Pearcey, Newby, and the Vulcan

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ABSTRACT

In 1955 flight testing of the prototype Avro Vulcan showed that the aircraft's buffet boundary was unacceptably close to the design cruise condition. The Vulcan's status as one of the two definitive carrier aircraft for Britain's independent nuclear deterrent meant that a strong connection existed between the manufacturer and appropriate governmental research institutions, in this case the Royal Aircraft Establishment (RAE) and the National Physical Laboratory (NPL). A solution was rapidly implemented using an extended and drooped wing leading edge, designed and high-speed wind-tunnel tested by K W Newby of RAE, subsequently being fitted to the scaled test version of the Vulcan, the Avro 707A. Newby's aerodynamic solution exploited a leading edge supersonic-expansion, isentropic compression* effect that was being investigated at the time by researchers at NPL, including H H Pearcey. The latter would come to be associated with this 'peaky' pressure distribution and would later credit the Vulcan implementation as a key validation of the concept, which would soon after be used to improve the cruise efficiency of early British jet transports such as the Trident, VC10, and BAC 1-11. In turn, these concepts were exploited further in the Hawker-Siddeley design for the A300B, ultimately the basis of Britain's status as the centre of excellence for wing design in Airbus.

Abbreviations

BS	Bristol Siddeley	L	Lift
D	Drag	M	Mach number
C_L	Lift Coefficient	NPL	National Physical Laboratory
C_p	Pressure coefficient	RAE	Royal Aircraft Establishment
$C_{p\cdot te}$	Pressure coefficient at trailing edge	RAF	Royal Air Force
c	Chord	Re	Reynolds number
G	Load factor	t	Thickness
HS	Hawker Siddeley	WT	Wind tunnel
HP	Handley Page	α	Angle of Attack

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* When the airflow past an aerofoil accelerates its pressure and temperature drop, and vice versa. Isentropic means at constant energy without frictional losses. Supersonic expansion / isentropic recompression refers to a low pressure peak close to the leading edge in a region of supersonic flow, followed by deceleration and rising pressure to reduce the severity of the shock that slows the flow to subsonic.

1 INTRODUCTION

1.1 2015 - A communication

In 2015, Dr Robert Pleming in his capacity as Chief Executive of the Vulcan to the Sky Trust *, made contact with Professor Herbert Pearcey, whom he had been advised had been involved in the design of the Vulcan and particularly the leading-edge modifications, widely known to have been embodied to improve buffet performance. The resulting brief correspondence between them included Pearcey's own description of his actual involvement, which concluded with a remarkable implication – the Vulcan's redesigned leading edge was a point on the development path to the supercritical aerofoil.

> "Our back-room research received quite a boost from retrospective tests on two-dimensional aerofoils by comparing the flow for the section normal to the leading edge of the Vulcan in its drooped form as designed by Ken Newby of the RAE with that for the original. The drooped leading edge produced the rapid "peaky" supersonic acceleration that, after reflection with change of sign at the boundary between locally supersonic and subsonic speeds in the outerflow, helps to reduce the strength of the ultimate shock wave.
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> "It was the understanding and exploitation of this phenomenon that was to lead us ultimately to the supercritical wing sections that are now commonplace on most civil airliners (1)."

The aim of this work is to place these first-hand views, as expressed by one of the key participants, within the context of other published work on the Vulcan. The popularity of the aircraft and its central position within the story of the Cold War period has ensured that there is no shortage of written material on its history, but this incidental contribution to the efficiency of the subsonic transport aircraft that would follow has rarely, if ever, been commented upon.

1.2 1952 - A problem appears

The white-painted prototype of the Avro 698 (VX770) first flew under the famously pin-stripe suited command of Chief Test Pilot Roly Falk in August 1952. Barely three weeks later, it appeared in public at RAE Farnborough, for one week annually the venue of the SBAC airshow and, on a more permanent basis, the Royal Aircraft Establishment (RAE). It was far from the only new and futuristic British aeroplane to be demonstrated, but its dramatic triangular shape (see Figure 1), sheer size, and startling performance made it newsworthy. The limits of technology were ever present though; the week is also remembered for the breakup of the DH110 and the loss of its crew, together with 29 spectators on the ground. These would remain the most recent spectator fatalities at a UK airshow until, with tragic coincidence, the year of the final airshow appearances by a Vulcan, in 2015.

Development of the airframe had run ahead of that of the definitive Bristol Olympus engines around which the aircraft was planned. VX770 therefore flew initially with Rolls-Royce Avon power, providing only around 70% of the static thrust anticipated for the production aircraft. This

* The Vulcan to the Sky Trust is a registered charity that returned the final airworthy Avro Vulcan, XH558, to flight and operated the aircraft between 2007 and 2015.

obviously limited the extent to which the flight envelope could be explored, but by July 1953 VX770 had graduated to Armstrong Siddeley Sapphire engines, to be followed rapidly in the September by the second aircraft (VX777), equipped from the start with Olympus 100s. The latter began the process of finding the limits at altitude and high Mach numbers, unfortunately halted by a heavy landing in July 1954. It fell to the first prototype, catching up in thrust, to confirm that the buffet boundary at cruise was inadequate. Stuart Davis, Chief Designer for the Avro 698, commented with some understatement,

> "With the straight leading-edge of the prototype it was apparent that the performance boundary of the production Vulcan aircraft with later versions of the Olympus engines would be uncomfortably near the high Mach number buffet threshold. It was considered that modifications could be made to the wing planform in the region of the outer portion of the wing." (2)

In fact, this was severe enough to prevent the aircraft achieving a combination of lift coefficient and Mach number that would allow the mission requirements to be met, in terms of speed and height over target, let alone manoeuvrability. Although the issue was not identified in the wind tunnel test programme, it had become apparent in the early testing of the high-speed version of the delta test aircraft, the 707A. In the slightly stronger words of Avro test pilot Tony Blackman, "unless this buffet could be cured, the aircraft would be of no use as a bomber." (3)

Figure 1. Vulcan prototype VX770, probably at Farnborough in 1952. The aircraft has the baseline planform wing, with straight leading edge. (Joe Barr Collection)

In reality, the buffet boundary was extended sufficiently by the incorporation of new outboard wing leading edge. This was aerodynamically designed by K W "Ken" Newby of the RAE at Farnborough. In Figure 2, this modification is illustrated on the 707A one-third-scale high-speed test aircraft. The general arrangement drawing shows the aircraft in its original form, with a very highly tapered 50° LE swept delta planform. This can be compared to the photograph of the first of the two 707As, which first flew in late 1951. The pronounced leading-edge kink is clearly visible, caused by the almost constant chord extension of the outboard-most region, blending back in plan view. The apparent simplicity, which was certainly true from a mechanical perspective and enabled the rapid implementation of the substantial modification into the production line, perhaps masks the aerodynamic complexity of the solution. The resolution is specifically referenced by Küchemann in his (albeit, posthumous) manifesto, The Aerodynamic Design of Aircraft (4). Discussing the challenge of transonic swept wing aircraft, he noted that

> "…. no improvements in numerical and experimental design tools are ever likely to dispose of the need for physical insight. On the other hand, a good understanding of the flow phenomena involved has led to successful designs even in the early days when the available design tools were still rather poor. An example of this kind is the modification of the wing of the Avro Vulcan aircraft by K W Newby (1955), which effectively converted the original delta wing into a wing where sweep effects were successfully exploited."

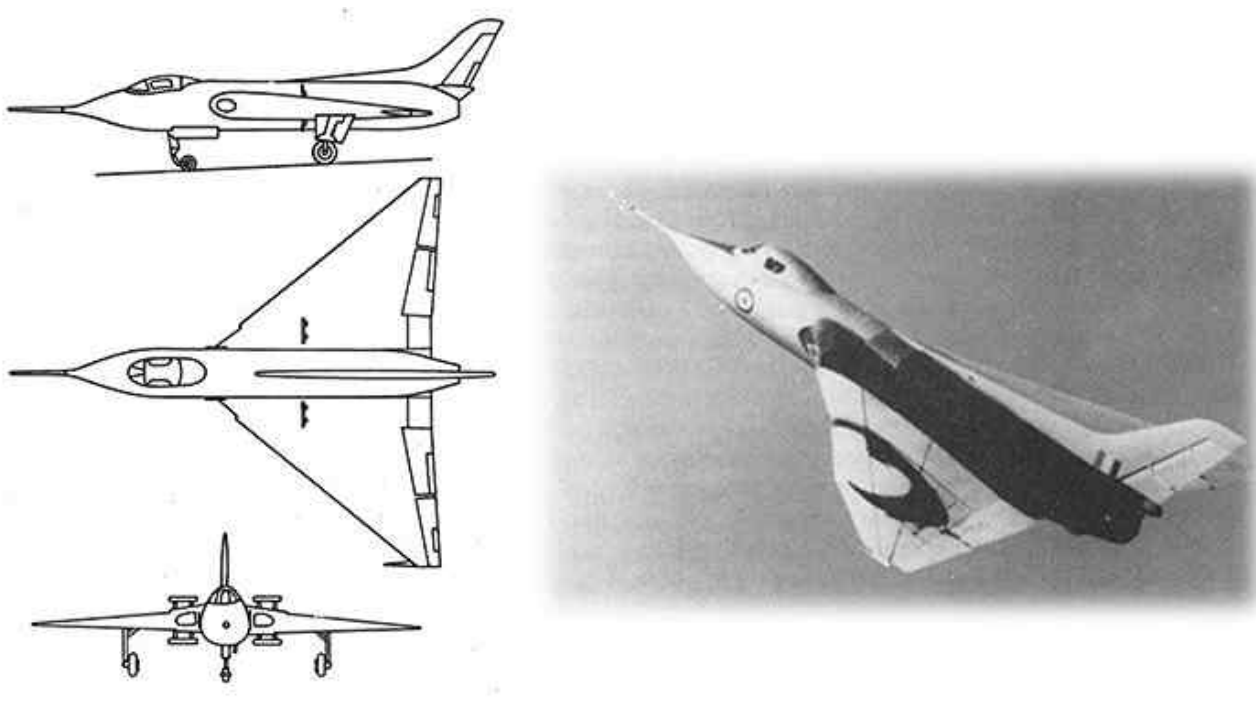

Figure 2. Avro 707A, (Left) three view GA drawing in original condition (5) and (right) WD280 in flight, when fitted with Phase 2 leading edge modification (6)

It might have been justifiable for the earlier RAE contributors to the aircraft's aerodynamics to feel aggrieved at the implication that Newby alone had made the Vulcan work, while of course Küchemann himself had been deeply involved in the design of the Victor. A former wartime Blackburn Aircraft apprentice, Newby was a contemporary of two others who would subsequently forge very notable careers in the British military aircraft industry; Alec Atkin and Ralph Hooper, known respectively for their work on the Lightning and Harrier in particular.

Hooper would say of their time at University College Hull, "I think really Ken Newby set a particularly high standard and the rest of us had to try and be competitive. He did go into the scientific civil service, waste of a good man but there we are." (7)

2 THE TECHNOLOGICAL CHALLENGE

2.1 Brief view of early Vulcan aerodynamic development

Although well covered elsewhere, it is worth including a brief description of relevant aspects of the Vulcan's early development. A key resource in the academic record is the 14th Chadwick Memorial lecture given by former Avro Chief Designer Stuart Davis to the Royal Aeronautical Society's Manchester branch in March 1969.(2) As he spoke, Vulcan B2s stood on active nuclear alert at RAF Waddington and RAF Scampton in Lincolnshire in the UK, the latter equipped with the Blue Steel stand-off missile. Two further squadrons were in the process of transferring to RAF Akrotiri in Cyprus to bolster the nuclear capability of the RAF Near East Air Force (NEAF). Change was in the air however, or perhaps more accurately under the sea, where some nine months earlier the Royal Navy's first Polaris submarine had commenced her maiden patrol. It was envisaged that the Vulcan would remain in service until 1975 supporting the primary Royal Navy deterrent, but the rest of the V-force had already gone. Critically weakened by stress corrosion cracking of the DTD683 alloy in its wing structure, the interim Vickers Valiant had achieved its objective of providing a credible strategic nuclear delivery capability as early as possible. By 1965 when its metallurgical problems became apparent, it was not worth the investment to repair a fleet that had largely transferred to secondary roles such as air-to-air refuelling (AAR), reconnaissance, and tactical nuclear strike.

The Vulcan's competitor for the B35/46 specification,† the Handley Page Victor, had also left the deterrent field. The Sapphire-powered B1 fleet had moved into the Valiant's AAR role, while the extremely capable but small B2 fleet had suffered from rapid fatigue life usage in the Hi-Lo-Hi mission profile that the V-force had been forced to adopt. In 1968, the two Victor bomber squadrons were disbanded and the aircraft stored pending their conversion to tankers. Ironically, the collapse of Handley Page (HP) would see this work undertaken by Hawker Siddeley at Woodford, where the Vulcans had been built originally.

To have any hope of meeting the B35/46 specification, exploitation of aerodynamic technology specifically designed to operate in the transonic, high Reynolds number regime was required. The understanding of swept wings was in its infancy, while suitable wind tunnel facilities were also in short supply. The low-speed requirements were implied from a requirement for relatively stringent field performance, allowing operation from standard RAF Bomber Command airfields. These, coupled with a desired maximum gross weight of 100,000 lb, were primary drivers towards the unusual configurations of the Avro and HP designs.

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† B35/46 was the Air Ministry specification for an aircraft to meet Operational Requirement (OR)229, with five companies invited to tender on 9th January 1947(59). Amongst other requirements, this called for a 500 kt cruise speed and height over target of 50,000 ft [15,240 m] (equivalent to M = 0.875 at standard conditions), with a combat radius of 1500 nm. A number of loads were specified, although at this stage the requirement was not exclusively for a nuclear weapon delivery system. The Valiant was built to the less rigorous B9/48.

The Avro proposal evolved from a logical starting point in early 1947 as a relatively conventional high aspect ratio, 45° swept and 12% thick wing and tail aircraft, targeting a maximum C_L of 0.2 for the cruise. The relatively high sweep angle (compared to subsequent aircraft designed for similar cruise Mach number) was presumably a mitigation for the thickness of the wing, in turn a structural requirement. The perceived impossibility of meeting the weight requirement, together with the inherent longitudinal stability and control capability of the swept wing, led to the investigation of an otherwise similar tailless layout. This was, ironically, the position from which HP had started their own B35/46 jet bomber development, having studied the tailless configuration as part of a wartime large piston-engined bomber development programme.(8) However, from here the paths taken by the two companies would diverge. Both had significant concerns over the ability of the tailless design to meet the specification and that the development directions necessary would invalidate the strategy. These would include:

- The tailless design would inevitably lack longitudinal damping compared to one with a tailplane. (9)
- The relatively large speed range implied a requirement for a powerful high lift system. This would inevitably create a large nose down pitching moment, itself exacerbated as the load would be biased inboard and hence (due to the sweep angle) forward. This would be challenging to trim without a tailplane.
- The effect of wingtip stall would be exacerbated by the additional sweep angle necessary to provide sufficient moment arm for longitudinal stability and control; it would cause a relatively larger movement forward of the centre of pressure. This was a major issue for an aircraft required to manoeuvre near its service ceiling and subject to transonic aerodynamic effects.
- The weight benefit of the tailless configuration was still unlikely to allow the specification to be met without a significant step in weight efficiency of the structure.

HP's concern with tip stall led them to develop the Crescent Wing, in which sweep angle was traded for reduced thickness outboard. This had the dual effect of reducing the tendency of the tips to load up and also positioning them physically closer to the centre of gravity, reducing the pitching effect of a tip stall. However, the accompanying reduction in the total longitudinal dimension of the wing (root leading edge to tip trailing edge extent on the longitudinal axis) then made a tailplane necessary for stability and control, in turn allowing trim at high lift.

Davis made it clear that the initial drive to the delta planform at Avro was structural; the region behind the wing was simply "filled in" and aspect ratio reduced to retain the same wing loading as the tailless design. J R Ewans, Avro's Chief Aerodynamicist, gave a more detailed description in a contemporary article (10) (pre-dating the first flight of the 698 prototype), highlighting four design aspects as aerodynamic drivers towards the delta;

- Sweep
- Thinness [*sic*]
- Low Aspect Ratio
- Low wing loading

Both Ewans and Davis recognised in their writing that by keeping lift coefficient, parasitic drag, and structural weight low, the penalty of low aspect ratio on induced drag could be paid for. For Avro, this was attractive as it offered a way of using a conventional structural design and construction method, which was likely to prove inadequate in yielding the stiffness needed by high aspect ratio configurations at acceptable weight. HP used a spot-welded honeycomb structure for the Victor wing, a pioneering application which required considerable time, effort, and at least one restart to make ready,[11] while the projected delta's inherent stiffness was something of a short cut. Nonetheless, it is clear that Avro viewed the proposed delta aerodynamically as a low aspect ratio, high taper ratio swept wing; there was no philosophy of exploiting controlled leading-edge separation and the slender wing aerodynamics that were still in the future.

Three substantial changes were made during the final development phase using the understanding of three-dimensional transonic wing design that was being concurrently generated. Notably, these all featured inputs to varying degrees from the RAE into Avro's design team:

- Across the central plane of the aircraft (or indeed wing), the geometric sweep angle must pass through zero. The important effects of this on the spanwise isobar formation and seeding of the rear shock was a hot topic and Avro used the advice (usually attributed to A B Haines of RAE) on sweeping the maximum thickness well forward in the inboard region.[2] The strategy also required taper of the thickness/chord ratio over the span of the wing, with the rate being highest near the root.[12] Ultimately, this manifested itself as a 12.3% thick bespoke inboard section, with maximum thickness line displaced well forward to about 15% chord. The t/c taper was achieved by blending back to the existing 10% section outboard of the engine bays, then a very subtle taper down to a tip thickness of 8%. The decision to proceed with this change was made in late 1949 and the 707A high speed test vehicle was delayed in order to ensure this feature was incorporated.

- The inboard spanwise sweep was aided further by data from RAE High Speed WT tests on alternative configurations of the engine intakes. As the design coalesced in 1948-49, the inlets evolved from the large single pitot design of the original proposal, to a squared off plan view projection ahead of the wing root and rectangular slots, each feeding a pair of engines. In the relevant RAE tests, compared to fuselage side nacelles (of which the pitot inlets were essentially a form of), the squared off inlets were found to provide an effective sweepback improvement equivalent to 10° over the inboard 10 - 30% semi-span, while a similar arrangement retaining the leading edge sweep of the wing for intake lip increased this increment to 22°. The result was an increase in critical Mach number from 0.85 for the squared off inlet, i.e., below the specified cruise M, to 0.94 for the swept leading-edge inlet. This was not for free; the ram pressure recovery was reduced by nearly 5%, but it was also shown that ducting the fuselage boundary layer away from the inboard wall recovered most of the deficit. At the point of design freeze therefore, the swept leading-edge inlets had been adopted and would incorporate a boundary layer splitter and inboard bleed duct.[13]

- Control effectiveness through the flight Mach number range was also investigated in the High Speed WT, leading to an incidental planform change. Early studies show pointed tips, i.e., a true delta planform with tip chord reducing to zero. The RAE tests showed the benefit of finite tip chord (with a taper ratio of 0.115), particularly in the situation of control deflection. For a given lift coefficient, the local lift at the tip was reduced, alleviating tip stall and improving the linearity of the pitching moment characteristics. This modification was an improvement under cruise conditions and therefore carried forward.(14)

As Figure 3 reveals, the changes in the configuration between the proposal of April 1949—by which time the Avro 698 had moved away from its initial flying wing configuration to a thinner delta wing and fuselage—to the final design were drastic.

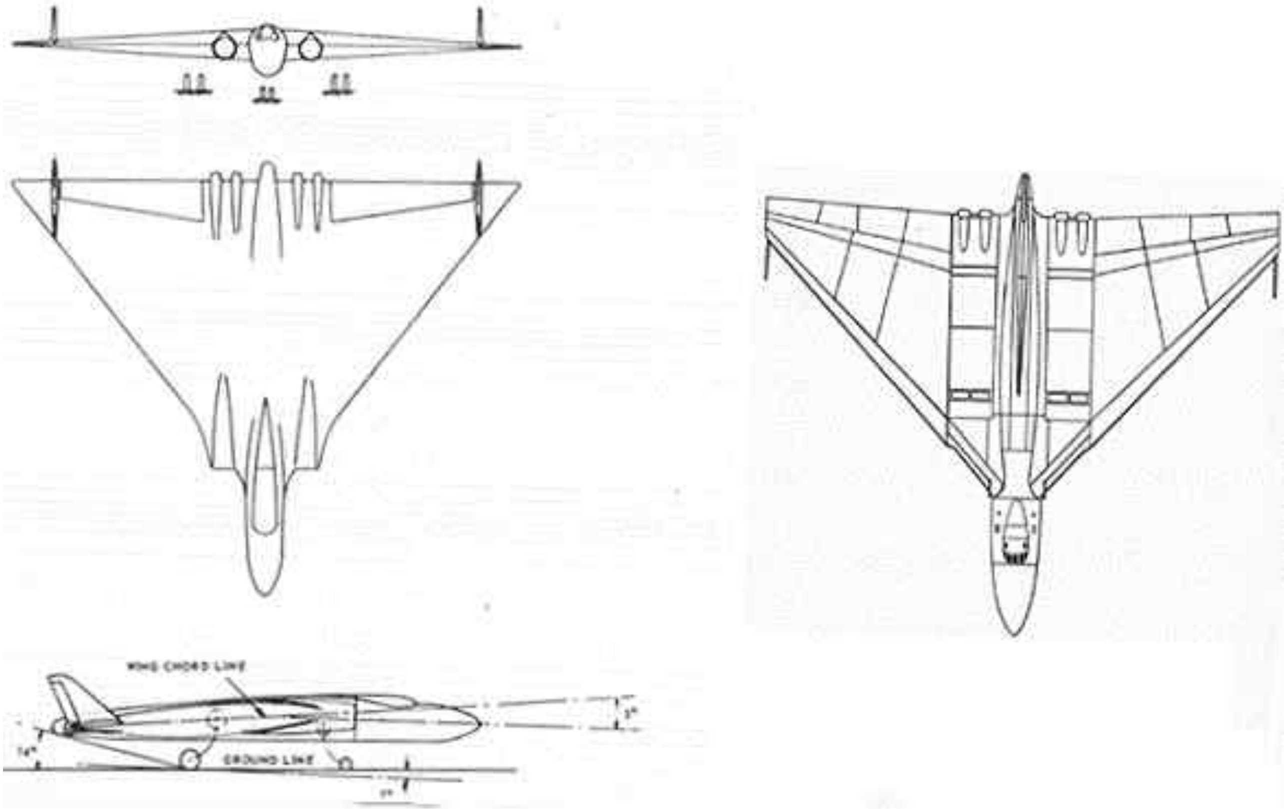


Figure 3. Development of Vulcan geometry. April 1948 (Left) (2) and approximately April 1950 (design freeze for prototype) (right)

2.2 Aerofoil design

The process of wing design in the period immediately prior to the issue of B35/46 rested on the ability to translate 2D aerofoil section information into a 3D world that accounted for planform effects. For classical straight-wing aircraft, the calculation of the aerodynamic loads to compare wing planforms during design was a perhaps surprisingly new but well-established technique. For the wings of moderate to high aspect ratio in use for typical piston-engined bomber aircraft, the use of the available catalogued aerofoil sections such as the NACA 230xx in the Lancaster (1941) provided adequate, documented aerodynamic performance together with structural pragmatism, at an acceptable level of research and development cost.

The emergence of an additional dimension to the problem, that of compressibility, was a challenge to this order. The linearity of the aerodynamic loading with dynamic pressure disappeared as sonic flow was established, continuing to vary in a manner that was certainly much more difficult to predict, as the discontinuities in the pressure field allowed by the presence of shock waves themselves moved with Mach number. This was not to say that information on flows affected by shock wave formation was not available; on the contrary, high speed piston-engined fighter aircraft deployed towards the end of the Second World War encountered the effects of compressibility and some results from pressure plotting in flight tests had been generated.(15) Notably, while work in the United States at the National Advisory Committee on Aeronautics (NACA) was focussed on laminar flow aerofoils for reducing drag at high speed, the importance of Mach-number effects (coupled with some scepticism about the practicality of laminar flow in service) was seen as most significant in the UK.(16) To some extent, this was driven by the increasing possibility of achieving transonic cruise speeds, through the advent of gas turbine propulsion, the progress on which was only revealed to NACAs aerodynamicists in 1943.(17) The new problem therefore was to design aerofoils that would behave in a manner that was sufficiently linear to be useful while minimising the wave drag caused by the entropy rise associated with the presence of shocks. In the words of Prof D W Holder looking back on this period in 1964:

> "Largely because the sections for which compressibility effects were first studied were designed on the basis of low-speed performance, they were thick and unsuitably designed for high-speed operation. The notorious difficulties of a direct theoretical attack, even for inviscid flow, were thus reinforced by viscous and scale effects that are now known to be large …" (18)

Pearcey himself commented on the value of aerofoil research and how it should be targeted:

> "... it should be aimed at the derivation of chordwise distributions of thickness and loading which in combination will produce a favourable chordwise distribution of velocity and at the same time meet the structural and lifting requirements." (19)

The use of symmetrical aerofoil sections rather than those 'properly' cambered and aligned for the design lift coefficient was in keeping with the advice of the RAE. The approach of designing an aircraft with full plan view symmetry (for which symmetrical aerofoils were an enabling technology) was promoted as a mitigation for the trim changes encountered as sonic conditions were encountered.(20) Symmetrical aerofoils were "known" to give the lower profile drag at low lift coefficients, smaller change in pitching moment with Mach number, and a numerically small value of C_{mo}. This conclusion had also been drawn with a NACA summary paper on high-speed aerofoils from 1948 concluding that camber was not beneficial for L/D at flight above M = 0.73. In turn, this analysis was partially based on German data, which itself showed that L/D continued to increase in this high subsonic range as camber became negative. Remarkably, and freely admitted by its author John Becker, the progression beyond symmetrical to negative was assumed to be impractical and ignored. It was thought that the relatively forward location of the upper surface shock wave on a symmetric aerofoil occurring in a thinner boundary inherently more resistant to separation was the mechanism at play. In retrospect, it was realised that this was an early and unrecognised application of the "peaky" mechanism, which Becker himself attributed to Pearcey.(21)

Consequently, Avro would have used the best information that they had available (while accepting that it was incomplete), coupled with advice from the government agencies in their aerofoil selection. As the 698 approached design freeze towards the end of 1949, this had settled on the four digit NACA symmetrical profile at a thickness of 10% (NACA 0010). The rationale of this choice, as opposed to the more recently designed British high-speed aerofoils of the Squire series (for example), is less immediately obvious. These were designed to give a gradual, favourable pressure gradient; the relatively low magnitude suction extended over a long region of the chord towards a rearwards peak, giving rise to the "rooftop" description of the pressure distribution. A comparison of the geometry and zero lift, incompressible pressure distributions of the NACA 0010 and RAE 101 (originally Squire B) is given in Figure 4, extracted from an RAE report by Newby, Haines, and Capps,[22] that describes the wing redesign work undertaken in 1949.

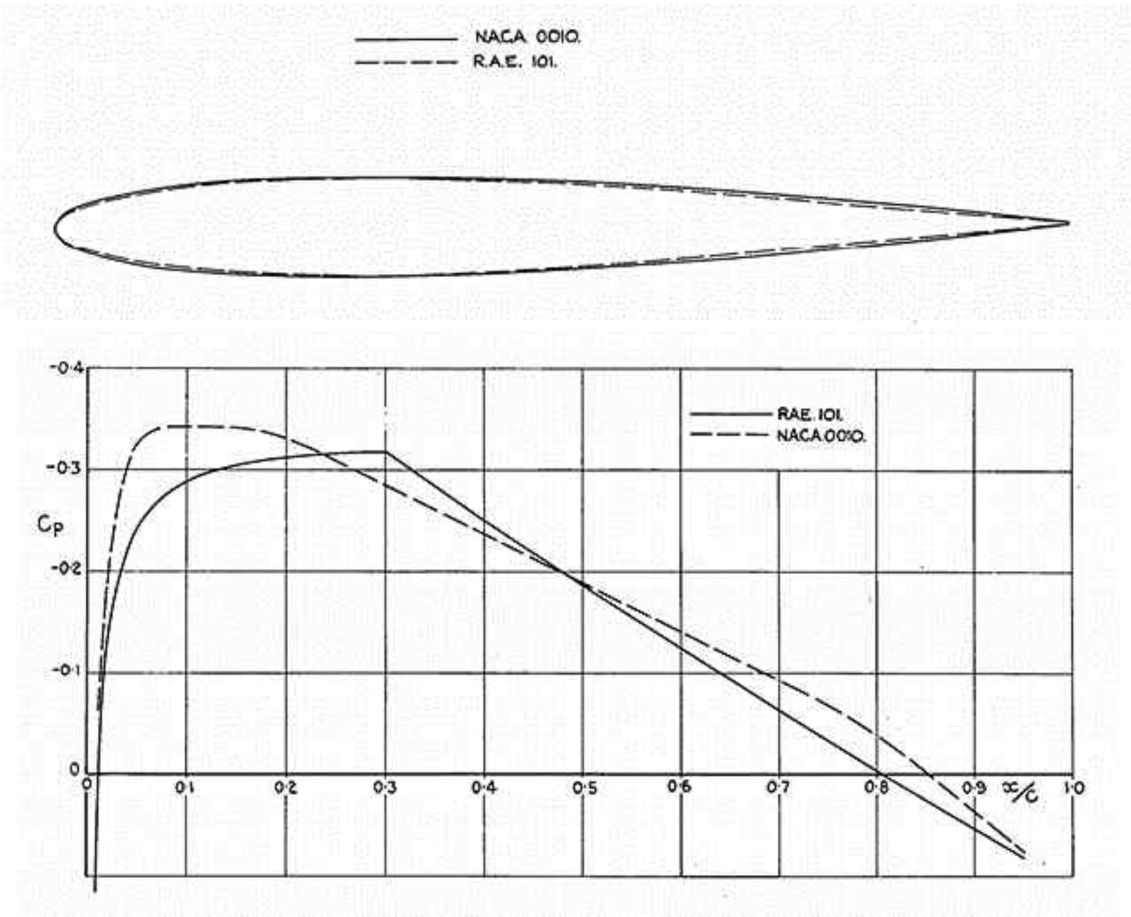


Figure 4. Profiles (top) and pressure distributions at $C_L = 0$ for NACA 0010 and RAE 101 aerofoils, as used during Vulcan development work at RAE Farnborough [22]

Although both sections had maximum thickness at around 30% chord, the peak suction on the RAE 101 is intentionally further aft, with the pressure recovery commencing at around 30% chord compared to 17% chord for the NACA 0010. Here, the three-dimensional effect of the Vulcan's delta wing came into play. The geometric sweep (i.e, the lines formed by plotting constant percentage chord) gradually reduces from ~50° at the leading edge to less than 10° at the trailing edge. Assuming the isobars (lines of constant pressure) would approximately follow the geometric chord, the further aft peak suction of the RAE 101 section would generate an isobar that was less swept, hence analogous to operating at an increased Mach number. At the low lift coefficient levels typical of cruise for the Vulcan, this might be expected to manifest itself as causing the drag rise to occur at a lower Mach number, which a comparison between similar planforms using the two sections did in fact show in the wind tunnel. This difference reduced as lift coefficient was increased and the peak suction naturally moved forward, such that at $C_L = 0.2$ there was little to choose. The report observed that in a general case (i.e, an aircraft with a design point at a higher lift coefficient or with a wider intended operating/manoeuvre range) the RAE 101 would be the better choice.

The reduced level of peak suction of the RAE 101 was primarily of interest for another reason however: protecting the outboard wing from tip stalling. Because the sectional lift coefficient outboard would naturally be higher due to the effects of sweep and planform taper, the British design would more often be operating above the cross-over threshold in drag divergence with the NACA 0010, allowing it to play to its strengths. The final design incorporated this section therefore, at 8% thickness at the tip.

What could certainly be said about both sections was that, in spite of the relatively good high Mach performance of the RAE 101 (like the analogous NACA 6 series), they were designed firmly with incompressible operation in mind. They worked to mitigate the effects of compressibility rather than exploiting the potential of the flow physics that was found in the transonic regime. In the words of Ramaswamy,

> "The main disadvantage of a conventional aerofoil is that the development of supersonic region on the aerofoil is associated with strong shocks and consequently there is a rapid drag rise beyond [the critical Mach number] and also buffet due to separation caused by shock boundary layer interaction" (23)

The unpleasant discovery of the inadequate buffet boundary on the final design showed the importance of this distinction and highlights the advanced thinking of the Pearcey's underlying flow physics in Newby's solution.

2.3 Working with the Transonic flow

The implied cruise Mach number from the B35/46 specification made localised supersonic flow an inevitability for practical combinations of wing thickness and sweep. Acceleration of the flow close to the leading edge would give rise to a closed "sonic boundary", because at some point ahead of the trailing edge compression back to the external subsonic conditions would have to occur. In a purely supersonic flow, this would have happened at the trailing edge itself via a shock wave – a simpler and more predictable state of affairs. However, in transonic flow the presence of the shock at some intermediate position along the chord, variable with Mach number and incidence, would certainly result in wave drag due to the increase in entropy and loss of total pressure across it, but also potentially in flow separation behind it.

Referring again to Ramaswamy, (23)

> "However, Pearcey (19) in UK showed experimentally that nearly shock-free flow over aerofoils could be developed, and significantly, he showed besides, that small perturbations either in geometry or in free stream Mach number would result only in small changes in the flow field. He also gave a physical picture of how the development of supersonic flow depended on the curvature distribution of the aerofoil in that region and consequently how the contour could be modified to support a shock-free flow. This was a crucial and important development which gave a tremendous fillip to the revival of transonic aerodynamic research throughout the world."

The realisation of Pearcey and his colleagues at NPL was that the sonic boundary might offer a method to partially mitigate the effects of the shock wave by a combination of increasing leading edge thrust through rapid supersonic expansion, and, subsequently, controlled isentropic recompression to reduce the local Mach number and hence the strength of the shock when it occurred. Figure 5 shows, on the left, a segment of the leading edge of a typical aerofoil in transonic flow.(24) The stagnation point (at which the flow is brought to rest and divides to pass around the upper and lower surfaces) would be somewhere on the lower side assuming a lifting configuration, resulting in an accelerating flow around the highly curved leading edge to a supersonic suction peak. From this point, further acceleration takes place through weak expansion waves while the surface curvature remains high. It is the reflection of these waves from the sonic boundary, resulting in compression waves, that is the critical mechanism. By abruptly reducing the surface curvature, the supersonic expansion is halted, limiting both peak velocity and the chordwise extent of the supersonic region. Instead, the low surface curvature causes the relative strength of the compression waves to be dominant and, so long as they do not coalesce, a region of isentropic compression can exist. This relationship of curvature and velocity is shown in a schematic form in the right-hand plot of Figure 5.

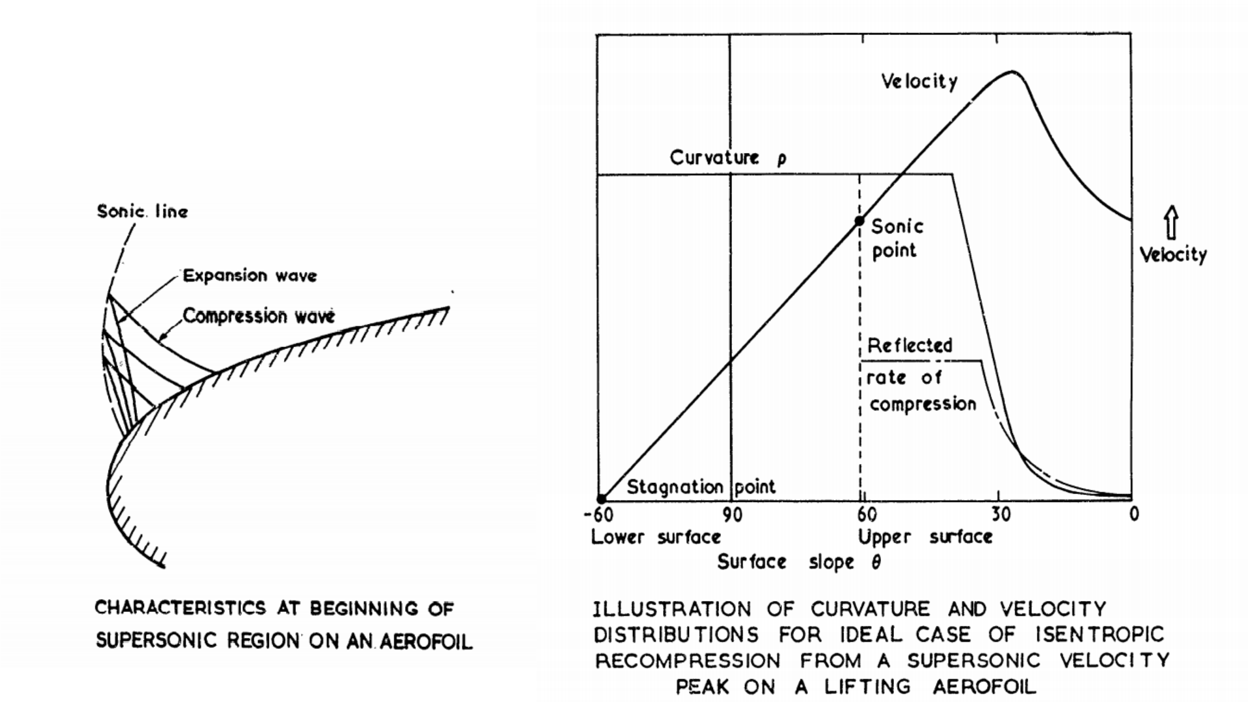


Figure 5. Illustration of idealised Supersonic expansion – Isentropic compression phenomenon. (Left) leading edge of an aerofoil in high subsonic Mach number stream, showing sonic line and expansion/compression waves. (Right) idealised pressure distribution on a similar aerofoil with abrupt reduction in surface curvature resulting in termination of expansion waves and dominant effect of reflected compression waves to slow the flow.(24)

To quote a report on the NPL work from 1966,

> "The exact form of the curvature distribution, at and after the curvature change, is very important in controlling the rate of the compression and the isentropic nature of the flow. Even when a shock wave does form, its strength can be minimised by a well-designed curvature distribution." (25)

Clearly, while this was true, in the general sense and for the purpose of understanding the technical thread described in this document, the initial descriptions of a suitable aerofoil geometry from Pearcey's work emphasised a very highly curved (potentially small radius circular arc) leading edge, changing abruptly to an upper surface of minimal curvature. This was a very different profile to either the early NACA symmetrical four-digit aerofoils or the newer high-speed aerofoils of the RAE 10x or NACA 6 series.

3 WHY WAS THE HIGH SPEED BUFFET NOT PREDICTED?

3.1 Wing buffet – the nature of the problem

In order to define the issue encountered by the Vulcan, it seems reasonable refer to some approximately contemporary sources. Mabey reported in 1964 on wind tunnel studies investigating buffet on several wing planforms, stating that:

> "Wing buffet means the wing response, mainly at its fundamental bending frequency, to the random excitation from pressure fluctuations in separated flow. Wing buffet can limit aircraft performance by producing unpleasant vibrations for the aircrew and/or passengers, by disturbing sensitive equipment or even by endangering the structural integrity of the aircraft. Wing buffet often occurs before stalling or longitudinal instability and hence buffet boundaries are as important as stability boundaries." (26)

Buffet could be encountered by any aircraft in which regions of separated flow existed due to its fundamentally unsteady nature. However, the significance to the then-new transonic aircraft being developed was the existence of a new mechanism by which separation was triggered. The local regions of supersonic flow on the wing inevitably terminated in a shock wave; the pressure rise across this would in turn result in boundary layer separation when it became sufficiently large. This was alluded to by Seal in a report published in 1959.

> "Two types of flow separation give rise to buffeting, firstly, the actual flow separation over the wing itself and, secondly, premature flow breakaway, which may occur at the wing-fuselage or tailplane-fin junction, for instance. Although it is unlikely that flow separation can be completely eliminated it may be postponed and alleviated by good design, ….
>
> "Decreases in thickness-chord ratio and aspect ratio and increase in sweepback all tend to alleviate buffeting at high Mach numbers and moderate C_L where compressibility triggers off the vibratory flow. In this region sweepback can reduce the buffet amplitudes by as much as 50% to 70% as compared with a similar straight wing aircraft and it may also delay the onset of buffeting to a higher Mach number." (27)

While Avro had encountered problems with buffet before, notably in the development of the Tudor airliner (28), these had typically been related to the second type of separation highlighted by Seal. The new challenge was the mitigation of flow separation specifically associated with shock-induced flow separation on the wing—an example of Seal's first type, but with a novel cause.

3.2 Contemporary engineering capability related to buffet

The high-speed buffet problem involved the interaction of a flow separation and the structural dynamics of the aircraft. Irrespective of how these might have been modelled during design, it would have required both of these factors to have been resolved correctly in order to either avoid them (in the case of the aerodynamic issue) or bound them (applicable to either positioning the structural modes or ensuring the aerodynamic issue was shifted out of the planned flight envelope). In 1950, when the Vulcan design was frozen, this was simply impractical and helps to explain the significance of the scaled flight test programme that was instigated for both the Avro and Handley Page proposals. Indeed, nearly a decade later, an RAE report would note that no method had yet been developed that could accurately predict the onset of buffet or the magnitude of the loads generated [(27)].

In terms of detecting the flow separation in the wind tunnel, the only facility that was available to provide the required Mach number was the 10 ft x 7 ft High Speed tunnel at RAE Farnborough. This could have shown the presence of a steady shock-induced separation, providing a likely upper limit on Mach number before buffet might occur. The models built to survive in this environment were not necessarily dynamically representative, so could not show how the real aircraft would statically deform and dynamically move, changing both shape and incidence in a time variant manner. Also, it could not simultaneously provide Reynolds number similarity, which was important for a boundary layer effect. There was a level of confidence that increasing Re would postpone problems beyond the cruise condition.[(14)]

Some calibration of the Vulcan's development issues against the state of the art can be made by considering the contemporary development of the other two V-bombers. The Valiant had the benefit of a less rigorous specification, but the associated challenge of a compressed development timescale. George R (later Sir George) Edwards described it as "far and away the hardest aeroplane that I ever did", making that further point that it was "… given no mercy because we could not build flying scale models; it had to be right first time." [(29)]

Buffeting of the tailplane was encountered on the Valiant prototype when the wing-mounted airbrakes were extended. Clearly this was the effect of wake impingement rather than local shock-induced separation, but nonetheless was unexpected despite the extensive WT testing that had already taken place. It was temporarily eliminated by deletion of the upper surface airbrakes, which was not a long-term solution due to the reduction in drag increment and increase in nose-down pitching moment caused by the circulation from the lower surface pressurisation. Tests of alternative arrangements to reinstate the upper surface devices were undertaken at Farnborough, with the report noting "No reliable guide was available in the model tests for indicating whether the brakes would cause buffeting …" [(30)]. At high M (>0.8), the effect of the upper surface air brakes was perceived as likely to cause shock-induced separation and consequently wing buffet, due to the exacerbated adverse pressure gradient. Again though, this could only be inferred "in the absence of any measurements of buffeting..." This illustrates that in a report issued contemporaneously with Newby's work on the Vulcan leading edge (early 1955), another test designed specifically to cure buffet also looked to improve a surrogate parameter in the wind tunnel.

Flight test of the first *production* Valiant aircraft revealed an unrelated buffeting of the tailplane and fin at high M and EAS conditions, cured by improved sealing and fitting of a vortex generator (VG) array. Although these fixes were relatively simple to incorporate, it does still emphasise how far through the programme the issue had remained hidden. More concerning perhaps was suspected buffet-induced fatigue failure of an aileron control rod at high M and with applied G, indicative of manoeuvring under typical cruise conditions. This was addressed both aerodynamically and structurally; a strengthened rod and another row of VGs ahead of the aileron.[27] WT tests on the closely related V-1000 wing had shown that a separation boundary associated with outboard shock formation existed for moderate incidences at cruise M, which was correlated well to changes in the lift and pitching moment slopes. These were however steady measurements on a rigid model, again providing a local upper bound (assuming Re similarity) but without quantifying the dynamics of the separation and assessing the structural response.[31]

Although not an issue at high speed, the Victor suffered from an analogous low speed aeroelastic problem which would manifest itself with fatal results. The aircraft's characteristic fin and large dihedral tailplane evolved at a similar time to the final Vulcan configuration, in 1949. The Head of Aeroelastics at HP would report that "At the time, before analogue or digital computers were available, anything like comprehensive flutter calculation was out of the question". [32] The approach for validating the design was the manufacture of a dynamically representative low-speed wind tunnel model, with iterations being made between it and completed full scale parts to gradually close in on the expected structural performance. The final inputs to the flutter calculations were from ground resonance tests of the completed aircraft to identify the modal frequencies.

The timescales for this work are striking: the low-speed WT model began running in 1952, produced useful results, and influenced the requirements for elevator mass balancing and the control circuit stiffness. However, the overall Victor programme was advanced to the stage that the first prototype flew in December 1952; clearly, the WT model was driving retrospective updates rather than the original design. The results of the flutter calculations based on the aircraft ground resonance results were not available until early 1954, over a year after the prototype had flown. Although it was known that simplifying assumptions had been made in these calculations, including neglecting the tailplane dihedral, the agreement between the results and the WT model gave confidence that the appropriate trends had been captured. However, in July 1954 and while performing low altitude position error work at Cranfield, the prototype suddenly dived into the ground, instantly killing pilot Squadron Leader Ronald Ecclestone and three flight test observers.

The urgency by which the introduction of the V-bombers was viewed at the time is illustrated by a parliamentary question asked of Duncan Sandys (Minster of Supply) a few days later by Frank Beswick MP. After a being asked to make a brief statement on the accident, it is clear from Beswick's follow up as to where his concern lay;

> "While appreciating that expression of sympathy and wishing to associate my hon. Friends with it, may I ask whether this unfortunate tragedy will have the effect of greatly delaying the production of this aircraft?" [33]

The "what" of the accident (failure of the tailplane) was rapidly obvious, given the eyewitness accounts and its relatively intact although detached status. The "why" took considerably longer—several months and the availability of a complete full-scale tail unit for testing. These tests eventually revealed a level of flexibility about the fin-to-tailplane junction that had not been modelled, while the aerodynamic effect of the dihedral had not been applied to the ground resonance-based calculations. The proximate cause was the induced fatigue failure of the tailplane attachment bolts.

The accident to Victor WB771 was not caused by high Mach number effects but does serve to illustrate the profound difficulties at the time in analysing aerodynamic-structural interactions of any kind, in a timely manner during the design cycle. Although the Vulcan phase 2 leading edge would be one of the most visible "fixes" applied to a V-bomber, it is nonetheless apparent that the requirement for such a retrospective modification was consistent with the contemporary analysis capability. In the absence of such analysis, a substantial rig test was essential, and the earliest available "laboratory" was the first Avro 707A, WD280, flown over a year after the 698 prototype design freeze in June 1951. The thoughts of Sir George Edwards are pertinent; he specifically highlighted the risk imposed on an equivalent programme at the time by not using scaled flight test aircraft. The known cost of this—accepted in advance—was an inability to meet B35/46. In the words of Avro Technical Director Sir William Farren,

> "We had plenty of warnings, but then we had plenty of warnings of other problems as well. If you set off on such a venture with nothing to help you but a list of warnings, you are never quite likely to start at all." [34]

4. RESOLVING THE VULCAN'S HIGH-SPEED BUFFET

The initial attempt to solve the problem was through an array of vortex generators on the 707A itself, at 35% chord ahead of the ailerons. This proved ineffective in solving the buffet, although it successfully improved shock-induced separation above M = 0.9. However, this did bound the problem: at the M = 0.87 cruise condition the shock was both ahead of the array and moving rapidly forward. The aerodynamic problem was close to the leading edge and the solution would be found there.[35]

At the RAE, Ken Newby first had to identify the indicative problem to solve in the wind tunnel where, as discussed in section 3, the nominally rigid model was not of course subject to buffet. The assumption was made that buffeting was likely when the flow separated at some point on the wing and failed to reattach ahead of the trailing edge. Because this would mean that static pressure (relatively simply measured by a pressure tap and manometer) would not recover to "attached" level, this steady phenomenon could be detected practicably in the WT. By sweeping through an Incidence-Mach space, a boundary could be plotted between conditions potentially corresponding to buffet-free and buffeting at full scale.

Looking back on this period after six decades had elapsed, Herbert Pearcey wrote:

> "We were using our small-scale wind tunnels to explore the details of the transonic flows that were limiting the flight envelopes of the aircraft then being developed. The opportunity to interact with the full-scale test flying was motivating and provided the all-important confirmation that what we were doing was relevant to the real problems. For example, it was clear that the buffeting that was being experienced was caused by the shock-wave induced separation of the boundary layers and that the flight conditions for its onset could be predicted from observations at model scale of a divergence in the variation of pressure at the trailing edge." [1]

The development of this criteria for relating wind tunnel measurements to the flight buffet boundary was described in a number of reports by Pearcey and his NPL High Speed Aerodynamics section colleagues, roughly concurrently with Newby's work on the Vulcan leading edge. It is not therefore explicit from the documents considered for the present paper where the idea originated, but given the depth of understanding being generated in terms of shock wave/boundary layer interaction, it is tempting to think that the NPL aerfoil work was the source, filtering in the direction of the RAE. In a paper presented at an NPL symposium in early 1955 and in the text later published as an ARC report, Pearcey stated:

> "The onset of the effects of separation on the overall flow for a two-dimensional aerofoil, or for a given spanwise station of a three-dimensional wing, can be detected by observations of the divergence of the trailing-edge pressure from its normal variation, or of that of the static pressure at a point just upstream of the trailing edge on the suction surface." (36)

These conclusions were drawn from previous work at NPL, certainly predating the publication of Newby's report (May 1955), if not the tests described. Farren stated that he believed the technique to have been first described by the NPL team, in a paper of 1954. Figure 6 adapts the figures he showed to illustrate this in his RAeS Wilbur Wright Memorial lecture of 1956.(34) The corresponding data from Newby's report is replicated in Figure 7, including the plotting of the WT separation boundary points (which were defined as M where $\Delta C_{p.te} = 0.01$ from the linear curve) at the most loaded 83% semi-span position, against the flight buffet boundaries for the 707A and 698 (Vulcan). In terms of the differences between the two aircraft, the CG position and wing geometry were not identical, leading to a difference in elevator angle to trim. This would be expected to have an effect on shock position.(14) Note also that the orientation of the C_p axis is reversed between the two figures.

At least three conclusions can be drawn from the data of Figure 7b):

- The Vulcan's baseline buffet boundary was very close to the typical $\alpha \sim 3.5°/M = 0.875$ cruise condition.
- Newby's criteria were indeed a useful surrogate for the flight buffet boundary.
- Flight tests on the 707A would be expected to yield results transferable to the Vulcan, allowing a more rapid and cheaper validation.

Any solution was constrained by the need to be retrofittable to the existing primary structure of the Vulcan's wing, which in practice meant a new leading-edge shape that faired into the baseline geometry at approximately 11% chord. This provided the opportunity to tailor the spanwise camber of the new leading edge, improving alignment to the local flow direction and hence reducing the suction peak.

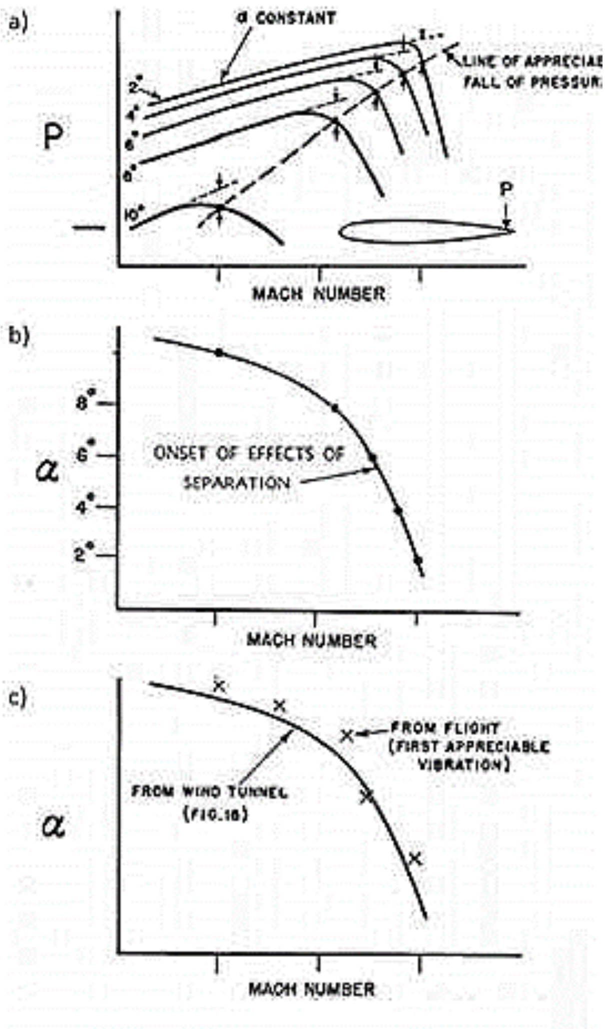


Figure 6. Example of correlation between wind tunnel measured trailing edge pressure and flight buffet boundary. a) Establishment of incidence-Mach boundary in WT; b) Plotting Separation boundary on incidence-Mach plane; and c) mapping of flight test data. (34)

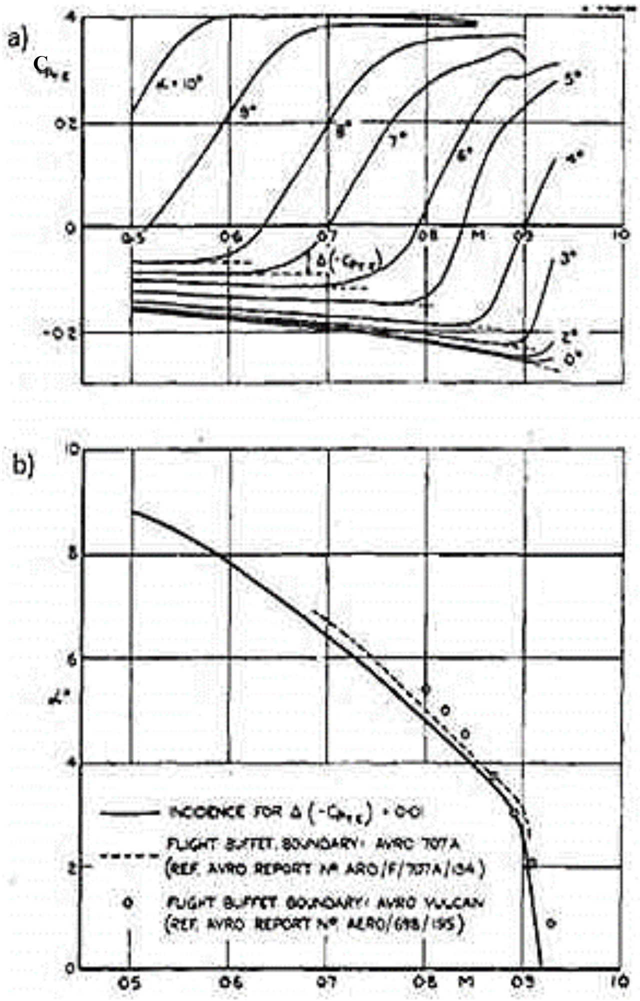


Figure 7. Corresponding data for the Vulcan baseline configuration: a) mapping of Separation Boundary from WT tests and b) comparison of WT Separation Boundary with inflight measured Buffet Boundaries for baseline Avro 707A (WD280) and Vulcan prototype (VX770). (35)

The two planforms tested (the larger of which also had two different sections) are illustrated in an adapted version of Newby's original figure (Figure). The small extension was found ineffective at the Vulcan's cruise Mach number in flight tests on the 707A, and so attention was switched to the larger extension, which maintained a 19.5% chord increase from the tip to the 78% semi-span point, thereby capturing the 83% peak load position. The new planform then kinked to blend back to the original by about 49% semi-span.

In terms of section, the "Straight" extension was based on the leading 30% chord of a 5% thick RAE 101 symmetrical aerofoil, with the axis drooped at 7° from the chord line of the basic wing. The "Cubic" extension cambered the chord line of the extension such that the curvature continuity was achieved with the upper surface of the basic wing at 10.5% chord, which reduced the local incidence but generated a longer region of curvature. Although the source of the information is not discussed, the Newby's report states

> "The drag results for most thin wings (t/c = 0.04-0.06) at incidence, show a sudden decrease in C_D at about M = 0.8-0.9 when plotted at constant incidence; this suggested that forward movement of the main shock might be prevented when supersonic expansion of the flow round the leading edge and onto the upper surface occurred." (35)

This convincingly explains the aerodynamic mechanism that Newby was targeting in his design and the reason for the incorporation of the already thin leading-edge profile as a forward extension, as opposed to simply reducing the nose radius of the existing wing. It also implies a reason for the disappointing high M results of the small extension. As Pearcey and his colleagues had theorised, the supersonic expansion relied on a significant curvature over a small chordwise extent, rapidly changing to a region of very low curvature behind to allow the isentropic recompression. Clearly, Newby did not stumble across the "Peaky" pressure distribution concept

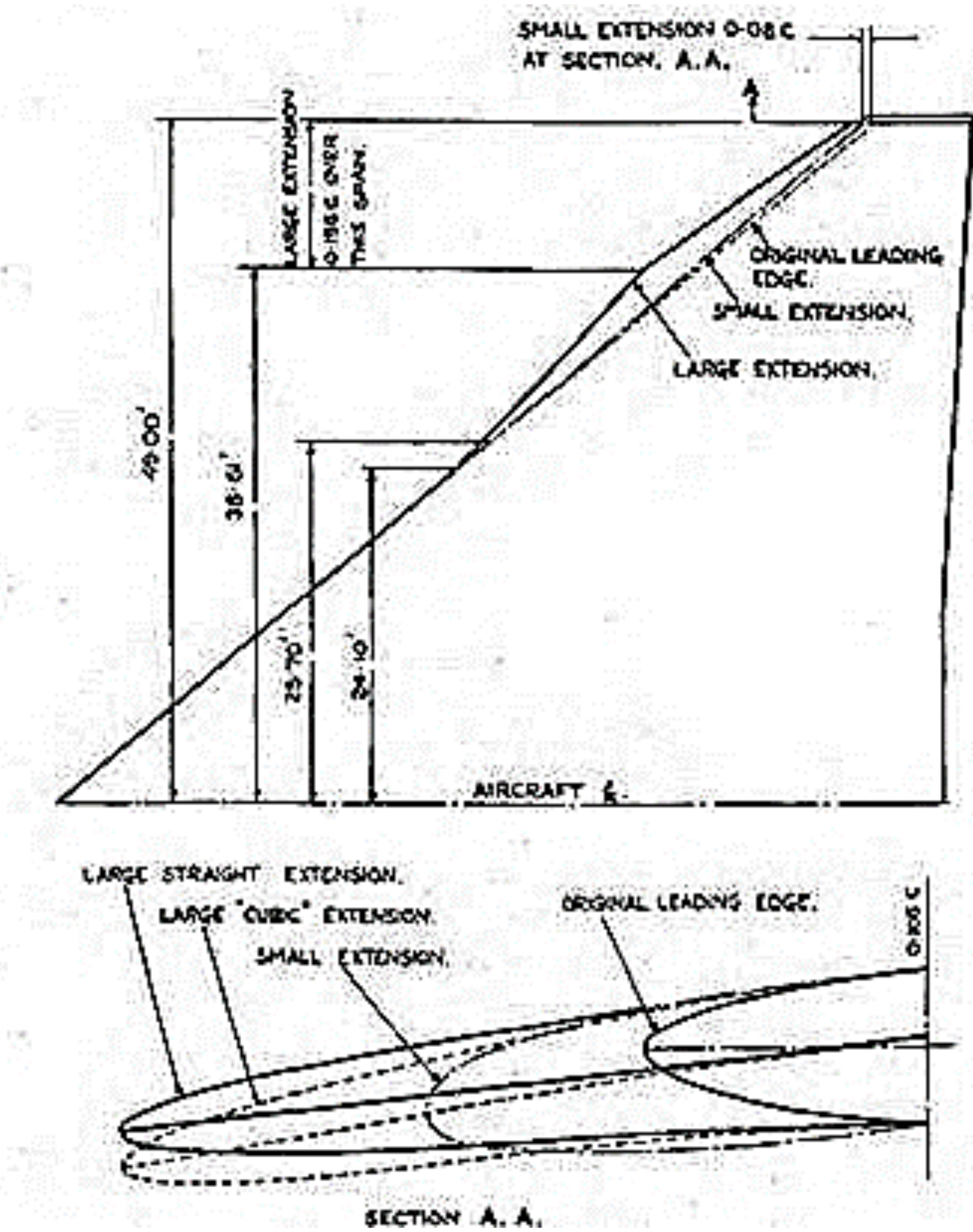


Figure 8. Vulcan wing leading edge modifications as designed and tested by K. W. Newby at RAE Farnborough (35)

but was familiar with its application. Simply drooping the leading edge of the existing profiles, which was essentially the approach of the small extension, would not provide a suitable geometry for the desired aerodynamic mechanism.

The comparison between the two "large" extensions yields further information on this exploitation. Figure is extracted from a more comprehensive figure in the report, showing the upper surface pressure distributions at M = 0.85 and angles of attack of α = 0° (close to zero lift), α = 4° (slightly greater than cruise) and α = 6° (well above cruise lift). The key is the relationship between local pressure and that which would occur at M = 1, above which the flow would decelerate nominally through a shock wave. Note also that the C_p at which M = 1 is attained reduces along the chord, as the geometric sweep does due to the almost unswept trailing edge.

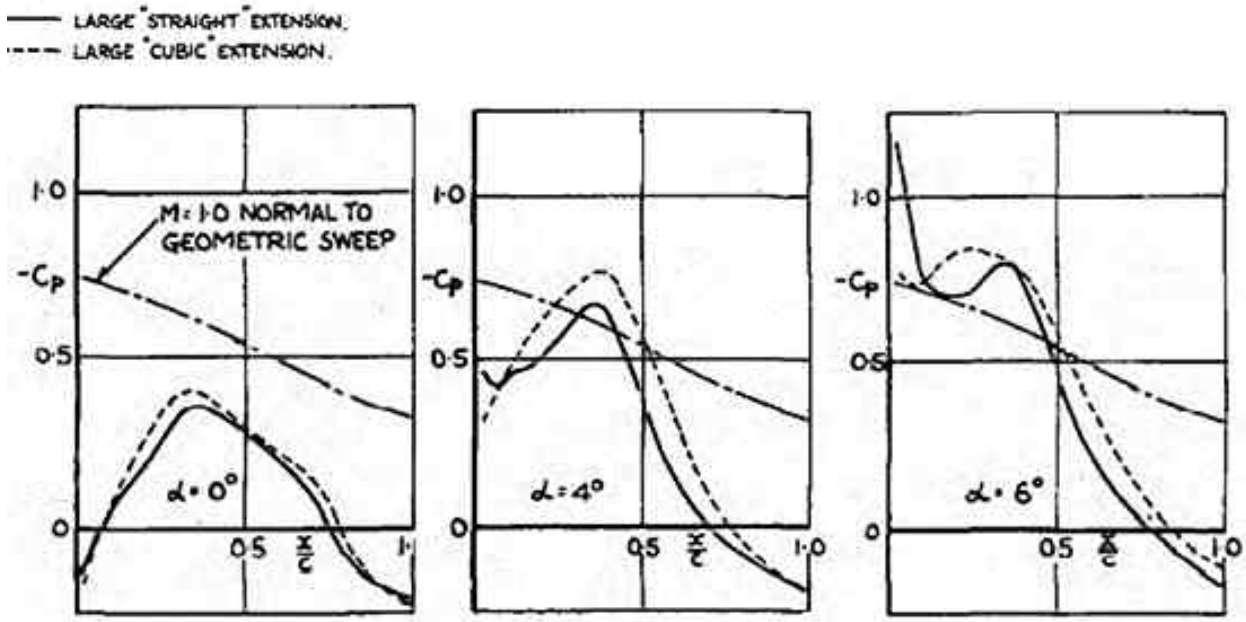


Figure 9. Upper surface Cp distribution at M = 0.85 with Straight (solid line) and Cubic (dashed line) extensions (35)

At very low lift, the margin to sonic flow is large at all points on the chord, which illustrates in general terms the attractiveness of the strategy of using a large area and low wing loading (allowing operation at low α) for an aerodynamic perspective, as previously exemplified by the English Electric Canberra. Then, referring to the central figure as a lift coefficient comparable to cruise, it can be seen that there is a gradual increase in suction on both designs towards approximately 40% chord, as would be expected ahead of the eventual shock, but that the straight extension has consistently lower velocities (using Cp as the indicator). The paucity of pressure tappings available on the wind tunnel model meant that the rapid changes in Cp around the leading edge were not completely captured, but what is clear particularly in the α = 6° case is the significant suction peak at leading edge, followed by a subsequent recompression towards sonic velocity and then an acceleration again. This is much more significant for the Straight extension; indicative of "Peaky" behaviour at relevant incidence.

The straight extension was just beginning to demonstrate a $C_{p\cdot te}$ rise at this α-M combination (Figure 7a), whereas data in the report shows that the conic extension was beyond the $\Delta C_{p\cdot te}$

threshold and hence the flight buffet boundary. Newby's conclusion was that more rapid leading-edge acceleration (and hence strongly favourable pressure gradient) caused by the continuous curvature of the cubic extension was responsible for a laminar boundary layer being maintained to the shock position, whereas the straight extension was turbulent at the same station. Although evidence is not offered for this, the point is made that the laminar boundary layer would separate more readily at the shock position (due to the lack of turbulent mixing and implied reduction in ability to maintain the equilibrium with the shock pressure rise in the subsonic boundary layer flow adjacent to the wing surface).

The Straight extension was the clear winner in the wind tunnel test, but the impact of boundary layer transition and knowledge that the Reynolds number was far below that of flight must have been a warning flag. The perils of scale effect at transonic velocities would catch out the engineers involved in several aircraft programmes for some time after this work, one of the more notable examples being the Lockheed C-141 Starlifter. It was normal RAE practice at this time to allow natural transition in the wind tunnel, rather than forcing at a fixed location using a trip strip, although there was growing evidence that at the Reynolds numbers achievable in the 10 ft x 7 ft WT with complete aircraft models, extrapolation to flight scales was far from assured.[37] In this case, was it luck that the geometric requirements that promoted the "Peaky" supersonic expansion-isentropic compression phenomenon also favoured early transition, thus placing the wing in an aerodynamic regime that was more representative of flight?

The final results, as flight tested on the 707A and which as we have seen earlier could be considered aerodynamically representative of the Vulcan itself, are shown in Figure .

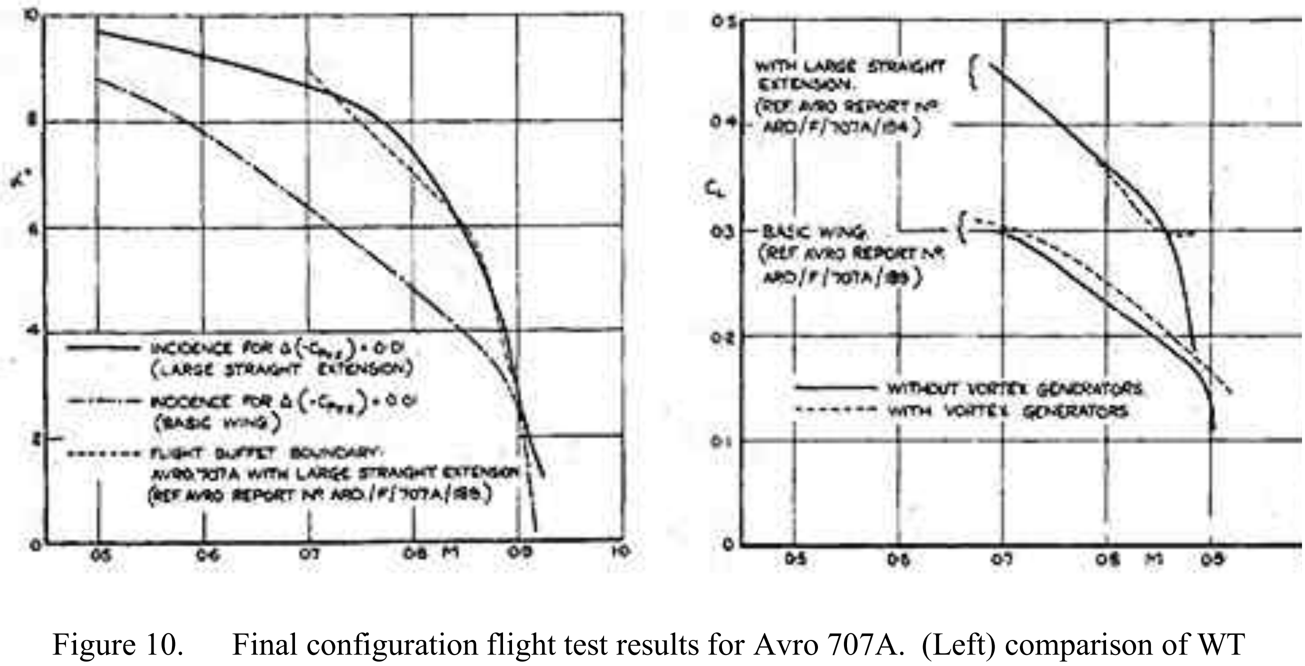


Figure 10. Final configuration flight test results for Avro 707A. (Left) comparison of WT separation boundaries with flight buffet boundaries and (right) flight buffet boundaries as altered by the addition of vortex generators. [35]

The surrogate parameter ($\Delta C_{p.te}$) was again correlated well with the flight buffet boundary on the modified wing—the final validation of the strategy. The buffet boundary was enhanced at all Mach numbers below M = 0.9.

Herbert Pearcey's communication with Robert Pleming also referred to the work at NPL on vortex generators and their role in the suppression of shock-induced boundary layer separation.

> "Their flight tests also confirmed that we were justified in recommending that vortex generators scaled up from our tests on small aerofoils (5 in. chord) would be successful in delaying the onset of the buffeting." (1)

Newby's report describes the implementation of an array of VGs at 25% chord as a further step on the Vulcan wing, providing an additional increment above M = 0.86 by reducing the effect of the rear shock. The combination of the leading-edge extension and vortex generator array therefore provided the final implementation, with Newby noting that the Vulcan should experience an improvement in usable C_L over the 707A of 0.07 due to the reduced elevator angle required to trim in the cruise. This then defined the aerodynamic design of the Vulcan B. Mk.1 wing, such that cruise performance was acceptable enough to the RAF for sign-off in its role as a bomber. Known as the Phase 2 configuration, it is illustrated on an early Vulcan B. Mk in Figure 11.

Figure 11. A near plan view image of Vulcan B. Mk.1 XA896, showing the phase 2 wing as implemented in all production aircraft delivered to the Royal Air Force. (Rob Mather – www.vickersvaliant.com)

5. PEARCEY'S SUBSEQUENT USE OF THE VULCAN RESULTS

NPL's sectional work remained a valuable input to industrially (and strategically) important aircraft design programmes as the decade continued. The "Peaky" pressure distribution was now a flight-validated technology for the mitigation of wave drag in transonic aircraft. New aeroplanes would of course have properly designed aerofoils which inherently exploited this mechanism, but it is clear from the available literature that the Newby implementation was being used to tell the story amongst the aerodynamic community. For the purposes of this work, this provides a second source of data that shows what Newby inferred but could not observe: the supersonic expansion and rapid isentropic compression certainly did occur in two dimensional experiments on the same sections.

In Figure 6, the results of Pearcey's NPL experiments as described at a conference in 1960 are collected. The original article makes no direct reference to the Vulcan but uses as a case study an aerofoil of NACA 0009 ½ (sic) section. This non-standard thickness seems an odd choice for a nominally generic study, until it is noted that the Vulcan baseline wing design used a 9.4% thick NACA 00XX section at the spanwise station corresponding to the eventual kink location. This is surely beyond coincidence but may of course have been the result of hands tied by security considerations. A year later however, he "was able to show some of these results in a contribution in 'Boundary Layer and Flow Control' in Lachmann", a very significant and influential work that has been referenced frequently in the intervening decades. In this book, Pearcey did imply the application, by describing it as work by Avro and Newby; enough evidence for those in the know.[38]

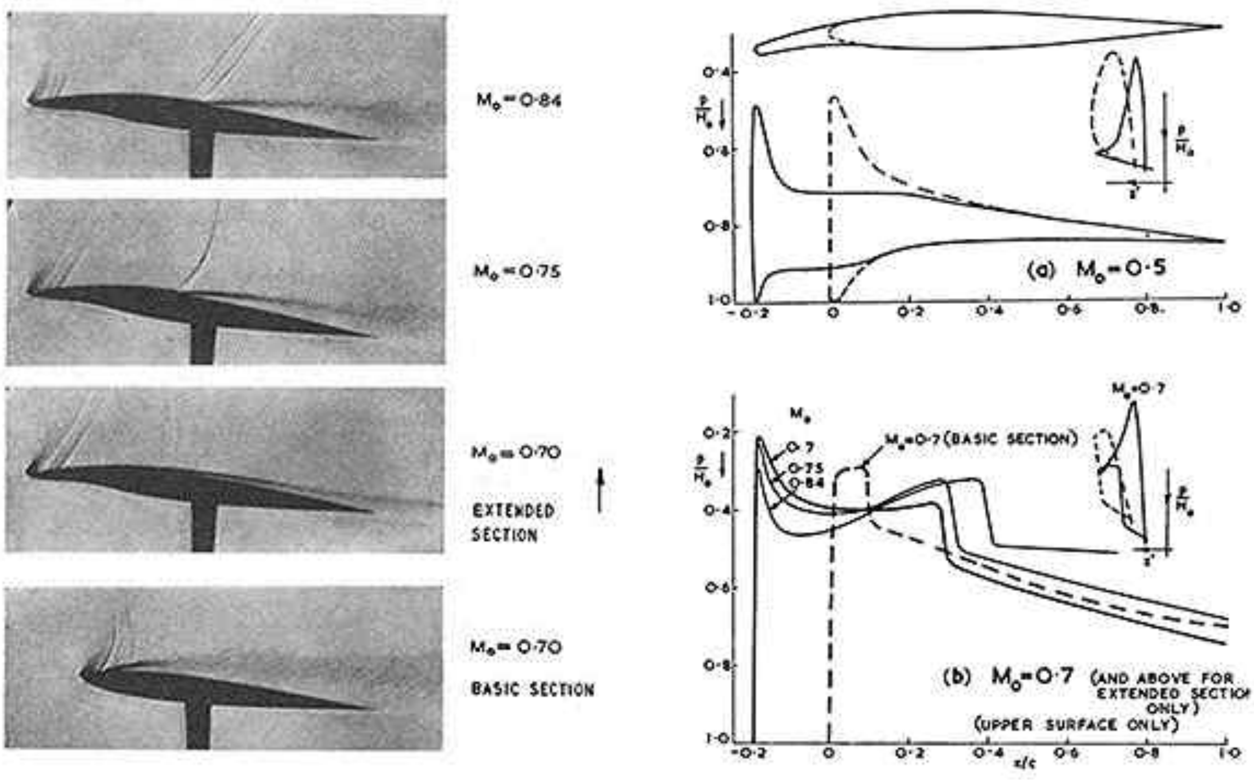


Figure 6. Schlieren images of the baseline NACA 0009.5 and extended chord version (left) at α = 7°, comparative upper surface pressure distributions (right lower) for these conditions and additionally at M = 0.5 (right upper) [19]

The critical points in this data from the perspective of the current work are the direct comparisons between baseline and modified aerofoil at $\alpha = 7°$, M = 0.7. The pressure distribution for the baseline shows an acceleration to supersonic flow at the leading edge (peaking, according to Pearcey's data at M ~1.4), and a short plateau ahead of a rapid compression (the shock wave), which is well forward on the chord. In contrast, the modified aerofoil shows a much more significant leading-edge peak, with the flow accelerating to M ~ 1.7 before rapidly compressing back to M ~ 1.24. The local Mach number ahead of the eventual shock wave is therefore reduced, in turn reducing the strength of the shock itself and the local adverse pressure gradient imposed on the boundary layer. The continuous nature of the pressure recovery ahead of the shock on the modified aerofoil is the key; it cannot be caused by the discontinuous mechanism of a shock wave as seen on the baseline aerofoil, hence implying the only plausible alternative of compression waves being reflected from the sonic boundary.

In contrast to the balance and limited pressure data available to Newby, the NPL team were able to add the final piece to the puzzle using flow visualisation through a Schlieren system. The corroborating data is reassuringly clear: the baseline aerofoil shows the sharply defined, curved line of the shock just aft of the leading edge, with the corresponding dark boundary in the flow initiating at the foot, extending tangentially to the local flow and marking the separated boundary layer. On the modified aerofoil under the same conditions, the shock is only weakly visible towards the mid-chord, with the thickening of the attached boundary layer a more obvious marker. The Mach number could be increased markedly to M = 0.84 (causing a movement of the stagnation point towards the upper surface and reducing the supersonic expansion), until separation to a similar extent as on the unmodified aerofoil at M = 0.7 is seen.

It should be noted that the Mach numbers quoted in these two-dimensional experiments are equivalent to those normal to the leading edge of the three dimensional wing in Newby's tests. This accounts for the Mach number at which shock-induced separation occurred being much less than the cruise Mach number for the Vulcan; its leading edge was of course swept for this purpose. As described above, this configuration was also improved in the final phase 2 configuration using vortex generators, which was not the case here.

Pearcey's use of the Vulcan data specifically is fascinating, as it validates the interplay that he describes in his communication with Robert Pleming. Conceptually, Newby had taken the "peaky" theory and applied to the Vulcan wing; conversely, Pearcey recognised the Vulcan application as a simply understood proof-of-concept and hence eminently suitable for the process of dissemination to industry that was necessary for it to make an impact. Following this successful application, it would not need to wait for long.

6. BEYOND THE VULCAN: EXPLOITING A NEW TRANSONIC CAPABILITY

6.1 The wider impact of the Vulcan leading edge work

Herbert Pearcey's statements that "Our backroom research received quite a boost [from the Vulcan leading-edge work]" and "It was the understanding.… that was to lead us ultimately to the supercritical wing sections that are now commonplace on most civil airliners" (as related in the opening paragraphs of the current work) are investigated in this section. The temporal aspect of this story is important: in mid-1955 as results of Newby's work were being disseminated, the

UK civil aviation industry had no operational big jets analogous to the V-bombers but was in the process of developing such types with anticipation of export sales. As will be described, these contemporary plans would not come to fruition, but subsequent requirements for new civil aircraft able to efficiently operate at high subsonic Mach numbers, would in turn necessitate the employment of aerodynamic technology that further delayed drag divergence.

6.2 Immediate military applications

A direct and immediate beneficiary of Vulcan work was the ambitious Canadian supersonic all-weather fighter, the Avro Canada CF-105 Arrow. This was a large delta design that for part of its gestation was also planned to be powered by the Olympus, albeit the Curtis-Wright built J67 version. As a part of the same wider industrial group, Avro Canada had access to data on the development of the 707 and 698 (Vulcan) projects. Although the underlying choice of the tailless delta configuration had a top-level similarity—a weight-efficient method of providing low t/c and wing loading—the supersonic requirement drove the actual t/c down to just 3.5% at the root and 3.8% at the tip.(39)

The Arrow demonstrated a reduction in longitudinal stability at moderate angles of attack during early wind tunnel tests at Cornell University in New York. At the same time, there was awareness of Convair's work on conical camber for induced drag reduction and Avro's Vulcan modifications for buffet boundary extension in high subsonic cruise. It was clear that an outboard drooped leading-edge extension might well achieve improvements in all three areas. The eventual 10% chord drooped extension chosen incorporated an inboard notch for leading edge vortex control (to improve the pitch stability) and at the planned subsonic cruise Mach number of M = 0.925, the droop achieved a significant improvement in the (wind tunnel assessed) buffet C_L limit, from $C_L = 0.26$ to $C_L = 0.41$, without a detrimental supersonic drag penalty.

From 1955 onwards, that is, concurrently with the Vulcan leading edge implementation, Pearcey's aerofoil work had certainly piqued the interest of another HS group company, the namesake Hawker itself. Concerning himself with the integration of propulsion into supersonic fighter aircraft, work which would eventually result in the P.1154 V/STOL proposal for the RAF and Royal Navy, C L Bore wrote many years later that,

> "Pearcey was describing how isentropic supercritical recompressions actually worked, while in other countries people were still arguing whether such behaviour might be possible." (40)

In discussion with Pearcey, Bore suggested that an increase in nose radius from the typical 0.3% chord to 0.8% would increase the extent of the advantageous recompression. This was followed through with geometry developed under the auspices of the Supersonic Air Transport Committee (SATC) and indeed shown to be positive; it might be logical to assume that the C_{Lmax} capability was also improved, which was important for the manoeuvrability of the combat aircraft that were Hawker's business. This research provided the basis of the aerofoils for the P.1154 and ultimately the P.1127(RAF), the first-generation Harrier that entered service in 1969. Hawker would describe the design generically as Blunt Peaky and highlighted (Figure 7) the relatively good performance of the Harrier at high lift and high Mach number, compared to the earlier generation Hunter.(41)

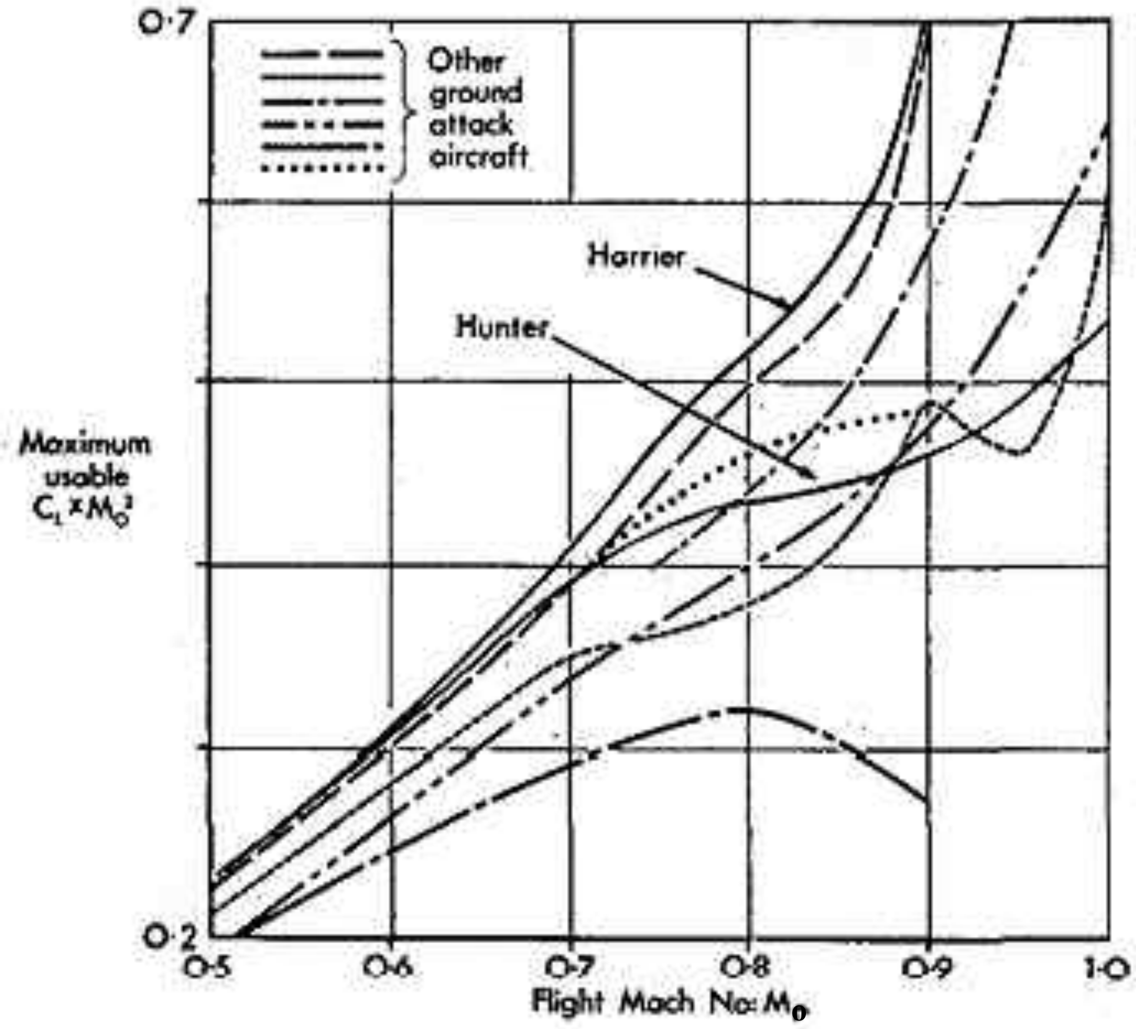


Figure 7. Wing lifting capability of Harrier GR.1, Hunter and other ground attack aircraft (41)

Bore's recognition was that the "peaky" profile was equally applicable to supersonic inlet design, particularly given that some of the NPL shapes were demonstrating shockless behaviour up to M = 0.9. Without the ability to sweep a fighter fuselage inlet in a manner analogous to a wing, a significant pressure recovery and integration efficiency advantage could potentially be realised. Bore applied such shapes to the P.1154 in 1963 and showed remarkable shockless recompression following leading-edge peaks of nearly M = 1.9. The project was cancelled in February 1965 (prior to the perhaps better-known demise of TSR2 in the following April), but the design was transferred to the subsonic strike fighter that rose from its ashes as a development of the P.1127 and Kestrel proof of concept aircraft. Bore claims the Harrier inlet was the first such design to fly anywhere in the world; he described it as Supercritical rather than "peaky", having been using such terminology since 1953.

As a point of interest therefore, the fixed wing combat aircraft used by the UK in the South Atlantic conflict of 1982 (Harrier, Sea Harrier, and Vulcan) can all directly trace substantial parts of their aerodynamic philosophy back to the work of Pearcey in the mid-1950s.

6.3 The Vickers V-1000 – behind the state of the art

All three V-bombers had corresponding planned transport versions, as their manufacturers understandably looked to exploit their investment in transonic technology. By definition, these would be large, long-range aircraft aimed at requirements for British Overseas Airways Corporation's (BOAC) eventual Transatlantic Comet 4 replacement and an RAF intercontinental troop transport. Part of the Vulcan leading edge study undertaken here was actually conducted on the wind tunnel model of Avro's contender, the Atlantic.(35) Ultimately, BOAC's enthusiasm was limited and the MoS viewed Vickers as the only contractor with the capacity to take on such a project, which crystallised as the V-1000 long range transport.(42)

The aircraft was certainly reminiscent of the Valiant but was far from simply a transport version of the bomber. It was much larger, with a wingspan of 140ft as opposed to the 115ft of the earlier machine. The planform strongly indicates the acceptance of the spanwise tailoring concepts espoused by the RAE, with a significant increase in sweep and thickness taper on the inboard region and curved Küchemann tips, all aiming to maximise the extent of the "sheared wing"-like flow. Excluding the inboard region, the majority of the wing was of 9% thickness Vickers cambered section and 26° sweep. These sections had been finalised by 1954, and hence used the state of knowledge of the time.

There is no shortage of opinion on the V-1000 and its fate, including from those involved. Sir George Edwards would state in 1973 that it had been cancelled for "short term political reasons", and given that he recounted being asked a year later if the programme could be reinstated and subsequently observing BOAC ordering Boeing 707s because "No suitable British aeroplane can be available ….", he was doubtless left sore.(29) Dietrich Küchemann would make an almost identical statement, implying a belief amongst the notables of the sector that a potential lead had been snatched away. However, a rather more prosaic reality has been retrospectively discussed by others taking a less subjective view.(4) BOAC never committed to the aircraft and the requirement for Transatlantic range had, by 1954 delayed the entry into service until 1960.(36) As such, the V-1000 would have lost the claimed advantage in lead time over the American jets which were recognised as inevitable (if not precisely defined at the time). For the purposes of this work, we are concerned with the development of transonic aerodynamic technology and there is something to offer to the story.

The world that the civil version of the V-1000, the VC7, would have been born into in 1960 had moved on considerably from the assumptions made when assessing the new aircraft's likely competitiveness. In reality, BOAC would that year commence operations with the Boeing 707-436 Intercontinental, powered by a developed version of the same Conway engine. It was, however, considerably developed beyond the Boeing Stratocruiser's four-abreast cabin version associated with the 1954 launch announcements, or indeed the limited payload-range performance of the initial -120 series. This was a true, non-stop Transatlantic machine cruising at M = 0.83 and with a Maximum Takeoff Weight (MTOW) of the order of 25% greater than planned for the VC7. In Table 1, relevant aerodynamic data for the VC7 (planned) and 707-420 (actual) are compared and used to calculate a typical required C_L value for the aircraft near the start of cruise. The physical parameters reveal that the substantially lighter VC7 had a slightly larger wing area and lower aspect ratio, generally indicative of lower overall efficiency. However, the required C_L is also lower, working in the opposite direction to aspect ratio in terms of reducing induced drag.

Significantly, the majority of the span of both wings are of similar t/c ratio, but the sweep of the Vickers design was much less. Without a step in the transonic performance of the aerofoil sections used, the latter would therefore be expected to have a lower drag-rise Mach number and efficient cruise speed capability.

Table 1. Pertinent aerodynamic parameters for VC7 and 707-420

Aircraft	VC7	707-420
MTOW (kg)	112,727	141,700
Wing ref area, S (m^2)	303	283
Sweepback, 25% chord, typical OB (°)	26	35
AR	6	7.1
t/c (root)	14%	11%
t/c (tip)	9%	9%
Wing loading, W (N/m^2)	3,650	4,912
Cruise Mach number, M_{cruise}	0.78	0.83
$C_{L\ cruise}$	***0.340***	***0.404***

Reference to available high-speed wind tunnel data for the V-1000 was made in section 3. This was used by Pearcey in report from 1954 that was classified until the late 1960s, due to the sensitivity of the aircraft it described. While pressure plotting data was not available, oil flow and tufts had been used to identify rear shock-induced separation with M, which could then be compared with C_L vs. α for a representative M = 0.84 condition. These two charts are shown in Figure 14. Noting that the calculated value of C_L required for the M = 0.78 cruise condition was 0.34, it can be seen from the C_L vs. α that this was achieved by an incidence of α ~ 4°. At M = 0.78, the separation boundary was encountered at α ~ 6°, giving C_L = 0.47 and an available margin to buffet of 1.38g. Compared to the JAR requirement of a minimum margin of 1.3g in the cruise, then the VC7 in its baseline incarnation, that is without considering weight increase in service to meet future customer requirements, was not generously endowed with growth potential.

The mythology of the V-1000/VC7 rests on the idea that Britain surrendered its stake in the long-range airliner market for want of completion of this worthwhile competitor. Against this must be set the tenuous operation requirement of the RAF for such an advanced and expensive aircraft, together with the knowledge that its principal domestic customer preferred the 707. The data examined here would tend to suggest that aircraft as planned would have been limited in at least one aspect of its performance – cruise Mach number – when compared with the Boeing and Douglas designs that would also have been available at the time of its service entry. Was this important? Boeing's George Schairer documented two relevant experiences from the development of the 707. The first was the decision to offer two very different derivatives of the aircraft (the domestic 707-120 and intercontinental 707-320/-420) to customers, following rejection by Pan American of the original concept that compromised both missions. The second was the desire to operate at the maximum possible cruise Mach number by United Airlines, which resulted in Boeing seeking to offer M = 0.84 rather than the M = 0.80 originally planned, with the aim of beating the M = 0.82 of the DC-8.(43)

Speculating on analogous situations that would likely have arisen had the VC7 come to fruition, then is it plausible that Vickers could have addressed them? The history of the UK manufacturers

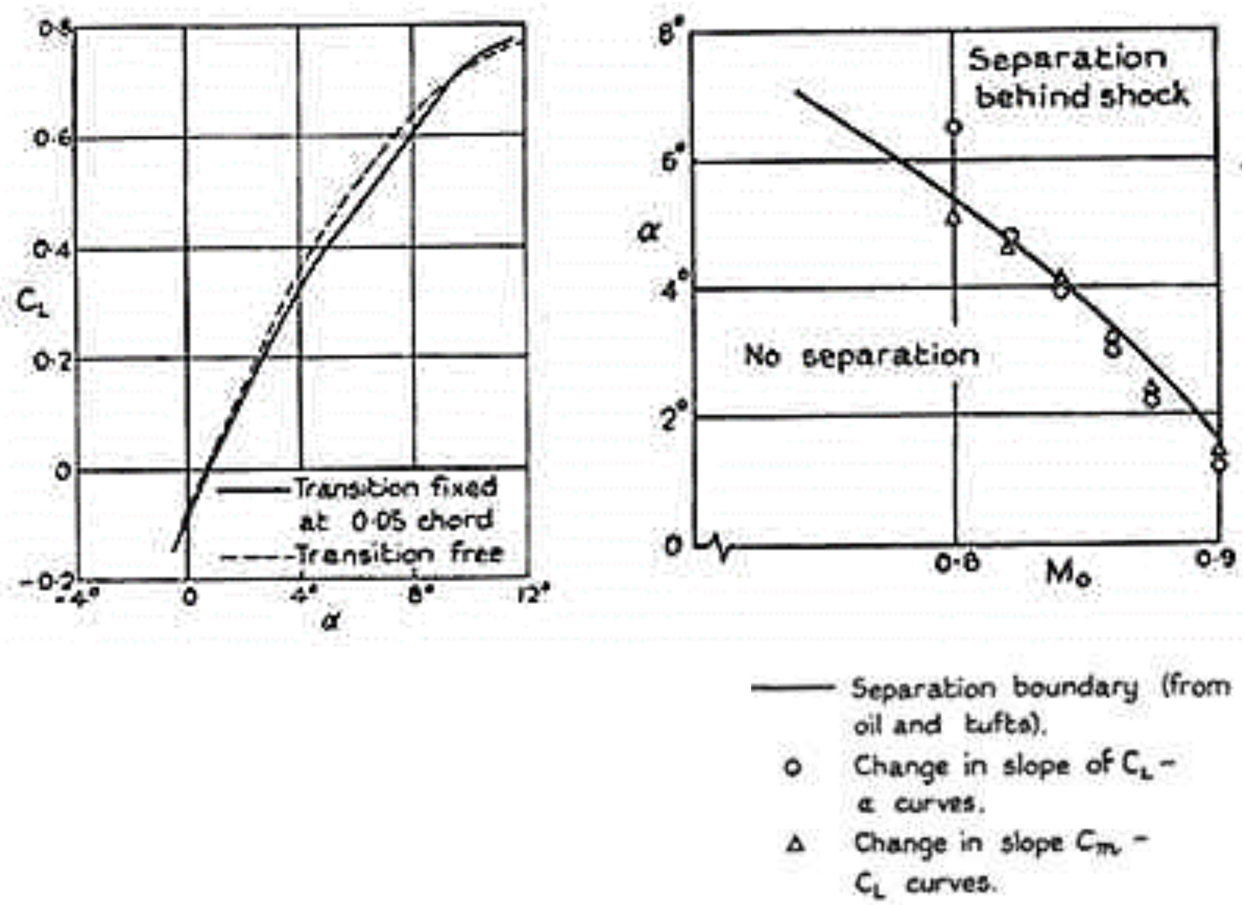


Figure 14. Wind tunnel data pertaining to the Vickers V-1000. C_L vs. α at M_o = 0.84 (Left) and α vs. M_o (25)

being able to fund product development in this period suggests that there would have been difficulties. Vickers were developing the Vanguard turboprop as a private venture and would eventually lose £16m on the project; an unhealthy underlying position if it is assumed both aircraft programmes were running concurrently. Elsewhere, sales of the Trident would be lost because of the inability of Hawker-Siddeley to fund re-engineering of the aircraft beyond its original, tailored specification. Even the mighty Convair in the USA would struggle to crack the market just a few years after the service introduction of the DC-8 and 707, using more modern transonic technology and – on paper at least, offering improved performance. It is hard to conceive of a positive outcome for the VC7 against the already entrenched incumbents; its uncompetitive aerodynamic configuration played its part in this.

In Figure 15, the rapid development in terms of Range Factor (a measure of aircraft efficiency, accounting for aerodynamic and propulsive elements) of the 707 and DC-8 are shown. The large steps between the 707-320 and -320B and the DC-8-30 and -50 are the result of the substitution of similar thrust turbofan powerplants for turbojets in the earlier aircraft, together with aerodynamic improvements.(44)

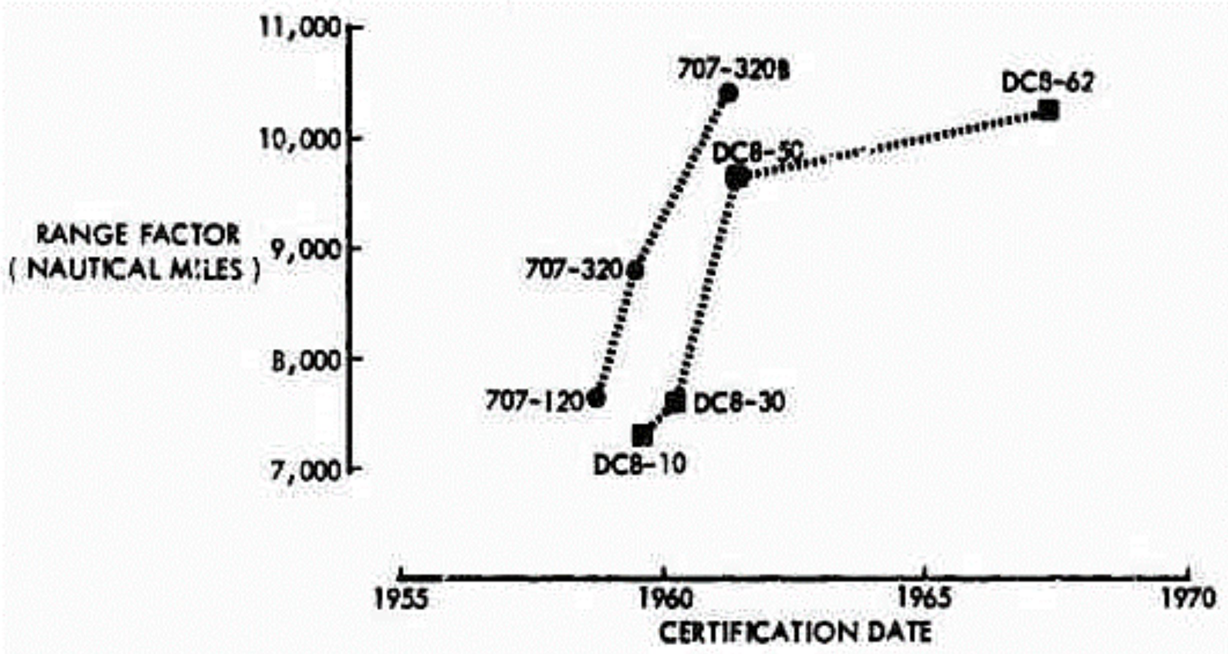


Figure 15. Development in terms of range factor of Boeing 707 and Douglas DC-8 (44)

6.4 Meeting the technological challenge – The VC10 and Trident

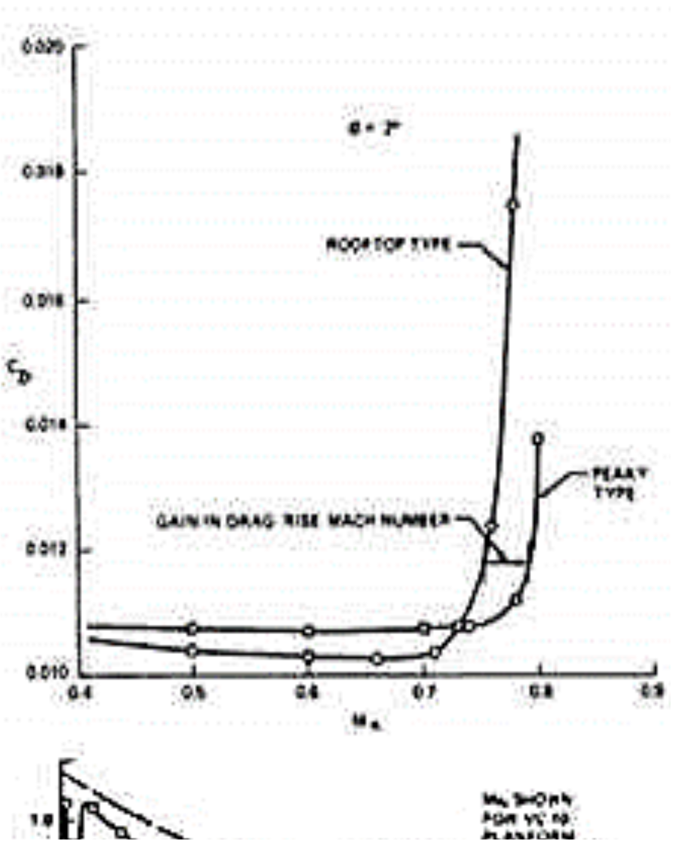
In the period following the V-1000's cancellation in late 1955, BOAC's initial belief in the combination of the turboprop Britannia and turbojet Comet as competitive equipment for North Atlantic services began to erode. A year later, it received permission from the Minister of Transport and Civil Aviation, Harold Watkinson, for the purchase of fifteen 707 Intercontinentals with which to plug the gap. This was on the condition that British equipment was bought for the remainder of the network and led to the development of a new Vickers proposal that became the VC10. Watkinson would state in parliament,

> "When the big Britannias start meeting the competition of the Boeing 707's nobody knows which will win …. It was right for the Corporation to back itself both ways."

However, having seemingly not viewed the 12 hr Atlantic crossing in the Britannia as a defining factor in the discussion, within minutes he would continue on to say,

> "Beyond that, we must look, for the last big conventional jet aircraft, the VC10 ... B.O.A.C regard this aircraft as a world beater. It is faster than the Boeing 707 and has completely different characteristics ... It is able to fly the North Atlantic and the Eastern routes, and fly into airports that the Boeing 707 could not use at present." (45)

By the time the aerodynamic concept of the VC10 was formulated, the "peaky" distribution was available to contribute. Describing the design in 1962, Vickers showed data that compared a representative actual VC10 wing section with a rooftop design that had been considered as a competitor. The pressure distribution of the actual wing at M = 0.74 (Figure 16) showed an almost constant supersonic Mach number normal to the local geometric sweep, over the forward part to 25% chord. Because on a tapered planform the local normal tends towards the longitudinal direction with increasing distance along the chord (i.e. the geometric sweep reduces, as seen in extreme form on the Vulcan's delta wing), this represents a gradual reduction in actual streamwise velocity, achieved by isentropic recompression. The terminating shock is the cause of the large step between 30% and 40% chord, but the gradual compression ahead has reduced its strength. Compared to the VC7, the achievement of this controlled pressure distribution implies a significantly more advanced understanding of both the recompression effect itself and the three-dimensional tailoring required in practice. Indeed, this certainly was the case and once again would involve the insight of the key RAE personnel associated with the V-bombers. Johanna Weber is credited with combining the existing linearised theories of wing design to enable thickness, camber, twist and sweep to be analysed together. With her long-term collaborator Küchemann, she had been deeply involved in the creating the physical understanding of wing-body and wing tip effects for swept wings. According to Green, Vickers saw Weber's method and Pearcey's "Peaky" pressure distribution and "seized on these two advances," resulting in the VC10's wing being more advanced aerodynamically than any previous civil aircraft.[46]



The aircraft that would result from this process was more conceptually like the American-built competition in terms of cruise design point, typically M = 0.8 and C_L = 0.45, but in service often M = 0.866.[48] The wing was swept outboard to 32.5° at the quarter chord (cf. 35° for the 707), of typical outboard thickness of 9.5% and of AR = 7.6, all of which promoted more efficient cruise at a higher Mach number than would have been possible with the V-1000. The contribution to this of the "peaky" pressure distribution is obvious from the left-hand plot in Figure 16; the point of drag rise was delayed by M ~ 0.03.

In 1971, a comprehensive study was undertaken by the Aircraft Research Association to compare transonic WT data for the VC10 with that from flight test which had been undertaken by BAC (of which Vickers had become a constituent) in 1965.(49) From the perspective of the current work, the data is of interest as it shows the extent to which the desired two-dimensional "sheared wing" flow (near constant isobar spacing along the span, when viewed along lines normal to the leading edge) had been achieved, together with the substantial region of supersonic flow, undergoing steady compression ahead of the shock. Flight data for the representative cruise condition above is given in Figure 17, which shows that the isobars in the mid to outboard region between stations 179 and 576 are predominantly aligned well with the geometric sweep. The shock is evident as the closely spaced set of isobars that pass through x/c = 0.3 at the intermediate station 358; although the data is not for the same condition, it can be seen that qualitatively the pressure distribution there is similar to illustrated in Figure 14. By design, the leading-edge suction shows rapid expansion to $C_p < -1.0$, which is compressed to $C_p \sim -0.8$ ahead of the shock. Clearly, the combination of Pearcey's aerofoil function and the Küchemann-Weber planform design insight was effectively implemented on the VC10.

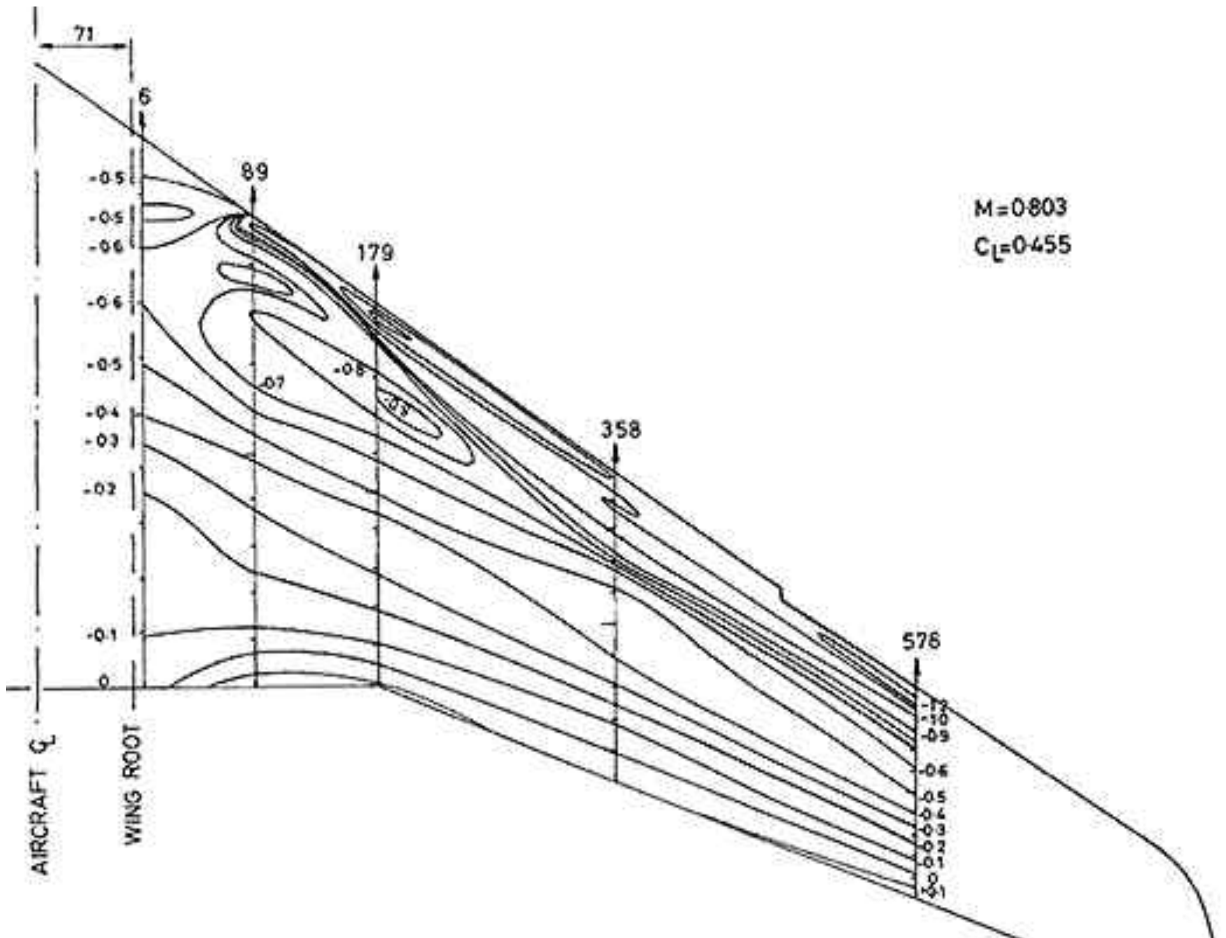


Figure 17. C_p distribution measured in flight test on a Super VC10 wing (49)

By 1959, De Havilland was developing the Trident airliner for British European Airways (BEA), closely tailored to that airline's requirements of a 1,000 nm range and 600 mph maximum speed. The resulting 585 mph economical cruising speed was equivalent to M = 0.89 in the stratosphere, greater than any other jet at the time.(50) Even with 35° sweep and with the VC10 experience, this specification was a challenge for contemporary aerofoil design capability. Three concepts that were known then to be critical to a successful design were identified by Dykins *et al*:

- Using sweep to delay the onset of compressibility effects
- Using sectional design to delay boundary layer separation at high lift
- Using sectional design to carry supersonic flow but avoiding strong shock waves

The last was of course the rationale behind the "peaky" aerofoil. De Havilland studied a matrix of three pressure distribution families: triangular (as NACA 0010, the Vulcan baseline), Rooftop (as RAE 101, subsequent Vulcan outboard), and rooftop with a supersonic leading-edge peak (as 'Newby' modified Vulcan), each with constant spanwise section and an alternative inboard region that promoted isobar sweep. As one might suspect, the combination of "peaky" section and tailored spanwise shape offered the best performance, showing, "very definite benefits in high Mach number drag characteristics." (51)

As discussed with reference to the development of the Victor in section 3, it is the compressed timescales by which new technology was adopted to achieve performance benefit that remains impressive. The Fluid Dynamics Group was inaugurated at De Havilland's Hatfield base specifically for the development of the Trident wing in 1956.(51) The company was confident enough in the basis of its performance estimates (and here it is implicit that the use of advanced aerofoils was inherent), that by September 1957 BEA was requesting permission from Her Majesty's Treasury to purchase the DH121 to meet its requirement.(42) De Havilland had been very recently bailed out by the UK government after the disaster of the early Comet programme, had lost the future long-range jet market for BOAC to Vickers, and was now essentially beholden to BEA and its changing views on what the new jet should be. Indeed, it may have been DH's willingness to sacrifice the wider commercial prospects of the aircraft and tailor entirely to BEAs very specific (and as it would transpire, misguided) specification that positioned them as the preferred bidder. Under these circumstances, is it plausible that they would have based the fundamental aerodynamic design of the aircraft, around an aerofoil technology unproven by flight test in the relevant Re-M space? Again, the words of Sir George Edwards, bemoaning the lack of model flight tests are appropriate. The successful Vulcan implementation must have been, at the very least, of some comfort.

By the end of 1962, two prototype jet airliners that made extensive use of Pearcey's two-dimensional aerofoil design principles to confer improved transonic performance had made their first flights in the UK. As shown in the contemporary sources examined, both were biased towards high speed cruise performance due to the requirements of their respective prime customers, in turn making this technology essential for competitive efficiency. In a 1968 review of the state of the art in transport aircraft wing aerodynamics, Wallace (Boeing Commercial Airplanes) noted the use of "peaky" aerofoils on the newest US transport aircraft, the Douglas DC-9 and Boeing 747, writing,

> "… Pearcey and his co-workers at NPL in England were energetically pursing the optimisation of airfoils with the best possible transonic flow properties that could be developed experimentally. Also, they were working diligently to evolved semi-empirical airfoil design criteria and to determine the basic trades between airfoil nose thickness and camber.
>
> "…. For the British designs of the BAC 111, the Trident, and the VC-10, perhaps much of the consistent improvement must be attributed to Pearcey for his airfoil work and to the Küchemann-Weber development of three-dimensional wing-body theory." (47)

It was therefore clear to (and acknowledged by) the competition, that the UK technology effort with the "peaky" transonic aerofoil as its two-dimensional basis represented the state of the art for civil transports in this period.

6.5 Exploiting the lead in Europe

The prospect of European cooperation in the design of civil transport aircraft was perceived as an important strategy in several quarters by the middle of the 1960s. One of the findings of the 1965 Plowden report on the aerospace industry immediately emphasised by the UK government was the need to promote European collaborative projects; this also sat well with the concurrent policy that pursued membership of the European Economic Community (EEC).(52) Both BAC and Hawker Siddeley were keen to develop future subsonic aircraft, initially as outgrowths of the existing VC10 and Trident designs, while in France Sud Aviation (BAC's partner on Concorde) was seeking government launch aid for its proposed Caravelle replacement. A Memorandum of Understandng (MoU) that would establish a committee to investigate further the market and technical requirements for such a collaborative aircraft was signed by the UK and French governments in May 1965, while Germany would join the effort in February 1966.(53)

Essentially on an independent basis, aircraft companies opened negotiations across borders to form groups that would submit proposals to this committee. In September 1967, the three governments signed a further MoU for a 12-month project definition phase, still without launching the then-proposed 267 passenger Airbus A300 but committing funding to development. In contrast to the final situation however, there was a strong emphasis on the UK involvement in the bespoke engine programme, with a 75% workshare being allocated to the UK (with Rolls-Royce as prime contractor) for development of the RB207, compared to 37.5% for the airframe under sub-contract to Sud Aviation.

BAC would eventually withdraw from negotiations with Dassault and Sud Aviation, pursuing an alternative strategy involving UK-only projects. Hawker Siddeley responded to the collaborative challenge by partnering initially with Breguet and Nord, resulting in a proposal aircraft called HBN-100. (54) However, the French government preferred Sud Aviation to act as its project lead, resulting in HS forming an alternative alliance, focussed on its acknowledged expertise in wing design. By June 1968, the result of the project definition phase was the baseline A300 design, now with over 300 seats and with thrust requirements beginning to present a challenge for even the 'paper' RB207 design, by some margin the highest thrust turbofan available in Europe.

The relevance of this early history is in what happened immediately afterwards. Rolls-Royce was already committed to the RB211 for the Lockheed TriStar and could not allocate the necessary resources to two programmes, leading to abandonment of the RB207. Without an engine in this thrust class, the A300 as envisaged was technically dead. Even had that not been the case, an MoU requirement for the end of the project definition phase was 75 firm orders from the respective national airlines. With the concept of government-owned flag carriers still highly relevant to the future sales prospects of a civil aircraft at the time, the ambivalence of BEA and Lufthansa regarding the proposal added further difficulty to the situation. Fundamentally, the programme was offering the airlines an aircraft that was too big for their requirements and which was not technically feasible in the absence of the RB207 engine.

Post-Trident 1, the Hawker Siddeley team at Hatfield (formerly De Havilland) had contributed to improved developments of that design (long range Trident 2 and high capacity Trident 3), the HS125 executive jet and the HS.681 military transport. Progressively, the aerofoils used on these aircraft incorporated nose droop and rear loading, innovations that improved the low- and high-speed performance respectively. These concepts were also being pursued at NPL and the RAE, in support of the various military and civil programmes for which transonic aerofoil design remained a critical technology.[55] NPL assisted HS in the wind-tunnel-led development of controlled increases in rear loading by extending the region of "sonic rooftop" on the upper surface, thereby increasing the pressure delta between this and the positively loaded lower surface. By 1965, NPL had tested an aerofoil that incorporated the combined aerodynamic concepts of "peaky" leading edge, "sonic rooftop," and rear loading, while a year later HS would commence the design along these lines for the HBN-100; ordinates being passed on to the RAE in July 1966. By the time of the September 1967 MoU therefore, Hawker Siddeley could demonstrate an appreciation of the state of the art in transonic transport wing design, coupled with access to the complementary UK government research agency knowledge and (also via ARA) transonic wind tunnel capacity, that was likely challenged in Europe only by BAC.

The aerodynamic development of what would become the wing for the A300B was discussed in a contemporary account by D M McRae, from which Figure 18 showed the inputs to the aerodynamic philosophy. We shall consider only the third column, which traces a direct line from Pearcey's NPL work on the "peaky" aerofoil (of which he has stated the Vulcan application was the validation), through the Trident to the A300B concept. As with the VC10 and Trident applications, the supersonic expansion-isentropic compression phenomenon was the vital physical mechanism that reduced the strength of the inevitable upper surface shock. The adaption of additional mechanisms (most importantly the rear loading) improved cruise efficiency considerably compared to the earlier aircraft, but also opened up the design space at aircraft level. The A300 and A300B aircraft were not designed to operate at such high cruise Mach numbers as the VC10 and Trident, so that the improved transonic aerodynamics could be "cashed in" as reduced wing sweep and increased thickness, both of which reduced wing structural weight. This was illustrated by Dykins et al [51] in Figure 19, showing that the step from Comet to the initial "peaky" + three dimensional design geometries of the VC10 and Trident, then the subsequent step to the A300B were each worth of the order of 2% in equivalent thickness to chord ratio.

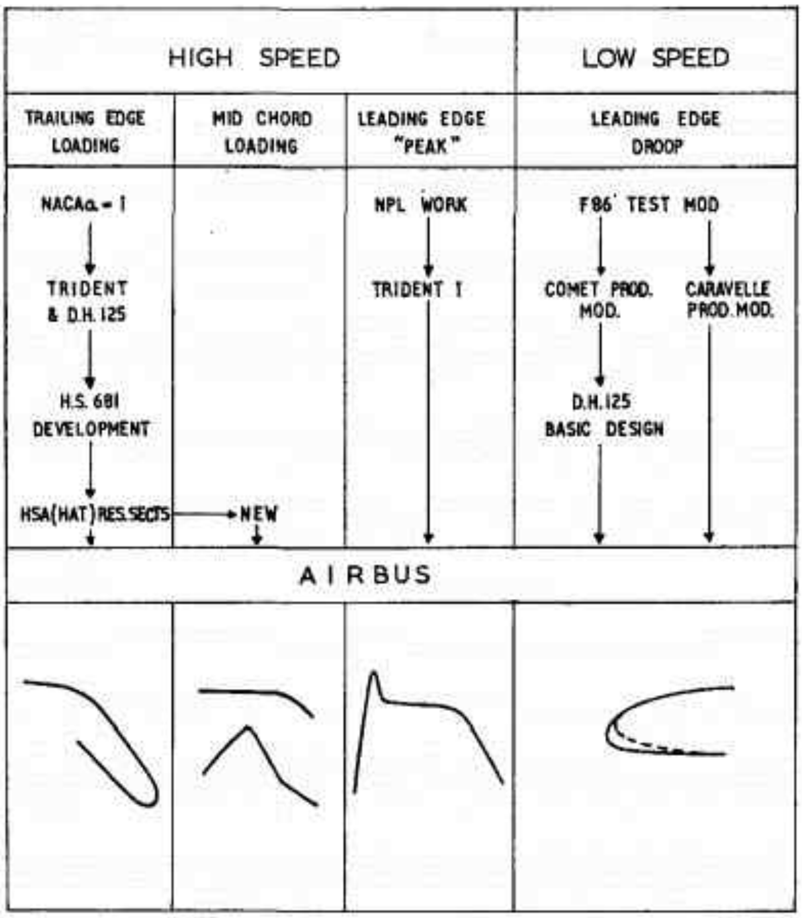


Figure 18. Inputs to A300B section design from previous development [56]

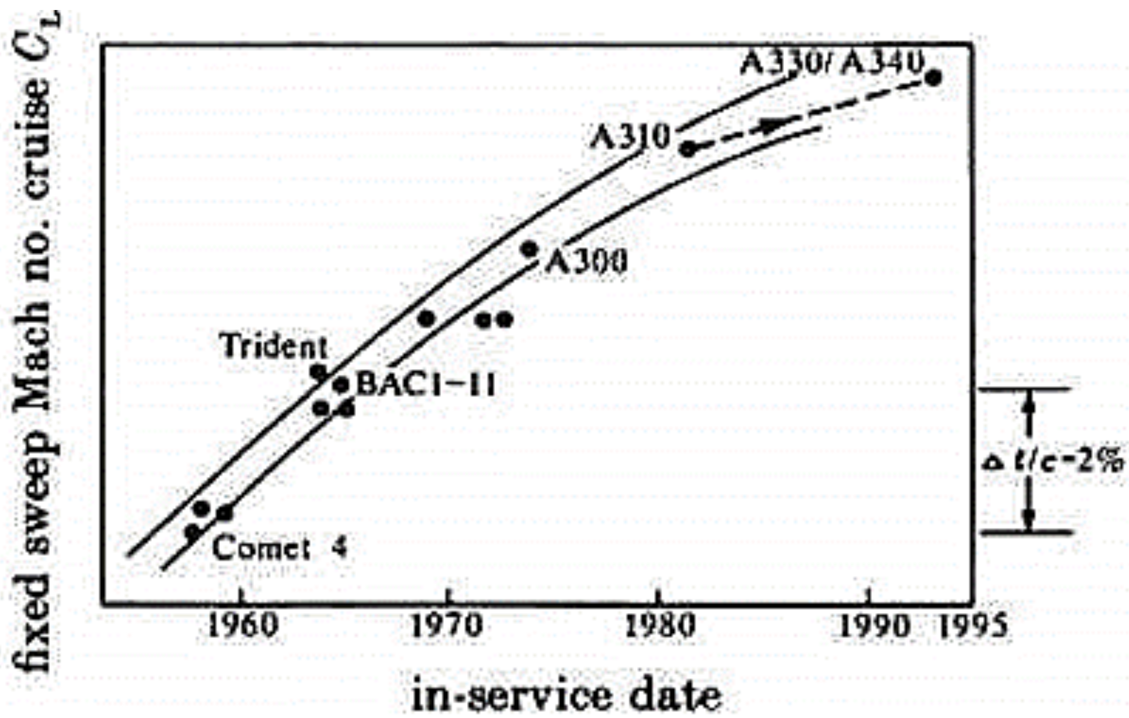


Figure 19. Illustration of the contribution of improved wing aerodynamic design to aircraft at the system level, in terms of equivalent allowable t/c increase with time. From Dykins et al [51]

The decision by Rolls-Royce to abandon the RB207 created an engineering necessity to reassess the size of the new aircraft in the direction that the airlines wanted. Now a 250-seat aircraft designated A300B, it could use the same powerplants already planned for the Boeing 747 and McConnel Douglas DC-10. To the UK government and BEA, there were complicating factors. The 75% engine workshare had evaporated, with the return on investment now hinged on involvement in the airframe. The nationalised airline clearly preferred the UK-only BAC 3-11 powered by the RB211, the latter already subject to launch aid but with the risk spread by its exclusivity on the TriStar.

Consequently, it is easy to understand the scepticism with which the UK government viewed the European Airbus programme as 1968 drew to a close. It had already heavily committed to one airliner programme (Concorde) that was struggling for firm orders and was now in danger of adding a second to its portfolio. The choice was between supporting a pan-European design with significant UK workshare (albeit without engine exclusivity), a completely UK design that was approximately one year behind and would need to compete with the Airbus, or none of the above and require industry to support itself commercially. As is now well known, the last was the chosen course of action, although it was well into 1970 before the final decision not to provide launch aid for the BAC 3-11 was announced.

The A300B programme still needed expertise in advanced transonic wing design and Hawker Siddeley remained keen to provide it. In a remarkable turn of events, HS invested £35m of its own money and obtained launch aid not from its own government, but from that of the Federal Republic of Germany, taking a strategic long view on how to rebuild its aerospace industry. While clearly not the only factor, the stature of HS in this field was such that, on behalf of its tax payers, a foreign government underwrote the original UK involvement in what would shortly become Airbus Industrie. As it came to pass and with the disappearance of the combined airframe-engine programme, the position in which the UK finds itself at the time of writing of this paper as a major constituent and beneficiary of its involvement in Airbus, hinged entirely on the proven transonic wing design expertise of Hawker Siddeley.

6.6 The connection to Supercritical aerofoils

The current author is not an expert in marketing, but it could perhaps be considered a missed opportunity that the "Peaky" tag was used by Pearcey and the wider UK aerodynamic community, rather than following Bore's advice and hence "Supercritical". The latter has come to be associated with the parallel effort in the USA by Richard T Whitcomb at the National Aeronautics and Space Administration (NASA) to exploit the wave drag benefit of near-shockless aerofoil concepts, for which the review by Harris [57] provides a comprehensive overview. He noted the large leading-edge radius and flat suction surface of the Whitcomb aerofoil, designed to create supersonic expansion and limited recompression, commenting further:

> "… these two concepts are consistent with the work done by Pearcey, when he demonstrated that the essential geometric feature of sections designed to exploit the isentropic compression due to waves reflected from the sonic line is an abrupt change on the upper surface from the relatively high curvature of the leading edge to a relatively low curvature downstream and that this can be provided with a large leading-edge radius."

Whitcomb himself discussed the early NASA work on supercritical aerofoils in a 1974 ICAS paper, again linking the pioneering work of Pearcey and colleagues to the new concepts:

> "The first airfoils designed specifically to delay drag rise by improving the supercritical flow above the upper surfaces were the 'peaky' type airfoils of Pearcy. They provide an isentropic recompression of the supersonic flow ahead of the shock wave located on the forward region of the airfoil …. These airfoils or their derivatives were used on the second generation of the subsonic jet aircraft designed in the USA." (58)

While Harris mentioned Whitcomb's "intuitive reasoning and substantiating experimentation", the published material from the NPL team on the subject meant that the US effort did not commence from a cold start. The first Supercritical aerofoil incorporated a slot at around 75% chord, with the specific aim of suppressing boundary layer separation following the rear shock. Following this investigation in 1964, a non-slotted version was developed incorporating the features now recognised; data on this geometry was circulated internally at NASA Langley in 1967, with the general concept classified. However, as alluded to earlier, this effort was paralleled independently by the work at NPL and subsequently RAE, with a recognisable UK Supercritical aerofoil being wind tunnel tested in 1965.(55) Over the next decade, both organisations would continue to refine and selectively disseminate information on their work. A major topic that can be extracted is the need to operate effectively off-design, with the recognition that near shockless flow might be achieved within a very narrow operating window, but that this was not practical for a real aircraft and that the aim had to be effectiveness and efficiency in the presence of a weak rear shock.

The ultimate outcome was the understanding of the flow physics of the Supercritical aerofoil, that meant it was available to be incorporated in the design (using also the huge advances in computing in the intervening period to create the specific three-dimensional geometry) of the third generation subsonic transports such as the Airbus A310 and Boeing 757. The major review works referenced above notably all discuss the variation in leading edge radii to ensure that the supersonic expansion-isentropic compression phenomena occurred, as described by Pearcey widely at the start of the 1960s and in his communication with Robert Pleming.

7 CONCLUSIONS

This paper initially set out to investigate the work of Pearcey, Newby, and others in connection with the Vulcan, in the context of the former's communication with Robert Pleming. There is little doubt that the aerodynamic intervention of Pearcey's new aerodynamic technology, coupled with Newby's insight into its rapid application, saved the Vulcan programme at a critical juncture. It is difficult to imagine that with production already underway and an alternative aircraft available to fulfil the same role, a major structural redesign would have been viable. Pearcey's point on the significance of the leading-edge modification, which may well have been the pioneering application of the "peaky" pressure distribution, is measured. It must have been, as he wrote, "a boost". Was it essential? It is likely that in the fullness of time, confidence would have grown to allow new aircraft designs to be based around the concept if the Vulcan had never existed. However, it is also clear that the absence of a method of providing aerodynamic validation of designs at full scale Mach and Reynolds numbers was thought to be a severe problem. Would Vickers really have been confident in the performance of the VC10, combining as it did excellent high lift and high Mach capability, *at the time that it did* without a full-scale demonstration? This seems to the author to be the most interesting question raised; without the Vulcan demonstration, would the VC10, Trident, and BAC 111 have lacked the aerodynamic advantages that they gained. If so, where would that have positioned the UK at the time of the European Airbus discussions in 1965?

In terms of definitive conclusions, it has been shown that:

- Predicting the buffet boundary of transonic aircraft was very difficult at the time of the design of the V-bombers.
  - This was exacerbated by the relatively poor tools and lack of high-speed WT capacity available, together with the general lack of knowledge of the flow physics implied by the M = 0.875, 50,000 ft altitude cruise requirement.
  - Prior knowledge that this was a driver of the high-speed model test programme (Avro 707A).
  - The concurrent flight test programme of the 707A and production of the full-scale Vulcan was an accepted necessity in order to have the B35/46 compliant aircraft in service as soon as possible.
  - The usefulness of the 707A to the programme should be viewed in this context; although often perceived to have been too late to contribute, on the contrary it provided a relatively quick and cheap method both of identifying issues and validating significant aerodynamic modifications to the Vulcan.

- The leading-edge modifications were developed by a combined Avro/RAE programme, but the insight of NPL transonic work was essential to this
  - The use of the $\Delta C_{p.te}$ criteria as a surrogate for the flight buffet boundary allowed the wind tunnel tests to predict the full-scale resolution.
  - The concept of the "Peaky" upper surface C_p distribution was exploited to provide the necessary effectiveness (postponement of buffet) and efficiency (reduction in total pressure loss and drag increment).

- The Vulcan implementation was not a necessary step to the use of "Peaky" aerofoils on future transonic aircraft, but may have provided an early boost to confidence in both the concept and available design tools
  - The Trident and VC10 both used the concept and, bearing in mind the experience of V-bomber development, would have been placed at significant risk from a performance perspective without available flight test confirmation prior to design.
  - Herbert Pearcey, deeply involved with and associated with the concept, wrote that he believed this to be the case.

- The Supercritical Aerofoil was ultimately an evolution of the "Peaky" concept; it required the understanding of the supersonic expansion-isentropic compression phenomena
  - The major players, including the groups at NASA Langley and NPL, were aware of and referenced Pearcey's work
  - His statement on the relevance of his work, including the Vulcan implementation, to the Supercritical Aerofoil concept appears entirely supportable based on the available reference material.

This work is dedicated to the memory of Dr Robert W Pleming, through whose vision and determination a new generation were able to enjoy the remarkable spectacle of a Vulcan in the air.

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