consumed by skin friction.'[27] Using suction for Boundary Layer Control (BLC) had already been explored at the Langley laboratory of the National Advisory Committee for Aeronautics (NACA) in the US, though the initial focus there was on increasing lift rather than reducing drag.[28]

However, concern about German military intentions meant that rearmament was the main focus of UK aviation policy in the late 1930s, and LFC work was limited in nature. The RAE was keen to pursue the matter, with RAE's Superintendent writing to the Director of Scientific Research at the Air Ministry in May 1937 to say that 'we propose to commence an investigation into the possibility of reducing the drag of wings by suction.'[29] Later that year, he reported that: 'The experimental results show that the application of the method to improve the maximum lift has been successful but that the application to drag reduction has met with very little success.'[30]

As well as increasing lift and reducing drag, BLC was also investigated as a technique for aerofoil control. The aforementioned AW52 flying wing aircraft incorporated suction on the outer wing surfaces in an attempt to counter the 'early wing tip stall' that was seen as 'a weakness of the swept-back wing', and the AW52 system was designed to 'delay considerably the loss of control due to the stalling of the wing tips carrying the control surfaces'.[31] However, in practice lack of control was still a problem, and the AW52 flight tests did not go well. Armstrong Whitworth's two AW52 prototypes were first flown in 1947, but tests pilots complained of difficulties in controlling oscillations, and on 30 May 1949 one aircraft was lost when the pilot felt compelled to eject (this being the first use of the British Martin-Baker ejector seat).[32]

The Boundary Layer Control Committee and the 'Thick Wing'

The Second World War diverted most British aviation research towards the war effort, but some work on boundary layer control continued at both the RAE[33] and the National Physical Laboratory.[34] Towards the end of the war, the Ministry of Aircraft

Production (MAP) began to take an interest in innovative approaches to aircraft design, concerned not only about military potential, but also post-war competition in commercial airliners (as evidenced by the establishment of the Brabazon Committee that led to the pioneering Comet jet airliner).[35] The Tailless Aircraft Advisory Committee was set up by MAP in 1943, and this was followed in early 1946 by what was first termed 'the Committee on Suction and Blowing', but formally named the Boundary Layer Control Committee (BLCC).[36] Its formation stemmed from the belief that 'we can now foresee a considerable future for methods of reducing drag, increasing lift and providing control by means of suction or blowing.'[37]

An early preoccupation of the BLCC was the Griffith 'thick wing' aerofoil, a concept devised by A. A. Griffith, co-author of the 1936 paper that had proposed the idea of reducing drag through suction. A 1945 study by the National Physical Laboratory (NPL) noted that 'the use of thick suction wings holds out prospects of greater range or pay load because of the increased aerodynamic and structural efficiency obtainable.'[38] The study also noted that 'the employment of thick wings may be expected to lead to the abolition of the fuselage as a compartment for passengers and cargo and to complete submersion of the engines in the wing at much smaller all up weights … than up to now has been thought possible.' However, there were disadvantages, including complexity, difficulty of control, and limited top cruising speed.

Griffith's thick wing concept was discussed in the 1946 Wilbur Wright lecture, given at the Royal Aeronautical Society by E. R. Relf of the College of Aeronautics. He noted that with boundary layer suction 'very great increases of maximum lift have been demonstrated experimentally both here and abroad'.[39] However, these applications of BLC had involved conventional wing shapes, whereas Griffith's distinctive idea was 'to *design the shape to suit the suction*.'[40] The resulting thick wing was designed to have natural laminar flow over most of its surface, with suction slots towards the rear of the wing. Although experiments suggested that these suction slots could not restore laminar flow towards the trailing edge, it was concluded that 'the suction principle still has great attractions, one of which is that it enables very thick sections to be used without fear of any turbulent separation and probably with a laminar boundary layer up to the slot.'[41] A potential advantage of this was that it could have 'a profound influence on the minimum size of "flying wing" that is a practical proposition from the point of view of internal space.'[42]

However, there was a downside, and a report on Relf's lecture noted that 'these thick sections appear to have a fairly low critical Mach number, so that they are likely to be useful at moderate speeds only.'[43] Compressibility effects placed a practical limit of around 450 mph on the speed of a thick wing aircraft, but with the advent of engines based on gas turbine technology (the turbojet and the turboprop), increasing speed was seen as a desirable aircraft characteristic for most applications. Opinions were divided at the BLCC's second meeting in May 1946. Mathematician Professor Sydney Goldstein argued that 'he was sure that except for the very high speed civil aircraft for VIP's [sic] the suction wing would pay', but others thought that 'that economic arguments … suggested that speed was all-important in the operation of civil air lines.'[44]

Nevertheless, the BLCC continued to support work on thick suction wings. One of the industrial participants in the BLCC, Armstrong Whitworth (the contractor for the all-wing AW52), was asked to prepare thick wing aircraft design studies, and testing was carried out of models in wind-tunnels, and of thick wing gliders in Australia.[45] In November 1947, the BLCC 'decided to go ahead with the construction of a tailless aircraft with swept back wings using a 30% symmetrical section of the Griffith type.'[46]

Professor Goldstein, then President of the Aeronautical Research Council (ARC), proudly described British suction wing work in the Eleventh Wright Brothers lecture, presented at the Institute of Aeronautical Sciences in Washington, DC on December 17, 1947.[47] On his return to the UK he pressed for progress to be made, arguing that 'the decision must now be taken either to put a great deal of effort into getting the Armstrong Whitworth thick wing aircraft flying or to drop the idea altogether', and he sounded a familiar warning by noting that 'to proceed on low priority would only mean that the Americans would be first in the field.'[48]

Armstrong Whitworth's chief designer John Lloyd had agreed to design a thick wing aircraft, but at the BLCC's 11th meeting he made it clear 'that no useful purpose would be served by further design work until wind tunnel results on a model of the proposed lay-out were available.'[49] Accordingly Professor Goldstein pushed for access to scarce wind tunnel facilities, arguing that the thick wing work should be given higher priority than defence work. The BLCC, 'without going so far, agreed that the work should have at least as high a priority as the military projects.'[50] Gaining such priority, however, required more evidence. Before offering more wind tunnel access the Director of RAE wanted to see 'a comparison in which an aircraft with suction showed on paper an advantage over a conventional aircraft.'[51] Likewise, the Performance Sub-Committee of the Aerodynamics Committee of the Aeronautical Research Council 'considered that design studies were needed to show the overall gains to be expected from practical applications of boundary-layer control.'[52]

Such a study ('Thick Wing Suction Civil Design Study') was produced by Armstrong Whitworth in February 1949, but, if anything, it undermined the case for the thick wing. The study showed the thick wing aircraft would 'have a performance very much the same as the Brabazon 1' – a very large conventional airliner intended for transatlantic operation. According to Lloyd 'the reason why the suction aircraft appeared no better than the conventional aircraft was the low propulsive efficiency of the jet, together with the need to fly considerably slower than the critical Mach number.'[53] If paper studies were only supportive when moderate speed was acceptable, tests were even less encouraging. Flight tests of a Griffith type wing provided mixed results due to both insufficient surface smoothness of the wing causing transition to turbulence before the suction slot and inadequate suction. Following modifications, wind tunnel tests achieved the expected drag reduction, but the overall conclusion was that a very high standard of surface finish would be required for such a wing to be effective.[54]

It was now clear that enthusiasm for the thick wing's theoretical elegance, and its structural advantages in offering large internal spaces for a flying wing aircraft, had obscured serious practical limitations as regards speed and the difficulty of manufacturing smooth wing surfaces. Moreover, for the size of aircraft then under consideration the thick wing stowage was of limited value because 'in practical sizes, space is insufficient to allow the advantage in load to be taken in extra passengers.'[55] This was (and continues to be) a recurring concern with flying wing airliners: providing standing room in the wing space means a very large aircraft, unsuited to many airports.

Reporting the discussion of the ARC Performance Sub-Committee on 6 December 1949, H. F. Vessey concluded that 'the application of thick wing suction is severely restricted to a few types of a specialised aircraft. The question now is whether we can afford the large effort (say £2,000,000) which will be required to bring one of these applications to fruition.' Vessey acknowledged that 'we must decide whether we are to concentrate a large amount of effort on thick wing suction or to cease work altogether.'[56] In February 1950 the ARC's Performance Sub-Committee 'came to the broad conclusion that research on the maintenance of larger areas of laminar flow on wings of ordinary thickness was likely to be more fruitful in the near future, and have a wider application, than the development of the very thick suction wing.'[57] According to a later report, UK thick wing research was stopped in 1952 'because of the demand for higher cruising speeds.'[58]

Handley Page and Laminar Flow Control

Thereafter the main thrust of UK research focused on achieving drag reduction by 'laminarisation' of ordinary wings, and Handley Page Ltd, driven by the enthusiasm of chief designer Gustav Lachmann, became the main industrial advocate of this approach. Lachmann was determined, as he later wrote in 1961, to 'ponder independently on the question what is really worthwhile doing', and for him this was laminar flow research.[59]

One of the challenges was establishing whether theoretical predictions of LFC could be demonstrated in practically useful aircraft over a range of speeds higher than hitherto experienced, and across a range of altitudes. The key characteristics for airflow over an aerofoil are expressed by the Reynolds Number, a ratio of inertial resistance to viscous resistance. Higher Reynolds Numbers typically mean more turbulence, and thus more challenging conditions for restoring and maintaining laminar flow.

In 1950 the ARC's Performance Sub-Committee pointed out 'that the acceptance by aircraft designers of boundary-layer suction as a reliable method of improving aircraft performance depends upon conclusive experimental results being obtained at a high Reynolds number.'[60] It was noted that the RAE were 'investigating the possibility of using both wind-tunnel and flight experiments to provide such information.'[61] As to the practical applications of LFC, the Sub-Committee was sceptical:

> It finally concluded that since the military application of this technique is extremely limited, it is doubtful whether the cost necessary to develop a successful civil aircraft could be afforded at the present time; further it is uncertain whether such aircraft have any economic advantages over the conventional jet-propelled airliner.[62]

However, enthusiasm was revived with a significant development in 1953 when Handley Page achieved the world's first flight-test demonstration of LFC across the whole wing chord (the distance from the front to the back of the wing) using a suction sleeve fitted to a de Havilland Vampire fighter. Once the system of suction had been redesigned to ensure a sufficiently aerodynamic surface, laminar flow 'was then maintained repeatedly in flight.'[63] Similarly promising results were achieved the following year in the US with the Northrop F.94 sleeve, and 'such encouraging results were repeated during well over 100 flights, some over 1000 miles range.'[64] In all these flight-tests the problem of 'insect and dirt contamination was prevented by covering the nose of the wing at take-off and discarding the cover at altitude.'[65]

However, progress in the development of LFC was hindered by advances elsewhere in aircraft design, as the move to faster aircraft powered by jet engines and with swept-back wings complicated matters. The ARC's Performance Sub-committee first recommended that 'an experimental aircraft be built to study the application of boundary-layer control for laminar flow' in 1955, but progress was slow because there 'were still serious doubts as to whether suction would be effective on a sweptback wing.'[66] The AW52 flight tests, along with other flight tests in 1952, had indicated 'that sweepback could precipitate transition quite close to the leading-edge, because of the instability of the boundary-layer cross-flow associated with pressure gradients normal to the stream direction.'[67] The AW52 wings had been designed to maximise natural laminar flow (i.e. based on the shape rather than active sucking or blowing), but the flight tests had 'revealed an unexpected phenomenon – that sweep has a profound de-stabilizing effect on the laminar boundary layer as it passes round the nose of a wing.'[68] The conclusion was reached that it 'would seem that no laminar flow is present on normal wings of any appreciable size and speed if their sweep exceeds roughly 20 degrees.'[69]

These doubts were later allayed as 'more elaborate theories and a wind-tunnel experiment with suction in America showed that the early theoretical results were far too pessimistic.'[70] This work suggested 'that the suction quantities that would be required for say, a 40° sweptback wing might be only about 50% greater than for an unswept wing.'[71] By the late 1950s it was thus thought the challenges of laminarisation of swept wings could be overcome. An April 1959 RAE review reported that:

> The use of suction for the maintenance of laminar flow has been studied in this country and the USA for over 20 years, and developments towards a practical scheme started some 10 years ago. Until 1952, attention was mainly concentrated on two-dimensional flows as appropriate to unswept wings of large aspect-ratio, but since then the three-dimensional flow problems associated with sweepback effects have been successfully tackled.[72]

In the same month, Handley Page produced an analysis of the benefits of LFC based on 'frequent consultations with representatives of the Ministry of Supply and the Royal Aircraft Establishment, and also with members of British Overseas Airways Corporation and British European Airways.' Based on a Boeing 707 type aircraft, with or without laminarisation, and flying on the London/New York route, it concluded that with even 'the most adverse assumptions the saving is 16.3%.'[73] However, the problem for Handley Page was that convincing evidence of the benefits of LFC in practice could only be obtained by building and operating a LFC aircraft. Wind tunnel and flight testing in the UK and USA indicated that the concept was feasible, but many practical issues needed to be addressed to show that a LFC aircraft would be reliable and economic. As Lachmann wrote in 1961: 'The step from the present state of the art to the successful application on an economical transport aircraft is obviously still very big but there is sufficient promise that the reward is worth the effort.'[74]

Building an LFC Aircraft (on Paper)

The challenge was making this step. Even if feasible, there still remained doubts about whether laminarisation would be worthwhile given the extra cost of development, the likely need for more maintenance, and the weight penalty involved. Thus the 1959 RAE review noted that:

> The reduction in drag achieved by maintaining laminar flow over the wing and tail unit is of course only obtained at the expense of some additional weight – the extra weight of the suction surfaces, and of the suction pumps, drives and ducting. Design studies by Handley Page have indicated that this weight penalty amounts to between 4% and 4½% all-up weight for a large aircraft. (More recent studies by Handley Page suggest a somewhat lower figure.)[75]

Given that fuel was then a relatively small part of the cost of aircraft operations (taking into consideration R&D, construction, crew, and maintenance), it was clear that the greatest potential benefits would be for long-range aircraft. However, there were doubts about whether civil aircraft needed a range greater than the 3000 miles that was then the longest range available. It was concluded that: 'If a requirement for a very long range civil transport can be established laminar flow designs become even more attractive.' The RAE were sceptical about the civil need, but noted that: 'Although the requirement for a very long range civil aircraft may be in doubt that for a troop transport aircraft, it may be argued, is more real.'[76]

However, with many other procurement programmes considered more pressing by the armed services, there was no sign of financial support for such a military requirement. Without defence bankrolling of LFC work there was a 'chicken and egg' stalemate. Large-scale funding, either from government or industry, was unlikely until the technology was proven, but such 'proof' could not be obtained unless a laminarised aircraft was built and tested. The need for such a demonstration had been recognised by the ARC's Performance Sub-Committee which had recommended 'in 1955 that an experimental aircraft should be built to provide data from which a proper assessment of the advantages of such a technique could be made.'[77]

Handley Page's first plan for such a demonstration was the HP 113 - a small two-engined 'high performance long-range executive aircraft.'[78] Funded by the Ministry of Supply (MOS), the HP 113 design study was delivered in May 1958. In the accompanying letter, F. Handley Page noted that work with the RAE, the National Physical Laboratory, and the College of Aeronautics, Cranfield, along with US data, indicated 'clearly that the application of boundary layer control to transport aircraft is entirely practicable and would have the effect of considerably increasing the range for a given weight.'[79]

The benefits projected for LFC in the HP 113 study were substantial:

> A comparison between this aircraft in conventional and laminarised forms shows to good advantage the substantial range benefit from the elimination of a turbulent boundary-layer airflow. It increases the maximum range from 3,870 to over 6,300 miles. When operating with maximum payload the range with full allowances is increased by over 60 per cent from 2,240 to 3,640 miles.[80]

However, the MOS response was discouraging:

> I am bound to say that my first reaction is that the aircraft you are proposing is likely to be too expensive for us to consider solely on the research ticket – although I take your point that it may be the smallest to which boundary layer control could usefully be applied. On the other hand it seems to me very doubtful that the MOS will be able to sponsor it as a civil project.[81]

Nevertheless, the MOS enlisted RAE to provide an assessment, noting that 'despite the uncertainty of how we should be able to finance such a project it deserves a careful technical appraisal.'[82] A meeting was held in Whitehall on 24 June 1958 with participants from the Ministry and RAE. Also present was Sir Melvill Jones who 'stressed his conviction that laminarised commercial aircraft would eventually be developed.'[83] Although there was some scepticism about Handley Page's estimates of the benefits and costs of LFC, the bottom line from the Ministry's point of view was 'that there was little chance of finding the three million pounds which would be required to build and test the HP. 113.'[84] Flight testing of a laminarised half tail plane or wing were discussed as cheaper options and 'it was agreed that Handley Page should be asked to submit an estimate of the economic advantage of the laminarised airliner and to suggest less costly means of demonstrating its practicability than the building of the H.P. 113.'[85]

Further discussion with Lachmann continued in July, when it was confirmed that Handley Page was 'continuing with the design of the Midge wing with distributed suction on both surfaces' and would have detailed drawings and design detail by the end of the year.[86] Lachmann also described their work on understanding the problem that insects might pose for maintaining a LFC system in flight, particularly as regards the degree to which fly contamination would naturally be cleaned away in flight: 'The experiment consisted of firing live flies at the leading edge of a Victor wing, climbing to altitude and flying at high speed to erode the remains of the flies.'[87] Lachmann's belief was 'that flies collected at low altitude would be eroded sufficiently for laminar flow to be established at high altitudes.'[88]

The meeting also discussed 'possible cheaper methods of demonstrating the practicability of a laminar flow airliner than the building of the HP. 113.'[89] The need for cheaper ways of demonstrating LFC was also stressed in a September 1958 report from the MOS's Transport Aircraft Technical Committee:

> The money likely to be available for research aircraft in the next few years will support only the minimum essential programme. In view of this and of doubts

> about the economic advantages of boundary layer control in practice, less costly ways of investigating the problems must be considered and the firm are at present looking into this.[90]

Despite the scepticism of the MOS and RAE, Handley Page's endeavours were now strongly supported by the ARC Sub-Committee which noted that 'the outstanding need was for the application of suction to be demonstrated in a comprehensive flight experiment involving either the construction of a small aircraft such as the H. P. 113 or the extensive conversion of a long range jet transport.' Its preference was for the smaller aircraft 'on account of its lower total cost and shorter time scale and since it was thought likely to offer a more convincing proof of the benefits of laminarisation.'[91]

However, Handley Page's next proposed laminarised aircraft was, if anything, more ambitious. The HP 117 study produced in June 1960 not only made use of suction to maintain laminar airflow, but it also used a flying wing design. Whereas the main selling point of the HP 113 had been distance, the combination of laminarisation with a flying wing in the HP 117 was seen to offer a radical transformation in the economics of air travel. The HP 117 study thus envisaged a different technological vision for civil aviation to one that was based on ever increasing speed. In sync with that era's technological optimism, Handley Page acknowledged that supersonic air travel was 'a new and inevitable development', but it argued that its expense would only make it more exclusive: 'With costs at a level making air travel a luxury, passenger air transportation can be expected to remain the preserve of the expense account traveller or the wealthy, and a significant increase in air passenger traffic is unlikely without a correspondingly significant reduction in fares.'[92]

Handley Page argued that the HP 117's greater fuel efficiency could enable air travel for the masses: 'It is considered that conditions for general adoption of long range air travel would be met, if operating speeds of current jet transports are maintained with a spectacular reduction in direct operating costs.'[93] The HP 117 would achieve this through 'the full exploitation of low drag associated with laminar flow in combination with the low structure weight of the all-wing aeroplane.'[94] The all-wing design meant that the HP117 would not have passenger windows, as there was simply no fuselage in which to put them. Instead Handley Page proposed to replicate outside views by the use of televisions placed throughout the cabin:

> Because both of the all-wing layout and the need to apply suction over nearly all of the external surface, it has not been possible to provide windows for the passengers. It is intended that in lieu of direct vision from windows the passengers will be provided with a view from one or more suitable points on the aircraft by means of closed circuit colour television. It is believed that in this way feelings of claustrophobia will be avoided and that the really excellent view-point that can thus be provided will, in fact, constitute additional passenger appeal.[95]

Although the HP 117 was juxtaposed in contrast to the presumed technological trajectory of increasingly speedy aircraft, Handley Page's paper studies also extended to supersonic airliner concepts. One study showed that a fully integrated design could enable an increase of at least 25% in payload.[96] However, the ARC's Performance

Sub-Committee was also interested in the use of laminarisation on more conventional supersonic designs along the lines of Concorde, and recommended in 1962 'that a further study should be undertaken comparing a laminar and turbulent supersonic transport of the "Bristol" type carrying say, 100 passengers.'[97] Interest in applying LFC to supersonic aircraft would continue throughout the 1960s, though its usefulness remained contested with, for example, one 1969 report claiming that 'the benefits to be derived from the laminarisation of supersonic transport aircraft could be seen to be insignificant.'[98]

With the HP117 again having failed to gain development funding, Handley Page produced its final design study for a LFC aircraft in late 1966. Attempting to find a less expensive approach, this proposed a conversion of Hawker Siddely Aviation's successful small (6 to 8 seater) HS 125, described in 1964 as 'a business-man's transport.'[99] Handley Page's laminarised version, known as the HP 130, would retain most of the HS 125 design, but with the addition of laminarised wings and extra powerplants fitted under the rear of the fuselage to provide suction. The cost of providing one such aircraft was put at £4 million, and with the aim of demonstrating the feasibility of LFC it was argued 'that the proposed aircraft conversion probably represented the cheapest and quickest means of realizing these objectives.'[100]

But paper studies alone were not enough. Lachmann himself had summarised the situation in 1962, noting that 'various projects for laminarized research aircraft have been put forward but have shared the fate of so many other projects, gyrating once or twice through the prescribed tortuous course of committees, sometimes dying of sheer exhaustion even before the final coup de grace was administered by the controller of the purse strings.' The problem, Lachmann lamented, was that this 'malaise is symptomatic for British aviation': 'Available funds for research and development are restricted, of course, and the chances of official support of development are particularly poor for any scheme which is not completely cut and dried and for which no immediate requirement exists. No fundamentally new scheme, of course, can make such a claim.'[101]

Calculating the Incalculable

There was a Catch-22 situation. Funds to build an operational aircraft would only be forthcoming if an operational aircraft could demonstrate that the concept was effective in practice, but no such aircraft could be built without funding. As the ARC Sub-Committee 'noted with concern' in March 1965, 'despite its frequent reiteration of confidence in the application of boundary-layer suction, no aircraft has yet been built in this country to demonstrate the principle under actual operating conditions.'[102]

Further collection of empirical data on laminarisation in the UK was limited to tests with a Handley Page swept wing with suction that was both flown on a Lancaster aircraft at Cranfield and tested in the 13 ft x 9 ft wind tunnel at RAE Bedford.[103] An RAE report noted that 'although this relatively inexpensive experiment will provide useful aerodynamic background together with experience in suction wing construction and operation, its value as a confidence demonstration to aircraft designers and operators leaves much to be desired.'[104]

Throughout the 1960s the ARC's Performance Sub-Committee continued to recommend further work on LFC, without having the authority to provide the funds to do so. Its March 1965 review endorsed the 'previously expressed views of the Sub-Committee that at both subsonic and supersonic speeds, laminar flow aircraft appear commercially attractive and technically feasible.'[105] Its key recommendations were that 'the design study contract recently placed should be followed by the construction of an aircraft to demonstrate the effectiveness of boundary-layer suction at subsonic speeds under actual operating conditions'; that 'the work in progress or planned at NPL, RAE and Cranfield with the aim of obtaining a better understanding of the leading-edge contamination problem and of the most effective solutions should be pursued vigorously'; and that 'a programme of basic research on laminar flow at supersonic speeds should be undertaken.'[106]

However, given funding constraints this was easier said than done. The UK had great ambitions in aerospace and defence technology (including the Anglo-French Concorde supersonic airliner), but lacked the economic resources to fulfill them all. Even within the ARC's Aerodynamics Committee there was ambivalence about how to proceed. In June 1965, the Committee's secretary wrote that 'some criticism was expressed, by members not present at the previous meeting, of the wording of the recommendation made at that meeting … that an aircraft making use of boundary-layer suction should be built.' In effect, this ambivalence reflected the same doubts that had inhibited large-scale government support. The Committee did not want to commit to 'an aircraft which is unsatisfactory in some respects and which would not therefore be the best one to be built', but at the same time felt that 'when an acceptable design study has been completed, that aircraft should be built with as little delay as possible so that the effectiveness of boundary-layer suction at subsonic speeds may be demonstrated under actual operating conditions.'[107]

While the ARC's Aeronautics Committee was generally supportive of LFC, the RAE provided a more sceptical counterpoint. An April 1967 RAE report concluded that 'the future for subsonic laminar-flow aircraft looks bleak, unless there is a strong military case for extremely long range. The technique was not supported for civil use ten years ago, and advances in technology in conventional aircraft since then have tended to reduce its attractions.'[108] This report did not consider the use of flying wing type designs, such as the HP 117, but instead focused on two comparisons of aircraft with what was now considered the standard layout along the lines of the Boeing 707, one with suction laminarisation of wings and tailplane and the other without. One comparison involved aircraft with 1960 technology, the other with expected 1975 technology.[109] However, the key comparison emphasised by the RAE report was not between aircraft of the same vintage, but rather between the 1960 laminarised aircraft with the conventional 1975 one:

> A comparison between the estimated performance of a 1960 laminar-flow aircraft and a 1975 conventional aircraft is now revealing ... It shows that the performance of the 1960 laminar-flow aircraft is appreciably worse at all design stage lengths than that predicted for the 1975 conventional aircraft, and it suggests that unless design stages of even more than about 5500 nm are required by airlines, the continued development of the conventional aircraft will be able to cater for the growth in required range.[110]

The report conceded that for military applications, ‘if very great ranges (say, more than 7000 nm design stage) are required for transport purposes, the developed laminar-flow aircraft appears as a strong contender.’ But ‘for civil operation, all that can be said on the basis of the present estimates is that a laminar-flow aircraft, which was judged (rightly or wrongly) to be not worth proceeding with in the 1955-60 era, has not been made more attractive with the passage of time, and advances in conventional aircraft technology.’[111] The main reason for this was the increasing efficiency of turbofan engines that reduced the benefits of the aerodynamic efficiency offered by laminarisation.

The RAE’s econometric analysis of the costs and benefits of LFC involved many assumptions. As the report noted, there was a crucial ‘lack of experience in this country of operating such an aircraft under realistic operational conditions.’ Lack of knowledge from practical experience was a problem because ‘the benefit from laminar flow control depends on quantities which cannot be adequately tested by wind-tunnel, rig, or even research flight testing alone.’ As the report noted: ‘Unless practical experience is gained and satisfactory results demonstrated by transport operations over typical routes for a substantial period, it seems unlikely that any prospective user could be persuaded to select a laminar-flow aircraft.’[112]

By 1968 the end of the line had almost been reached. LFC work at NPL, RAE and Cranfield had ground to a halt, and in May the ARC’s Performance Sub-Committee reported that ‘no work is now proceeding; some items have been completed; others have been stopped.’[113] The Sub-Committee returned again to discussing the potential merits of LFC, and the apparent difference of opinion between the negative conclusions of the RAE and the optimistic analysis of Handley Page:

> Initially, the Sub-Committee was very concerned about these differences, but following discussion between RAE and Handley Page Limited, they have now been explained satisfactorily. Many of the assumptions in the two studies were in reasonable agreement but there were two main reasons for the final differences.[114]

One difference concerned cost assumptions – that ‘since 1959, there has been a relative decrease in fuel costs and a relative increase in crew costs’ – making fuel savings less significant. The other concerned the extra initial and maintenance costs that would be incurred by an LFC aircraft over those of a conventional aircraft.[115] The problem, as the Sub-Committee had repeatedly pointed out, was that hard evidence was not available:

> Clearly, some of these other figures must be regarded as purely arbitrary estimates and so, as on many occasions in the past, the discussions have highlighted the difficulties of making any accurate assessment of the possible performance advantages from laminarisation in the absence of reliable and substantiated data on manufacturing and maintenance costs.[116]

The Sub-Committee took issue with the RAE analysis in one particular regard – the comparison of a standard aircraft with a laminarised one *of the same layout* - noting that ‘the comparison should be made by designing the two aircraft completely independently – to find the best aircraft of each type to meet a specified requirement. This approach could have a marked effect on the conclusions.’[117] Nevertheless, the analysis suggested that the shifting cost assumptions, particularly 'the better specific fuel consumption expected from high bypass-ratio engines', had moved the crossover point (when a laminarised aircraft would make economic sense) from around 3500 miles to more like 5500 miles.[118]

Whatever the exact figures, the trend did not favour investment in a laminarised aircraft, and the Sub-Committee noted that it had 'been informed that at present, the Ministry of Technology foresees no civil or military requirement for an aircraft with a range of 5000 miles or more.'[119] Nevertheless, the Sub-Committee was reluctant to let go, noting that it 'appreciates that it is difficult in present economic circumstances to press for the construction of any research aircraft, but nevertheless, they urge most strongly that this decision not to proceed with any operational research aircraft for laminar flow should not be thought of as a final decision but rather, that it should be kept under regular review. Requirements have changed in the past and may well change again in the future.'[120]

LFC technology fared not much better in the USA, where more comprehensive flight-testing had been carried out. Starting in 1963, the Norair X21A swept-wing laminar-flow aircraft had completed 'about 110 flights with 360 hours in the air.'[121] The X-21, 'despite encouraging results from model tests in various wind tunnels', initially demonstrated no laminar flow in flight tests. The problem, it seemed, was turbulence emanating from the join of the wing to the fuselage.[122] These problems with span-wise contamination, as well as with surface smoothness, 'consumed significant periods for their solution.'[123] By the time this problem was solved, high level Air Force support had waned, perhaps because of the increasing demands of Vietnam, and the programme was cancelled, although the X-21 was by then achieving laminar flow over 95% of its laminarised surfaces: 'Unfortunately, top management in government and industry remembered the difficulties and time required to reach this point more than they did the accomplishment.'[124]

Postscript: Laminar Flow Control and Flying Wing Technology since the 1960s

While the UK had foregone its initial strengths in LFC research by the end of the 1960s, the concept was not dead in the USA. There was no immediate follow-up to the Northrop X-21 flight-testing because the potential benefits of LFC fitted no urgent requirements, whereas Vietnam posed a very pressing challenge for the US Air Force.[125] On the one hand, there was 'a lack of contemplated need for very long-range missions for commercial aircraft for which the benefits of active laminar-flow control were a *necessity'*, and on the other, 'the price of jet fuel was then so low that the estimated fuel-cost savings for commercial transports with ranges of interest was almost offset by estimated increases in manufacturing and maintenance costs.'[126]

This calculus changed with the 1973 'oil crisis', when the OPEC oil embargo resulted in a dramatic increase in the price of jet fuel. As a result, NASA established the ACEE (Aircraft Energy Efficiency) program.[127] Of the six major projects aimed at increasing aviation efficiency, one of the most radical was LFC. The task of the LFC group was in some ways more challenging than it had been in the 1960s test programme because now the aim was to develop technology that would be suitable for the civil airliner industry 'where manufacturing and operational costs are more important.'[128] The ACEE/LFC program carried out, and sponsored, a wide range of activities, from basic research to flight-testing, in order to establish the practicality of LFC. Key concerns included insect contamination and the consequent in-flight loss of laminarisation, along with maintenance costs. Flight tests on a relatively small aircraft demonstrated that LFC could be maintained over a portion of the wings under operational conditions that were typical of commercial airliners: 'during four years of flight testing from November 1983 to October 1987, no dispatch delays were caused by LFC systems.'[129]

Despite these findings, uncertainty over maintenance costs and potential in-flight loss of LFC deterred airliner manufacturers from using LFC.[130] Both Boeing and Airbus have flight-tested hybrid LFC, in which a combination of natural and active laminar flow control provides a more reliable, though less efficient solution than active LFC, and this was implemented on the Boeing 787-9 variant (Kingsley-Jones 2014; Goldhammer, 2010; Mecham, 2012).[131] Nonetheless, an airliner with extensive suction-LFC does not appear to be a near-term prospect.

The operational and economic arguments made against LFC in the 1950s and 1960s continue to militate against adoption of active LFC in airliners. Although there has been considerable testing of the technology, actual operational experience is lacking. Airline operators and manufacturers are wary of anything that might interfere with routine, frequent aircraft operation. The average airliner flies more than four times a day; some short-haul aircraft go through a remarkable ten cycles per day.[132] While the extra time and cost of maintenance could be justified by greater fuel efficiency, a more intractable concern stems from the worry that some flights – maybe a very small percentage – might suffer loss of laminarisation due to insect contamination or adverse weather conditions. The consequent loss of efficiency and thus range might mean that aircraft would either have to carry extra fuel – thus undermining the efficiency gains provided by LFC – or would have to be able to divert to airports short of their intended destination.

Different considerations inform the potential for a flying wing airliner, with or without LFC. In 1947 *Flight* magazine predicted that: 'Some day the flying wing will emerge as the accepted form of a passenger air liner.'[133] That day is not imminent, although the operational performance of the B2 bomber since 1997 means that the feasibility of the technology is no longer in doubt. Developed more for stealth rather than efficiency, the B2 nevertheless shows that fly-by-wire avionics negate earlier concerns about stability. However, the efficiency gains from eliminating non-lift structures in flying wing designs must be balanced by other disadvantages. The classic cylindrical airliner fuselage is well-suited to providing pressurised cabin space with minimal use of structural materials, whereas cabins that extend along the wings produce more complex geometries with a concomitant requirement for more structural materials that add to overall weight. In addition, flying wings big enough to accommodate standing passengers in the wings would be very large and heavy, and many airports could not handle such planes without expensive improvements. Moreover, the perception that passengers like to have windows (contrary to what was espoused in the HP 117 design) means that modern flying wing designs usually take the form of a compromised 'blended wing' in which there is sufficient fuselage to provide windows.[134]

Conclusion

Historical and sociological studies of technology have shown that many, often contingent, factors shape how some technologies emerge successfully from competing possibilities.[135] This history of LFC technology, intertwined with consideration of flying wing aircraft design, tells a tale that is familiar for post-war British innovation. The capacity of the UK's research base to generate new technological possibilities – many of them stemming from military R&D – appeared to outpace the ability of industry and/or the government to nurture those inventions to commercial maturity. Within this overall generalisation, there are illustrative examples that indicate the importance of both investment and market demand. The pharmaceutical industry proved successful in turning inventions into products, aided by British procurement mechanisms that ensured both a demand for its products and unusually high levels (for the UK) of R&D investment.[136] Elsewhere, as in the case of carbon fibre, the more typical problem in other sectors was that British industry struggled to match the consistent investment approach taken by key competitors.[137]

However, simply to lament 'short-termism' would be naïve because it is not always possible to judge how long it will take to turn a promising invention into a commercial success. For example, research done at the defence research establishments meant that between the 1960s and 1980s the UK was a world leader in compound semiconductors such as gallium arsenide. However, commercial success was elusive and for many years gallium arsenide was described with the well-known aphorism: 'the technology of the future, always has been, always will be.'[138] It was only a convergence of several other technologies that reached maturity during the 1980s and 1990s, leading to many unexpected digital applications, that created a large demand for gallium arsenide.[139] In effect, the UK had helped created the technology base for others to exploit, but the time between research advances and commercial opportunity was so great as to have required a 'long-termism' well beyond most governments, never mind industry.

In the case of aviation technology, government support and direction in the post-war years was framed by twin competitive rationales – one military, directed at the Soviet Union; the other economic, directed at the USA. These were mutually supportive with regard to underlying knowledge and enabling technologies, but also in competition for resources. The UK's post-war ambitions in military and aerospace technologies quickly came up against economic reality, with retrenchment by governments of both colours, leading to a catalogue of cancellations of aircraft projects.[140] Commercial success for civil airliners depended on large production runs because of the very high initial costs of design, testing, and production tooling, but without a compelling technological edge it proved hard for UK manufacturers to gain a significant share of the much larger US market (not helped by the disastrous crashes suffered by de Havilland's pioneering Comet airliner).[141]

Indeed, government investment in civil aviation rarely paid off, as shown by the oft-quoted data on the returns to government civil aerospace investment between 1945 and 1974 show.[142] Governments instead sought to justify investment in civil aviation on the grounds of economic 'externalities' that could not readily be quantified, such as employment, spin-off, or even national prestige.[143] Perhaps the most significant externality of all – that of the 'tragedy of the commons' – was not a consideration for these governments. It is now - and if the idea of a 'climate emergency' is to be taken seriously, innovation in aviation technology should no longer be considered in terms either of narrow economic costs or nationally focussed benefits.

The question remains as to whether LFC technology (perhaps in combination with a flying wing design) can still have a role in greener aviation. Should LFC be considered a failed technology, or just one that has not succeeded yet? Technologies that fail - what have been termed 'extinct innovations' – can be revived when social conditions become more suitable.[144] This history shows how the proponents of LFC faced an insurmountable Catch-22 situation whereby funding to develop an operational aircraft could only be obtained if operational efficacy had already been demonstrated.

If anything, recent decades have seen such barriers to entry become even stronger for the commercial uptake of new technologies by civil aviation. In the immediate post-war years a variety of designs appeared possible, but the more that the paradigmatic Boeing 707 type airliner gained acceptance, the more difficult it became for radical potential entrants to break into the market. Alongside a growing consensus amongst airlines and their customers about what an airliner should look like, there also developed a number of path dependence effects that helped to lock in the established paradigm and lock out less conventional designs. The paradigmatic airliner approach benefitted from the 'increasing returns' that accrue from well-funded R&D and from 'learning by doing' in design, manufacturing and operation, while alternative aerodynamic designs were relatively neglected.[145] Similarly, there are 'network externalities' involved in the infrastructure of aviation (the physical structure of airports and supporting maintenance facilities) that can militate against other aerodynamic approaches, such as large and heavy flying wings.[146]

Perhaps the most significant of these path dependence effects stems from concerns over safety. It is a moot point as to whether the Comet would have presaged enduring commercial success for the UK aviation industry, but its catastrophic failures due to metal fatigue not only led to the establishment of new testing methods for airliners, but also provided a salutary lesson in the risks of reputational damage. This culture of safety (recently undermined at Boeing to its great cost[147]) became embodied in a regulatory environment that has been remarkably stable over the last fifty years, and persistent in promoting risk-averse incrementalism.[148]

In contrast, any pressures to improve environmental performance, particularly as regards fuel efficiency have been notoriously fickle. While fuel efficiency has always been desirable, the fluctuating price of fuel has favoured innovation focussed on small, predictable gains from improving familiar technologies. Radical, but potentially more efficient, approaches have mostly failed to move beyond R&D.[149] For many years, the only significant environmental considerations concerned the impact on those living nearby airports, with solutions to address local air pollution and noise often leading to engine designs that were less fuel efficient.[150]

Concern about climate change has now brought 'green aviation' firmly onto the agenda, potentially changing what counts as important in aircraft design. This has revived R&D, with for example funding provided 'to support NASA's environmentally responsible aviation program.'[151] However, fluctuating oil prices continue to mean that airline companies and airliner manufacturers have no stable rationale for adopting radical solutions to achieve greater fuel efficiency. As one account notes: 'Although since the 1960s the level of interest in laminar flow has fluctuated with the price of oil, the price has never stayed high enough for long enough to persuade any aircraft manufacturer to take the plunge.'[152]

Whether or not LFC and/or flying wing airliners are part of the solution, the commercial uptake of radical greener aviation technologies would thus seem to require a substantial reshaping of the societal context in order to align commercial interests with those of the environment. Perhaps the last word should go to Gustav Lachmann, whose advocacy of laminar flow control was frustrated during his lifetime: 'Non-conformists never have an easy life, in fact it can become very frustrating in this era of take-over bids and the "Corporation man". But I venture to suggest that in the past they often contributed to important reorientations of thought and development – and not only in Aviation.'[153] Clearly, in an age of 'climate emergency' there needs to be a radical reorientation of thought so that the commercial 'realities' of the 'Corporation man', that have stymied the adoption of radical technologies such as LFC and flying wing aircraft, are no longer seen as the most pressing realities.

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