



CRANFIELD UNIVERSITY

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**THE INTRODUCTION OF LAMINAR FLOW TO THE DESIGN
AND OPTIMISATION OF TRANSPORT AIRCRAFT**

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I. Abstract

A methodology has been developed to model the direct consequences of laminar flow technology on wing, empennage and nacelle surfaces. In particular two concepts were considered, namely Natural Laminar Flow (NLF) and Hybrid Laminar Flow Control (HLFC). The methodology was introduced into an existing numerical design synthesis for commercial transport aircraft, which was linked to a non-linear constrained optimisation code. This permitted the impact of laminar flow technology on the optimum aircraft configuration and Direct Operating Costs (DOC) to be assessed.

Comprehensive design studies were performed to consider the impact of introducing various HLFC applications to a wide range of aircraft types. These showed that DOC benefits were possible for all aircraft types with the various applications. Optimising the configurations with HLFC showed substantially larger DOC benefits relative to corresponding derivative configurations due to reduced aircraft size and improved aircraft efficiency. In addition, significant variation in the DOC benefits was observed between aircraft types due to a number of factors - the most important being that the benefits generally increased with the design stage length of the aircraft. Further studies were also conducted to assess the sensitivity of the configuration and DOC to issues where some degree of uncertainty existed. These studies have served to validate the modified design synthesis and demonstrated its robustness with the inclusion of the laminar flow methodology. The flexibility of the methodology will permit easy incorporation of improved data as it becomes available.

II. Acknowledgements

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V. Abbreviations

α	Alpha - Angle of Incidence
2D	Two-Dimension
3D	Three-Dimension
ACEE	Aircraft Energy Efficiency
ALT	Attachment Line Transition
ARA	Aircraft Research Association
ASM	Available Seat Mile
BAe Airbus	British Aerospace (Airbus) Limited
CFI	Cross Flow Instability
C_L	Lift Coefficient
C_q / C_Q	Suction Coefficient
DLR	Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt
DOC	Direct Operating Costs
DRA	Defence Research Agency
ELFIN	European Laminar Flow INvestigation
FAA	Federal Aviation Administration
G.E.	General Electric Aircraft Engines
GASP	Global Atmospheric Sampling Program
HLFC	Hybrid Laminar Flow Control
HYLDA	HYbrid Laminar flow Demonstration on Aircraft
JAA	Joint Aviation Authorities Committee
JAR	Joint Aviation Requirements
L/D	Lift - Drag Ratio
LARA	Laminar Flow Research Action
LEFT	Leading Edge Flight Tests
LFC	Laminar Flow Control
M	Mach Number
MTO	Maximum Take-Off mass
MVO	MultiVariate Optimisation
NAE	National Aeronautic Establishment
NASA	National Aeronautics and Space Administration
NLF	Natural Laminar Flow
OEM	Operating Empty Mass
ONERA	Office National d'Etudes et de Recherche Aérospatiales
R	Attachment Line Reynolds Number
$R\theta$	Reynolds Number based on Momentum Thickness of Attachment Line Boundary Layer
Re_c	Chord Reynolds Number
SAS	Simulated Airline Service
SLS Thrust	Sea-Level Static Thrust
SPL	Sound Pressure Level
TSI	Tollmein-Schlichting Instability
USG	U.S. Gallon

1. INTRODUCTION

Given the considerable investment required to acquire transport aircraft, (Airbus A340-300 - \$105,000,000, A320-200 - \$37,500,000, January 1995 [11]), it is imperative that airlines select appropriate aircraft that will allow them to operate in an extremely competitive industry.

Fuel burn is often used as a measure of aircraft efficiency as it reflects improvements in aerodynamic, structural, system and engine technology. Generally fuel burn is measured in terms of Available-Seat Miles (or kilometers) per unit volume of fuel, to allow comparison between aircraft types of differing capacity. In economic terms, the benefits of a 1% reduction in fuel burn for A320 and A340 aircraft, each operating over two typical ranges, with different fuel prices, are shown in Figure 1 from [134].

Aircraft	Range (nm)	Flights/year	Fuel Saving 1 year (kg)	Fuel Saving 15 years (kg)	Cost Saving 0.5\$/USG	Cost Saving 1.0\$/USG
A320	500	2,175	70,000	1,050,000	\$175,000	\$350,000
	2,000	802	84,000	1,260,000	\$210,000	\$420,000
A340	3,000	657	220,000	3,300,000	\$550,000	\$1,100,000
	6,000	400	310,000	4,650,000	\$775,000	\$1,550,000

Figure 1: Impact of 1% Fuel Reduction, from [134]

If this is considered on a larger scale, during the first **three months** of 1993, a fleet of 3602 aircraft (approx. half the world transport aircraft fleet) operated by various U.S. airlines were issued with **13,161,314,780 litres** (3,481,829,306 U.S. Gallons) of fuel [12], representing over 10.5 million tonnes. A 1% reduction in fuel burn would represent a saving of 132 million litres across this fleet. The importance of fuel burn reduction is particularly important as the energy use by air-traffic could increase by 180% during the next ten years [120].

Advances in transport aircraft technology, since the Boeing 707 revolutionised transport aircraft configuration, have led to major improvements in fuel consumption, indeed fuel burn per passenger kilometer has been halved since the 1960s [120]. This is supported by in-service performance data for the Airbus A320-200 and Boeing 757-200 [12] aircraft (1980s technology), with approximately 75 Air-Seat-Miles (ASM) per U.S. Gallon (USG) of Fuel compared with a figure less than 40 for a Boeing 727-100 designed in the 1960s. However, the current level of understanding that has been achieved in transport aircraft design means that further improvements are limited to fractions of one percent.

One of the few technologies remaining that is potentially capable of significant efficiency improvements is laminar flow through reductions in the aircraft profile drag (full description in section 2). Local skin friction coefficients associated with laminar boundary layers are approximately 10% of that for a turbulent equivalent, thus reducing the profile drag, which typically constitutes approximately half of the total aircraft drag, Figure 2.

On current transport aircraft, boundary layer transition from laminar to turbulent flow occurs very close to the leading edge due to a number of transition mechanisms. Clearly, delaying this transition on parts of the external airframe surface will result in profile drag reductions.

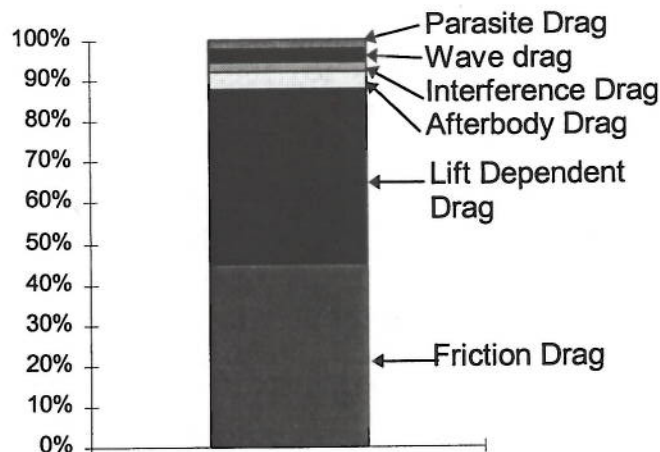


Figure 2: Typical Drag Breakdown for a Transport Aircraft

During over 50 years of laminar flow research, the level of interest has fluctuated with periods of concentrated activity separated by periods of little work. The periods of interest have generally ended due to infeasibility of the achieved technology level for practical applications. For early periods of research, this was due to technical limitations. While successive research programs have solved many of these technical issues, the economic viability of practical applications has been of increasing importance for recent studies. It is therefore not surprising that recent periods of activity, namely mid-1970s, early 1980s and the early 1990s, have been driven by increasing fuel prices, Figure 3, with reduced interest as fuel prices decreased. Current fuel prices are at their lowest for some time, although the trend appears to be upward [51], with the imposition of an aviation fuel tax in the United States [52] pushing fuel costs even higher. If this is a long-term trend, rather than a short-term fluctuation, interest in laminar flow may further increase.

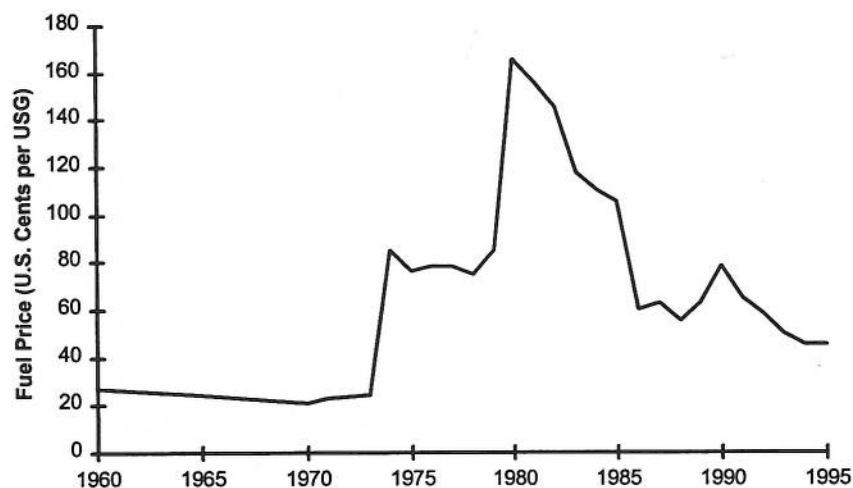


Figure 3: Historical Fuel Price Variation, from [34]

A number of approaches to overcome the various transition mechanisms have been investigated, with a view to achieving extensive laminar boundary layers. Many wind-tunnel and flight tests have successfully demonstrated the potential drag

reductions for laminar flow technology applied to the wing, empennage, nacelle, and in some cases the forward fuselage.

To realise the potential drag reductions available through laminar flow technology, additional requirements are placed on the aircraft and its operator, which represent penalty factors. These penalty factors include increased manufacturing complexity, and a number of practical problems associated with the operational environment that have prevented the widespread application of laminar flow on aircraft other than those in the general aviation class. Solutions for many these problems are now becoming sufficiently understood to permit laminar flow applications in the near future.

The balance between the drag reductions and the penalty factors will define whether the introduction of laminar flow technology produces a net benefit or penalty. This benefit can be measured in operating economics or payload/range performance, depending on the application. As this study is considering laminar flow technology applied to commercial transport aircraft, operating economics is used as the primary measure of feasibility.

Previous project studies [140] [24] have concluded that fuel burn reductions in excess of 10% are possible where extensive laminar flow is achieved. If the above values for a 1% reduction are considered, the potential financial savings become very attractive.

In addition, reduced fuel burn will also have a significant beneficial effect on the environment, for which concern has greatly increased during recent years, and is likely to continue at an accelerated rate. A study of emissions associated with various transport modes [134] showed that aircraft emissions, in West Germany during 1988, were comparable with those for trains and inland shipping, all of which are drastically less than that due to road traffic. However, air traffic emissions are placed directly into the upper atmosphere where they may be particularly harmful [120], given the minimal level of mixing in the stratosphere.

At present, consideration for the environment has little direct impact on the running of airlines, although possible restrictions on 'dirty' engines or increased fuel taxes may increase its significance. Indeed, the U.K. Secretary of State for Transport, John Gummer, has recently suggested the imposition of an aviation fuel tax for environmental reasons [30].

Any study investigating the impact of laminar flow must first address the associated basic aerodynamic phenomena, in particular those associated with boundary layers. This includes boundary layer formation and development, the various forms of instability along with any means of avoiding or countering them. Such issues are discussed in Chapter 2.

To assess the impact of laminar flow technology on commercial transport aircraft it is necessary to consider the current level of technology, and opinions as to how it might be applied. A technology review considered recent and ongoing research throughout the world, with a summary of the state-of-the-art given in Chapter 3.

The introduction of any new technology, including laminar flow, onto commercial transport aircraft will only occur if the airlines are prepared to operate such aircraft,

which generally implies that the technology must offer the airline long term economic benefits, through reduced operating costs. However, in some cases improved safety or increased range capability may be the most important consideration.

Certification authorities may feel it necessary to impose restrictions on the operations of an aircraft employing a new technology to ensure safety levels are maintained. This may reduce the economic benefits achievable with the aircraft. Potential areas of concern for certification authorities and airlines are discussed in Chapter 4.

Minimum drag conditions for aircraft can be shown to occur when profile drag is equal to lift-dependent drag [66]. Current transport aircraft configurations are designed to achieve maximum economic efficiency through a compromise between aerodynamic and structural efficiencies, as well as various economic and operational factors. This typically results in profile drag and lift-dependent drag coefficients each making up approximately half of the total aircraft drag, as shown in Figure 2.

Simply introducing laminar flow technology to a current turbulent design will significantly reduce profile drag and hence the fuel mass requirements. This in turn reduces the lift-dependent drag although these reductions are minor relative to profile drag reductions. This upsets the balance between the two types of drag, and results in an aircraft that does not achieve maximum efficiency. The aircraft may also be oversized for its design mission, although it will have an improved payload/range capability. Any DOC benefits through reduced drag will be limited, and in some cases negated, by the penalty factors.

One approach followed by a number of previous studies is to linearly re-size, or scale, a turbulent configuration using a given set of rules [2] [121]. This typically involves reducing wing area and engine re-rating, to achieve constant wing loading and thrust to weight ratio, respectively. This takes advantage of a reduced aircraft size but does not consider whether the balance between the two drag components is retained.

To maximise the potential benefits afforded by laminar flow technology, the aircraft configuration must be re-optimised taking into account the drag reduction. The optimisation of an aircraft design is a highly iterative process encompassing many disciplines, such as aerodynamics, structures, systems, and performance. All of this must occur within operational and procedural limitations imposed by the regulatory authorities and operators.

To facilitate the rapid determination of optimised aircraft configurations, a MultiVariate Optimisation (MVO) approach is followed where a transport aircraft design synthesis is linked with a constrained numerical optimisation code. An optimum aircraft configuration is defined as that which is capable of performing a given design mission for minimum DOC per seat kilometer, whilst meeting all operational and procedural constraints. These FORTRAN codes were supplied by the Propulsion Department, Defence Research Agency (Pyestock), in a form capable of considering conventional configurations with turbulent boundary layers.

The penalty factors associated with laminar flow were identified, assessed and subsequently modelled, along with the profile drag benefits, within the design

synthesis. This has permitted the effects of two forms of laminar flow technology to be considered on the wing, empennage and nacelle surfaces. Laminar flow can be applied to these surfaces individually or in any desired combination. The methodology used is described in Chapter 5.

Project studies conducted using this modified code have considered the net DOC benefits of introducing laminar flow to the various surfaces of transport ranging from 100 seat regional jet aircraft through to a 600 seat 'super-jumbo' aircraft. Sensitivity studies have also been performed to assess the influence of various factors on the DOC. This is necessary as the likely extent of many factors is not yet fixed. Other factors such as fuel price, are controlled outside the aircraft design process. The results from these studies are presented in Chapter 6 and discussed in Chapter 7.

1.1 Project Objectives

This three year study is supported by the United Kingdom Department of Trade and Industry under contract FRN/9/4/2028/223 and performed in conjunction with the Defence Research Agency. This contract required that the design synthesis code be modified to consider the impact of laminar flow technology on commercial transport aircraft. Both Cranfield College of Aeronautics and the DRA, previously Royal Aircraft Establishment (RAE), have a history of laminar flow studies. Early British laminar flow control flight tests were performed at Cranfield, during the 1950s. Project studies considering laminar flow control applied to a Boeing 707 and a 300 seat tri-jet were performed by the RAE (late 1960s) [151] [152] and Cranfield (1980s), respectively [71].

It was intended from the outset that the study would be the basis for a PhD research topic. To satisfy the requirements for the PhD, it was necessary to use the modified design synthesis code to perform a number of design and sensitivity studies.

Although the emphasis of the contract and thesis objectives (detailed below) differ, they complement each other. While the modification to the design synthesis provides a means to rapidly investigate the impact of laminar flow technology, the design studies provided an opportunity to check the integrity of the modifications on a wide range of aircraft.

1.1.1 Contract Objectives

- i) To identify and assess the individual importance of aircraft design factors related to laminar flow technology, such as the profile drag reductions, increased production complexity, and modified operational requirements.
- ii) To model the above factors within an existing commercial transport aircraft design synthesis tool linked to a constrained numerical optimisation code, in such a way as to allow the impact of laminar flow technology applied to the wing, empennage and nacelle surfaces, to be assessed.

1.1.2 Thesis Objectives

- i) To conduct project studies investigating the economic viability of two concepts for delaying laminar-turbulent transition.

- ii) To conduct studies to investigate the sensitivity of the DOC to the individual aspects of laminar flow technology, particularly important where no consensus has yet been reached on the likely degree of any one aspect.
- iii) To analyse the results of these studies and assess the practicality and benefits of laminar flow technology on a wide range of subsonic transport aircraft.

2. LAMINAR FLOW

This study is primarily a design exercise to determine the impact of laminar flow on transport aircraft. However, a basic insight into boundary layer aerodynamics is necessary to consider the theory behind laminar flow technology and correctly integrate its effects into a design model. (Boundary layers are described fully in [37]).

If 2-Dimensional (2D) flow past a stationary surface is considered, friction with the surface will reduce fluid velocity close to the surface. The fluid velocity decreases from the freestream velocity with proximity to the surface (Figure 4). Boundary layer thickness can be defined as the distance from the surface at which the flow velocity is 99% of the freestream. For a surface moving through a stationary fluid, the friction will impart some velocity into the fluid across the moving surface. The magnitude of this velocity will reduce with distance from the surface. The outer limit of the boundary layer is defined as the distance from the surface at which the flow velocity is 1% of the surface.

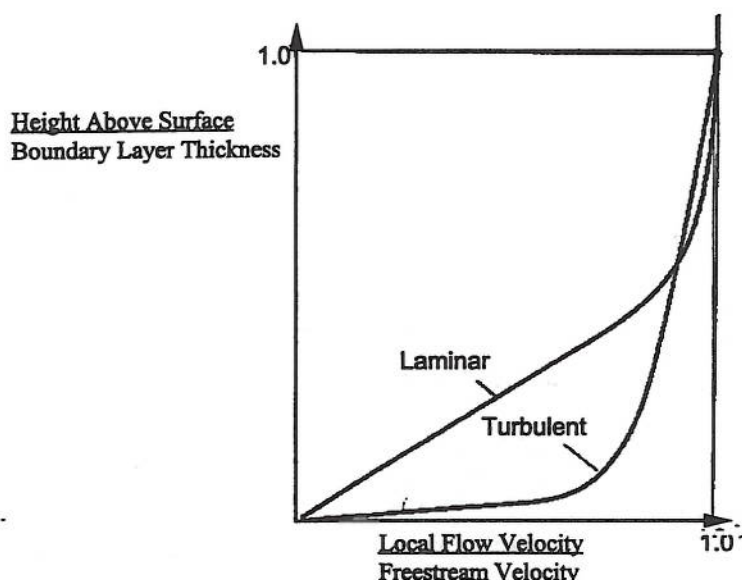


Figure 4: Typical Boundary Layer Velocity Profile, from [66]

Laminar flow is an aerodynamic term used to define a smooth boundary layer where the air travels in streamlines roughly parallel to the surface. Although the general mean motion within a turbulent boundary layer is also parallel to the surface, there is a large degree of random fluctuation in velocity direction and magnitude [37]. This results in the turbulent skin friction coefficients being a factor of approximately 10 greater than for laminar flow.

If the flow past a flat plate is considered (Figure 5), a boundary layer forms at the leading edge and increases in depth with distance from the leading edge, whilst remaining laminar. At some point, transition to a turbulent boundary layer occurs with a corresponding rapid increase in boundary layer thickness. Given the reduced local friction coefficients associated with laminar flow, the total friction drag of the plate falls as transition moves downstream.

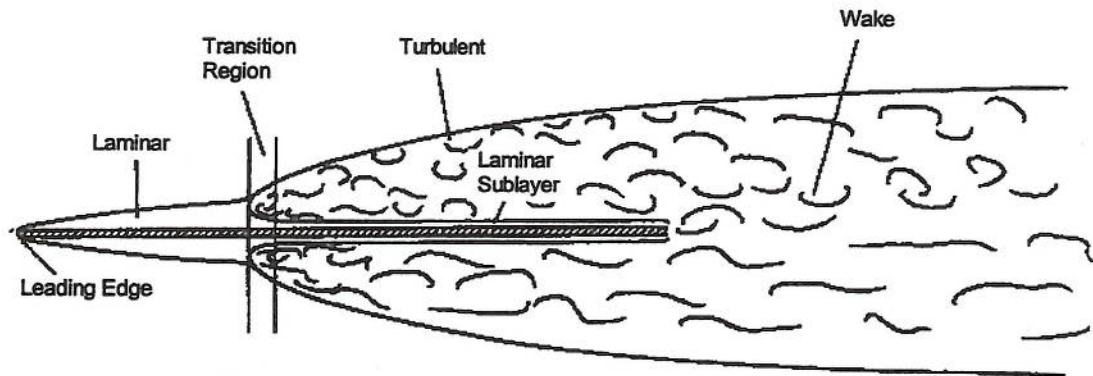


Figure 5: Boundary Layer Development, from [66]

2.1 Boundary Layer Instabilities

For the 3-Dimensional (3D) flow over an aircraft's surface, there are four basic types of natural instability which can cause transition, Tollmein-Schlichting, Cross Flow, Attachment Line Transition and Taylor-Goertler Vortices. Transition occurs when the limits for any one of these mechanisms are exceeded, with local conditions determining by which mechanism.

The first three instabilities are briefly described below, although more detail is available in [4], which in turn summarises many other reports. Taylor Goertler instabilities are omitted as they are more associated with concave surfaces, more likely to be found in pipe flow [58].

Where suction is used to stabilise the natural disturbances (see section 2.2.2), the suction itself can create boundary layer disturbances. These are also discussed below.

2.1.1 Tollmein-Schlichting Instability (TSI)

Transition due to TSI occurs when 2D wave disturbances that propagate within the laminar boundary layer in a streamwise direction become unstable. With increasing distance from the leading edge, the disturbances are amplified until transition occurs. The location of transition is dependent on the flow Reynolds number, pressure distribution, surface quality and disturbance environment.

2.1.2 Cross Flow Instability (CFI)

In regions close to the leading edge of an infinite swept wing, the chordwise velocity component changes rapidly, while the spanwise component is constant. Hence the streamlines are curved region.

The streamline curvature causes an imbalance between the pressure forces and centrifugal forces within the boundary layer, which in turn creates a boundary layer velocity distribution normal to the local external streamline, Figure 6. This has a point of inflection, which makes the profile intrinsically unstable.

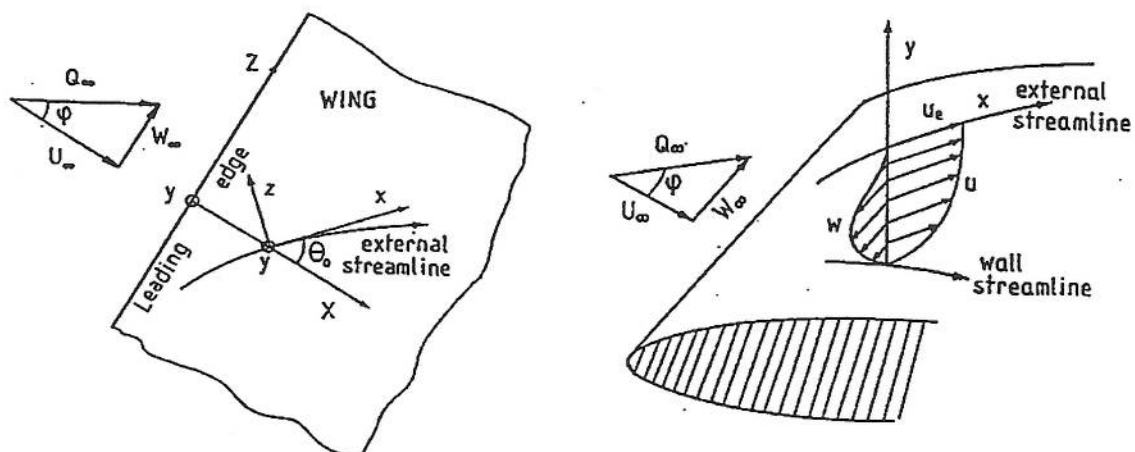


Figure 6: Cross Flow Instabilities, from [4]

Cross-Flow Instability is a major concern for high Reynolds number flow over swept surfaces. It is the predominant transition mechanism in the forward 5-10% of the chord where the magnitude of spanwise flow is at its greatest [106]. The degree of CFI over a surface is a function of the leading edge sweep, and 3D surface profile.

Significant 3D flow also occurs in the trailing edge region, although the boundary layer will generally be turbulent in this region.

2.1.3 Attachment Line Transition (ALT)

On 2D aerofoil sections the streamline dividing the upper and lower surface flow meets the body surface forms a stagnation point, where the static pressure is at its highest. On a wing the stagnation points form an attachment line along the span.

This is also true for flow over a swept wing, although a component of the flow velocity will move along the attachment line will exist [4] [105], Figure 7. This spanwise velocity component gives to the attachment line boundary layer, which is susceptible to disturbances similar to TS instabilities, although the boundary layer development is complicated by complex flow fields and that it is effectively starting at all points along the leading edge.

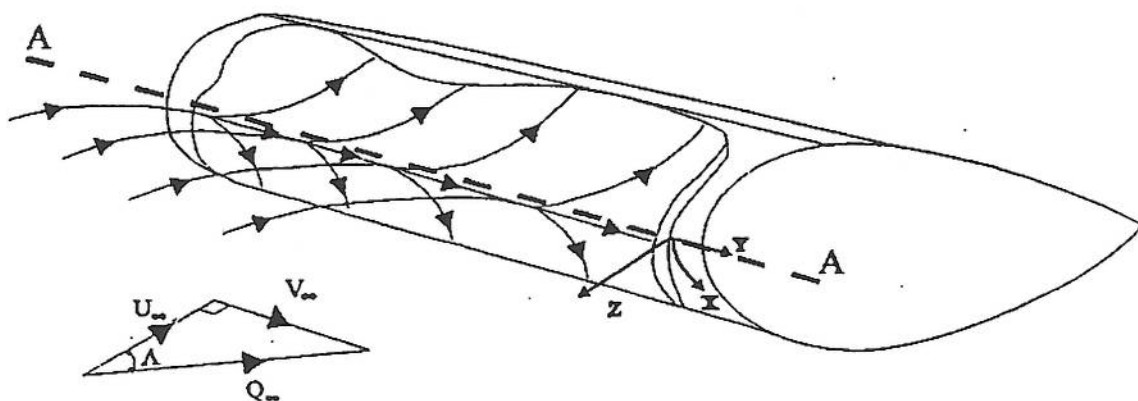


Figure 7: Attachment Line Flow, from [105]

Two Reynolds numbers, R_θ and R (described in detail in [21] and [4] respectively) have been suggested to predict the onset of ALT. For an isolated leading edge, i.e.

inboard extremity of model not connected to wall or fuselage, a number of experiments, summarised in [4], have concluded that for $R\theta < 236$ and $R < 583$, small disturbances within the attachment line boundary layer will be damped out. However, if these values are exceeded, disturbances are amplified leading to "Natural transition" of the attachment line boundary layer. Although some experiments, described in [4], have concluded that transition can occur at values of R as low as 385.

Should this flow become turbulent, all flow downstream, along the leading edge and over the both surfaces will become turbulent. Therefore the prevention of ALT is critical where extensive runs of laminar flow are desired.

The attachment line Reynolds number is a function of the wing sweep, free stream Reynolds number and the nose radius. To reduce attachment line Reynolds number, and hence the probability of ALT, the leading edge radius can be reduced provided the off-design performance is not adversely effected, or the leading edge sweep reduced provided drag-rise conditions are not exceeded.

2.1.3.1 Attachment Line Contamination

In all practical aerospace applications, the wing, fin, or tailplane will be attached to the fuselage. This will lead to turbulent boundary layers over these surfaces lying within the turbulent fuselage boundary layer. More importantly the turbulent fuselage boundary layer will give rise to disturbances which will propagate along the leading edge causing extensive loss of laminar flow across the span. This process is referred to as attachment line contamination.

Numerous experiments, again summarised in [4], have concluded that, in such cases, the critical values of approximately $R\theta = 100$ and $R = 250$, above which the turbulent fuselage boundary layer will contaminate the attachment line boundary layer. Below these values, the attachment line flow will re-laminarise.

2.1.4 Suction Induced Transition

One method of delaying laminar-turbulent transition is to suck small quantities of air into the aircraft from the boundary layer, (section 2.2.2). As suction rates are increased from zero, a point is reached where boundary layer disturbances are suppressed resulting in transition moving rapidly downstream. Further increases in the suction rate result in only minor improvement in the extent of laminar flow, until a point is reached where additional suction moves transition upstream. This is referred to as Suction Induced Transition, or Oversuction, the act of suction actually introduces disturbances into the boundary layer

2.2 Concepts for Delaying Laminar-Turbulent Transition

In the history of laminar flow research, a number of concepts for delaying transition have been investigated. For aerospace applications, these have generally been grouped into two main categories, Natural Laminar Flow (NLF) and Laminar Flow Control (LFC). More recently, Hybrid Laminar Flow Control (HLFC) has superseded LFC for many applications, as it incorporates many of the benefits of NLF and LFC whilst limiting their associated penalties.

A future possibility not discussed here is the use of surface cooling to delay transition in 2D flows. This option will become more attractive if cryogenic fuels, such as liquid hydrogen, are introduced [4].

2.2.1 Natural Laminar Flow (NLF)

Natural Laminar Flow involves tailoring the surface in question to delay transition. If a favourable pressure gradient, (reducing pressure), is formed across a surface, the Tollmein-Schlichting amplification rates are reduced, delaying the point at which the critical disturbance level occurs. The magnitude of the stabilising effect increases as the favourable pressure gradient is increased. Conversely adverse pressure gradients (increasing pressure) increases amplification rates, precipitating early transition.

To produce an aerofoil or nacelle suitable for NLF, the forward regions must be shaped to create favourable pressure gradients. An NLF pressure distribution typically requires a favourable pressure gradient over the first 50% chord, with no leading edge pressure peak. This is achieved through the use of a sharper leading edge profile. A comparison between a typical NLF and conventional pressure distributions is shown in Figure 8.

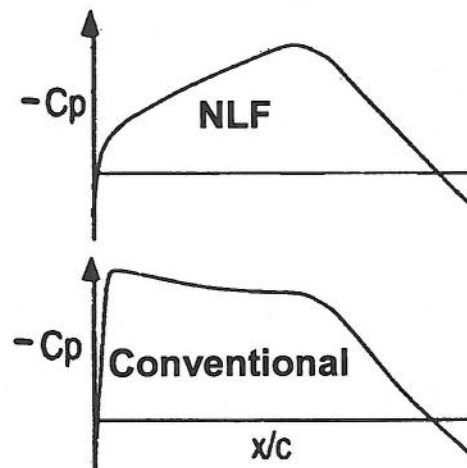


Figure 8: Typical NLF Pressure Distribution, from [26]

As discussed in sections 2.1.2 and 2.1.3, the 3D disturbances, Cross-Flow Instabilities and Attachment Line Transition, are highly dependent on the leading edge sweep. Therefore NLF is limited to applications with moderate sweep. The sharper leading edge of the NLF sections also reduce the $R\theta$ and R values, thus delaying the onset of ALT.

It should be noted that the pressure gradient will only reduce the disturbance amplification rates, and that the disturbances will continue to grow until at some point the boundary layer transitions to turbulent flow. This imposes a further limitation on the extent of laminar flow achievable using NLF. The stabilising effect increases as the favourable pressure gradient is increased.

2.2.2 Laminar Flow Control (LFC)

Sucking small amounts of air from the base of the boundary layer into the aircraft via a porous surface, can suppress all instability types over long distances, even in areas of highly 3D flow and unfavourable pressure gradients. Sucking over large areas

permits extensive laminar boundary layers to be achieved on large subsonic aircraft with considerable leading edge sweep. This is defined as Laminar Flow Control.

The principal effect of suction is to modify the boundary layer velocity profile such that its stability is improved. Secondly, it reduces the boundary layer thickness, and hence its associated Reynolds number [4].

The suction levels necessary to stabilise the boundary layer are small, although they are a function of the predominant instability at any given location. For each instability type the required suction level varies as a function of disturbance severity. Generally only low suction rates are required to stabilise TS instabilities. Higher rates are needed to suppress CF instabilities, while ALT requires the highest rates. The effect of suction on ALT and CF is described in further detail in [106].

This removes all need for surface shaping, allowing conventional sections to be used. LFC, however, requires large complex suction systems, which impose significant penalties in terms of production and maintenance costs, system mass, structural interference to the wing box, reduced fuel volume, and energy requirements.

2.2.3 Hybrid Laminar Flow Control (HLFC)

Hybrid Laminar Flow Control is a combination of NLF and LFC. Suction is applied to the leading 15-20% chord to suppress all 3D disturbances associated with a small suction peak and a subsequent region of adverse pressure gradients. This delivers a largely 2D flow to the region aft of the suction, whose surface is typically tailored to create a mildly favourable pressure gradient over the mid-chord surface to allow extended laminar boundary layers, (left hand illustration in Figure 9). An alternative approach has been to use a mildly adverse pressure gradient in the mid-chord region (right hand illustration in Figure 9). Although this can reduce the extent of laminar flow, the increased pressure coefficients and associated local Mach numbers over the forward part of the surface allow improve high speed performance.

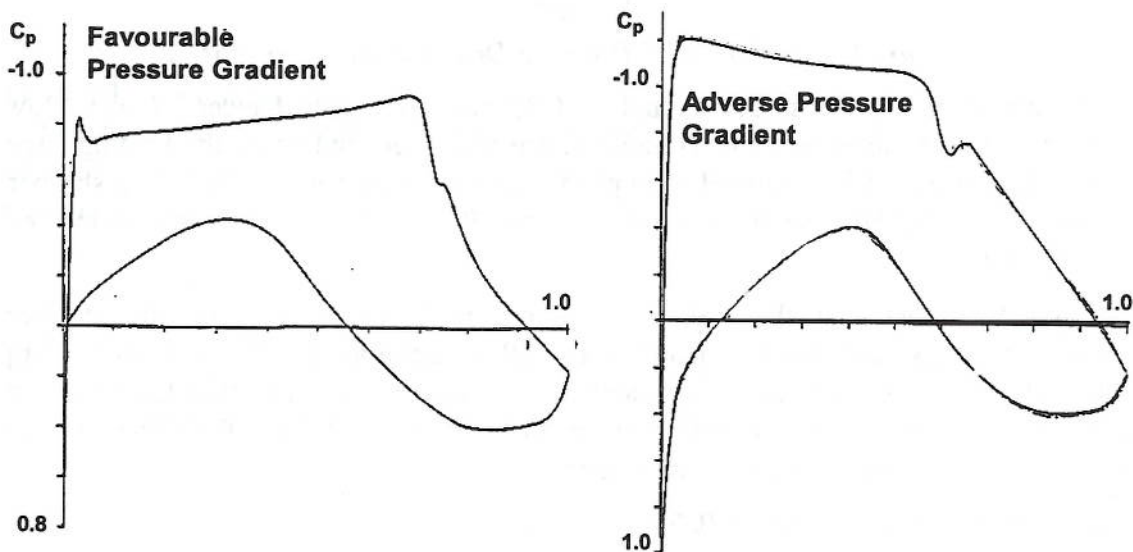


Figure 9: Typical HLFC Pressure Distributions

HLFC limits many of the problems inherent with LFC, by using a smaller less complex suction system. It also overcomes the surface constraints imposed by NLF. The inherent advantages of HLFC over both LFC and NLF makes it more suitable for use on subsonic transport aircraft.

3. TECHNOLOGY REVIEW

Laminar flow technology has received considerable attention during the last twenty years. Numerous wind-tunnel and flight test programs have been conducted to investigate and understand the associated aerodynamic phenomena and the practical issues related to application onto production aircraft. If the effects of this technology on an aircraft's aerodynamic and economic performance are to be assessed, the current standard of technology must first be assessed, and subsequently incorporated into the aircraft design process.

A technology review was performed for Natural Laminar Flow and Hybrid Laminar Flow Control, using technical reports, conference proceedings, and journal articles describing the various experimental programs and studies. Relevant points from these are summarised below. Much greater detail is provided in appendix A.

Full chord Laminar Flow Control has been omitted as this has now been largely superseded by Hybrid Laminar flow Control, in that significant laminar flow is still achievable for high Reynolds number applications with considerably smaller, less complex suction systems. However, many of the conclusions resulting from LFC studies are still at least partially relevant to HLFC, and as such are included where necessary.

3.1 Natural Laminar Flow

The history of NLF flight testing conducted during the last fifty years is reviewed in [63] and [38]. Of particular interest to this study are flight and wind-tunnel tests involving high subsonic transport aircraft, business jets and military combat aircraft. Most of these programs have investigated the application of NLF to wing surfaces, although a small number of studies have considered NLF on surfaces such as the fin, tailplane, engine nacelles and forward fuselage.

3.1.1 Natural Laminar Flow Wings

NLF wings have already been introduced to production aircraft, namely the 9 seat Piaggio p180 Avanti turboprop aircraft [118] and the 6 seat Cessna Model 525 Citationjet [49]. Both are capable of Mach numbers of 0.7, hence requiring little or no wing sweep. A military derivative of the Citationjet, of a somewhat altered configuration but retaining the NLF wing, was entered unsuccessfully into the JPATS competition for a basic trainer aircraft for the U.S. Air Force/Navy. The T-33 basic military trainer was also used to perform flight tests at Mach numbers up to 0.7 with 20° leading edge sweep [53].

A number of other flight tests have investigated NLF at higher Mach numbers. NASA conducted tests using a 10 seat Lear 28/29 aircraft [78] at transonic cruise Mach numbers up to 0.81 with leading edge sweep of 17°. F-111 and F-14 combat aircraft [20] [86] with variable geometry and a transonic capability permitted the influence of sweep to be investigated at high Reynolds numbers.

In Europe, flight tests have been conducted on the DLR 40-seat VFW-614/ATTAS regional turbofan aircraft [65], and the Dassault Falcon 50 executive jet [23].

To date, only two sets of flight tests have considered NLF wings on transport aircraft capable of accommodating more than 100 passengers. The first phase of the European Laminar Flow INvestigation (ELFIN) included a fifteen hour series of NLF flight tests using a glove on a Fokker 100 wing, Figure 10 [38] [147]. NASA conducted flight tests using a Boeing 757 gloved wing section [117] at transonic speeds. Although the main objective of these tests was to study the impact of noise on the extent of NLF, a significant run of laminar flow was achieved.

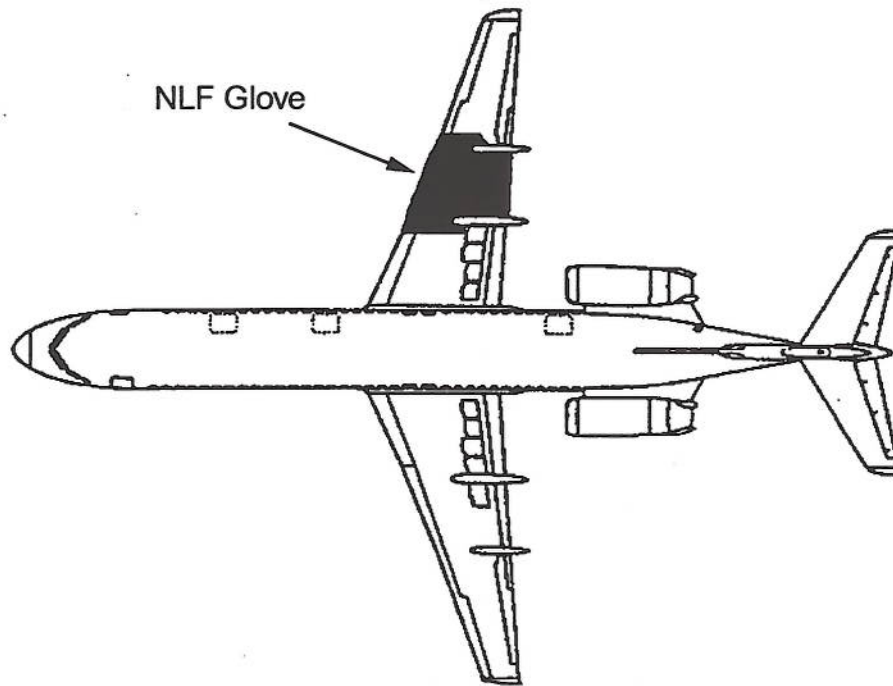


Figure 10: ELFIN 1 Fokker 100 Flight Test, From [147]

Flight tests performed in Russia have investigated the application of NLF to a Tupolev Tu-22M bomber whose chord Reynolds number are similar to that for a small transport aircraft such as an A320 or 757. Possessing a swing-wing (20° - 65°) capability, flight tests were planned for various configurations, although the loss of the aircraft in an accident limited flight tests to the lower sweep settings. Further flight tests are planned to investigate NLF and HLFC, although these are conditional on suitable funding. These tests may take advantage of the aircraft's Mach 2.0 capability to investigate laminar flow at supersonic speeds [22].

The maximum transition Reynolds numbers (based on the streamwise distance from the leading edge to the onset of transition), achieved during the experiments described above, are plotted in Figure 11 against their corresponding leading edge sweep angles. It should be noted that although only the Citationjet and Piaggio p.180 aircraft are production surfaces, transition is likely to be limited by TSI amplified by adverse pressure gradients or surface imperfections.

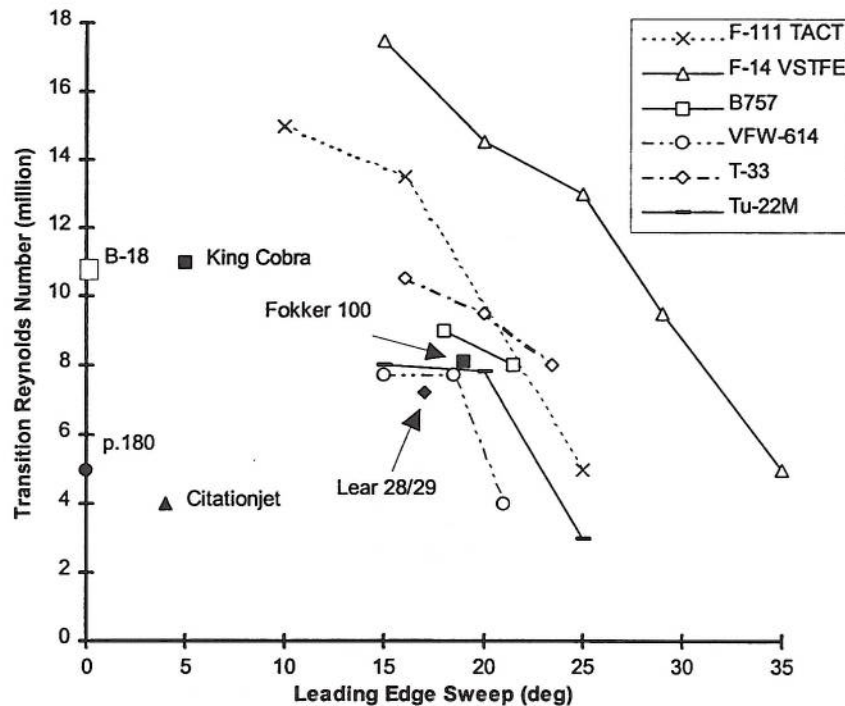


Figure 11: Summary of NLF Flight Tests, based on Figure 16 [148]

Although Figure 11 shows large variations in the transition Reynolds number at a given sweep from the various tests, there is a clear trend for a marked reduction in maximum transition Reynolds number as the leading edge sweep angle is increased.

More detailed data on NLF section design as well as performance is provided in Appendix A.2.

3.1.2 NLF on Surfaces other than the Wing

In recent studies, work has been initiated into the application of NLF to aerodynamic surfaces other than the main wing, such as engine nacelles, empennage and fuselage.

It is unlikely that the last of these would be considered for transport aircraft as any NLF would be limited by high Reynolds numbers as well as the presence of windscreen, step/gap at the radome joint, static strips as well as air data sensors. Any small potential drag reduction on a transport aircraft would likely be nullified by higher maintenance and production costs. However, larger potential benefits for business aircraft, due to lower Reynolds numbers and greater importance in the total aircraft drag, have led to studies investigating the application of NLF to the forward fuselage [35] [36]. Indeed production versions of the Piaggio p180 aircraft have achieved a degree of laminar flow on the forward fuselage [118].

3.1.2.1 Empennage and Winglets

The extent of NLF on empennage surfaces on transport aircraft is limited, due to the relatively high sweep angles, although the small size of the surfaces leads to low chord Reynolds numbers. No reports of NLF fins have been discovered although the fact that these surfaces do not produce lift forces for large portions of cruise should make them ideal for NLF.

Winglets have achieved some attention in [63] [64]. These, like fins, are usually highly swept and vertical. These tests achieved considerable runs of NLF on these surfaces in an area where the airflow is much more disturbed than that encountered around a fin. Despite the smaller size of the winglets, it is likely that the results would also be applicable to fins.

Two examples of the application of NLF to horizontal tailplanes have been found in the literature. It is likely that the results from these might also be relevant for fins due to similarities in size and sweep, though fins do have symmetrical sections rather than the lifting ones used on tailplanes.

The first example comes from French research, involving ONERA and Dassault, which considered an NLF tailplane on an executive aircraft [123] [140]. This achieved laminar flow over 50% of the wetted area at cruise conditions of $M=0.8$ and 3-dimensional $C_L=0.55$, resulting in a reduction in total aircraft drag of 1.5%. As Mach number and lift coefficient were varied around these points, only small variations in drag reduction were reported. The aerofoil characteristics of these tailplanes were similar to the Canadian aerofoils, i.e. gradually reducing drag with increasing Mach No to the design condition followed by a sharp increase. Drag rise occurred at $M=0.82$, only 0.02 above the cruise condition.

The second example of an NLF tailplane is that of the Piaggio p180 aircraft [118] which uses a NACA 64-series aerofoil swept at over 30° . Little information is available on its performance although [118] reports that limited, 15-20% chord, laminar flow is achievable.

3.1.2.2 Turbofan Nacelles

The increase in the wetted area of nacelles due to larger by-pass ratios has increased the significance of the nacelle profile drag. For some current transport aircraft/engine combinations, the nacelle wetted area is equivalent to approx. 20% of the wing wetted area [128] or 5% of the total aircraft surface area. Nacelles are suitable candidates for laminar flow as the flow is largely 2D. Additionally they are non-lifting surfaces, and therefore can be shaped to allow the maximum extent of NLF. Potential benefits of NLF to 60% chord for conventional nacelles are 1%-2% of total aircraft drag [92].

In the early 1980's, General Electric, in conjunction with NASA and Rohr, conducted a series of wind tunnel and flight tests on NLF nacelles [42]. Rolls-Royce, together with DLR, conducted tests during 1992 utilising the nacelle of the VFW-614/ATTAS aircraft [128]. Flight tests of both nacelles achieved laminar flow to this point, although for the G.E. tests Mach Numbers were limited to 0.25 without an engine installed. The Roll-Royce/DLR program [91] [92] replaced the existing nacelle on a VFW-614 aircraft. Flight tests were performed at Mach numbers up to 0.6 over the full range of engine throttle settings.

3.1.3 Configuration of Transport Aircraft Employing NLF

A number of reports [140] [56] [43] suggest that NLF applications to the wing are limited to aircraft with 100 passengers or less, namely regional aircraft. This is due

to their small size, and hence low chord Reynolds numbers, relatively low cruise Mach numbers (<0.75) requiring only moderate, $<20^\circ$, leading edge sweep, and that high lift requirements are met by trailing edge flaps alone, avoiding the added complexity, weight and structural steps associated with leading edge devices.

Many of the aircraft in this class (Fokker 70/100, MD-80, -90 series) have fuselage mounted engines to provide ground clearance and to facilitate servicing. The resulting clean wing is beneficial for NLF as interference between wing and nacelle/pylon pressure distributions is avoided. However, wing mounted engines can be used if desired as the destabilising effects of engine noise have been shown to be minor (Appendix A) although additional attention would be needed when considering the wing/engine interface.

MBB/Deutsche Airbus considered the possible benefits of an NLF wing against a conventional turbulent wing for a proposed regional jet transport aircraft [56] [43] with a design objective to carry 80 passengers over a 1500nm range. The design cruise conditions selected for this aircraft were $M=0.75$, $3D C_L=0.4$ and at chord Reynolds Numbers of approximately 20×10^6 . Furthermore, performance on stage lengths less than 500nm was considered important. A cruise L/D gain of up to 10% was foreseen due to laminar flow over approximately 60% chord on upper and lower surface. This, combined with an increased aspect ratio could provide an overall cruise L/D gain of up to 15%.

This aircraft, which has 17° leading edge sweep is shown in Figure 12. For a fuel price of \$1/gallon, a 9% fuel saving and a 2.0% reduction in engine price resulted in a 1.6% saving in D.O.C for the 1500nm design range. Over the 500nm stage the fuel saving was reduced to 7% reducing the DOC savings.

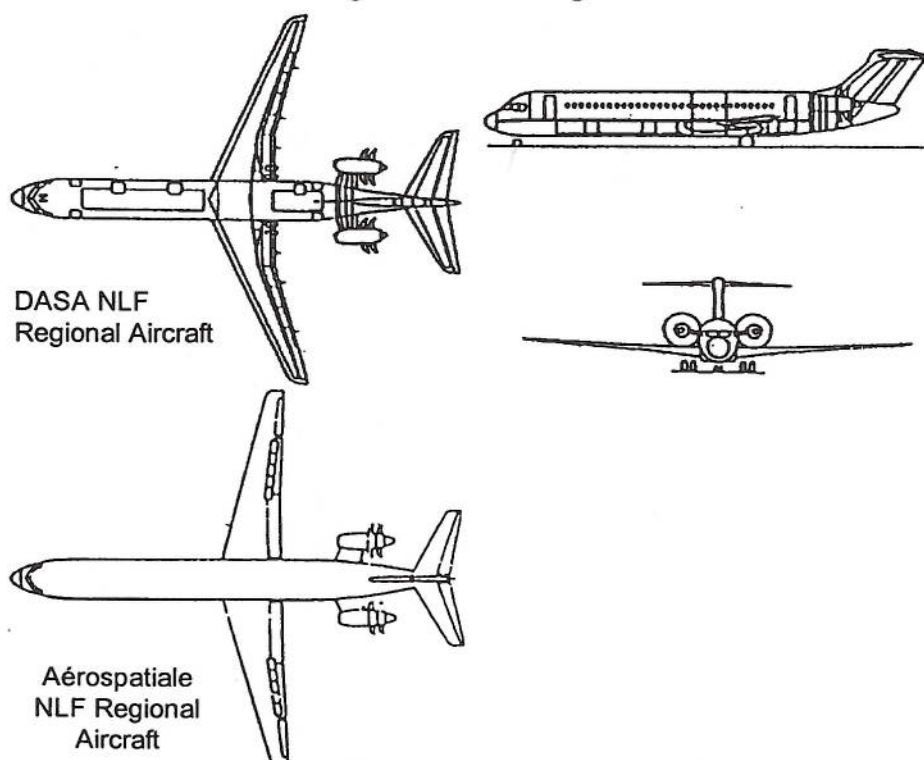


Figure 12: NLF Regional Transport Studies, from [43] and [140]

The aircraft considered by Aérospatiale and ONERA [139, 28] appears to be very similar in configuration to that studied by the MBB with rear mounted propfan engines and design cruise conditions of $M=0.74$, $0.36 < C_L < 0.5$ at $Re=22 \times 10^6$. This is not surprising as at the time Aérospatiale were partners, with Deutsche Airbus, in the Regioliner project. The major difference appears to be that the leading edge sweep is reduced to 12° on the French design from 17° .

With transition occurring at 60% chord on upper and lower surfaces, a total drag reduction of 10% is likely for the aircraft, which agrees with the German results. Results from wind tunnel tests also demonstrated that a wing skin friction reduction of 25% during climb which would result in 6% reduction in aircraft drag. This last point is of primary importance as the fuel used during climb on typical regional missions, less than 500nm, becomes significant.

These two studies, however, do not mention any of the penalties associated with NLF such as anti-contamination systems along with extra production and maintenance costs. It is likely that when these are considered, the savings in DOC will be reduced, or even negated. Due to operational problems, the German study concluded that the use of an NLF wing was not feasible for such an aircraft.

3.1.3.1 Forward Sweep

The use of forward sweep on laminar flow surfaces is discussed in detail within [111]. For a rearward swept wings, the leading edge sweep angle is greater than the quarter chord sweep due to wing taper. Conversely, for a forward swept wing, the leading edge sweep will be less than the quarter chord sweep. This results in more favourable conditions to delay attachment line transition and cross flow instability. Attachment line contamination is avoided as the attachment line boundary layer propagates inboard from the tip. In addition, the attachment line Reynolds number increases in the direction of the flow, allowing laminar flow at conditions that would remain turbulent on a rearward swept wing. However, aeroelastic concerns represent major obstacles to the widespread use of wings with significant forward sweep.

3.2 Hybrid Laminar Flow Control

As discussed previously (sections 2.2.2 & 2.2.3), instabilities within the boundary layer can be stabilised, or suppressed, by removing small quantities of boundary layer air through a porous surface. This is sometimes referred to as active laminar flow control, as opposed to passive laminar flow control or NLF. The advantage of active systems is that many of the constraints imposed by NLF are much less severe, though not entirely removed. This allows extensive runs of laminar flow to be achieved on surfaces at cruise conditions where NLF would not be possible.

The earliest flight tests involving suction occurred during the mid 1950s using gloved surfaces on British Vampire and American F-94 jet fighters. In these, and all subsequent research programs up to the mid 1980s, a full chord Laminar Flow Control (LFC) approach was pursued, the history of which is summarised in [150]. To achieve LFC, a porous surface must be installed over the whole surface where

LFC is required. This allows aerofoil sections to be used that are similar to conventional transonic profiles with the sweep angles required for transonic flight.

Since the mid 1980s, almost all active laminar flow control research has concentrated on Hybrid Laminar Flow Concept (HLFC), where suction is only applied in the leading 10-20% of the surface to suppress the extensive 3D instabilities associated with this region. Aft of this, a profiled surface is required to generate a suitable pressure gradient to maintain laminar flow to exist across the central area of the chord. Transition will eventually occur through the combined effects of the Reynolds number and pressure gradient but will never be further aft than the start of the pressure recovery.

HLFC still overcomes many of the NLF constraints, but with reduced suction system complexity compared to LFC. A further advantage is that the local skin friction is lower for NLF surfaces relative to a sucked surface [72]. In many cases, HLFC is capable of achieving as much laminar flow as LFC without compromising the load bearing wing box structure or reducing the available fuel tank volume. LFC offers improved drag reductions if it is used aft of the pressure recovery, an area of strong adverse pressure gradients, or on very large chords where the NLF, aft of the suction, is Reynolds number limited. The first of these is unlikely, as the area aft of the rear spar generally contains lift-dumpers, ailerons and flaps, suggesting a complex suction system installation for modest gains.

A leading edge suction system installation for an HLFC wing upper application is shown in Figure 13. This represents the current thinking, namely a perforated suction surface through which boundary layer air is sucked into spanwise plenum chambers. The sucked air then passes into collection chambers, through connecting pipes into a spanwise collector duct which are linked to the suction units. These consist of a compressor and some form of drive system, the most practical of which appears to be an electrical system. Other options include bleed air and direct mechanical off-take systems, although these are less efficient and have significant installation constraints.

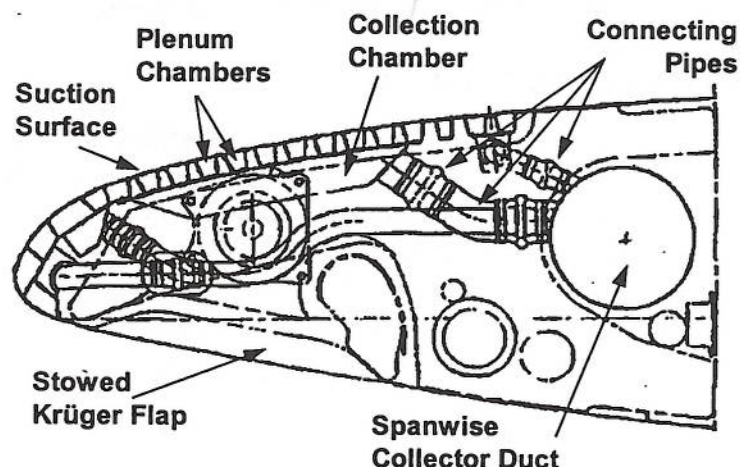


Figure 13: HLFC Wing Leading Edge, from [68]

Initial HLFC applications, like NLF, may appear on executive aircraft as the range requirements for such aircraft are critical, and utilisation rates are low, approx. 500 hours per year. The small size reduces Reynolds numbers and may ease ALT

concerns, permits representative wind tunnel testing and simple (relative to transport aircraft), slat free, leading edges, reduce development costs, and technical risk.

Dassault Aviation, have conducted HLFC tests on their Falcon 50 and Falcon 900 executive aircraft [23] [136]. The second of these has involved an operational evaluation of a "production standard" HLFC system. Suction systems have been installed into the inboard wing leading edges of a Falcon 900, from the Dassault Falcon charter service [48] [7], with composite panels attached to the upper wing-box surface to modify the pressure distribution.

Initial flight tests validated the system, after which the aircraft was returned to charter service for evaluation of the suction system performance in a truly operational environment. If these tests are successful, a future, or modified, Dassault executive aircraft could be the first to be offered to customers with a boundary layer suction system on the inboard wing. The aircraft might also have NLF over the less swept outer panels with laminar flow over 35% of the chord, across the span, resulting in a 5% reduction in total fuel burn. Although the utilisation rate may be lower than that for a airline aircraft, any experience gained with these smaller aircraft will provide operational data, such as system reliability and maintenance techniques, for the larger aircraft.

Two of the major transport aircraft manufacturers, Boeing and Airbus, have their own laminar flow programs, although the approaches taken have been quite different. A Boeing/NASA/USAF program conducted flight tests during 1990 to study the performance of a 6.7m (22ft) span HLFC system on the upper wing surface of a Boeing 757, Figure 14 [26]. The leading edge of this section was replaced with a modified structure containing a suction system, an anti-icing system and a Krüger flap/shield in place of a conventional slat. The wing box was the original production item with some minor clean-up. The limited published information has reported that laminar flow was achieved on all subsequent flights and extended to 65% chord at cruise conditions. Section drag reductions of 29% were measured, which represents a 5% saving in total aircraft drag [26] [38].

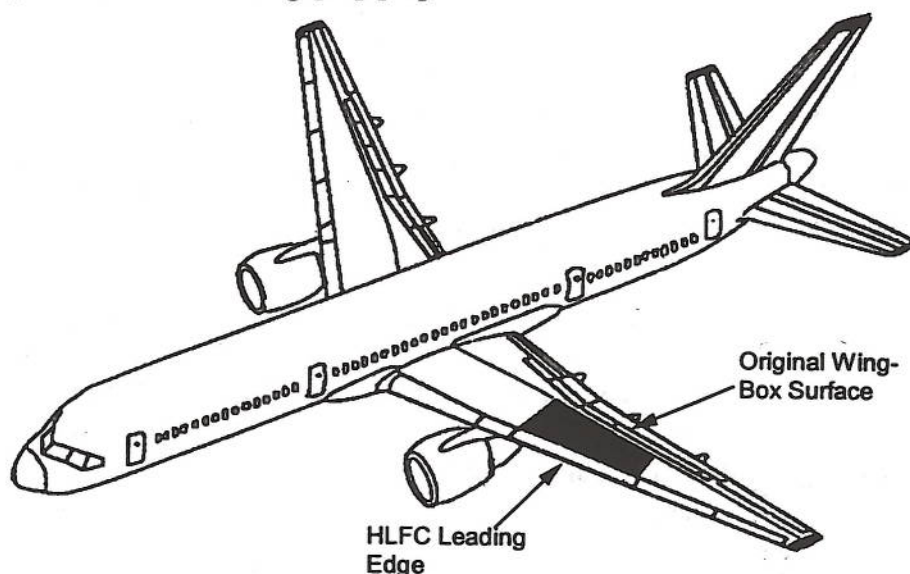


Figure 14: 757 HLFC Flight Test, from [26]

Continued Boeing interest in the technology was reported in 1996 [10], through a one year Boeing/NASA wind-tunnel program investigating Cross-Flow instabilities on a swept wing model, of 10ft chord and 7ft span.

The Boeing flight test investigated HLFC on the wing upper surface only. This appears to be the most likely HLFC configuration for wing applications, as the surface discontinuities associated with stowed Krüger flaps will prevent laminar flow on the lower surface. Higher benefits are possible from the upper surface as it produces about twice as much profile drag as the lower surface [119]. There are also requirements to provide access panels in the wing structure which can be located on the lower surface, thus reducing the extent of disturbances on the upper surface.

The Airbus partners, who initiated a laminar flow program in 1987 (the same year as Boeing), have followed a more considered approach. Although the ultimate goal is the same, to flight test an HLFC wing, a preliminary step was taken to investigate HLFC on an A320 fin [139]. This was suitable due to an easily removable leading edge, the absence of any de-icing system and most importantly, the possibility of large scale wind-tunnel testing at flight Reynolds numbers.

A320 HLF Fin



Figure 15: Airbus A320 HLF Fin

Flight tests of the HLFC fin are scheduled for mid-1997 with earlier wind tunnel tests [124] and theoretical analysis predicting laminar flow to 50% chord on both sides of the fin, resulting in a 1.3% reduction in aircraft drag. These year-long tests will also investigate operational aspects of the system. This data and experience is then intended to be used to conduct subsequent HLFC flight tests, possibly with a gloved section of A340 wing [62].

Since 1989, much of the European pre-competitive laminar flow research for wing and nacelle applications has been supported and coordinated by the European Community, through the European Laminar Flow INvestigation (ELFIN), Laminar flow Research Action (LARA), and HYbrid Laminar flow Demonstration on Aircraft (HYLDA) projects [38]. Participants of these programs include industry, research organisations and universities.

ELFIN is primarily concerned with investigating laminar flow at cruise conditions, while LARA addresses problems associated with the off-design performance. In

particular, it has considered insect contamination, Krüger flaps, and low-speed performance of nacelles.

ELFIN has considered the application of HLFC to a 40 seat commuter aircraft [17] [60] as a possible demonstrator, as large scale wind-tunnel tests at flight Reynolds number were possible. A half scale model of a VFW-614 aircraft was tested with suction on the upper surface and aft of two gaps, simulating a Krüger flap, on the lower surface. Transition was located as far aft as 50% and 35% chord on the upper and lower surfaces respectively, at $M=0.74$ and 28° sweep.

For transport aircraft, large scale wind-tunnel tests of complete wings are hindered by suction surface scaling problems and the Reynolds number compatibility of the tunnel. The application of HLFC to large wings is further complicated by leading edge high lift devices and de-icing/anti contamination systems. At present, it appears that the only practical solution is to assess the overall effect of HLFC during flight tests, which are extremely expensive. The ultimate objective of the HYLDA program is investigate the practical application of HLFC on a demonstration aircraft.

The application of HLFC to engine nacelles is currently receiving considerable interest from engine manufacturers and their associated nacelle producers. It is probable that nacelles will be the surface on which HLFC is initially offered to operators of large transport aircraft, due the relatively small size, and thus low risk, and largely 2D flow. It would also be relatively simple to retrofit the new nacelle to existing in-service engines.

As part of the European programs Rolls-Royce, DLR, Snecma, and ONERA are investigating the benefits of HLFC engine nacelles. To date, wind tunnel testing has achieved laminar flow to 38% nacelle length where the forward edge of a thrust reverser would be located. Subsequently, a suction system and its associated measuring equipment were installed in a nacelle of a VFW-614 aircraft for flight testing [91], on which transition was delayed to 60% chord of the short nacelle.

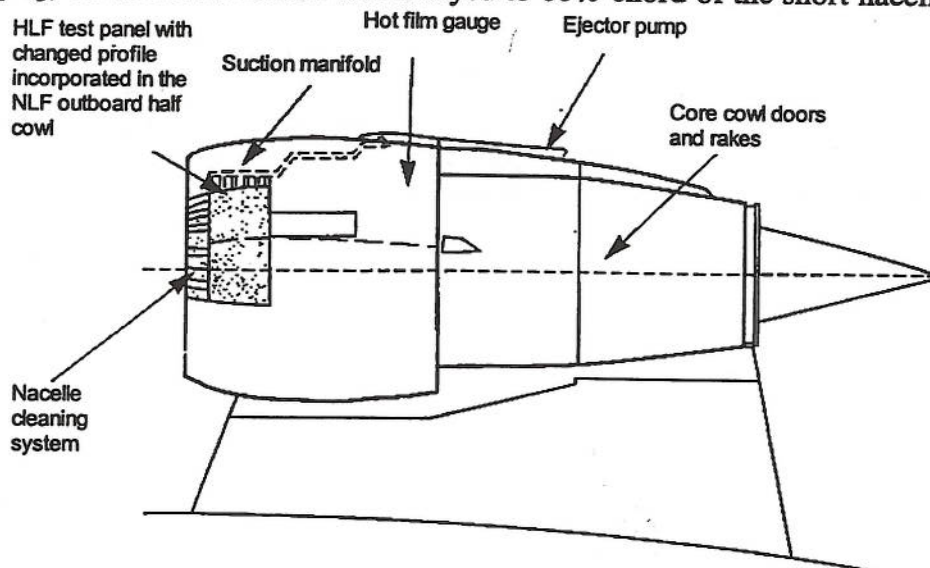


Figure 16: European HLFC Nacelle flight Tests, from [91]

Extrapolation of these results for the Rolls-Royce Trent nacelle estimates a 1.42% reduction in installed specific fuel consumption (SFC) is possible with the system as it currently stands, although the objective is 2% SFC reduction.

General Electric, in conjunction with NASA, Rohr and Allied Signal conducted flight tests in 1992 to investigate the application of HLFC to a CF6-50C2 engine on an Airbus A300/B2 aircraft. Composite panels, containing the suction system in the forward section with the aft section acting as a fairing, were attached to the inboard and outboard sides of the nacelle. Laminar flow was achieved up to 43% nacelle length, where the pressure recovery began, independent of altitude.

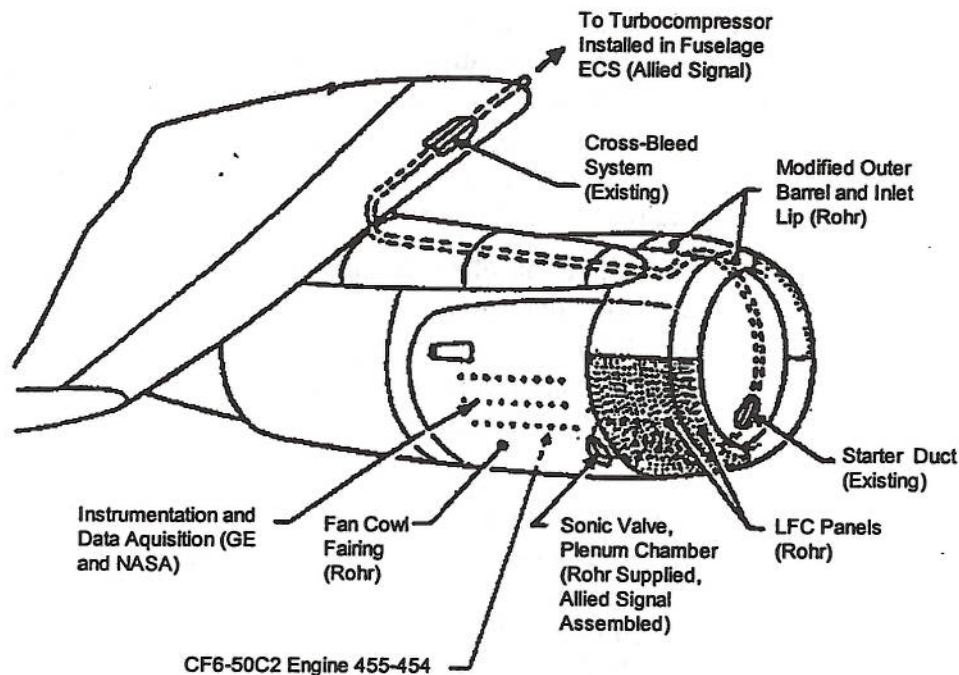


Figure 17: GE HLFC Nacelle Flight Test

After nacelle applications, the most likely HLFC application may be on empennage surfaces on new build aircraft, which although introducing sweep has a simple leading edge and relatively low Reynolds numbers. Nacelle and empennage applications would allow the airlines to assess for themselves the viability of HLFC.

Detailed information on HLFC section cruise performance, high-lift considerations and suction system technology are provided in Appendix A.3.

2.1 Configuration

The use of suction to stabilise boundary layer instabilities permits laminar flow to be achieved on surfaces with large leading edge sweep, $>25^\circ$, where the 3-dimensional disturbances would precipitate transition close to the leading edge of NLF wings. Therefore the benefits of laminar flow can be realised on aircraft designed for operation at transonic cruise Mach numbers.

Numerous previous design studies have been conducted where HLFC, or full chord LFC, technologies have been incorporated. Some of these have resulted in flying wing designs, Handley Page in the 1960s [47] and Lockheed in the 1980s [8], to

maximise the laminar flow area. Studies by Pfenninger [103], Lockheed [79] and Airbus [9] have all proposed forward swept wings in order to reduce ALT, amongst other reasons (section 3.1.3.1). The potential benefits of full chord LFC on a subsonic delta configuration are discussed in [33]. Those configurations in bold text are shown in Figure 18.

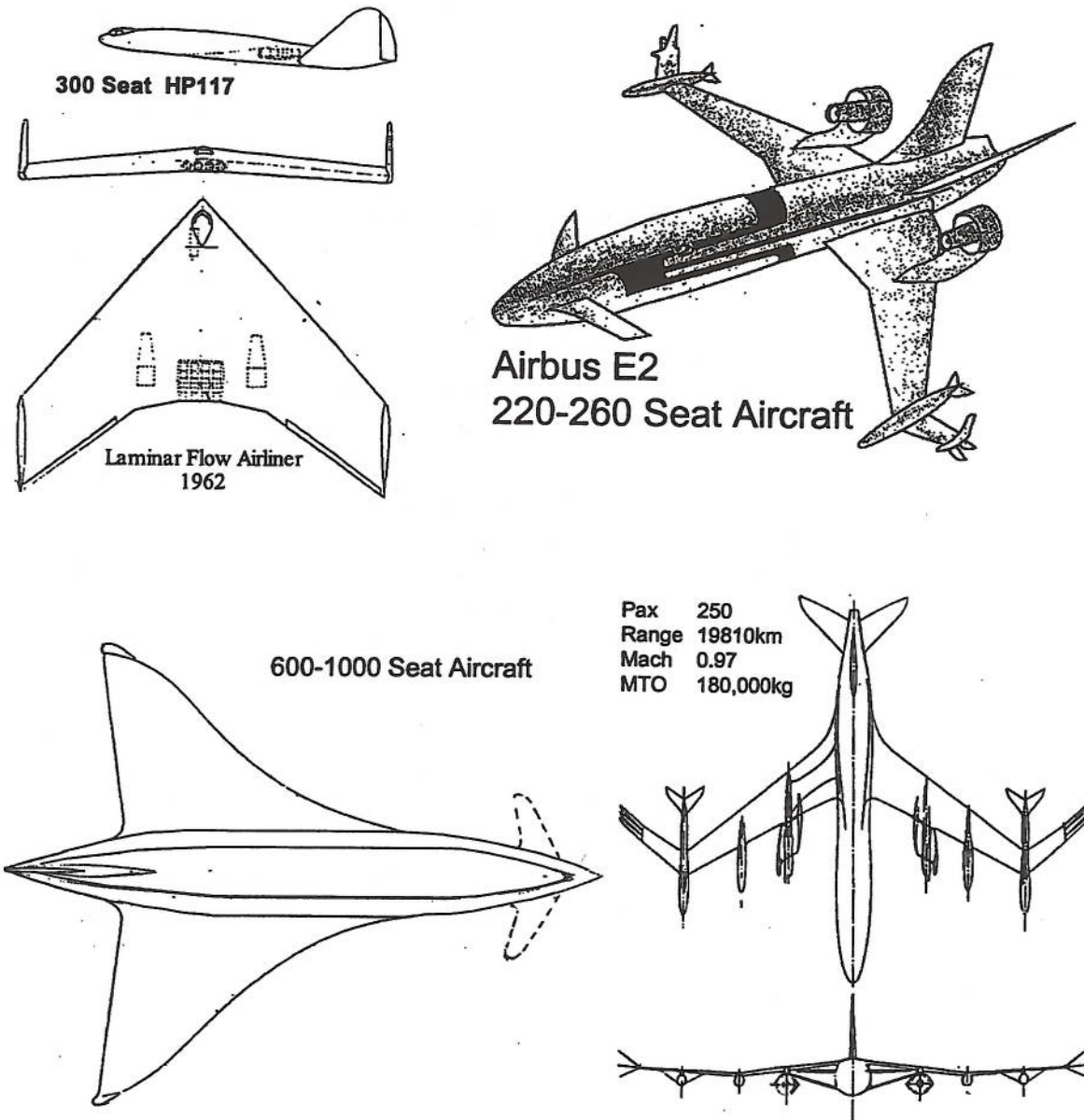


Figure 18: Unconventional Laminar Flow Control Configurations

It is probable that initial HLFC applications would involve conventionally configured aircraft, as certification of a novel configuration would be complicated in itself without introducing advanced technologies such as HLFC. A number of LFC and HLFC studies have considered such aircraft, although many of these have utilised fuselage mounted engines to prevent aerodynamic interference at the engine attachments, and to prevent engine noise and vibration de-stabilising with the laminar boundary layers [95]. Some of these configurations are shown in Figure 19.

Lockheed LFC Aircraft

Payload	400 Pax.
Range	6500 N.M.
Speed	0.80 Mach
Gross Weight	593,205 LB
Aspect Ratio	11.8

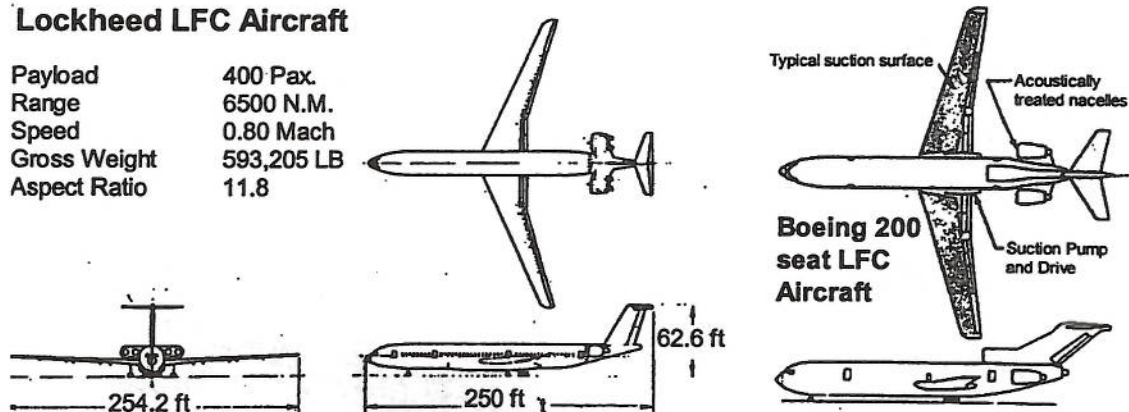


Figure 19: LFC Configurations - Fuselage Mounted Engines

More recent studies have typically involved the application of HLFC technology to conventional configurations, with engines mounted beneath high aspect ratio wings. Such configurations allow lower wing mass due to wing root bending relief effects from the engines. Flight tests have also shown that engine noise has only minor effects on the boundary layer stability (section Appendix A). A Cranfield study [71] considered two 300 seat LFC aircraft, based on the DC-10, with two wing mounted engines with a third fin-mounted engine. Douglas also considered a similar configuration in the late 1980s. This was an MD-11 derivative with increased aspect ratio, riblets and the option of LFC on the wing upper surface. The LFC increased C_{D} from 18.1 to 24.2.

Boeing [21] considered an HLFC 757 during the early 1980s, although the aircraft geometry was unaltered. A later NASA study [2] compared a 300 seat twin engine aircraft with and without HLFC applied to the upper surface of the wing and both surfaces of the vertical and horizontal tails. This studied different fuel reserve requirements, scaling wing area and engine size to achieve constant wing loading and thrust/weight ratio, but retaining the same aspect ratio.

A Deutsche Airbus study [121] considered HLFC versions of two baseline aircraft, a 300 seat medium range twin engine aircraft (A310) and a four engine, 300 seat, long range aircraft (A340). This study initially looked at HLFC applied to the baseline size, followed by a resizing exercise, for aircraft with HLFC on upper and lower wing surfaces and engine nacelles, keeping wing loading, thrust/weight ratio, and tail/fin volumes constant.

4. CERTIFICATION AUTHORITY AND AIRLINE PERSPECTIVE

When contemplating the introduction of laminar flow technology to commercial transport aircraft, the views of the regulatory authorities and potential operators are of crucial importance. Requirements, relating to safety or practical concerns, imposed by these organisations may place limits and/or constraints on the aircraft design, which in turn may influence the optimum configuration of an aircraft employing laminar flow technology. Thus, these issues must be addressed and, where necessary, incorporated within the design synthesis.

The principal concern of the regulatory authorities is the airworthiness of transport aircraft, ensuring that they will not jeopardise the safety of the aircraft, passengers, or public. This is regulated by the issuing of certification and operational requirements.

The certification requirements define a standard against which a new, or significantly modified, aircraft type must demonstrate compliance before approval is granted for the aircraft to be operated in commercial service. Operational requirements lay down the manner in which a commercial transport aircraft must be operated and maintained in routine service.

The regulatory authorities are generally national institutions that have each historically issued their own regulations. However, many of these now subscribe to either the European Joint Aviation Authorities Committee (JAA) or the Federal Aviation Administration (FAA) in the United States, and even these two are now converging towards a common set of regulations.

In addition to overriding safety considerations, the primary concern of airlines, as commercial organisations, is to transport people and goods in such a way as to generate profit for their owners. Many of the requirements laid down by the regulatory authorities have a direct cost impact on aircraft operation. If the safety concerns of the regulatory authorities, or economic viability requirements of the airlines can not be met, the introduction of HLFC to transport aircraft can be no more than a research exercise.

This chapter identifies a number of issues raised by the introduction of laminar flow, with particular reference to existing certification and operational requirements, namely JAR-25 and JAR-OPS 1, respectively. In particular, issues related to the use of HLFC are addressed although it is likely that they will also be valid for LFC. Additionally, those topics discussed which are not relevant to the suction system will be valid for NLF. Current airline opinion, with regard to laminar flow technology, is discussed based on communications with representatives from three European airlines, British Airways, Lufthansa German Airways and Virgin Atlantic Airways. The intention is to highlight some of the principal areas of concern, and not to be a definitive set of requirements to which all aircraft employing HLFC would have to adhere.

These issues are summarised below, with further detail and discussion included in Appendix B, a conference paper presented by the author at the 2nd European Forum on Laminar Flow Technology, Bordeaux, June 10-12 1996 [157].

4.1 Certification Considerations

Little information has been published defining any additional regulations that may be imposed on aircraft utilising laminar flow technology, although existing regulations may be applicable in their current, or slightly modified, form for many issues.

All existing requirements would have to be met independent of whether laminar flow can be achieved. The principal requirement covering the design of all 'Equipment, Systems and Installations' is JAR 25.1309. This comprehensive requirement can be summarised as:

All systems must be capable of operating under any foreseeable operating conditions [JAR 25.1309(a)].

All possible failure modes must be considered, along with their likely cascade effects on other essential services, the probability of multiple failures, the resulting effect on the aeroplane and occupants at any stage of flight, and the required crew warning cues [JAR 25 1309(a), (b), (c), and (d)].

Each installation whose functioning is required for certification and that requires a power supply, is an 'essential load' on the power supply. The power sources and the system must be able to supply the following power loads in probable operating combinations and for probable durations [JAR 25.1309(e)]:

In addition to the loads for normal operating conditions, essential loads must be supplied after failure of any one component in the power system, the failure of one engine on two-engined aeroplanes or two engines on three- or more engined aeroplane.

Loads not required for controlled flight need not be considered for two-engine-inoperative condition on three- or more engined aeroplanes [JAR 25.1309(f)].

Critical environmental conditions, such as vibration, acceleration, handling and fluid pressure effects must be considered [JAR 25.1309(g)]

The consequences, on the aeroplane and occupants, of any failure condition described above determines the allowable probability of occurrence as defined in Figure 20.

	Event Probability per flight hour	Class	Effect on Aircraft and Occupants
Frequent	$> 10^{-2}$		Normal
Frequent	$> 10^{-3}$	Minor	Nuisance
Reasonably Probable	$> 10^{-5}$	Minor	Operating limitations; emergency procedures
Remote	$> 10^{-7}$	Major	Significant reduction in safety margins; difficult for crew to cope with adverse conditions; passenger injuries.
Extremely Remote	$> 10^{-9}$	Hazardous	Large reduction in safety margins; crew extended because of workload or environmental conditions; serious or fatal injury to a small number of passengers.
Extremely Improbable	$< 10^{-9}$	Catastrophic	Multiple deaths, usually with loss of aircraft

Figure 20: Product Integrity, from AMJ 25.1309

A number other certification issues must be considered in addition to JAR 25.1309, including:

- Aircraft handling characteristics during and subsequent to loss of laminar flow, with regard to aircraft safety and passenger comfort [JAR25.143].
- Aircraft handling characteristics during deployment of Krüger flaps, if used in place of slats [JAR25.143].
- The use of a purging to clear the suction system ducting is classed as a pneumatic system, and thus subject to relevant requirements [JAR25.1438]

4.2 Operational Regulations

As with certification requirements, it is probable that any aircraft employing HLFC would have to comply with all existing operational requirements along with any additional regulations. These are summarised below:

- The aircraft must be capable of achieving a 91.4m/min (300ft/min) climb rate at any point on its route or diversion, in the expected meteorological conditions, JAR-OPS 1.540 & 1.575 (depending on aircraft class).
- Fuel load planning must take into account realistic aeroplane fuel consumption data and the expected meteorological conditions. These are both important for laminar flow operations as the drag reduction can reduce between maintenance inspections due to surface deterioration, or the fuel benefits of laminar flow limited by cloud encounter during cruise, JAR-OPS 1.255.
- Transport aircraft are operated in diverse environments, within which the HLFC system must be capable of normal operation.

4.3 Airline Considerations

Airlines are commercial organisations, and as such are required to generate profits for their share-holders. On all routes air travel competes for custom with other modes of transport, such as high-speed railways, shipping, and road travel. The extent of this competition is dependent on many factors, such as distance, availability of each mode, type of custom (passenger or freight), volume of traffic, and cost.

Generally, the advantages of air travel increase with greater distance, or where natural barriers, such as large bodies of water or mountain ranges, hinder other transport types. In such cases the airlines must compete among themselves for the available custom. The major factors in this competition are the service offered and cost. These two are related as enhanced standards of service generally increase costs. Obviously, any opportunity to reduce costs for an airline permits reduced fares or an improved service, thus enhancing the airlines competitiveness.

Three European airlines, British Airways, Lufthansa German Airlines, and Virgin Atlantic Airways, were approached with regard to the application of HLFC to subsonic transport aircraft. The first two of these represent major carriers with extensive established global networks, while Virgin Atlantic is a smaller, expanding operator with a developing route network.

The aspects raised by previous studies were used as a basis for a questionnaire that was provided to each of the airlines and to which they all responded. Further discussions were subsequently conducted with regard to their responses.

The prominent points from these consultations are summarised below. These are discussed in much greater detail in [157]:

- i) All airlines expressed interest in HLFC as a means to reduce costs.
- ii) Fuel prices not expected to increase significantly in the near future, although environmental taxes may be a long term issue.
- iii) Airlines were interested in Life Cycle Cost rather than Direct Operating Cost savings.
 - Initial costs for establishing of maintenance support for HLFC must be considered along with operating costs.
 - Significant DOC savings needed to sustain benefit of HLFC after changes to operating costs, such as reduced fuel price or increased maintenance rates.
 - Operating cost savings must be achievable throughout the service life of an aircraft.
- iv) HLFC represents an additional system, increasing aircraft complexity, resulting in higher maintenance costs, and possibly more operational disturbances.
 - Failure modes, and their respective probability of occurrence, important. Failures corrected during turn-round are of less concern than those requiring extensive maintenance actions.
- v) HLFC system must not be dispatch critical:
 - Aircraft must be capable of normal operation with turbulent flow.
 - Airlines would not want to withdraw aircraft with defective HLFC system from service. Increased fuel load, or payload (freight) reductions, required.
 - If mission exceeds turbulent payload/range limit, the aircraft could be exchanged with another operating on a non-limiting sector. However, this would be an unlikely option for smaller operators.
- vi) Altitude and speed losses are unacceptable in airspace with reduced “in-trail” and vertical separation criteria.
- vii) Unscheduled re-fueling stops due to range shortfall resulting from HLFC failure are extremely expensive, and unpopular with passengers.
- viii) Random nature of losing laminar flow due to cloud encounter poses problems for fuel planning, and range capabilities.
 - Monitoring system to report status of laminar flow to aid flight management.
- ix) Surface contamination and inclement weather are concerns for parked aircraft.
 - Ground de-icing fluid a particular concern.
 - Surface cleaning between each flight unpopular.

4.4 Flight Test Evaluation of Certification and Operational Factors.

A number of recent flight test programs have investigated the impact of laminar flow technology, many of which are summarised in [26] and [38]. Of these, two in particular have evaluated the operation of a suction system in airline service. The

NASA Simulated Airline Service (SAS) program, part of the LEFT program, assessed the performance of a porous and a slotted LFC suction leading edges, on a Jetstar business jet.

A preliminary flight test program to verify suction system performance [45], was followed by seventy flights [82], resembling typical airline mission profiles, made through various seasons between various city-pairs within the continental USA. Almost half of these flights were winter operations centred on Cleveland, Ohio, where the daytime temperature was routinely below 0°C (32°F) with frequent exposure to snow, frost and freezing rain. Others were flown from Atlanta, Georgia, where temperatures were routinely in excess of 27°C (80°F) and thus conducive to high insect activity.

The main conclusions from this program as reported in [82] are as follows:

- i) LFC systems performed as intended during routine airline service.
- ii) No schedule delays were caused by LFC systems.
- iii) No pilot control of suction system required, other than on-off commands.
- iv) No measurable degradation of the perforated titanium suction surface after four years of flight testing.
- v) Surface cleaning between flights not required when the LFC systems were operated.
- vi) No special care was required for the suction surface and ducting when they were exposed to inclement weather on the ground or in the air.
- vii) Snow and ice were removed on the ground with conventional equipment.

A similar program is currently being conducted by Dassault, who have installed suction systems into the inboard wing leading edges of a Falcon 900 business jet from the Dassault Falcon charter service [48 and 7]. Initial flight tests will validate the system and quantify the achievable drag reductions. Upon completion of these, the aircraft will be returned to charter service, where the system performance will be assessed in a truly operational environment.

5. METHODOLOGY

The objective of this study was to investigate the impact of laminar flow on the optimum design of subsonic commercial transport aircraft. Aircraft design is a highly iterative process, with many interdependent multi-disciplinary aspects, which can be complicated where optimisation of the aircraft configuration is required to meet specified criteria. To permit rapid determination of optimum aircraft configurations, a FORTRAN design synthesis and optimisation code, "CIVIL" was used. This generated conventionally configured subsonic civil transport aircraft capable of performing two specified missions.

At the beginning of this study (July 1993), the design synthesis, supplied, by the Propulsion Department, Defence Research Agency (DRA), was little changed from that described in [27]. As such, it was only capable of considering aircraft with fully turbulent boundary layers. Optimisation of the aircraft configuration was performed using the RQPMIN code [129], also supplied by DRA. This is a constrained non-linear MultiVariate Optimisation (MVO) code that uses a gradient search method to change the value of a number of key design parameters (referred to as independent variables) such that some feature of the design (the objective function) can be minimised, or maximised. For this study the objective function was minimum Direct Operating Costs (DOC), although minimum fuel burn or take-off mass can be used as alternativea. For the purposes of this study, RQPMIN was effectively treated as a 'black-box' and used under direction from the DRA.

To consider the net DOC benefit of laminar flow on transport aircraft, a method was developed that modelled the primary effects of the technology - profile drag reductions, system mass, additional power requirements and increased production/maintenance costs - as functions of aircraft design parameters, such as aircraft geometry, performance and mission profile. This method was integrated into the design synthesis in order to perform project studies on aircraft employing laminar flow technology.

5.1 General Approach

At the beginning of this study, it was envisaged that project studies would be performed on aircraft employing NLF, LFC and HLFC. However, for reasons detailed in section 3, LFC studies have not been pursued in this study. Although the aircraft types considered by this study, bar one, are too large for the application of NLF, its inclusion within the design synthesis provided a platform from which further modifications for HLFC could be made.

Both NLF and HLFC applications were considered to wing, fin, tailplane and nacelle surfaces. For both NLF and HLFC wing cases, laminar flow was assumed to be achievable on the upper surface only, although an option for laminar flow on the lower surface is included for NLF cases. For fin and tailplane applications laminar flow was assumed possible on both surfaces. Design constants within the design synthesis input file are used to select which of the surfaces are to be laminar, permitting any combination to be assessed, although it is not possible to mix NLF and HLFC surfaces in any one case.

It has been assumed that laminar boundary layers are only achievable during the cruise sector. Turbulent boundary layers are assumed at all off-design conditions, i.e. take-off, climb, diversion, descent, hold and approach, as extensive laminar flow will not be possible due to altered pressure distributions at low speed and high incidence, or increased Reynolds numbers at low altitudes.

Where appropriate the methods used to model laminar flow have taken into account potential certification and operational considerations (section 4).

All modifications, were incorporated into a single version of the design synthesis code such that NLF, HLFC or turbulent designs can all be considered as required, facilitating any future, non-laminar flow related, alterations. The basic structure of the modified section of the design synthesis is shown in Figure 21.

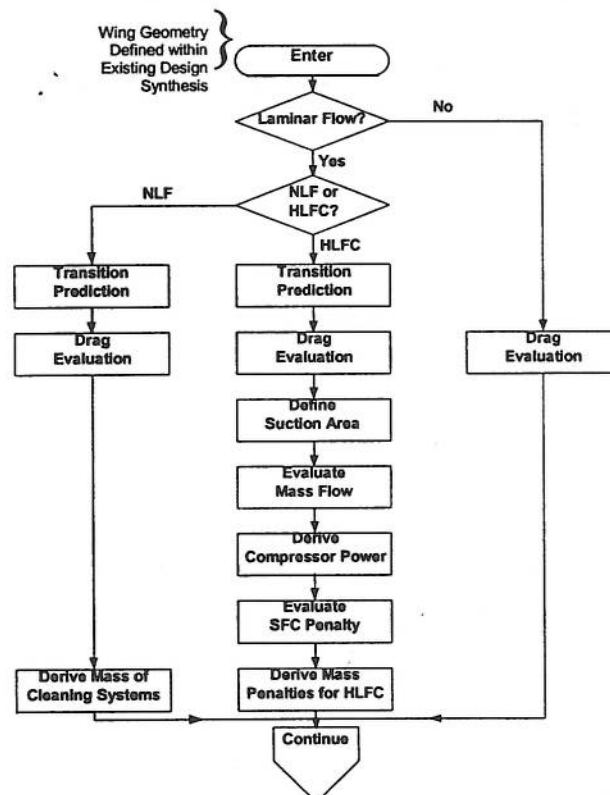


Figure 21: Summary of Laminar Flow Methodology

The modifications made to the design synthesis to model the impact of laminar flow can be categorised into two main groups - aerodynamics and laminar flow systems. These are described below in general terms, although further detail is provided in Appendix C.1.

During this study, other improvements were made to the design synthesis, some of which arose indirectly as a result of laminar flow studies. These are described in detail in Appendix C.2 and include aspects such as:

- Increased definition of wing, fin, tailplane and nacelle geometry,
- Improved turbulent profile drag determination,
- Gust load evaluation,
- Graphical output, producing plan-view of final configuration,
- Choice of cruise speed or Mach number as independent variable,

- Consideration of ovoid “double-deck” fuselages

Where relevant in the following text, direct references to expressions defined with these appendices are denoted by {*equation number*}.

5.2 Aerodynamic Modifications

The principal effect of increasing the extent of Laminar flow is to reduce profile drag, sometimes referred to as zero lift drag, which although not strictly the same are very similar. Limitations to the aerofoil shape to ensure suitable pressure gradients may effect high speed behaviour of a wing, resulting in changes to the drag rise Mach number. The presence of extensive laminar flow on an aerofoil can also effect the lift-incidence relationship. These factors are discussed below.

5.2.1 Profile Drag

The calculation of the profile drag associated with all aircraft surfaces uses the flat plate analogy [142] which can be written as:

$$C_{DO} = \frac{S_{wet}}{S_{ref}} \cdot C_f (1 + \psi)$$

Where S_{wet} Wetted area in question.

S_{ref} Reference area, typically gross wing area.

C_f Mean skin friction coefficient.

ψ Form factor.

Delaying laminar-turbulent transition reduces both the skin friction coefficient and the form factor.

As laminar flow on wings is assumed to be achievable on the upper surface only, the drag for each surface must be determined separately, although it should be noted that the upper surface is responsible for about two-thirds of the total wing profile drag [119].

5.2.1.1 Skin Friction

The skin friction over a smooth flat plate varies as a function of chord Reynolds number and transition position. Wing, fin and tailplane Reynolds number are taken as those corresponding to the geometric mean chord of the respective surfaces, while cowl length is used for nacelle cases. This provides a basis for establishing the mean turbulent (transition set at 0% chord) skin friction coefficient for each component of the aircraft; the same method being used for the fuselage, with Reynolds number based on fuselage length.

For surfaces with some degree of laminar flow, the turbulent skin friction coefficient is factored by a term based on transition position and chord Reynolds number [37]. Clearly transition position has a major influence on the degree of drag reduction.

For NLF wing cases, the maximum transition Reynolds number is assumed to reduce linearly with increasing leading edge sweep. This relationship {5} is defined by specifying the maximum transition Reynolds number at 0° leading edge sweep, and the leading edge sweep when transition Reynolds number is zero. This relationship

should be checked against the previous flight test results, summarised in Figure 11, to ensure that it is realistic. A maximum transition Reynolds number is set in the input data for HLFC wing cases as the suction suppresses sweep effects in the leading edge region, which at cruise conditions defines the maximum physical distance aft of the leading edge that transition can occur {equation 6}. This represents a line parallel to the leading edge.

In both cases, the extent of laminar flow may also be limited by adverse pressure gradients associated with the pressure recovery at the rear end of the pressure rooftop, which is assumed to be at constant percentage chord across the span.

The relative positions of these two lines are compared across the span and that nearest the leading edge is taken to define the extent of laminar flow at that point {7-10}. Typically, this is limited by the maximum transition Reynolds number at the wing root, and by the rear end of the pressure rooftop at the tip, Figure 22. At some spanwise location, the two lines coincide.

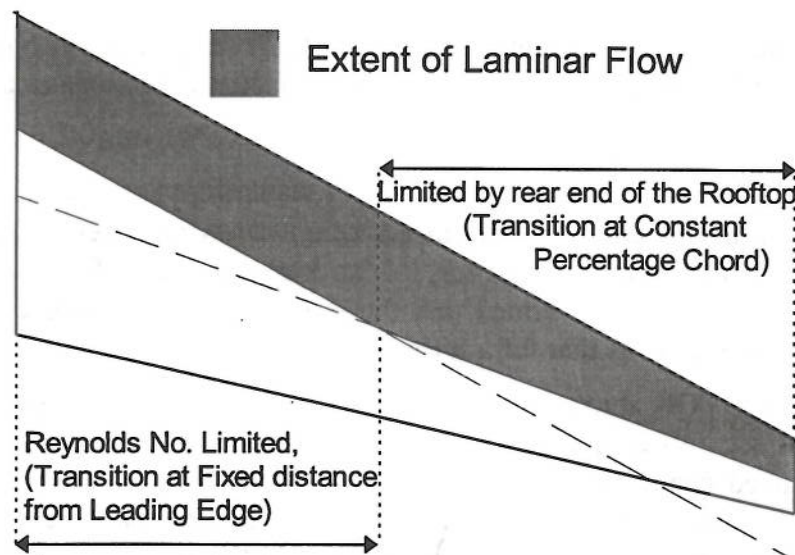


Figure 22: Extent of Laminar Flow on a Wing

The area of laminar flow is calculated {11 and 15} and used to define a mean transition position on the geometric mean chord {16}, from this a mean skin friction coefficient is easily deduced {18}. This is used for the upper surface only as no laminar flow is assumed possible on the lower surface, for which a turbulent friction coefficient is calculated.

The extent of laminar flow on fin, tailplane and nacelle surfaces are all design constants within the input data, and expressed as a constant percentage chord. The low Reynolds numbers, relative to the wing, imply that transition is likely to be due to adverse pressure gradients, rather than Reynolds number limited. This, however, may not be the case where very large aircraft are considered.

5.2.1.2 Form Factor

To derive the profile drag for a contoured surface from a flat plate profile drag, a form factor must be applied for reasons described in [142] (p497). A form factor expression was included in the original design synthesis {22}, although this was only

for turbulent flow. For various NACA sections, however, the form factor reduces with increased extents of laminar flow [142]. Although the actual relationship will be highly dependent on the actual surface in question, generic expressions for wing, fin, tailplane {23}{24} and nacelle {91} cases were developed.

To investigate variation of wing form factors, two sections representative of transonic NLF and HLFC aerofoils were assessed using the BVGK6 code, supplied by DRA. The BVGK code is a Computational Fluid Dynamics (CFD) tool for assessing the performance characteristics of aerofoil sections at selected incidence settings (lift coefficient calculated) or for a fixed lift coefficient (required incidence calculated). Transition was set at locations ranging from 2-60% chord on the upper surface and fixed at 2% chord on the lower surface, with a fixed lift coefficient. For each location, the ratio of viscous drag coefficient (from BVGK) and a corresponding calculated flat plate value was taken as the form factor. This process was repeated for the NLF aerofoil with transition on the lower surface set to the same position as the upper surface.

The results of this study, summarised in Appendix D, supported the NACA aerofoil data and provided a means to calculate the form factor reduction as a function of transition location

5.2.2 Wave Drag

If an aircraft's cruise speed is below that where wave drag occurs then drag rise performance is of no concern. However, where drag rise conditions do arise, for the purposes of this study, it is assumed that the drag rise performance of the laminar flow aerofoils is the same as that for a turbulent equivalent.

Results from the BVGK study, described in the previous section, also showed that, for the aerofoil sections in question, a small increase in wave drag was observed as transition is moved further aft at fixed C_L . This suggests that an aerofoil will have a marginally lower drag rise Mach number when laminar flow is present. This factor has not been accounted for in the design synthesis as it depends on section design.

5.2.3 Lift Coefficient - Incidence

Another factor observed during the BVGK study was that the incidence to achieve a desired lift coefficient reduces as the extent of laminar flow increases, as expected due to reduced boundary layer thickness. This is important when considering the wing setting angle, but is of little significance to the design synthesis as this aspect is not included. This factor will also cause a non-linear lift curve slope as changing incidence may alter the extent of laminar flow and hence the lift coefficient, although this effect is small.

5.3 HLFC System Sizing

When considering an aircraft employing HLFC, the suction system represents an increase in Operating Empty Mass (OEM), aircraft price and specific fuel consumption. The magnitude of these penalties must be assessed and compared with the benefits of reduced profile drag, to assess the economic feasibility of HLFC. A number of previous studies [2] [24] [76] [103] [141] considered the installation of

suction systems on transport aircraft wings. The first and last of these studied HLFC while the rest investigated the implications of full chord LFC.

While the previous studies have defined the suction system penalties, they have been specific to the aircraft in question. However, these penalties are functions of aircraft size and the required suction performance. Thus, the methodology developed for inclusion within the design synthesis continually re-evaluates the suction system penalties as a function of the evolving configuration, thus introducing these aspects into the optimisation process. Aircraft size-dependent terms use existing geometry data within the design synthesis, while expressions defining suction system performance have had to be added.

All sizing is performed assuming an electrically driven suction units. The suction system is required to operate throughout a performance envelope defined by speed and altitude. Therefore, a suction system design case is taken as a high speed, low cruise altitude case, namely the cruise Mach number at 30,000ft, which results in the highest Reynolds numbers likely to be encountered with suction operative. This is used to size the suction system, although suction system related specific fuel consumption penalties are derived for the cruise condition in question.

5.3.1 Suction System Power Requirement

The suction unit power requirement can be defined as the product of the total volume flow, Q , and required pressure rise across the compressor, Δp_c [21]. If a pump efficiency, η , is introduced, the suction unit power requirement can be defined as:

$$\text{Suction Unit Power} = \frac{\Delta p_c Q}{\eta}$$

Where Δp_c is pressure difference between ambient pressure and the pressure at the compressor face. A minimum pressure coefficient for the wing is defined, within the input data, from which a minimum local external surface pressure is determined. A pressure loss factor (input data), due to pressure losses in the suction ducting, is applied to this value to give the pressure at the compressor face. This pressure loss is of the order of 20% for an LFC suction system [102]. The pressure losses through the suction panels and ducting for a 757 HLFC project study amounted to approximately 25% [21].

5.3.1.1 Volume Flow of Sucked Air

The volume flow of sucked air is a function of the suction area and the velocity of the air passing through the surface. For fin, tailplane and nacelle applications, a mean suction velocity through the suction surface is set within the input data. Thus the volume flow of sucked air is the product of this velocity and the suction area, typically taken as 20% of the fin and tailplane wetted area (note: suction assumed on both surfaces) and 12% of the nacelle area.

A more complex approach is followed for wing cases. The suction surface is divided into three chordwise zones, based on the predominant boundary layer instability in each (section 2.1), for which separate suction coefficients are calculated. For simplicity, the attachment line zone is assumed to be a vertical flat plate covering

30% of the maximum aerofoil thickness, the cross flow zone and Tollmeim-Schlichting zones are assumed to be horizontal flat plates extending to defined percentage chord across the span (set within input data).

The suction coefficients for the attachment line and cross-flow zones are dependent on chord Reynolds, which decreases with distance from the root, due to reducing chord. For suction control, production and maintenance reasons (Appendix A.3.3.1) the suction surface is also divided into spanwise panels, Figure 23.

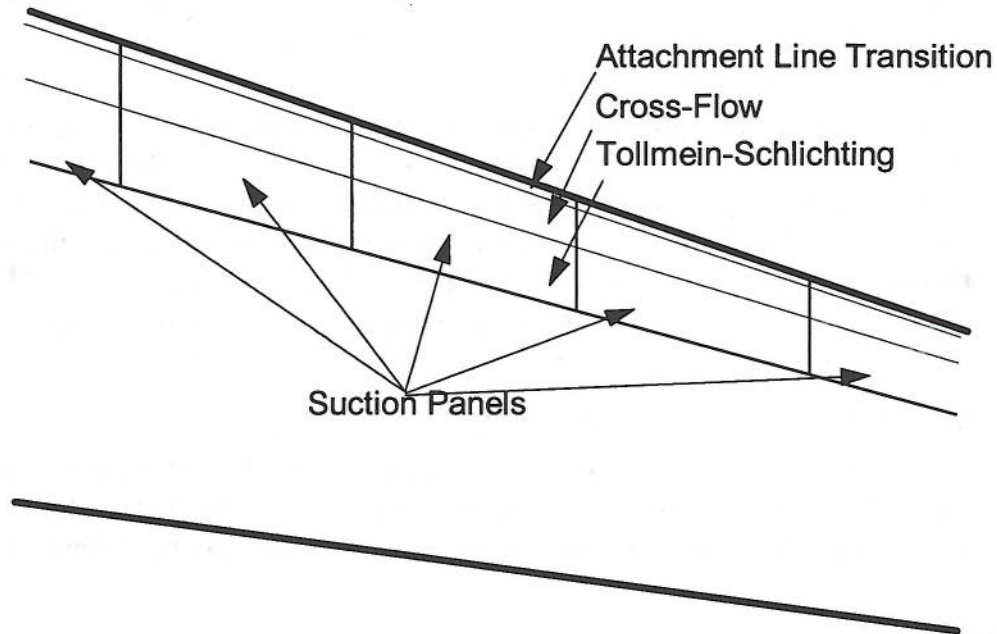


Figure 23: Suction Panel Layout

For each panel the suction coefficients are defined as those at the inboard end, where they are greatest due to the higher Reynolds number, Appendix C.1.3.1 {29 - 45}. For all three zones in each panel, the volume flow is the product of the zone area, the suction coefficient (C_q) and the cruise speed. These are added to give the total volume flow for the wing, Appendix C.1.3.2.

To reflect the increased thickness/chord ratio used for inboard regions of wings, the thickness/chord ratio is assumed to increase linearly from the outboard wing value at 40% semi-span to a value 40% larger at the wing root. This is used to determine the attachment line volume flow in the inboard wing.

5.4 Suction System Mass

Suction system component mass is defined as a function of aircraft size or suction system requirement, and some factor derived from mass data reported in previous project studies, Appendix C.1.4 {52 - 64}. Those providing a mass breakdown of system components are listed below:

- Boeing 757 HLFC study [21], 1982. HLFC on upper and lower wing surfaces, alternative case for HLFC on upper surface only with Krüger flap. Electrical compressor drive.

- Douglas DC-10 derivative with LFC wing [102], 1983. LFC to 70% chord on upper and lower surfaces. Suction engines mounted on rear of wing provided suction.
- Douglas MD-11 derivative with LFC wing [24], 1990. Laminar flow to 70% chord on upper surface. Electrical compressor drive.
- Boeing 200 seat aircraft with LFC wing [132], 1976. Laminar flow to 95% chord on upper and lower surfaces of composite wing. Suction engines used.
- Lockheed 400 seat aircraft with LFC wing [76], 1983. Laminar flow to 75% chord on upper surface and 65% on lower surface

It should be noted that the highest suction rates are in areas of significantly 3D flow, namely near the leading edge. Therefore the mean volume flow of sucked air per unit area of suction will be higher for HLFC, as the low suction rates over the wing box will lower the mean suction rates for LFC.

The terminology assigned to suction system components varies between different manufacturers, requiring some care when categorising components.

5.4.1 Suction Surface

In the absence of any relevant data it is assumed that the mass of the leading edge skin is unaltered. The increased density of titanium alloys relative to aluminium alloys would result in increased mass if the same skin thickness was used. However, this is countered by the higher ultimate strength of titanium possibly permitting reduced skin thickness, although minimum skin thickness may limit this. Additionally, suction substructure supporting the surface increases its stiffness and strength.

5.4.2 Plenum and Collection Chambers

Mass data from previous studies for items representing the plenum and collection chambers are summarised in Figure 24. A mass per unit area has been quoted as this is likely to be the primary driver for plenum mass.

	Component Mass, kg	Suction Area per Aircraft m ²	Mass per Unit Area kg/m ²
Boeing 757 HLFC Study ⁽¹⁾	127	47.6	2.67
Douglas DC-10 LFC Derivative ⁽²⁾	2633	442	5.96
Douglas MD-11 LFC Derivative ⁽³⁾	506	74.2	6.82
Boeing 200 Seat Comp. Wing LFC Study ⁽⁴⁾	---	---	2.59
Lockheed 400 Seat LFC Study ⁽⁵⁾	2346	660	3.55

Figure 24: Summary of Mass data for Plenum and Collection Chambers

- (1) "Channel Collector Ducts" 116kg, "Suction Channels" 11kg, Total 127kg. Upper and lower surface suction area per wing are given as 11.89m² and 12.11m² respectively. Total suction area for aircraft, 48m².
- (2) "Laminar Flow Panels" 2,633kg. Net wing area (281m²) assumed to be 85% of gross wing area (331m²). Wetted wing area (upper and lower surfaces) = 563m² with suction to 70% chord, thus suction area = 422m².

- (3) “*Suction Panels on Leading edge*” 506kg. Plan area ahead of the front spar is calculated as 74.2m^2 (37.1m^2 per wing).
- (4) “*Titanium Applied as Slot-Tapes*” 0.88kg/m^2 , “*Tributary Ducts*” 1.71kg/m^2 .
- (5) “*LFC Wing Surfaces*” 2,346kg. Net wing area (440m^2) assumed to be 85 % of gross wing area (517m^2). Wetted wing area (upper and lower surfaces) = 880m^2 with suction to 75% chord, thus suction area = 660m^2

Differences between the above studies may be due to the variation in the materials used, suction system configuration or what is included within the quoted mass, e.g., suction surface, plenum chambers and/or collector chambers as well as any necessary installation structure. The Boeing 400 seat LFC study assumed a slotted suction surface instead of a perforated configuration.

Some earlier Douglas work [154] investigating the use of Super Plastic Forming/Diffusion Bonding processes to produce LFC surfaces resulted in a mass of $5\text{--}10\text{kg/m}^2$. Although the suction surface was included, collector chambers were not.

5.4.3 Spanwise Collector Ducts

The 757 HLFC study quoted a mass of 93kg for the spanwise collector ducts. The total suction area was 47.6m^2 , resulting in 1.95kg/m^2 .

If the LFC studies are considered, the resulting mass per unit areas were 1.93kg/m^2 ($851\text{kg}/442\text{m}^2$ DC-10 derivative), 2.34kg/m^2 ($176.4\text{kg}/74.2\text{m}^2$ MD-11 derivative assuming 36% of ducting mass for the leading edge), 1.318kg/m^2 (Boeing 200 seat LFC study) and 0.99kg/m^2 ($651\text{kg}/660\text{m}^2$ Lockheed 400 seat LFC study). These are all in line with or lower than the HLFC value. The lower mean suction coefficients for LFC might imply lower values although the need for chordwise ducting may increase the mass.

A more representative approach is to consider duct mass as a function of the total volume flow of sucked air. Relevant information is supplied for the 757 study, with a design case, $M=0.8$ at $h=35,000\text{ft}$ and a 757 wing area i.e. 181.25m^2 , the total volume flow was $7.08\text{m}^3/\text{s}$ for $C_Q=0.000164$ (U.S. Method) corresponding to a realistic mean suction velocity of 0.1475m/s . With a total duct mass of 93kg, the mass of ducting per cubic metre of sucked air was 13.14kg/m^3 .

5.4.4 Compressors

Compressor mass can be considered as a function of volume flow and the required compression ratio, i.e. the compressor power requirement, which for the MD-11 LFC derivative study was 418.4kW (two 214.2kW (287hp) electric drive motors required) with a total compressor mass of 226.8kg (500lb), and hence a power/weight ratio of 1.89kW/kg . The 757 suction power requirements for upper and lower surfaces is given as 156.5kW, corresponding to a compressor mass of 75kg, a power/weight ratio of 2.08kW/kg , which is in agreement with the MD-11 study.

Mass data for the other LFC studies can not be used as insufficient volume flow data is available and in some cases, suction engines or bleed air is used to provide suction.

5.4.5 Electric Motors

Both the 757 and MD-11 studies opt for electric motors to drive the compressors. The MD-11 study used two 214.2kW (287hp) motors with a total mass of 195.5kg, giving a power/weight ratio of 2.19kW/kg.

For the 757 study, the mass of a 103kW motor consists of 26.7kg (motor itself) and 13.6kg (inverter), giving a total mass of 40.3kg, resulting in a power/weight ratio of 2.56kW/kg which is higher than that for the MD-11.

5.4.6 Electrical Cables

The mass of the electrical cable connecting the generators to the suction unit is defined using the cable length and the mass per unit length. Cable length is determined using aircraft geometry assuming suction units located in the wing root region for wing, in the rear fuselage for empennage cases and in the nacelle itself for fan cowl cases. A coefficient defining cable mass per metre per Watt is defined within the input data. The maximum power requirement for each section of cabling is based on a number of failure cases. A typical values of the input data is 3.2075×10^{-6} kg/m/W, assuming aluminium cable and a line voltage of 400V. If 200V systems are used this input value is doubled, and for copper cabling it is increased by a factor of 1.5.

5.4.7 Generators

The additional electrical power requirements for the suction system will require either increased capacity on the primary generators or the use of additional generators dedicated to the suction system. The required electrical load includes that for the compressor plus some increment due to inefficiencies pertaining to generation and transmission. A generator power/weight ratio of 2.98kW/kg, based on actual generator mass data, has been assumed where capacity of the primary generators is increased. Where additional generators are used the same power/weight ratio is used, although a mass increment of 38kg per engine is added to represent the additional installation mass.

5.5 Comparison of Mass Prediction Methods with other Studies

In addition to the previous studies described above, for which suction system component masses are provided, other studies have quoted total HLFC system mass for a number of configurations:

Case:

- A)• NASA HLFC Wing, Nacelle and Empennage study [2], long range, 300 seat, twin engined aircraft, similar to Boeing 777.
- B)• Deutsche Airbus HLFC Wing and Nacelle study [121], medium-range, 200 seat, twin engine aircraft, similar in configuration to an A310.
- C)• Deutsche Airbus HLFC Wing and Nacelle study [121], long-range, 300 seat, four engine aircraft, similar in configuration to an A340-300.
- D)• British Aerospace (Airbus) HLFC Wing, Empennage and Nacelle study [119], long range, 616 seat, four engine aircraft, similar to proposed A3XX-200.

Quoted masses from these studies were compared with calculations using the method described in section 5, the results of which are detailed in Figure 25, along with a comparison of the totals. Note that WFTN refers to HLFC wing, fin, tailplane and nacelles.

	Component Masses (kg)						Calculated Total	Quoted
Case	Plenum	Duct	Comp.	Motor	Cables	Generator	Mass (kg)	Mass (kg)
'A' WFTN	922	412	326	278	201	227	2366	1588
'B' Wing	234	118	96	88	18	72	626	845
'C' Wing	373	230	193	175	119	143	1233	1340
'D' Wing	855	538	444	404	393	330	2964	2800

Figure 25: Comparison of Calculated Suction System Masses with Quoted Values

The results follow the correct trends with good agreement with the quoted masses for cases 'C' and 'D'. Despite the calculated values being too low for case 'B' and too high for 'A', the method used appears to produce satisfactory values for suction system mass. It should be noted that the method is highly dependent on assumptions, which if necessary can be modified to model any specified component mass breakdown.

5.6 Engine Performance Penalties

To maintain the required constant cruise thrust, while extracting additional energy to drive the suction system, the fuel flow must be increased, resulting in higher specific fuel consumption {46 - 51}. The magnitude of this penalty defines the fuel load required to drive the suction system for the duration of cruise.

A study investigating the impact of increasing off-take power on the performance of various turbofan engines was performed. The performance of three modern engines (Trent 775, CF6-80C2-A2, CFM56-5C-2) was modelled using the "Turbo-Match" code. These results were compared with data within performance manuals for two versions of the RB211 engine, and for "Trent" and "Tay" data supplied by Rolls-Royce.

The results, presented in Appendix E, show that the SFC penalty is a function of the off-take power requirement over net cruise thrust, multiplied by a factor of 0.1773, for most engines, increasing to 0.213 for the Trent engine.

6. DESIGN STUDIES

The ultimate objective of this work was to investigate the implications of laminar flow technology on a range of conventional commercial transport aircraft. To achieve this, modifications were made to a commercial transport aircraft design synthesis to model the application of NLF and HLFC on wing, fin, tailplane and nacelle surfaces of conventional configurations. This provided a method to rapidly assess the impact of laminar flow on the aircraft design when optimised to minimise the Direct Operating Cost. The procedures for using the design synthesis are detailed in [158]. For this study, only the impact of HLFC has been considered as this is the most suitable for the aircraft types being considered.

The design synthesis with only initial modifications to model laminar flow was used to conduct preliminary studies, the results of which are presented in [156]. Significant improvements subsequently made to the methodology have increased the modelling accuracy and flexibility, in particular the definition of the wing suction coefficients are defined as functions of suction location, the wing planform and cruise conditions.

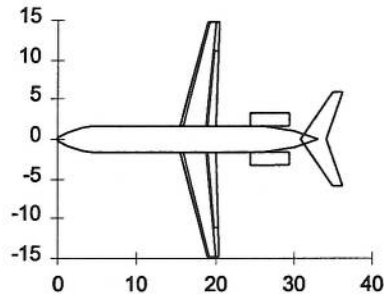
A more recent joint study with British Aerospace Airbus Ltd used the design synthesis, with almost all modifications included, to consider HLFC on a Large Subsonic Aircraft. Results from this study are presented in [119]. Comparison of the HLFC penalties derived within the design synthesis with BAe Airbus data showed good agreement permitting confidence to the methodology described in section 5.

6.1 Baseline Turbulent Aircraft

Five conventional aircraft types, covering a wide range in design mission and performance, provided a baseline from which the benefits associated with laminar flow could be measured. These were based on published payload, range, cruise Mach number, altitude and fuselage dimension data for existing or proposed aircraft, namely a *regional jet* (Fokker F100), *short and medium range twin-jets* (Airbus A320-200 and A330-300, respectively), a *long range quad-jet* (Airbus A340-200). and a double deck *super-jumbo* type aircraft (615 seat A3XX-200). All represent the current generation of transport aircraft, having entered airline service since the mid-1980s or are due to enter service early in the next century.

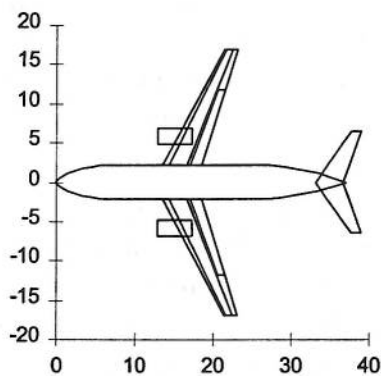
Optimum turbulent designs were modelled using the MVO approach to provide the desired baseline for each aircraft type. Although all aircraft were required to be capable of performing their respective design payload/range combination, each aircraft type was optimised for minimum Direct Operating Costs (DOC) on an average stage length representative of typical airline operations. For this 'average' mission, the payload and initial cruise altitude are assumed to be that of the design mission - in practice a higher initial cruise altitude may be used to reduce fuel burn, or the payload increased until maximum take-off mass or zero fuel mass is reached. Specific production costs (£/kg) for each assembly are assumed equal for each aircraft. A suitable wing technology factor is used for each aircraft, which is assumed constant for turbulent and laminar cases. A fuel price of £0.19 per kilogramme (85-90c/USG) is assumed for all cases as this is representative of a global average. All aircraft are designed to meet the most

recent gust velocity requirements. The five optimum turbulent configurations are shown in Figure 26, along with selected design parameters (Note: payload/range capabilities are shown in Figure 28).



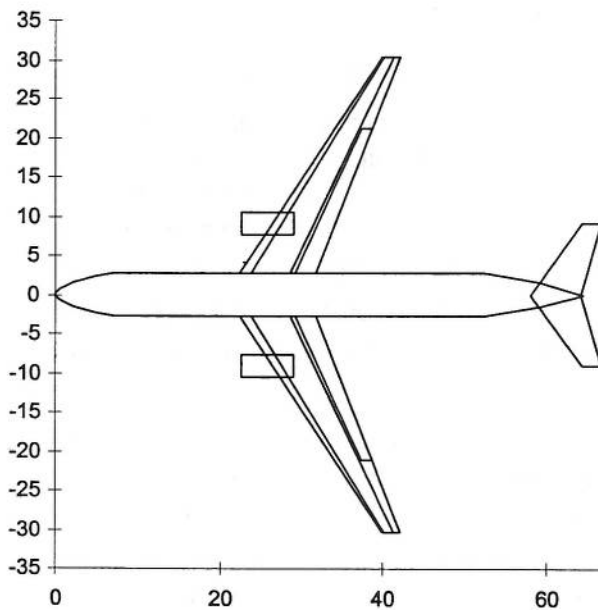
Regional Jet

Seats	107	OEM	25,661kg
Design Stage	2963km	MTO	45,318kg
Average Stage	929km	SLS Thrust	2×60.73kN
Span	29.5m		
Wing Area	96.6m ²		
Aspect Ratio	9.01		



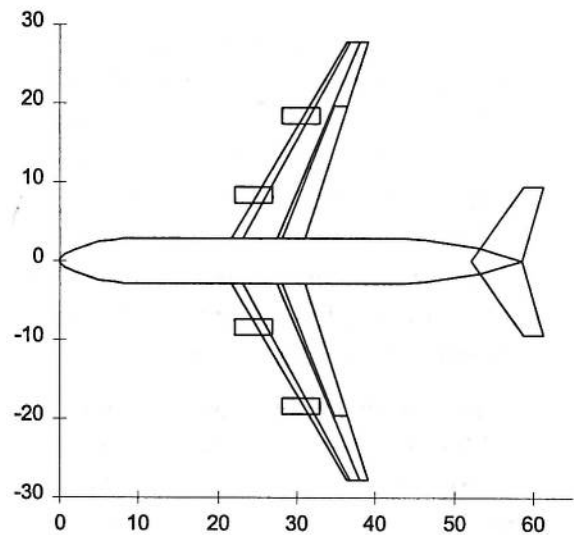
Short Range Twin

Seats	150	OEM	42,255kg
Design Stage	5463km	MTO	74,614kg
Average Stage	929km	SLS Thrust	2×116.64kN
Span	34.1m		
Wing Area	123.5m ²		
Aspect Ratio	9.40		



Medium Range Twin

Seats	336	OEM	116,413kg
Design Stage	8,334km	MTO	208,497kg
Average Stage	3,715km	SLS Thrust	2×257.51kN
Span	60.44m		
Wing Area	370.2m ²		
Aspect Ratio	9.87		



Long Range Quad

Seats	265	OEM	109,379kg
Design Stage	13,700km	MTO	233,775kg
Average Stage	5,573km	SLS Thrust	4×133.04kN
Span	55.6m		
Wing Area	350.0m ²		
Aspect Ratio	8.84		

Figure 26: Turbulent Baseline Aircraft

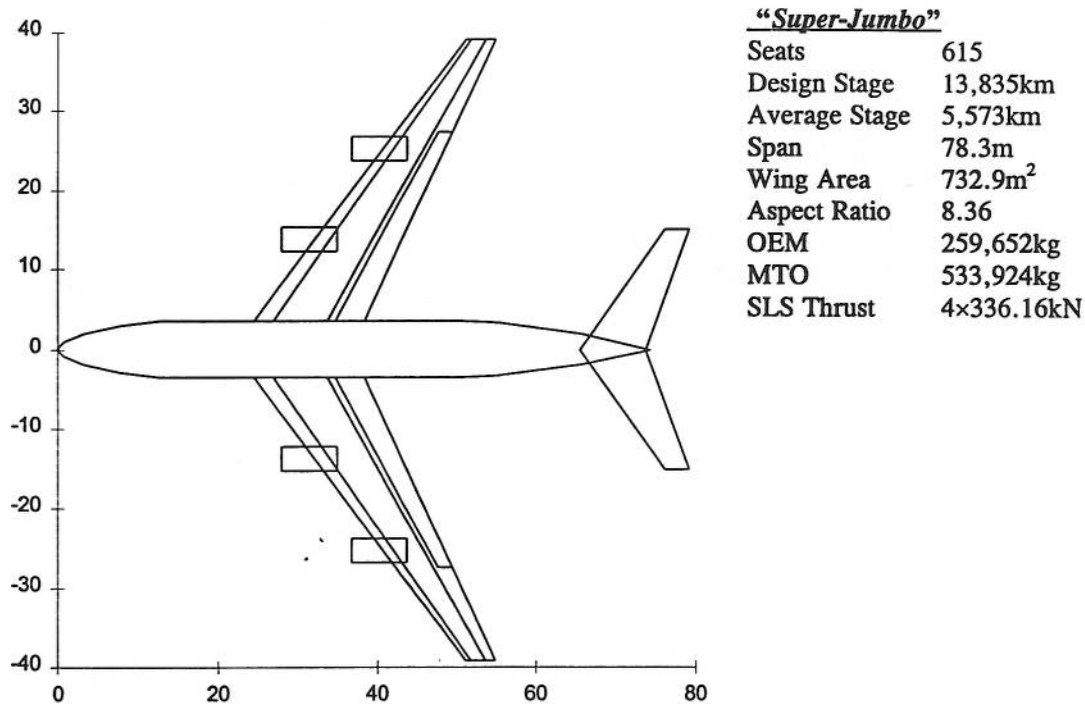


Figure 26: Turbulent Baseline Aircraft (Continued)

Further configuration, mass, performance, and DOC data for the turbulent aircraft is provided in Appendix G. In addition, similar data is provided for all HLFC configurations used for the project and sensitivity studies.

6.2 Direct Operating Costs

Direct Operating Costs are often used as a measure of commercial transport efficiency, indeed all aircraft configurations within this study are optimised for minimum DOC.. The method used by the design synthesis, described in detail within [27] calculates the landing fees, flight deck crew salaries and allowances, fuel costs, standing charges (finance, depreciation and insurance) and labour and material costs associated with airframe and engine maintenance. It should be noted that the items included in a DOC calculation can vary between the numerous different methods. Comparison of DOC data for a turbulent *super-jumbo* class aircraft calculated by the design synthesis and by BAe Airbus showed excellent agreement for all items [119], although the BAe method also included cabin crew costs and navigation charges.

The relative importance of the various terms in the average mission DOC for all five baseline configurations is shown in Figure 27.

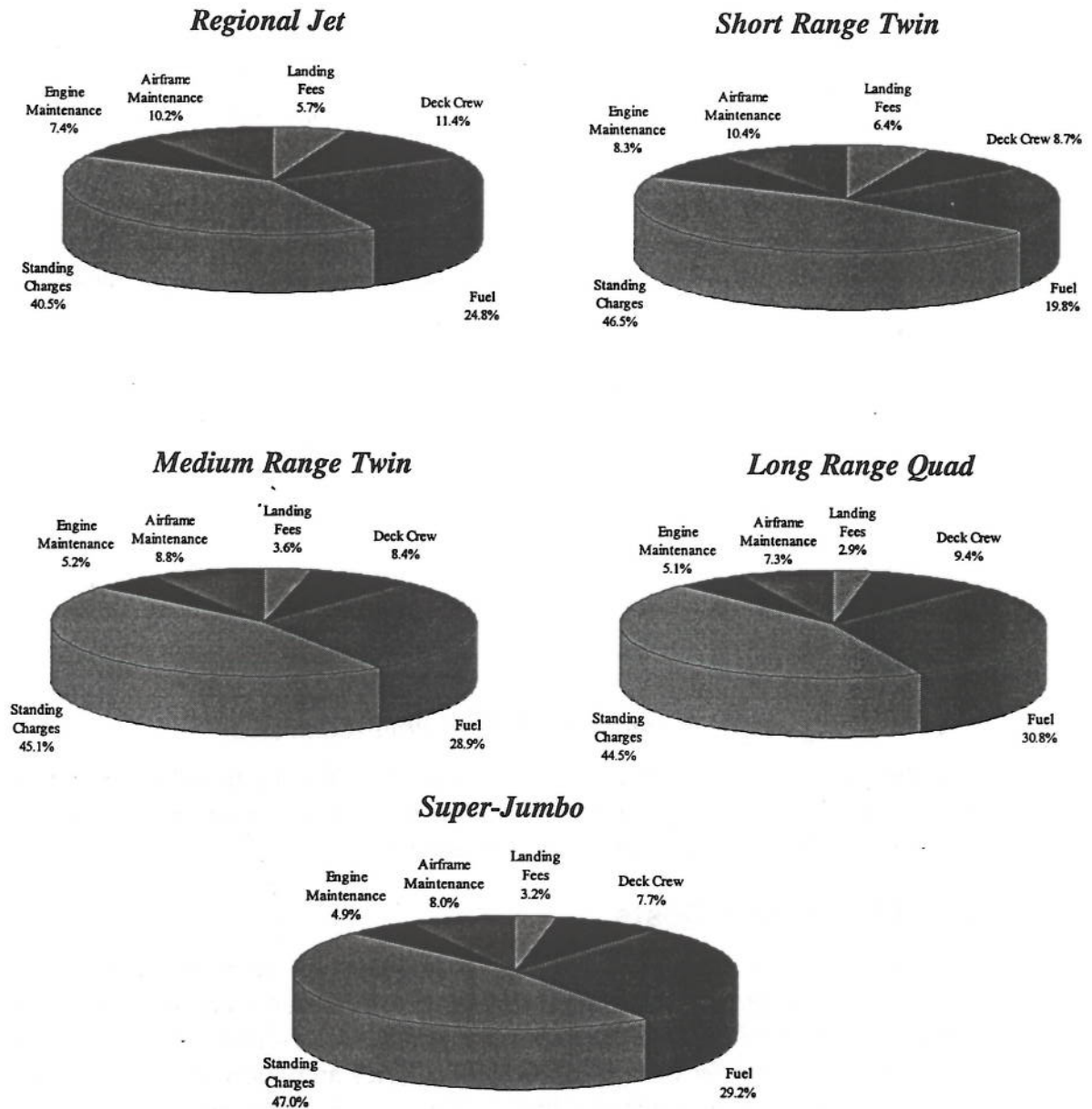


Figure 27: DOC Breakdown for Turbulent Baseline Aircraft

The most significant term for all aircraft types was the standing charges, which include finance, depreciation and insurance costs. These typically account for approximately 45% of the total, except for the *regional jet* for which they were still over 40%. Fuel costs are responsible for approximately 20-31% with a noticeable increase in importance as average stage length increases. *Regional jet* fuel costs are relatively high due to a high specific fuel consumption relative to the other aircraft. Flight deck crew costs account for approximately 8-11%, landing fees approximately 6% for the short range aircraft and 3-4% for the medium and longer range aircraft. Airframe maintenance costs represent 7-9% for the medium and longer range aircraft, and over 10% for the short range aircraft due to the very short average stage lengths.

All DOC terms increase in absolute value for the design missions due to increased flight times, except the landing fees which are dependent only on the aircraft

maximum take-off mass. For the medium and long range aircraft the importance of fuel costs increased by approximately 5 percentage points, with the deck crew costs increased by less than 1% percentage point. For the short range aircraft the fuel costs and deck crew costs increased by up to 10 and 3 percentage points, respectively, due to the very short average missions relative to the design missions.

Airframe and engine maintenance costs can be divided into cycle and flight time dependent terms. Clearly only the latter will increase, thus reducing the importance in the overall DOC. The standing charges still constitute the largest item within the DOC, although their significance is reduced in all cases due to the increased importance of fuel costs. Note that DOC was used as comparative figure, and should not be used to compare data from different aircraft.

6.3 Hybrid Laminar Flow Control

All studies investigating HLFC were performed using the same basic assumptions used for turbulent configurations, namely that all aircraft are optimised for their respective average missions, whilst being able to perform the corresponding design, missions, and that the fuel price was set at £0.19 per kilogramme unless stated otherwise.

A number of assumptions were also required in order to model the effects of HLFC:

- The most important of these being the maximum transition Reynolds number for HLFC wings was set at 25 million, unless stated otherwise. Values of approximately 20 million were achieved during the 757 HLFC flight tests, in which the laminar flow terminated at 65% chord probably due to adverse pressure gradients associated with the end of the pressure roof-top. Thus transition Reynolds numbers in excess of 20 million may well be possible.
- The suction coefficients used to define the suction velocities for the attachment line and cross-flow zones are dependent on the pressure gradient close to the leading edge. This is input data which for this study is set to a value representative of current turbulent aerofoils which results in relatively high suction coefficients [160].
- Laminar flow was assumed to achievable to 50% on both surfaces of the fin and both surfaces of the tailplane, and to 40% on the engine nacelles. A mean through surface suction velocity is assumed for these surfaces (set within the input data file at 0.15m/s) which is independent of configuration or flight conditions.
- Although laminar flow can be lost intermittently during cruise due to cloud encounter, it has been assumed to be uninterrupted throughout cruise with no additional fuel reserves loaded.
- It has been assumed that the production cost per kilogram of the HLFC suction system is comparable with as an average value used for the rest of the aircraft systems, due to similarities with a number of existing systems. For similar reasons, the maintenance cost per kilogramme of HLFC suction system is also assumed to be the same as the average value for the rest of the airframe. The

sensitivity of the optimum DOC to increases in these factors is investigated in sections 6.3.2.3 and 6.3.2.4.

- The leading edge structural mass is assumed to remain unchanged despite the use of drilled titanium in place of aluminium. The increased density of titanium is offset by increased strength requiring less material in some areas. However the production cost per kilogramme is assumed to increase by a factor of 25% to represent drilling and increased machining difficulty (Note that this excludes all HLFC related structure and systems). The mass and production cost factors for the leading edge structure and high lift devices is assumed to be unaltered from the turbulent values.
- In all optimised laminar flow configurations the engines are sized to ensure that cruise altitude and speed is attainable subsequent to a complete failure of the suction system.

6.3.1 Project Studies

When considering an aircraft to meet a new payload/range requirement the manufacturer faces the choice of developing a derivative of an existing airframe or designing a new aircraft type. The first option delivers an aircraft in a shorter timescale for lower development costs, although the resulting configuration will not necessarily be optimised for the payload/range requirement. Designing a new aircraft type, optimised to match the specified payload/range requirement, will result in minimum cash operating costs (fuel, maintenance, landing fees and deck crew costs). However it represents a major undertaking, requiring lengthy lead times and considerable financial investment, which can expose an aircraft manufacturer to substantial risk. Such a project would also have to consider potential derivatives in the future.

The introduction of laminar flow technology to commercial transport aircraft may follow either of these approaches. For either, DOC benefits are conditional on the balance between reduced fuel costs and increased costs associated with production and maintenance, increased airframe mass, and the suction system energy requirement. This balance can be further complicated where the reduced drag associated with laminar flow is used to increase payload/range capability.

The potential benefits of laminar flow technology, relative to the turbulent baseline aircraft, have been investigated for both minimum change derivatives and for fully optimised configurations.

6.3.1.1 Minimum Change Derivative

A minimum change derivative design retains the turbulent configuration and maximum take-off mass, whilst introducing a new leading edge or nacelle (depending in application) which contains the suction system. It may be possible to make limited changes to leading edge profiles, but for wing and empennage applications the surface profiles over the main structural box and trailing edge will be unchanged. For this study this issue has been assumed to have no effect, although in reality it may have a detrimental effect on the extent of laminar flow achievable.

The mass and performance of the leading edge high lift devices is assumed to be unaltered. An HLFC wing application would require a new leading edge, tighter surface tolerances for the wing-box skin, and installation of suction units. This represents a significant engineering task. Similar considerations apply for empennage applications, although matters are simplified due to less complex leading edge structures and lower Reynolds numbers. Introduction of HLFC nacelles is also less complex than wing applications due to the largely 2D flow and that they are non-lifting surfaces. It may be even possible to retro-fit HLFC nacelles to in-service aircraft.

To investigate the benefits of derivative applications, all five optimum turbulent configurations were considered with HLFC applied to the upper wing surface, nacelle surfaces, and a combined nacelle and empennage case.

6.3.1.1.1 Range Benefits

For each aircraft type, the design synthesis was run with input files for each aircraft type using the turbulent configuration as the starting point. The output from the design synthesis and optimisation code contains two sets of aircraft data, from the first and final runs. The output from the first and final runs defines the aircraft design corresponding to the starting and optimised values, respectively, of the independent variables.

Results from the first run were used to define the HLFC wing suction system mass, specific fuel consumption penalty and laminar profile drag. This was used with turbulent configuration data to evaluate the payload/range limits for the turbulent and laminar aircraft using re-arranged expressions from the design synthesis. The fuel load for cruise was based on that for the turbulent missions. The maximum zero fuel mass was assumed constant, which required a reduction in the maximum payload to be reduced by the mass of the suction system. The maximum payload corresponding to a full fuel load case is also reduced by the mass of the suction system. Fuel used for take-off, climb, descent, hold and landing is assumed unchanged as turbulent flow was assumed and that the aircraft is at a similar maximum take-off mass.

The resulting payload/range performance for all aircraft types, turbulent and laminar is presented in Figure 28 (Note: design Payload/Range denoted by markers).

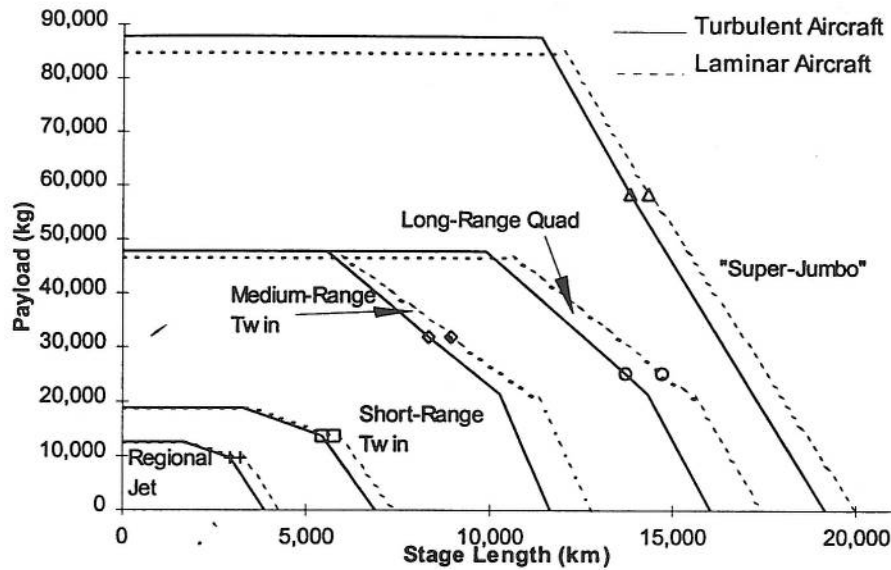


Figure 28: Payload/Range Envelope of Turbulent and Derivative HLFC Wing Aircraft

Maximum structural payload is defined by the horizontal line in the plots above. The take-off mass increases with stage length due to the increasing fuel load requirements. This continues to a point where the maximum take-off mass is reached, shown as the first corner point in the plot. To achieve further range increases, payload mass must be traded for greater fuel mass such that maximum take-off mass is not exceeded. This continues until all available fuel tanks are full, which is defined as the second corner on the payload/range envelopes above. After this, further reductions in payload permit increased range with constant fuel load.

Although the maximum payload of all laminar flow derivative aircraft was reduced, the corresponding maximum range was increased. It is also noticeable that the range increase becomes greater as the payload is reduced and the fuel load increases.

The process was repeated for HLFC nacelles, assuming 40% laminar flow on full length mixed-flow cowls, as this might be a potential retro-fit application to aircraft at some point after entering airline service. This case also provides an indicator to the benefits for HLFC empennage applications due to drag reductions of a similar magnitude. The resulting payload/range envelopes are shown in Figure 29.

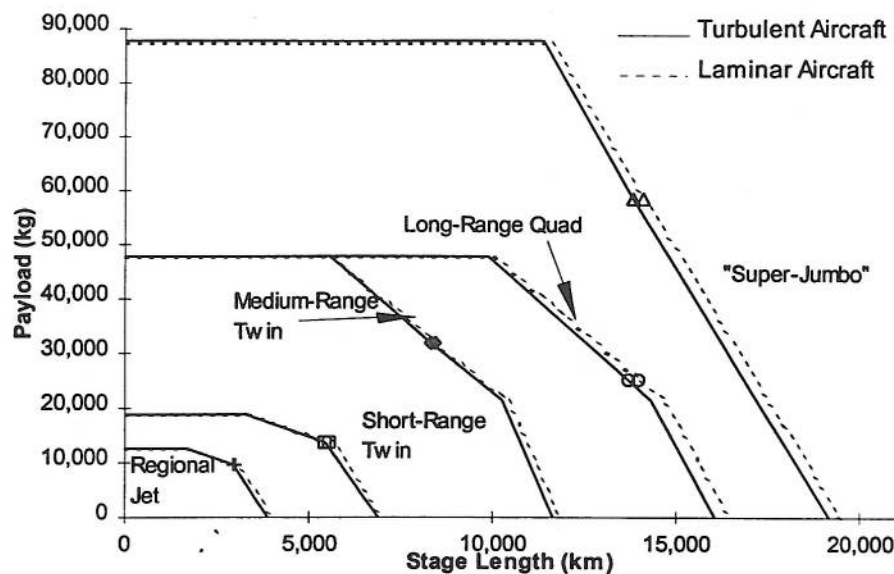


Figure 29: Impact of Derivative HLFC Nacelle on Payload/Range Envelope.

The increments in range is minor compared to the wing cases, typically up to 2%, which infers similar increments for fin and tailplane applications when used in isolation. For the *super jumbo* class aircraft, the use of HLFC on fin, tailplane and nacelle surfaces was proposed in [119]. The combined effect on the payload/range performance of these, denoted as the FTN case, is shown in Figure 30 assuming laminar flow to 40% chord on the nacelles and 50% on both surfaces of the fin and tailplane.

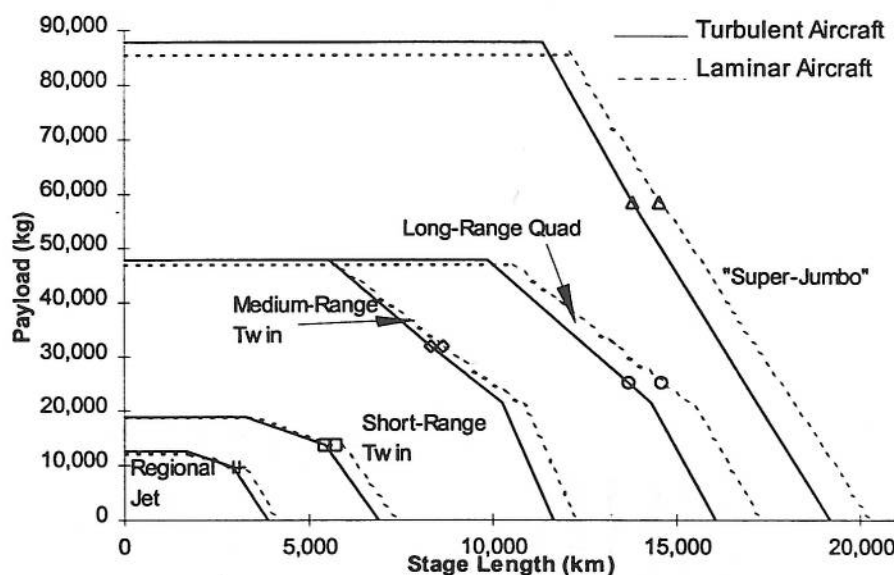


Figure 30: Impact of Derivative HLFC FTN Applications on Payload/Range Envelope.

The combined applications caused significant increases in the range capabilities, typically in the order of 4-7%. These are much greater than those for the nacelle case and in some cases approach or exceed the range increment for the wing cases.

The increment in maximum stage length, for all aircraft types, with the design payload are summarised in Figure 31 for the three derivative HLFC applications - upper wing surface, nacelles and a combined FTN (fin, tailplane and nacelle) case.

	Turbulent		HLFC Wing		HLFC Nacelle		HLFC FTN	
	Payload	Stage (km)	Stage (km)	% Inc.	Stage (km)	% Inc.	Stage (km)	% Inc.
<i>Regional Jet</i>	9,705	2,963	3,203	8.10%	3,020	1.92%	3,096	4.49%
<i>Short Range Twin</i>	13,608	5,465	5,791	5.97%	5,554	1.63%	5,739	5.01%
<i>Medium Range Twin</i>	31,920	8,334	8,924	7.08%	8,442	1.30%	8,659	3.90%
<i>Long Range Quad</i>	25,175	13,700	14,728	7.50%	13,987	2.09%	14,596	6.54%
<i>Super Jumbo</i>	58,425	13,843	14,356	3.71%	14,098	1.84%	14,577	5.30%

Figure 31: Increase in Maximum Stage Length for Derivative Configurations

The increase in maximum stage lengths is a function of numerous factors. The most important being the magnitude of drag reduction. This is the primary reason for the larger increases for the HLFC wing case, typically 7-9%, relative to the nacelle cases, 1-2%. The drag reductions for the FTN cases, 4-6.5%, are greater than the nacelle case and in all cases, bar the *super-jumbo*, less than the wing cases. This is reflected in the increases in the maximum stage lengths.

The relatively small benefit for the *super-jumbo* HLFC wing case is due to a reduced average extent of laminar flow (less than 40% chord) due to Reynolds number limitations. For all other HLFC wing cases the average extent of laminar flow was in excess of 50%. Note that for nacelle and FTN cases, where the extent of laminar flow is the same for all aircraft, the benefits for the *super-jumbo* aircraft are very similar to that for the aircraft with comparable stage length, namely the *long range quad*.

The profile drag and lift-dependent drag (including wave drag) reductions are presented in Figure 32 as a percentage change in the total turbulent drag of the baseline aircraft.

Average Mission

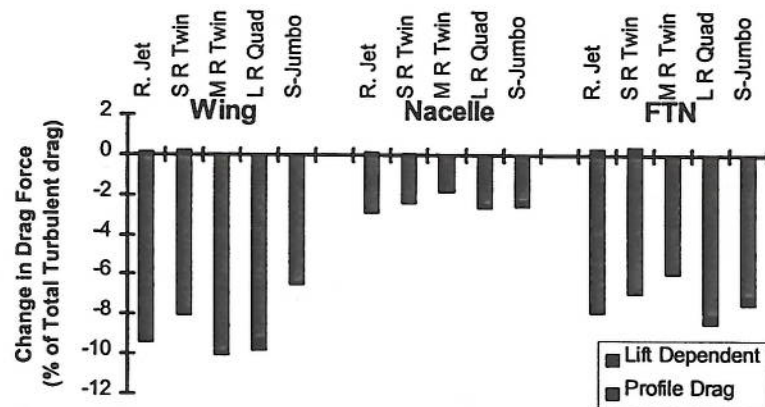


Figure 32: Drag Reduction for Derivative Configuration

Design Mission

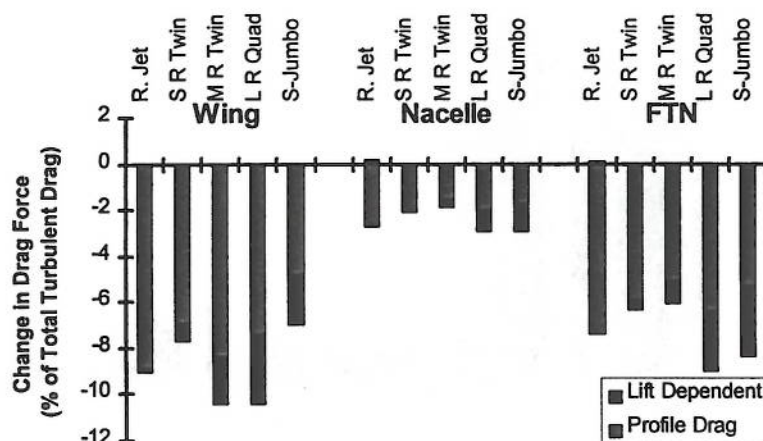


Figure 32: Drag Reduction for Derivative Configuration

(Continued)

For all cases, profile drag reductions are responsible for over 90% of the total drag reduction for the average mission, and over 70% for the design mission. The profile drag reductions are due directly to the reduced skin friction associated with HLFC, whereas changes to the lift-dependent drag are because of changes in aircraft take-off mass. The net change in take-off mass is the result of the balance between the suction system increasing aircraft empty mass and reduced fuel mass. The greater fuel mass reduction for the design mission, with no increase in system mass, leads to increased reductions in lift-dependent drag. The lift-dependent drag reductions increase as aircraft range, and hence the importance of fuel in the total DOC, increases.

The net drag reduction is the sum of the reduction of the two components. The wing cases show the greatest drag reductions, approximately three times greater than the nacelle case and approximately 10-20% greater than for the FTN case.

The fuel load as a fraction of the take-off mass is also an important factor in the extent of the benefits. Clearly a 10% fuel mass reduction will have a greater impact where the fuel fraction is high, namely for long range aircraft. This trend can be seen for the HLFC wing case, although it is distorted for the *regional jet* and *super-jumbo*.

The trend of increased benefits with longer stage lengths is not as clear for the nacelle and FTN cases, although the benefits for the *long range quad* and *super-jumbo* aircraft are greater than for the *short- and medium-range twins*. The contribution of the individual components to the total profile drag, shown in Figure 33 for all the turbulent baseline aircraft, can influence the increase in payload/range benefits. The most notable feature is the increase in importance of the wing in the total profile drag and the reducing importance of the fuselage. This may also explain the small increase in the payload/range capability for the *medium range twin* nacelle and FTN cases. The relative importance of the nacelle for this aircraft type is significantly lower than that for all other aircraft types, even though the extent of laminar flow is the same for each.

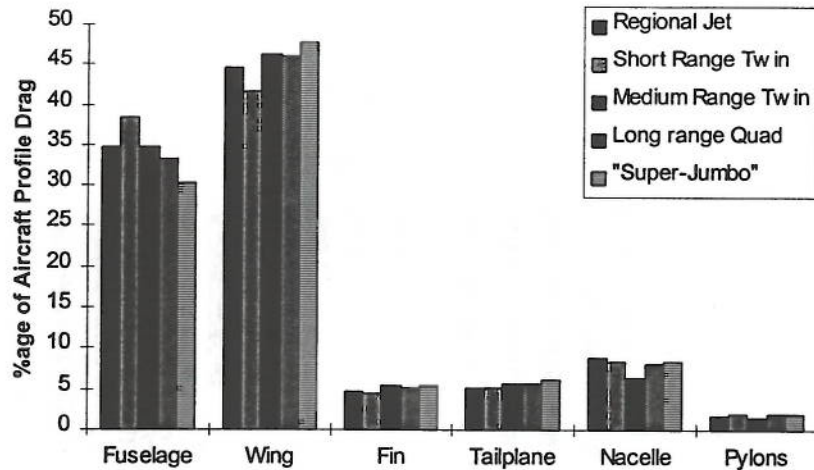


Figure 33: Profile Drag Breakdown.

Aircraft speed and altitude influences the Reynolds numbers which in turn alters the extent of laminar flow possible on a wing (extent of laminar flow fixed on all other surfaces). Suction coefficients for the attachment line and cross-flow zones are also functions of wing chord Reynolds number and wing leading edge sweep, such that higher Reynolds number increases the suction coefficients. Increased speed and altitude will also increase leading edge sweep thus further increasing attachment line and cross flow suction coefficients. Increased speed will also increase the suction velocities as the suction coefficients are often considered as a ratio between suction velocity and free stream velocity. This can all result in increased system mass and power requirements, both of which will reduce performance and DOC benefits.

Generally the optimum aircraft speed, and thus leading edge sweep, increases as design stage length increases. Aircraft size also tends to increase for longer range missions. The increased importance of fuel mass for long range aircraft results in increased wing area/passenger ratio and explains the increasing importance of the wing in the total profile drag with increasing design stage length (Figure 33).

These Reynolds number effects do not represent a major factor until the *super-jumbo* aircraft is considered. Not only is the wing geometric mean chord the largest of the aircraft considered, but its cruise Mach number is the highest. This results in reduced extents of laminar flow on the wing, and increased suction velocity requirements. This all implies that reduced drag reductions are achieved with a heavier, more powerful suction system.

The increasing importance of the suction system in the total aircraft empty mass (excluding crew) with increasing size is shown in Figure 34.

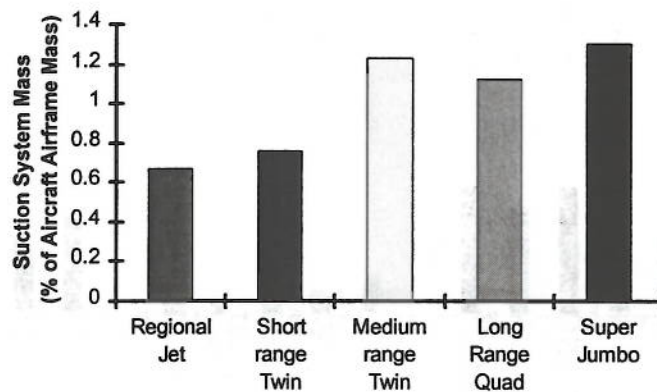


Figure 34: Suction System Mass as Percentage of Aircraft Empty Mass

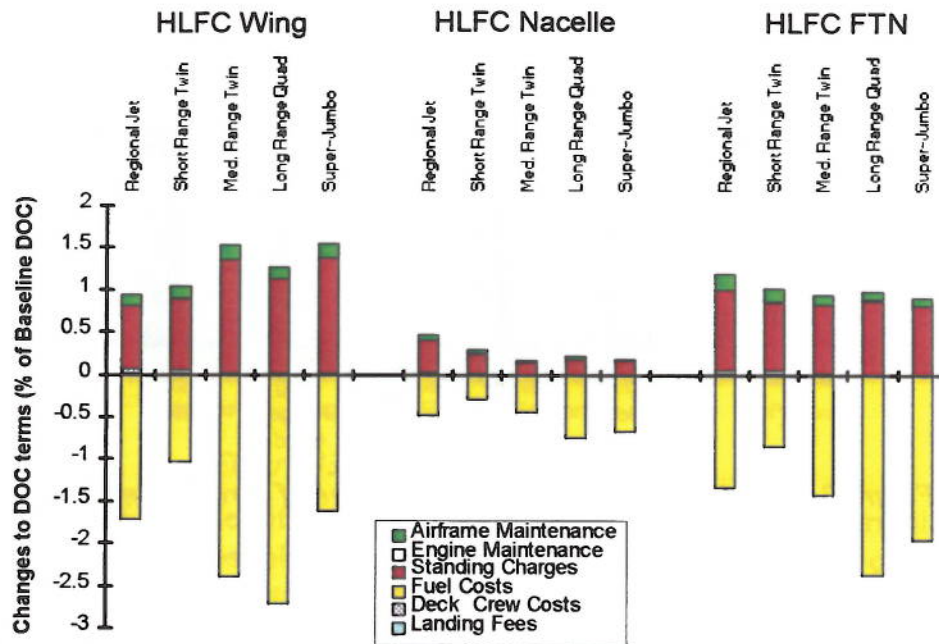
Suction system mass increases from 0.65% of the *regional jet* empty mass to over 1.3% of the *super-jumbo*. The smallest aircraft, which also has the lowest cruise Mach number and hence low leading edge sweep, requires relatively low suction coefficients. For much of the span, the attachment line Reynolds numbers fall below the critical value and thus the boundary layer is naturally stable within this region removing the requirement for suction. As wing area (Reynolds number) and leading edge sweep increase, a greater proportion of the span will require suction on the attachment line. This increases importance of the system mass for the larger aircraft.

6.3.1.1.2 DOC Benefits

The resulting maximum range with the design payload is used as input data with the turbulent configuration as a starting point. The results from the first run of the design synthesis provide the DOC at the increased design range, the turbulent design range and the average stage length.

Although the primary effect of HLFC is to reduce fuel burn, it also effects other DOC terms. The impact of laminar flow on individual DOC terms is shown in Figure 35 for all three cases on all aircraft types for the turbulent baselines average and design missions. The changes are all measured as a percentage of the total turbulent DOC. The bars shown above the axis contain all terms that are increased by the introduction of HLFC, whereas the bars below the axis contain all terms that are reduced. The net DOC benefit is the difference between the positive and negative bars.

Average Mission



Design Mission

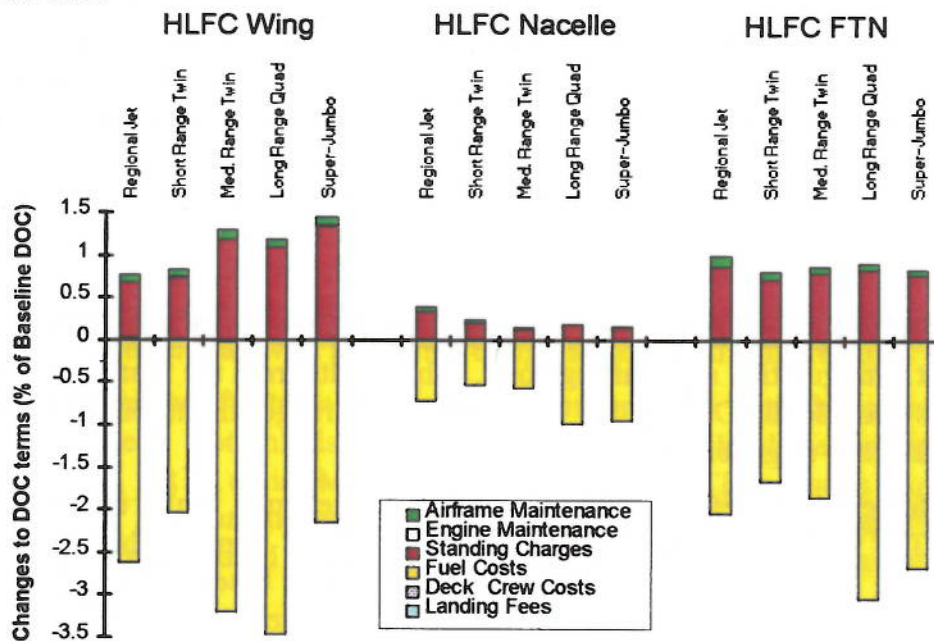


Figure 35: Change in DOC Terms for Derivative Aircraft
(Vertical scale not consistent with other DOC figures)

In all cases, fuel is the only term that is reduced, a direct result of the HLFC drag benefits. The introduction of suction systems represents an increase in system mass and aircraft cost, both of which increase the standing charges and airframe maintenance costs. Deck crew costs do not vary significantly, except for the *regional jet* and *short range twin* average missions which are very short. Changes to landing

fees and engine maintenance costs are insignificant when considered as part of the total DOC.

The net change in DOC from the turbulent baseline over the average and design missions (as defined by the baseline aircraft) for the HLFC wing derivative case are shown in Figure 36. Note that a consistent scale is used on the y-axis on all figures showing percent changes to DOC.

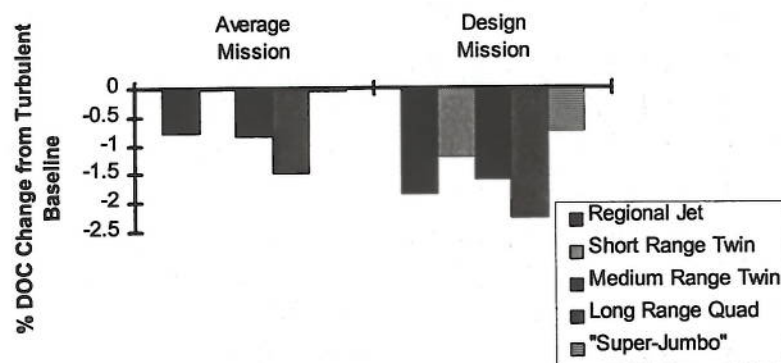


Figure 36: DOC Benefit of Derivative HLFC Wing Application.

For the average mission, the DOC was improved by 0.15-1.9%, increasing to 1.2%-2.6% for the design mission. The *short range twin* and *super-jumbo* showed only a marginal DOC benefit for their respective average missions, although benefits were observed for the design mission.

The net DOC benefits for the nacelle case, shown in Figure 37 for the average and design missions.

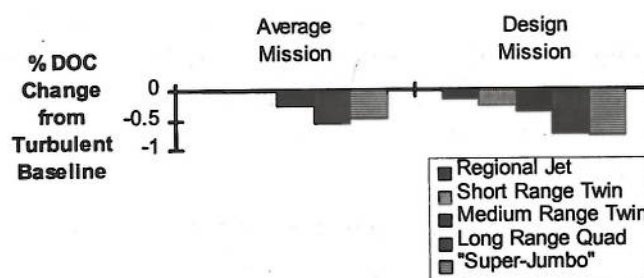


Figure 37: DOC Benefit of Derivative HLFC Nacelle Application.

For the *regional jet* and *short range twin*, the benefits are marginal for the average mission. In all cases the DOC benefits were greater for the design mission, although the benefits do not exceed 0.8%.

The DOC benefits for the FTN cases are shown in Figure 38.

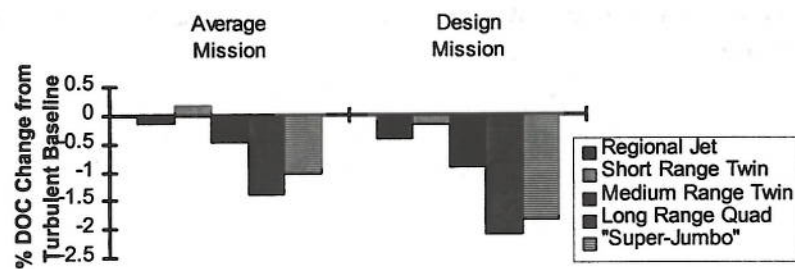


Figure 38: DOC Benefit of Derivative HLFC FTN Application.

The benefits for the *regional jet* and *short range twin* are marginal for both missions, while a net DOC penalty occurs for the latter on the average mission. The DOC benefits for the medium and longer range aircraft are comparable with the wing case.

The factors discussed previously for range benefits are also valid for DOC benefits. The most important being the magnitude of the drag reduction and the mission stage lengths. Other factors are aircraft size and speed, particularly for the *super jumbo* aircraft. Reduced aircraft take-off mass for the average and baseline design missions may permit operation at a higher altitude further reducing fuel burn, and hence DOC, although this effect is likely to be minor.

The results from these studies are valid for a new aircraft type optimised for turbulent flow with HLFC added subsequently. Using the current DOC method to assess the potential benefits for true derivative HLFC applications may be a conservative approach. The main advantage of such aircraft is the reduced development costs and technical risk which may limit the increase in standing charges (see Figure 35), although HLFC system will represent additional development costs. Given that increases to this term are primarily responsible for countering the fuel cost reductions, the increase in net DOC benefits could be significant.

Derivative HLFC configuration will have a very high degree of commonality with the turbulent baseline aircraft. With the exception of HLFC related items and increased surface finish requirements, the structure, engines and all systems will be common for both aircraft. These increased commonality should provide production and maintenance cost savings

The most important difference in aircraft handling characteristics is likely to be for high-lift performance should Krüger flaps be used in place of slats. These effects may be limited if the Krüger flaps are designed to achieve similar high-lift characteristics to the slats. Provided the HLFC systems require little more aircrew attention than on-off selection, the primary differences will be the changes in throttle settings to counter changes in aircraft drag when laminar flow is lost or regained. These issues should be easily addressed by the autopilot set to maintain constant cruise speed. Additional pilot training would be required to take into account aircraft operation subsequent to permanent loss of laminar flow, in particular fuel management. Commonality may also result in cross-crew qualification thus providing crew training cost benefits.

6.3.1.2 Configuration Optimisation

If an aircraft configuration is optimised to take into account HLFC from the outset of the design process, the potential benefits can be maximised. Reduced fuel loads lead

to lower maximum take-off mass if the design range requirements relative to a turbulent equivalent are retained. This allows a smaller wing to be used typically reducing the required wing structural mass, although this can be complicated by changes to the wing planform to achieve an optimum balance between lift dependent and profile drag. Reduced structural mass requires lower thrust, and thus smaller, lighter engines. Other smaller mass reductions are associated with the empennage, undercarriage and systems. The combined mass reductions reduces fuel burn further, permitting even further reductions in structural mass. This iterative loop continues until the configuration converges to an optimised solution that satisfies a set of constraints imposed to ensure a feasible aircraft. Reduced aircraft size limits any increase in aircraft cost due to HLFC system costs - in some cases it may actually reduce aircraft costs. This is very important as first cost related terms typically account for over 40% of the DOC, see Figure 27. Within the DOC method used for this study, reduced aircraft mass and production cost will also reduce maintenance costs, landing fees and crew costs.

6.3.1.2.1 DOC Benefits

The DOC benefits of introducing HLFC technology to the conceptual design phase were investigated by considering five applications - wing upper surface, fin, tailplane, nacelles, and a combined WFTN (wing upper surface, fin, tailplane and nacelle) case. For all cases, the payload, stage length, cruise Mach number and altitude for both average and design missions were retained. Optimisation was based on the DOC for the shorter range average mission although the resulting configuration was required to be capable of performing the design mission..

The impact of HLFC on the individual DOC terms, as a percentage of the corresponding total baseline DOC, for all applications is shown in Figure 39. Data is presented for both average and design missions

Average Mission

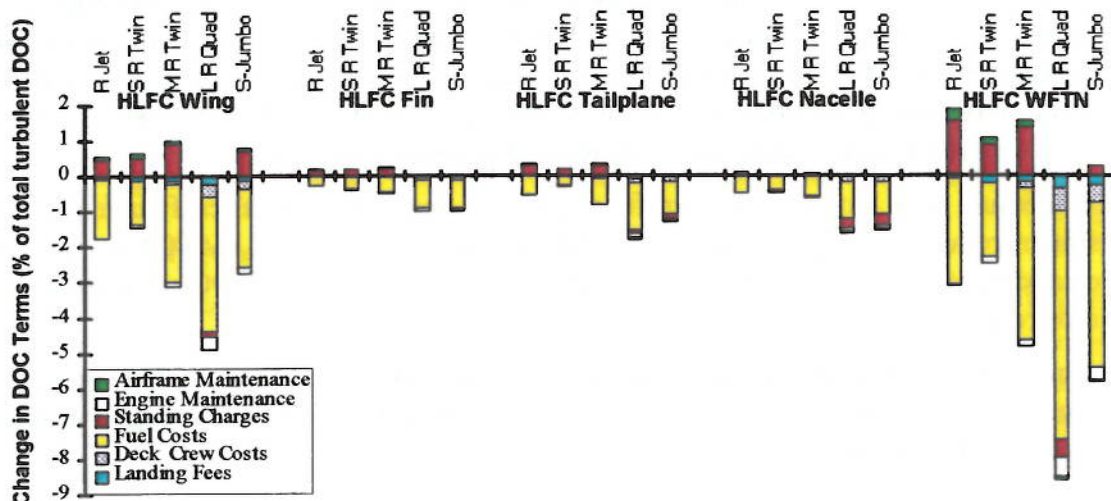


Figure 39: Change in DOC Terms for Optimised Configurations
(Vertical scale not consistent with other DOC figures)

Design Mission

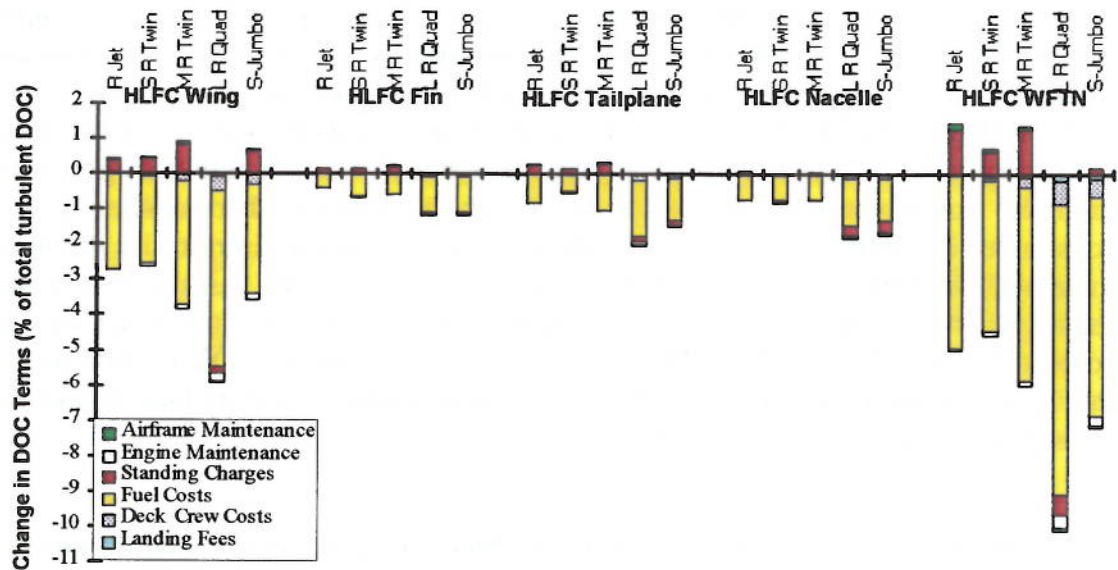


Figure 39: Change in DOC Terms for Optimised Configurations (Continued)

Direct comparisons can be drawn between the wing and nacelle cases and the corresponding results for the derivative studies. The fuel cost benefits are increased by a factor of approximately 1.4. Although the introduction of the HLFC suction systems represents a significant cost, this is partially offset on the optimised configurations by a smaller airframe and engines, thus limiting the increase in aircraft purchase cost and hence, standing charges. For the *long range quad* HLFC wing case, these reductions marginally outweigh the HLFC system costs, providing additional DOC benefit. Smaller engines give rise to lower engine maintenance costs, although airframe (structure and systems) maintenance costs were marginally increased for the average mission HLFC wing cases as the costs related to the suction system outweigh reductions due to a smaller airframe. For the design mission, changes to airframe maintenance costs were generally negligible.

For medium and long range aircraft, significant reductions in aircraft take-off mass result in reduced deck crew costs. Reduced maximum take-off (MTO) mass lowers the landing fees although their low importance in the overall DOC, results in very minor reductions.

The results shown above can be summarised by considering the net DOC change from the turbulent baseline aircraft. Results are presented for both the average and design missions in Figure 40.

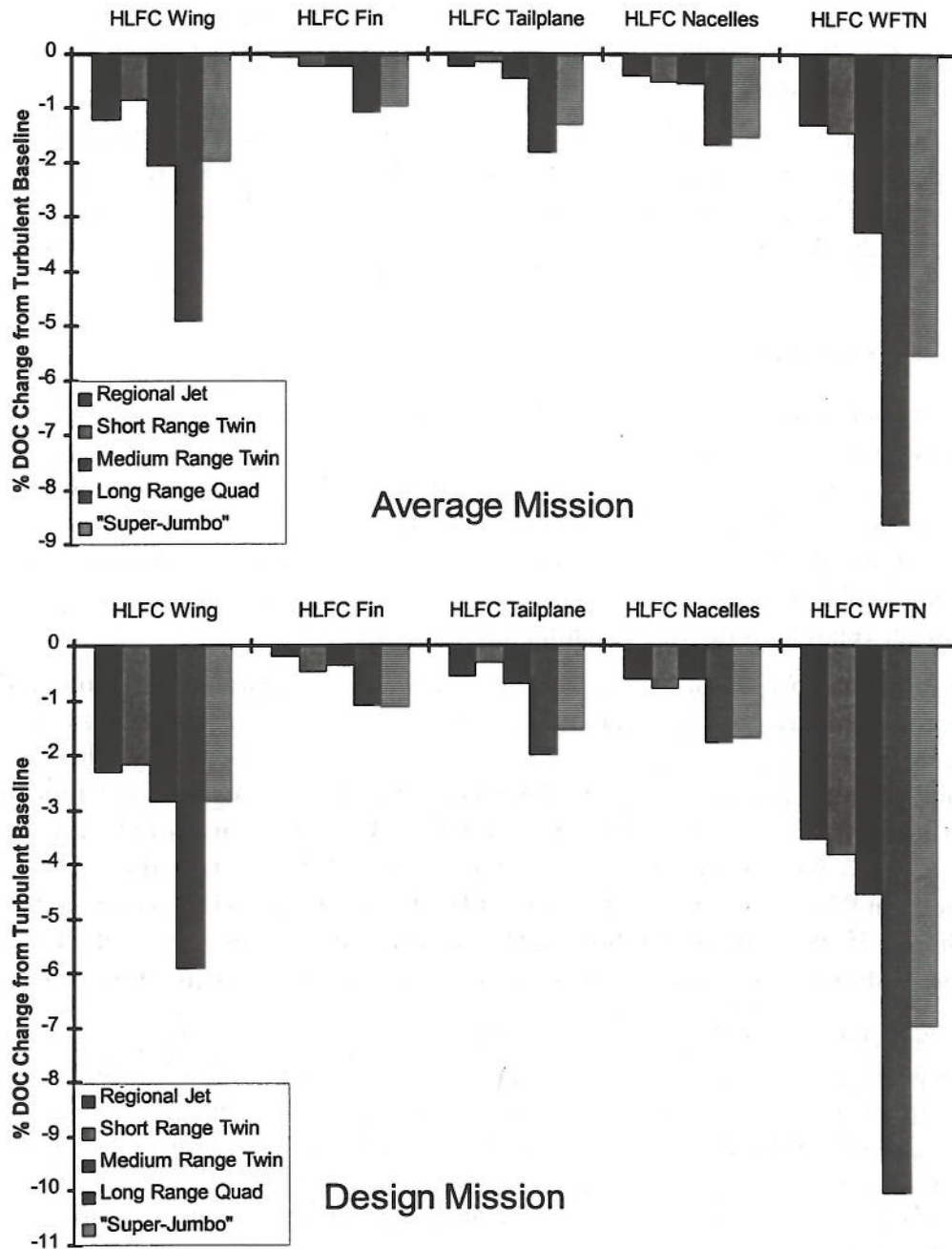


Figure 40: Net DOC Benefits of Optimised Configurations

It is clear for all aircraft types, on the average missions, that the largest DOC benefits of any single component are for the wing upper surface (0.8-4.9% improvement) relative to the fin, tailplane or nacelle cases (0.1-2% improvement). For all aircraft types, except the *super-jumbo*, the DOC benefit for the wing case was at least double that for the other cases. The same trend was observed for the design mission, although the net DOC benefits were increased in all cases. This is due to the increased importance of the fuel in the DOC.

The variation between different HLFC applications and between aircraft types is due to the same factors described in detail for the derivative applications, namely increased benefits due to larger drag reductions, the importance of fuel costs in the

total DOC, which in turn is a function of design stage length. Increasing aircraft size and speed results in increased suction requirements and for the *super jumbo* limits the extent of laminar flow.

Comparison of the HLFC wing and nacelle results with the corresponding derivative cases (Figure 36 and Figure 37, respectively), shows that the DOC benefits for the optimised configurations are up to four times greater. These substantially improved benefits are due to the changes to the aircraft configuration as well as reduced aircraft size.

6.3.1.2.2 Configurational Changes

Maximum aerodynamic efficiency theoretically occurs when profile drag and lift-dependent drag components are equal [66]. This is considered along with other factors, such as structural efficiency, flight time, aircraft cost, to optimise aircraft configuration for minimum DOC over the average mission. Generally, for optimum configurations, the profile drag is slightly greater than the lift-dependent drag. This difference tends to increase for shorter range aircraft as the other factors increase in importance, relative to the aerodynamic efficiency.

Where laminar flow is introduced to a derivative configuration, the profile drag is significantly reduced, the airframe mass is increased due to the suction system and the fuel mass for the average and design missions is reduced. Generally, the fuel mass reductions are greater than the airframe mass increase resulting in a net reduction in aircraft take-off mass for the HLFC aircraft. Clearly, the fuel mass reductions for the design mission will be greater than for the average mission, resulting in larger net reductions in take-off mass. This results in small reductions in the lift-dependent drag component. Therefore, although the total aircraft drag has been reduced, the balance between profile and lift-dependent drag is not that required for minimum DOC.

To achieve an optimum HLFC configuration, from a turbulent baseline, the lift-dependent drag must also be reduced to achieve maximum aircraft efficiency. This trend was observed for the optimised configurations. The results in Figure 41 show the changes of the drag components (force, not coefficients) as a percentage of the total aircraft drag for the turbulent baseline at the start of cruise. For simplicity, aircraft drag is considered as only profile drag and lift dependent drag (incorporating wave drag).

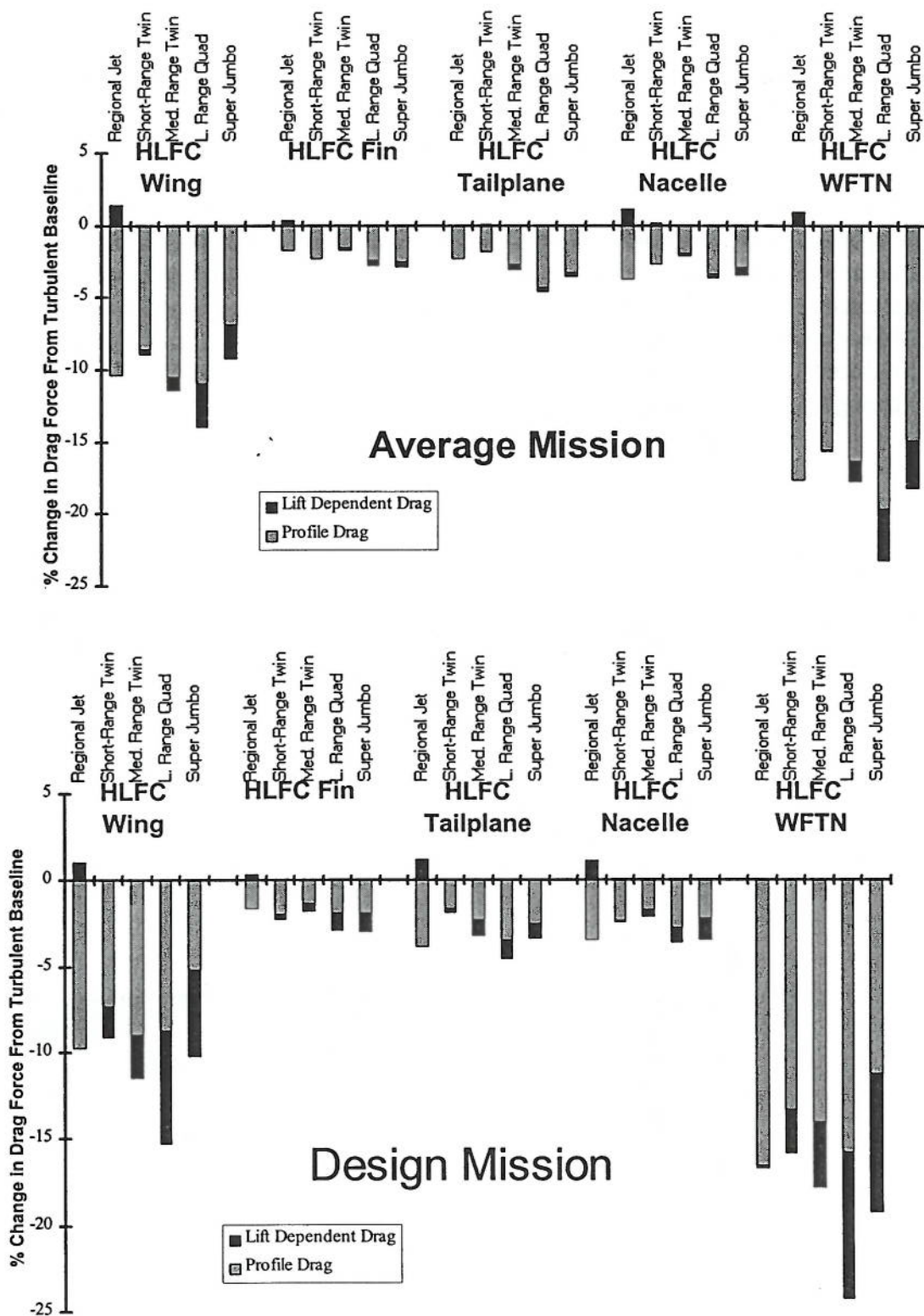


Figure 41: Changes in Aircraft Drag Force from Turbulent Baseline

Greater percentage profile drag reductions are shown for average mission as the profile drag accounts for approximately 60-63% of the total aircraft drag for the average mission and 53-55% for the design mission. The actual profile drag force is

equal for both missions, but the total drag is reduced for the average mission, due to lower lift-dependent drag resulting from lower aircraft mass for the shorter mission.

Comparison of the profile drag reductions for the HLFC wing and nacelle cases with the reductions for the corresponding derivative aircraft (Figure 32) show that the profile drag reductions are only slightly larger for the optimised configuration. This is due to reduced surface area of wing, empennage and nacelles, as aircraft speed and flight conditions are unchanged. However greater changes were observed for the lift dependent drag component which are due to configuration optimisation, namely wing area and wing loading (aircraft weight/wing area). This results in increased total drag reductions for no further increase in suction system mass. Although the wing area is likely to be reduced due to lower maximum take-off mass, it may not necessarily be reduced to the same extent as the take-off mass, thus reducing wing loading. The changes to wing loading and aspect ratio are shown for all cases in Figure 42.

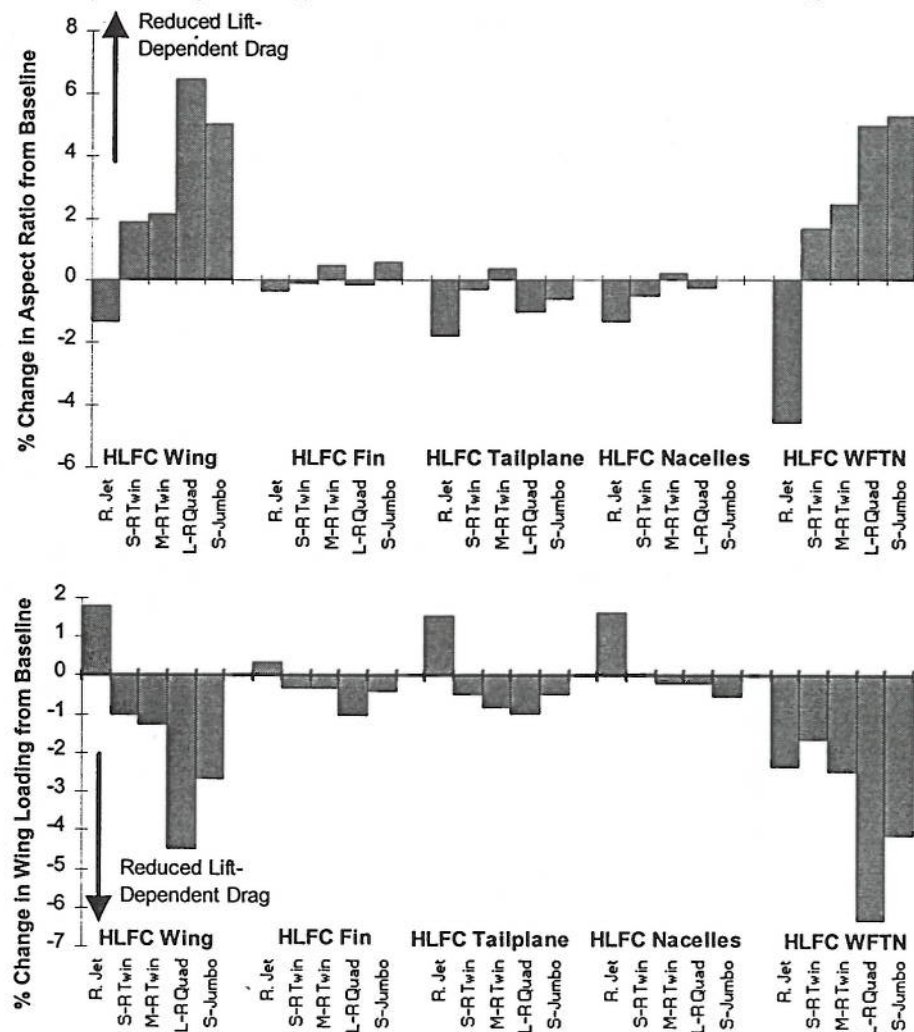


Figure 42: Changes to Wing Loading and Aspect Ratio for HLFC Wing Case

With the exception of the *regional jet* the wing loading was reduced for all aircraft types with all HLFC applications. Aspect ratio is increased for all aircraft types, except the *regional jet*, for the HLFC wing and WFTN cases. For the fin, tailplane and nacelle cases, all changes were small, although the aspect ratio is increased for

the *medium-range twin*, but reduced for the *regional jet* and *short-range twin* and *long-range quad*. For the *super-jumbo*, aspect ratio was increased for the fin case but reduced for the tailplane and nacelle case.

However, reduced wing loading and increased aspect ratio also increased wing mass. Thus the resulting configuration is likely to be a compromise between these two requirements, although wing mass appears to be more sensitive to aspect ratio than wing loading. This may explain the higher aspect ratios selected for the wing case relative to the WFTN case, while wing loading reductions are greater for the WFTN case than the wing case.

The alternative trend observed for the *regional jet* may possibly due to the very short average and design mission lengths. Thus the fuel mass reductions are small, with much of this negated by the HLFC system mass, in some cases the maximum take-off mass was increased.

Wing loading is also a factor in the high speed performance of the wing, as is aspect ratio, sweep, thickness/chord ratio, and pressure distribution. For a fixed Mach number, a reduced wing loading permits a reduction in wing sweep and/or an increase in wing thickness/chord ratio, both of which result in wing mass reductions. These trends are evident in the optimised configurations (Appendix G) with larger changes observed for the wing and WFTN cases.

As for the derivative case the benefits for the *super-jumbo* HLFC wing upper surface case are considerably less than for the *long range quad* which is of similar range. To illustrate the impact of the extent of laminar flow on the DOC benefits, both aircraft with HLFC upper wing surfaces were optimised for a range of maximum transition Reynolds numbers, Figure 43 (extent of laminar flow as a fraction of the wing chord shown as data labels).

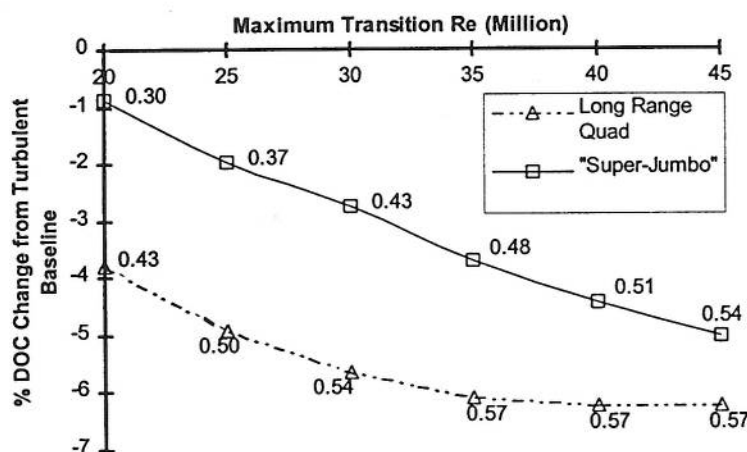


Figure 43: Impact of Maximum Transition Reynolds Number

It is clear that the chordwise extent of laminar flow increases with greater maximum transition Reynolds number (Re_t). It is also noticeable that the gradient of this trend for the *long range quad* approaches zero with increasing maximum transition Reynolds number, as the extent of laminar flow across the span becomes increasingly limited by the rear end of the pressure roof-top. In fact, above about 35 million,

further increases in Re_t bring no added benefit for this aircraft as the extent of laminar flow across the entire span is limited by the pressure distribution.

However, for the *super-jumbo*, with a much larger wing this does not occur until the maximum transition Reynolds number is in excess of 45 million. For the results in Figure 40 ($Re_t = 25$ million) the extent of laminar flow on the wing upper surface was 39% and 52% for the *super-jumbo* and *long range quad*, respectively, which corresponds to a three percentage points difference in DOC benefit. If the benefits for the two aircraft are considered with approximately equal extents of laminar flow, such as 57% chord ($Re_t = 30$ million for the *long range quad* and $Re_t = 45$ million for the *super-jumbo*), the difference in DOC benefits reduces to approximately one percent point.

The remaining difference is likely to be due to the increased speed and size of the *super-jumbo* necessitating higher suction coefficients, and hence increased penalties. Indeed, the suction system mass, as a percentage of the aircraft empty mass, for the *super jumbo* and *long range quad* are shown in Figure 44, as well as for the other aircraft.

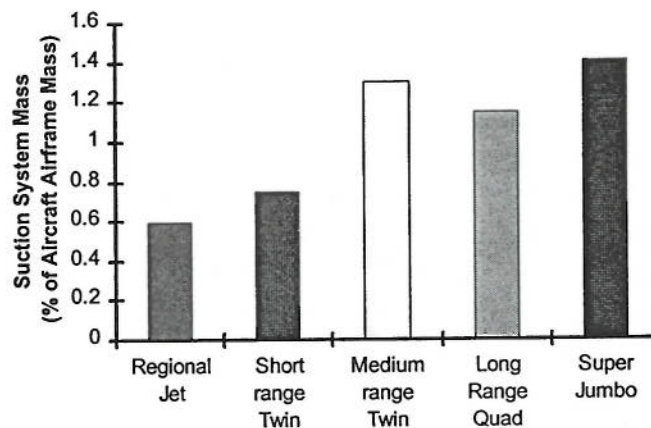


Figure 44: HLFC Suction System Mass as Percentage of Optimised Aircraft Empty Mass

This figure shows that the importance of the suction system mass does increase with aircraft size and speed and the additional mass penalty for the *super jumbo* compared to the *long range quad* is consistent with the observed 1% difference in DOC, mentioned above. For all aircraft types, the importance of the suction system mass is very similar to that for the derivative aircraft, Figure 34.

The payload/range envelopes for the baseline and HLFC wing *medium range twin* are shown in Figure 45. Although the baseline design mission payload and stage length were retained by all HLFC configurations, the maximum possible stage length is reduced, relative to the baseline aircraft, when the payload is greater than the design value and increased for reduced payloads. This is due to the reduced drag associated with HLFC applications increasing the specific range (range per unit fuel mass) making the aircraft range more sensitive to changes in fuel mass.

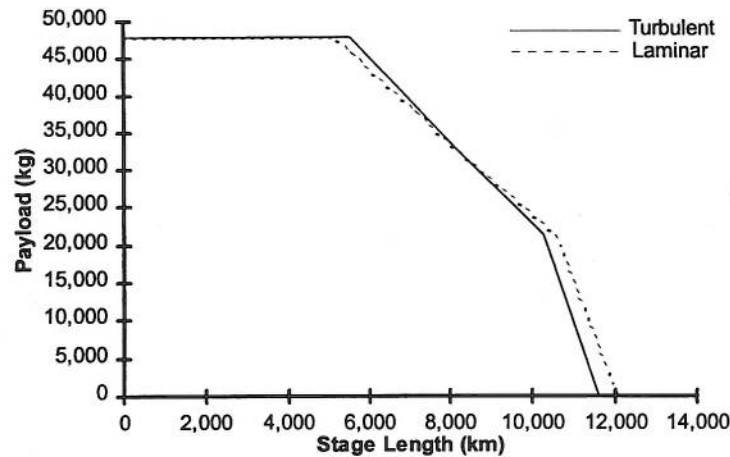


Figure 45: Medium Range Twin - Turbulent and HLFC Wing Payload/Range

6.3.1.2.3 Maximum Turbulent Range

In the event of complete failure of the HLFC suction system, aircraft drag will increase thus reducing the maximum range capability. The range reduction with the design payload, as calculated within the design synthesis, is presented for all HLFC applications for each aircraft type in Figure 46. This reduction is based on the calculated turbulent profile drag and fuel load, and the maximum take-off mass used for the design mission with HLFC fully operative.

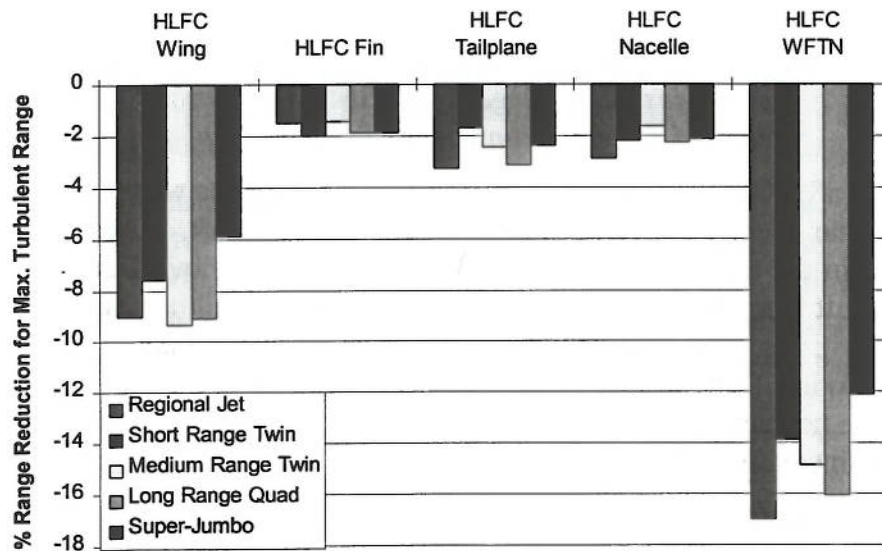


Figure 46: Reduction in Maximum Range Due to Loss of Laminar Flow

The reduction in maximum range is principally due to difference between the laminar and turbulent profile drag. This is shown by the greatest reductions for the WFTN cases, followed by the wing cases, with the lowest reductions for the fin, tailplane and nacelle cases. This can be seen by comparing the range reductions shown above with profile drag reductions for the design mission shown in Figure 41. The aircraft mass at the beginning and end of both the maximum laminar and turbulent ranges will be unchanged. Thus lift-dependent drag will be the same.

In airline service, the aircraft would frequently be used for missions shorter than 80% of the design range. Thus complete failure of HLFC would only rarely result in cancellation of flights or the need for en-route refuelling stops. Clearly, problems will arise where the aircraft are required to operate close to their maximum range with large payloads.

However, operating the aircraft without laminar flow will increase the fuel costs. To assess the impact on aircraft economics, DOC comparisons were made between the HLFC aircraft with an inoperative suction system and the turbulent baseline aircraft, both operating over the maximum turbulent range of the former. The changes to the individual DOC terms are shown in Figure 47.

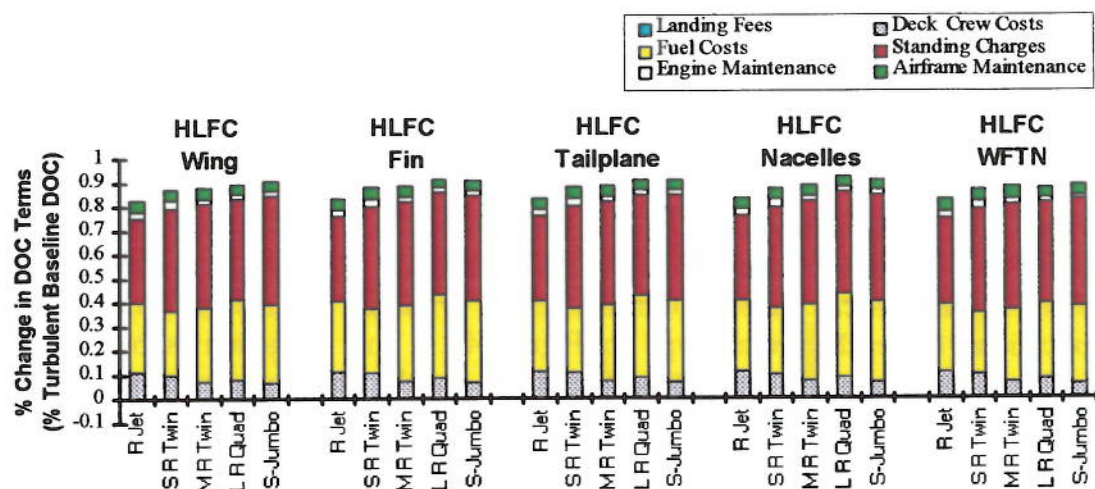


Figure 47: Change in DOC Terms for Optimised HLFC Configurations Operating at Maximum Range with HLFC inoperative
(Vertical scale not consistent with other DOC figures)

In all cases, all DOC terms are increased except landing fees which are reduced due to the lower maximum take-off masses of the HLFC aircraft. Due to their minimal importance in the total DOC, they are not visible in the above figure. Although the HLFC aircraft were smaller, with the inherent reductions in airframe production and maintenance costs, the cost and mass penalties of the inoperative suction system increase all other DOC terms. The combined length of the bars in the above figure represent the net change in DOC from the turbulent baseline aircraft. In all cases, the net DOC is increased by 0.8-0.9%.

For each aircraft type, the DOC benefits were very similar for each HLFC application. This is due to the correlation between the drag reduction and the difference between the maximum laminar and turbulent ranges. The DOC for the turbulent baseline aircraft increases as the stage length reduces. Therefore, for the HLFC wing and WFTN cases, with large drag reductions, the DOC for the maximum turbulent case will be compared against a baseline DOC that is greater than that used for comparison with HLFC fin, tailplane or nacelle cases. The reductions in aircraft size also increase with larger drag reductions, suggesting that the smaller designs for HLFC wing and WFTN cases offsets the penalties associated with larger suction systems.

6.3.2 Sensitivity Studies

Numerous assumptions and estimations have had to be made to perform the project studies due to lack of quantified information or uncertainty about in the operating environment. When considering the introduction of new technologies it is important to analyse the potential risks and assess these against the potential benefits. This requires studies to be performed to investigate the sensitivity of the DOC to any factors where a degree of uncertainty exists. Indeed, aircraft manufacturers often conduct detailed studies from which best and worst case scenarios can be defined and the risks assessed. This is not possible within the scope of this study, although the sensitivity of the DOC to changes in various parameters could be assessed. The HLFC wing case was used for these sensitivity studies as they result in the greatest changes to the configuration allowing any trends to be more visible.

6.3.2.1 Fuel Price

Although fuel price is not subject to the uncertainties of other assumptions it is, however, subject to market fluctuations and is susceptible to political events such as the 1970s oil crisis. At any given time, the cost of fuel can also vary greatly between regions as a result of local conditions. A figure of 60c/USG (£0.12/kg) was typical for western countries (mid 1994) while considerably higher charges could be found elsewhere.

As fuel mass, and hence costs, are reduced by HLFC, the fuel price will directly influence the DOC benefits. Therefore, turbulent designs and laminar designs with HLFC upper wing surfaces were optimised for all aircraft with a range of fuel prices. For each value, the difference in DOC between the corresponding optimised turbulent and laminar configurations is shown in Figure 48.

Average Mission

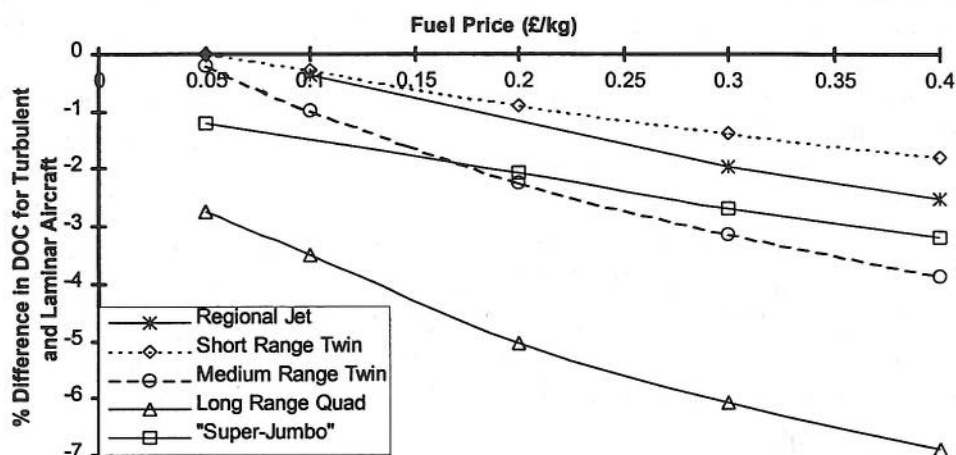


Figure 48: Impact of Fuel Price in Optimum DOC Benefit.

Design Mission

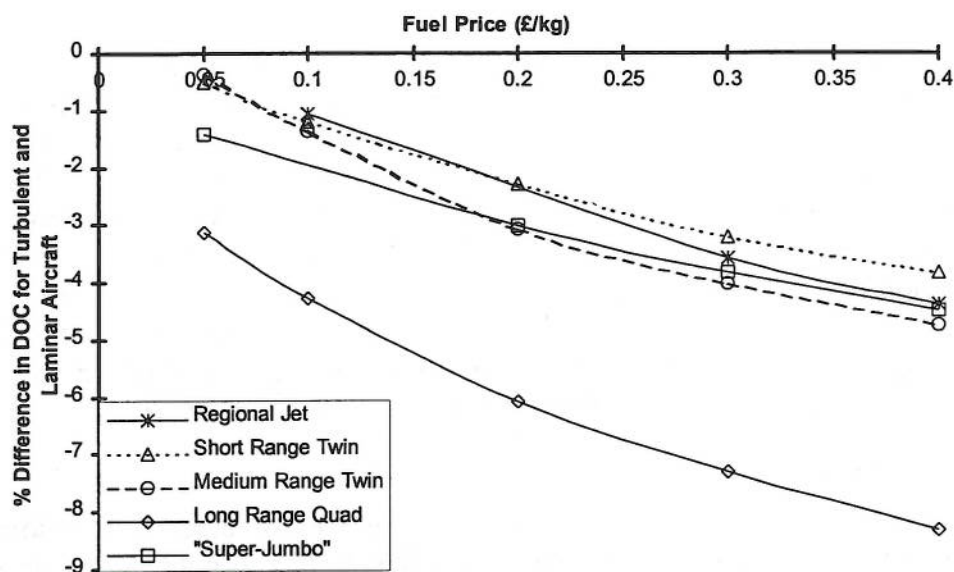


Figure 48: Impact of Fuel Price in Optimum DOC Benefit.

(Continued)

For all cases, on both average and design missions, the net DOC benefits reduced as the fuel price was reduced. The gradient on the plots is greater, in all cases, for the design mission as the significance of fuel costs in the DOC is greater.

It is noticeable that even for the lowest fuel price considered, DOC benefits were still possible for all aircraft types on their respective average and design mission. The reduced fuel load for the design mission results in a lower maximum take-off mass, and hence reduced structural mass through a smaller wing. The reduced structural mass limits any increase and in some case lowers the standing charge terms of the DOC. This also has a beneficial impact on the landing fees and flight deck crew costs, as well as maintenance costs, although maintenance of the suction system increases the airframe maintenance. Lower mass will also reduce the engine thrust requirements, and hence the engine purchase maintenance costs.

The optimum configuration of all aircraft types, with and without laminar flow, changed in a similar manner as fuel price varied, due to a trade-off between fuel mass and airframe mass. At low fuel prices, aerodynamic efficiency is of relatively low importance relative to structural efficiency and its effects on the airframe production and maintenance costs. This generally resulted in a relatively low aspect ratio and hence a low wing mass with higher lift-dependent drag and hence reduced lift/drag ratio. The higher fuel burn associated with such planforms has only a small effect on the DOC due to the low fuel price, although this is limited due to fuel mass considerations that may necessitate a larger wing and more powerful engines to meet the performance requirements.

The optimum wing aspect ratio increased with fuel price, as fuel costs became more important in the DOC, to reduce lift-dependent drag and thus increase lift/drag ratio. However, increasing aspect ratio results in heavier wing-box mass, and hence

However, increasing aspect ratio results in heavier wing-box mass, and hence increased airframe production costs, although lower fuel burn may allow a smaller wing limiting the increase in structural mass. Reduced aircraft mass will allow smaller engines to be used, providing further benefits. For both laminar and turbulent configurations of the *regional jet*, *short- and medium-range twin*, increasing fuel price caused marginally reducing trends for the maximum take-off mass with negligible changes to the wing area. For the *long range quad* and *super-jumbo* similar trends were observed, although they were more pronounced, due to increased fuel fractions.

Typically a fixed fuel price is assumed for an optimisation study. However, the actual price paid by an airline can vary greatly in different locations at any time, and during the 20-25 year service life of an aircraft. To assess the impact of fuel price variation, the DOC was evaluated for laminar and turbulent configurations optimised for a fuel price of £0.19 per kilogram, for a range of fuel prices from £0.05-£0.40 per kg. The results of this study are shown in Figure 49.

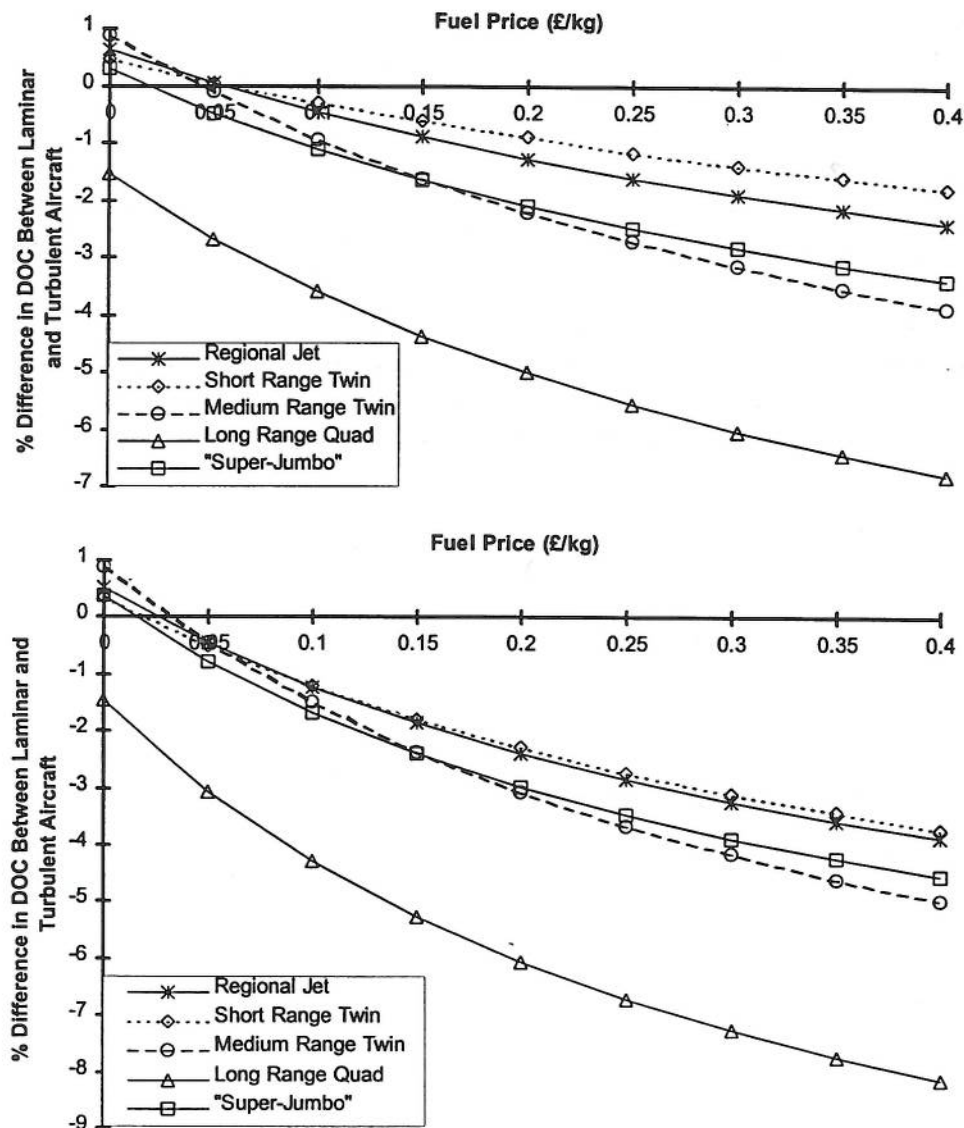


Figure 49: Impact of Fuel Price in DOC for Aircraft Optimised for Fuel Price of £0.19/kg

The trends observed in the figure above appear very similar to those in Figure 48, although the benefits were marginally less for all aircraft at all fuel prices due to configuration optimisation at each fuel price. Obviously, the two sets of results coincide at £0.19 per kg, for which the aircraft in Figure 49 is optimised.

6.3.2.2 Fuel Reserves

Laminar flow can be lost permanently during cruise, through system failure, or temporarily, through cloud encounter, see Appendix A.1.2.3. The ensuing higher drag will require greater thrust, and hence increased fuel burn to maintain speed and altitude. It is likely that operational regulations will require some amount of fuel reserves to be carried to ensure that the aircraft safety is never jeopardised and that it is capable of reaching its destination, rather than diverting, in all but the most severe cases.

It is unclear what degree of additional fuel reserves will be required for laminar flow aircraft, although the issue is discussed in detail in section 4. Therefore the five aircraft types were optimised for the project studies assuming that laminar flow was uninterrupted and hence no additional fuel reserves are considered. To assess the impact of additional fuel requirements for partial loss of laminar flow, the aircraft were optimised assuming that laminar flow was not possible for 33%, 67% and 100% of the cruise sector. This represents the worst situation in each case, where additional fuel reserves are carried and used. In practise, the DOC penalties would be somewhat smaller and in most cases would be carried but not used. The loss of laminar flow was assumed to be distributed throughout the entire cruise although concentration at either end of the mission will distort the results. The resulting DOC for each case was compared with the turbulent DOC for the corresponding mission, with the net percentage change presented in Figure 50.

Average Mission

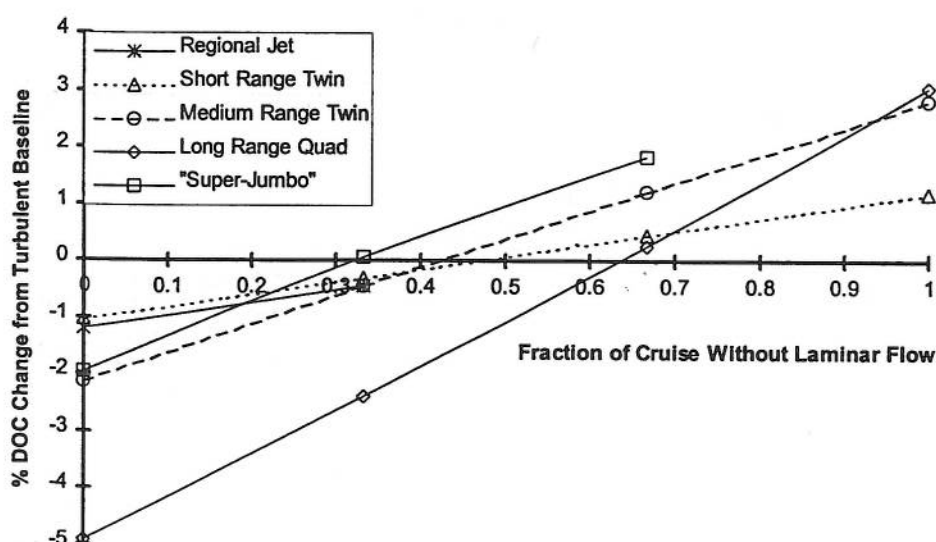


Figure 50: Impact of Losing Laminar Flow During Cruise.

Design Mission

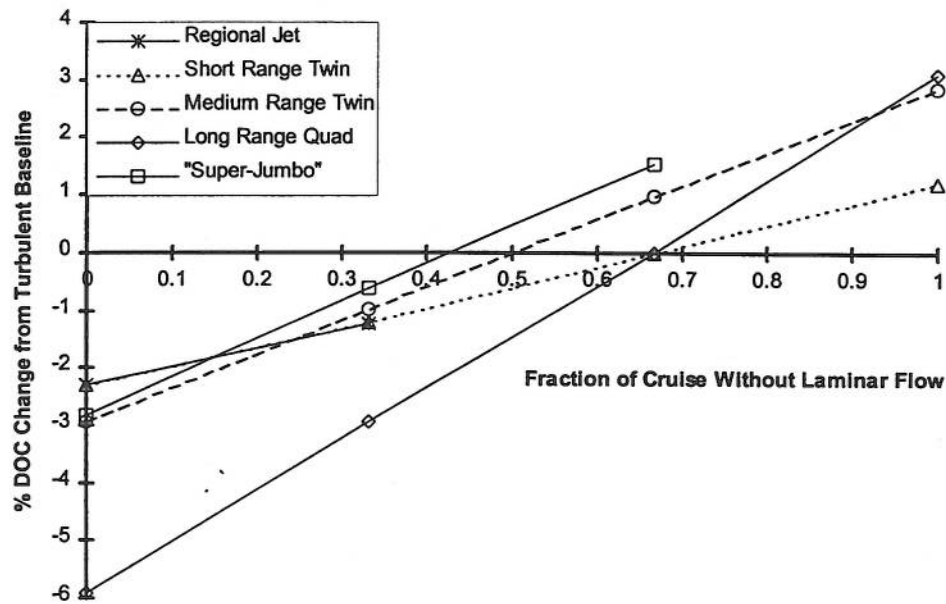


Figure 50: Impact of Losing Laminar Flow During Cruise.

Not surprisingly, for all cases on both missions, the DOC benefits were reduced as the portion of cruise without laminar flow was increased. The fuel load required also increased, requiring a larger heavier wing. This all increases the aircraft maximum take-off mass and suction system related costs and mass, and hence the DOC until, in all cases, it is greater than the turbulent equivalent resulting, resulting in a net penalty.

The results show that the *regional jet* and *short range twin* were the least sensitive, due to the lowest fuel fractions, while the *long range quad* and *super-jumbo* with the highest fuel fractions, are the most sensitive. The marginally reduced sensitivity of the *super-jumbo*, relative to the *long range quad*, is due to the lower drag reductions for the larger aircraft. In addition, the sensitivity is higher, in all cases, for the design missions where the fuel fraction is greater than that for the average mission.

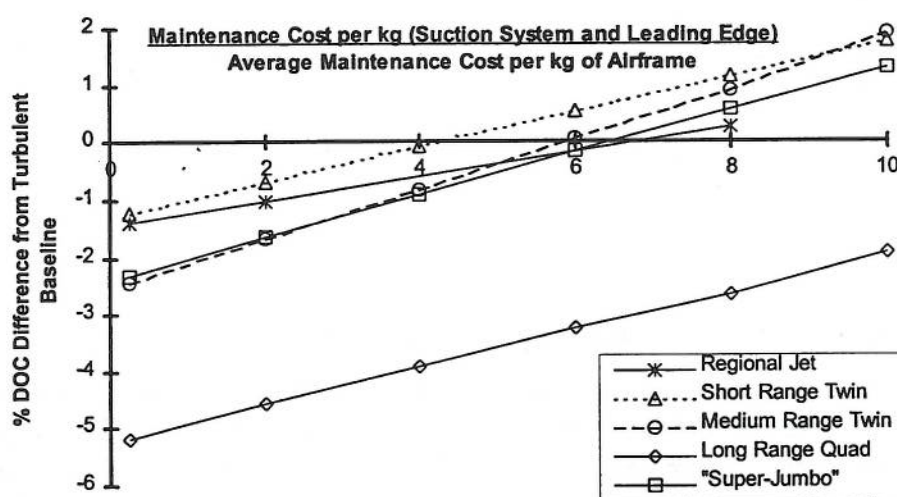
As the percentage of cruise flown without laminar flow is increased the fuel required to complete the average and design mission increases as the mean profile drag coefficient increases towards the turbulent values. This increases the aircraft take-off masses requiring larger wings (increased wing loading) and engines. The aspect ratio reduces as the percentage of cruise without laminar flow increases to allow greater fuel volume for a given wing area.

6.3.2.3 Maintenance Costs

Within the design synthesis, the airframe (structure, systems and furnishings) maintenance costs are calculated collectively as a function of stage length, airframe mass, production cost, labour rate, financial burden and a cost coefficient. The HLFC system maintenance costs are considered as apart of the airframe.

However, it is unclear how the maintenance costs of the HLFC suction system, per unit mass and per unit production cost, will compare to the average values for the rest of the airframe. Therefore, a factor was introduced into the design synthesis to increase the maintenance costs of the HLFC suction system and leading edge structure relative to the average values for the rest of the airframe (Appendix C.1.6). The maintenance costs were altered using factors ranging from 0.25 thorough to 10 relative to the airframe average (where 1 represents the value used in design studies), with the resulting impact on the net DOC benefits shown in Figure 51.

Average Mission



Design Mission

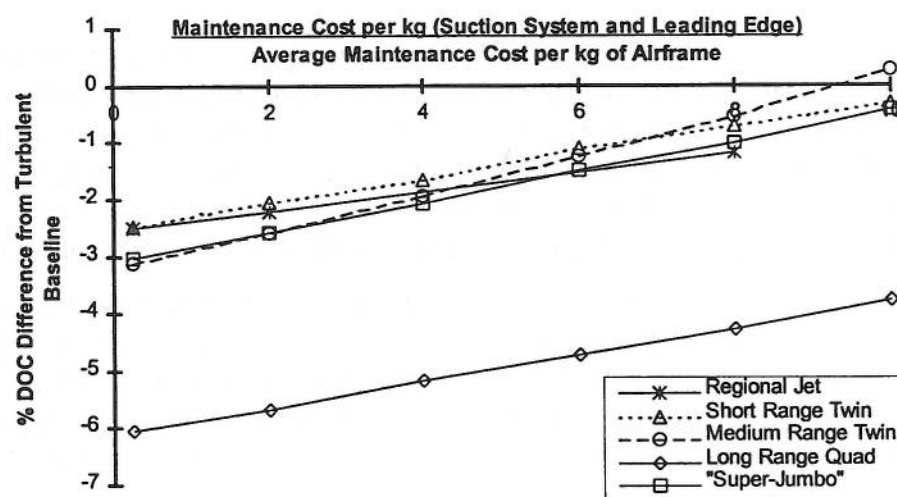


Figure 51: Impact of HLFC Suction System and Leading Edge Maintenance Costs

As expected, as the maintenance costs of the HLFC suction system and wing leading edge structure were increased, the DOC benefits reduced in all cases. The sensitivity of the DOC to increases in maintenance costs is greater, for all aircraft types, for the design mission. However, for both the design and average missions, the sensitivity does not vary much between aircraft types.

No significant trends in configurational change are evident as the maintenance cost factor increases, although at the highest values there were small changes, namely reduced HLFC system mass through smaller wing areas, lower take-off mass and reduced aspect ratio.

6.3.2.4 System Purchase Costs

The productions cost per unit mass of the HLFC suction system have been assumed to the same as the average value used for the rest of the airframe systems within the above design studies. However, it remains unclear what the production costs of HLFC systems are likely to be. As for maintenance costs, a factor has been introduced to allow the cost per unit mass of the HLFC suction system to be changed relative to the rest of the systems (Appendix C.1.6). Factors ranging from 0.25 through to 10 were used to investigate their effect on the net DOC benefit. Results from this are shown in Figure 52 overleaf.

For all aircraft considered, the DOC benefits reduced as the system production costs were increased. Although all DOC benefits are greater for the design mission, although if the plots for each aircraft on average and design missions are compared, the sensitivity is similar.

If the results for difference aircraft types are compared, the least sensitive is the *short range twin*, the most sensitive being the *medium range twin* and *super jumbo*. The differences in sensitivity are a primarily a function of the mass of the HLFC suction system relative to the aircraft empty mass. Clearly the more powerful suction systems of the bigger aircraft will represent a greater proportion of the empty mass, Figure 44, which results in a greater sensitivity to changes in the HLFC system production costs.

As the HLFC system production cost was increased, the optimum configurations showed a trend towards reduced HLFC system mass for all aircraft types. This was achieved through lower aspect ratios, reduced thickness/chord ratios resulting in lower leading edge sweep to reduce suction requirements, and slightly reduced wing area. These factors reduce the suction system mass and hence limit the impact of higher production costs. Maximum take-off mass increased slightly due to increases in fuel burn outweighing structure and HLFC system mass reductions.

For four of the aircraft types on the average mission, a threefold increase in the HLFC suction system production cost removed all DOC benefit. For *medium range twin* and *super jumbo* operating over the design mission, the cross-over between a net DOC benefit and penalty occurred when the production costs were increased by a factor of four. For the *short-range twin* this value was closer to seven. For the *long range quad*, this point does not occur until the production costs were increased by a factor of more than seven, primarily due to the large DOC benefits at low values. In all cases, further increments resulted in ever increasing DOC penalties.

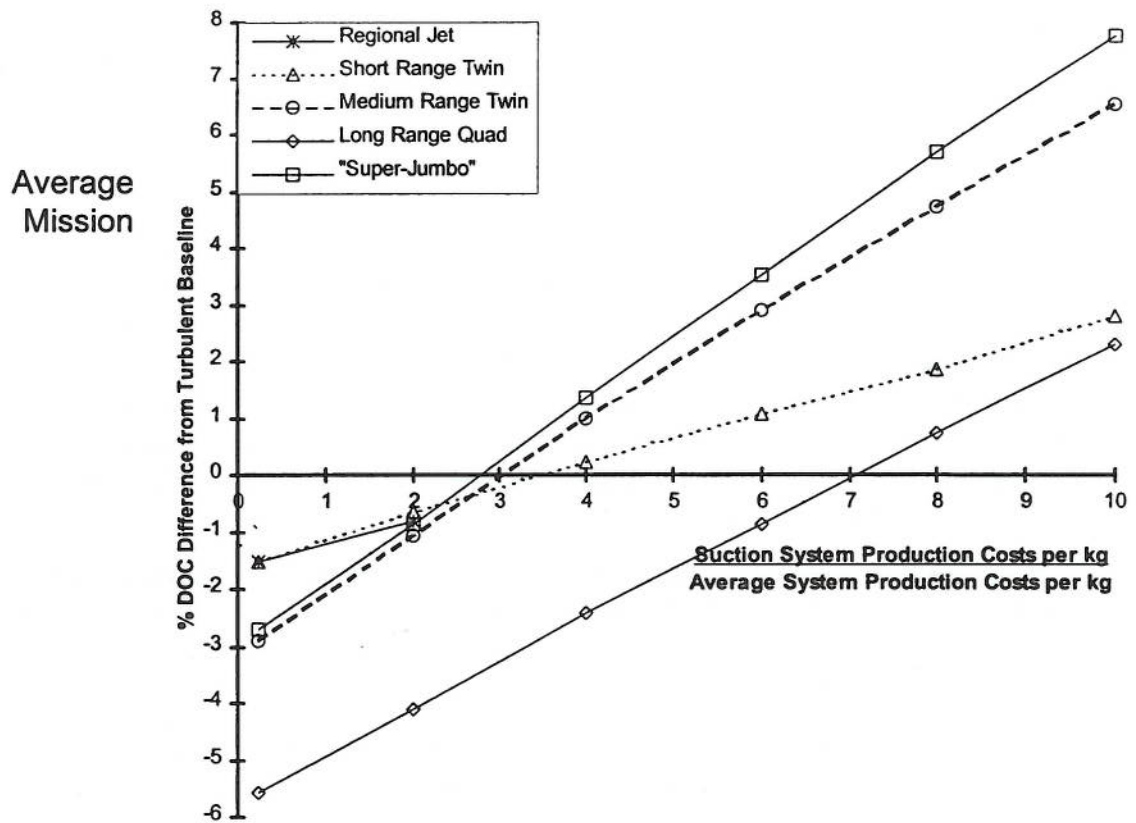
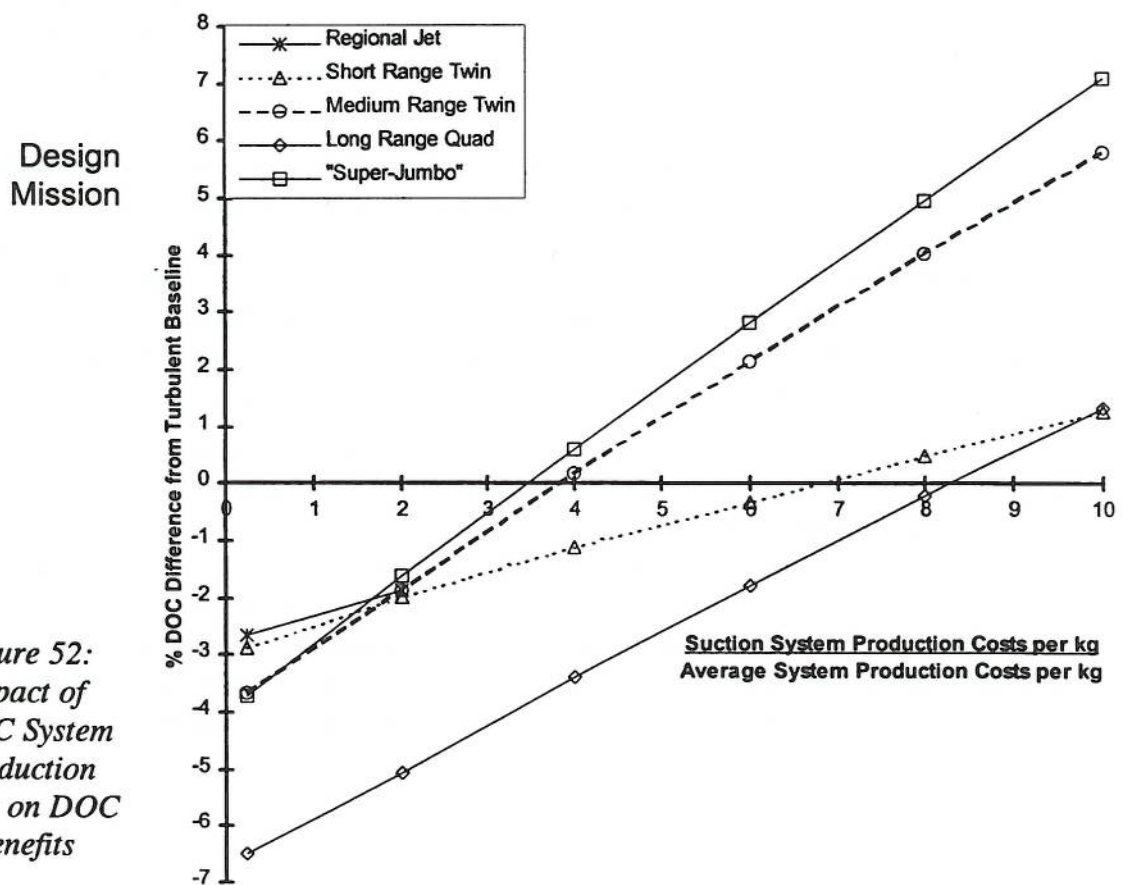


Figure 52:
Impact of
HLFC System
Production
Costs on DOC
Benefits

7. DISCUSSION

7.1 Design Synthesis

All results presented in the studies in Chapter 6 have been generated using the transport aircraft design synthesis, supplied by DRA, modified to consider the introduction of laminar flow technology to wing, empennage and nacelle surfaces. Where required, optimum solutions were achieved in the majority of cases on the first use of the design synthesis. In a few other cases the design synthesis either failed to converge to an optimum solution or converged to a “false optimum” - the optimisation code showed convergence but the resulting DOC was not at a global minimum value. A convergence notice included in each results file notifies the user if the optimisation code fails to converge. “False optimum” solutions in the sensitivity studies, section 6.3.2, were evident from discontinuities in the plots. In the project studies, section 6.3.1, “false optimum” solutions were detected either by inspecting the resulting configurations, or cross-referencing all results with the corresponding plots in the sensitivity studies.

In such cases, the design synthesis was re-run with changes made to the starting values of the independent variables. In almost all cases, this resulted in satisfactory optimum solutions, whilst others required further changes to the independent variables and additional runs before satisfactory optimum solutions were found.

The design synthesis was also used to evaluate the HLFC system mass and DOC for the derivative applications, although only the results from the first run of the design synthesis were used with the independent variables set to represent the optimum turbulent configuration.

Throughout the study, the design synthesis proved to be very robust. Only a small number of minor problems were observed which were corrected as they arose, with any affected cases repeated.

7.2 Project Studies

7.2.1 Derivative / Optimised Configurations

When considering a new payload/range combination, an aircraft manufacturer can select a derivative of an existing aircraft or develop a new aircraft type optimised for the mission in question. The derivative configurations offer an increased range capability, which may be desirable to some operators. However, the DOC benefits for the derivative HLFC wing and nacelle cases, were substantially less than those for the optimised configurations on both the baseline average and design missions. Although the HLFC configurations were optimised for the baseline average mission, they were required to be able to complete the baseline design missions. The lower fuel burn associated with HLFC reduced the maximum take-off mass required to complete the design mission, allowing a smaller wing to be used, which in turn further reduced the maximum take-off mass. The HLFC suction system represents

additional mass, although for all but the shortest range aircraft this was significantly less than the fuel mass reduction.

For the derivative configurations, the profile drag was significantly reduced, with only minor reductions to the lift-dependent drag due to a lighter fuel load, which moves the balance between the two away from the aerodynamic optimum. When the configurations were optimised to include HLFC, the most significant difference in the drag reductions was the larger reductions in lift-dependent drag. The profile drag reductions were similar for both derivative and optimised configurations, with marginal improvements for the latter due to reduced size. This all provides a greater total aircraft drag reduction for no further increase in HLFC system mass and cost.

The results shown for derivative applications are valid for aircraft optimised for turbulent with HLFC introduced subsequently. As discussed in section 6.3.1.1, it should be noted that the DOC method used within this study may be pessimistic when applied to derivative configurations. As the only difference between the derivative turbulent baseline airframe is the addition of the HLFC suction system, the production cost of the derivative aircraft is increased by the production cost of the suction system. This increased the standing charges term in the DOC which countered much of the fuel cost savings.

However, the principal advantage of derivative aircraft, namely the relatively low development costs which may limit any increase in aircraft production cost, thus improving the net DOC benefit. There may also be additional maintenance and crew cost benefits due to very high levels of commonality with the turbulent baseline. As the wing and engines are sized for the turbulent design mission, the reduced fuel load will allow the aircraft to reach a higher cruise altitude and possibly achieve further fuel savings.

7.2.2 Aircraft types

For both derivative and optimised configurations, there were significant differences in the net DOC benefits between the five aircraft types. Generally, increased benefits were observed as the average and design mission length increased, due to the increasing importance of the fuel costs in the total DOC. This was not true for the *regional jet* as the specific fuel consumption used in this model is significantly higher than that for the other aircraft types.

The extent of laminar flow can be limited either by the transition Reynolds number (constant physical distance from the leading edge) or the adverse pressure gradients associated with the shock at the rear end of the pressure rooftop (constant percentage chord). The furthest forward of these at any location was assumed to be the aft limit of the laminar flow. On relatively small surfaces, such as fin, tailplane and nacelles, the extent of laminar flow was assumed to be limited by the rear end of the pressure rooftop for all aircraft types. Therefore aircraft speed had no effect on the extent of laminar flow, although increased speed resulted in higher suction velocities and hence increased power requirements.

For wing surfaces, a comparison was made across the span between the transition Reynolds number and the position of the rear end of the rooftop (see Figure 22

section 5.2.1.1). A maximum transition Reynolds number of 25 million was assumed for the HLFC studies and the rear end of the pressure rooftop was taken to be in the region of 50-60% chord. For the optimised *regional jet* and *short range twin* the laminar flow was limited by the rear end of the rooftop across the entire span due to their small size. For the other three larger optimised aircraft, the laminar flow on the inboard wing was limited by the maximum transition Reynolds number, and by the end of the rooftop on the outboard sections. The cross-over between the two occurs at 32.3% semi-span for the *medium range twin*, 52.8% semi-span for the *long range quad* and at 80.6% semi-span for the *super-jumbo*.

At the wing-fuselage junction, laminar flow was achieved up to 48.6% chord on the *medium range twin*, 39.2% chord on the *long range quad*, and only 25.9% on the *super jumbo*. Therefore the average extent of laminar flow on these aircraft is reduced. Although the *medium range twin* and the *long range quad* have the same cruise Mach number and are similar in size, the increased extent of laminar flow at the root of the former is due to its higher aspect ratio. For a given wing area, this shortens the chord, thus reducing the chord Reynolds number across the span. This increases the proportion of laminar flow on the inboard wing and hence the average extent of laminar flow.

The reduced extent of laminar flow for the *super jumbo* is due principally its larger physical size, although its aspect ratio is also relatively low. This reduced extent of laminar flow is the primary reason for the reduced DOC benefits for the HLFC wing on this aircraft type relative to the *long range quad* despite both aircraft having similar design and average mission stage lengths. However, when the extent of laminar flow was set to a similar for both aircraft, the net DOC benefit for the *super jumbo* was only marginally less. This remaining difference is due to greater suction system requirements resulting from the increased chord Reynolds numbers, increased Mach number and leading edge sweep.

This implies that long range aircraft would benefit most from HLFC as the importance of fuel costs increases with stage length. However, for aircraft as large as the *super jumbo* the large chord Reynolds number will substantially reduce the extent of laminar flow in the inboard wing area, limiting the drag savings, and hence the DOC benefits.

7.3 Comparison With Other Studies

Where possible, it is important to compare the results from this study with those performed by other organisations, particularly as data from these has been extensively used within this study. However, such comparisons are difficult in many cases as a full set of the assumptions used were not available. Furthermore, the design requirements were often different from those used in this study.

7.3.1 Deutsche Airbus Study [121]

A Deutsche Airbus study considered the impact of two HLFC applications on a medium range 200 seat twin and a long range 300 seat quad, defined as the MR200 and LR300 respectively [121]. HLFC was considered on the wing upper surface to 60% chord (defined as Mod.1) and a combined application with laminar flow to 60%

and 40% on the wing upper and lower surface respectively, in addition to 50% on the engine nacelles (Mod. 2).

Both aircraft types were considered with both HLFC applications in “retro-fit” (derivative) configurations and with the Mod. 2 HLFC application on “re-sized” configurations which retained the baseline design range. The impact on the DOC was assessed for the “retro-fit” MR200 and LR300 on typical missions, 2,000nm and 3,000nm, respectively. For the Mod.1 cases DOC penalties were observed for both aircraft although it was smaller for the long range aircraft. For the MR200 with Mod.2 there was a DOC penalty while a marginal benefit was achieved by the LR300.

These results show that the DOC benefit is increased, or the penalty reduced, for the longer range aircraft, following the trend observed within the design studies, sections 6.3.1.1.1 and 6.3.1.1.2. This was due to the increasing importance of fuel costs in the total DOC increases with mission length.

Both configurations were re-sized assuming constant wing loading, tail/fin volume and thrust/weight ratio. The engines were re-rated to ensure they were suitable for the smaller aircraft. It appears that the wing planform was scaled, not re-optimised, thus retaining the original aspect ratio. DOC benefits were achieved for both aircraft types, although once more the benefits were greater for the longer range LR300. This agrees with the trend observed in the design studies, section 6.3.1.2.1, that “re-sizing” or optimising an aircraft design results in increased benefits. It should be noted, however, that the assumptions used to “re-size” the MR200 and LR300 are more limited than the full optimisation used in the design studies.

The similarity between the turbulent baseline LR300 and the *long range* quad permits a comparisons to be made for the HLFC upper wing surface (Mod.1) case. Both studies considered retro-fit or derivative cases from which a number of comparisons for the design mission could be made, Figure 53.

	<i>Long Range Quad</i>	LR300
Total Drag Reduction	10.5%	4.1%
Block Fuel Reduction- Design Range	9.4%	3.7%
Empty Mass Increase	1042kg	1340kg
Suction Volume Flow	14.2m ³	6.8m ³
Total Suction Power	297kW	150kW (200hp)
SFC Penalty	+0.456%	+0.3%
Direct Maintenance Costs	+1.8%	+1.2%
Aircraft Price	+\$2.4 million	+\$1.6 million

Figure 53: Comparison of Long Range Quad and LR300

The most important difference between the results is for the total drag reduction, which for the *long range quad* is greater by a factor of approximately 2.5. The assumptions used to define the drag reduction for the LR300 are unclear, in particular the split between the upper and lower surface profile drag. For the *long range quad*, the upper surface was assumed to be responsible for two-thirds of the profile drag. There is some evidence that this assumption was not used for the LR300, as introducing laminar flow to 40% on the lower wing surface and to 50% of the nacelle

length increased the drag benefit from 4.1% to over 11%. This suggests that despite the reduced extent of laminar flow, its contribution to the drag reduction is at least equal to that of the upper surface. It also appears that no account is taken of lift-dependent drag reductions for the LR300, which accounts for approximately 25% of the *long range quad* total drag reduction, 6.3.1.1.1. If the *long range quad* is considered without the lift-dependent drag reduction and for an equal split between upper and lower surface profile drag, its drag reduction is reduced to approximately 6.5%. Furthermore, if the form factor reduction for the *long range quad* is also removed, the resulting drag reduction will be similar in magnitude to that for the LR300.

Despite the larger drag reduction for the *long range quad*, the SFC, maintenance costs and aircraft price penalties were all significantly greater. These counteract much of the greater drag and fuel reductions.

Reduced suction system mass for the *long range quad* is due to this aircraft's smaller wing area and reduced leading edge sweep. When the wing area of the *long range quad* is fixed to that of the LR300, the calculated suction system mass was very similar, see Figure 25 in section 5.5.

The potential maximum range for the derivative (retro-fit) LR300 was calculated to increase by 446km (240nm), which for a stage length of 12446km (6700nm) represents a 3.6% increment, although it is not clear whether the baseline maximum take-off mass is retained, or whether it has been increased to include the suction system mass and retain the fuel load. For the *long range quad* the maximum range capability was increased by 7.5% where the baseline maximum take-off mass was retained - the fuel load was reduced by the mass of the suction system. In both cases, the increase was somewhat less than the drag reduction as the suction system mass increases the aircraft empty mass countering some of the fuel mass savings.

The impact of HLFC on the capital, maintenance and fuel cost DOC terms for the LR300 were presented in [121], along with the effect on the total DOC. A comparison of these terms with corresponding data for the *long range quad* is shown in Figure 54 for a typical 3,000nm mission. Note that this figure shows the percentage change in the individual DOC terms and should not be confused with the data presented in Figure 35 which shows the percentage changes in the total DOC.

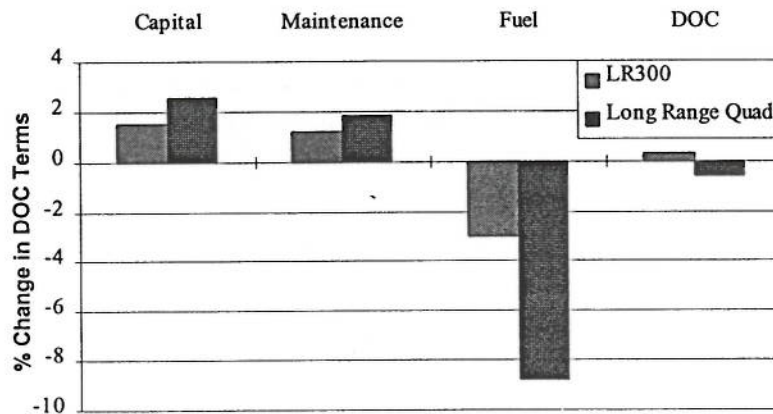


Figure 54: Comparison of DOC Changes for a 3,000nm mission

For both aircraft, the capital and maintenance terms increased due to the introduction of the HLFC system, whereas the fuel cost terms are decreased due to reduced drag. The substantial difference in the fuel cost benefits is due directly to the increased drag reduction for the *long range quad*. Conversely for this aircraft, the capital and maintenance cost penalties are greater. This suggests that the assumptions used for these terms were more severe than those used for the LR300, particularly as the suction system mass is more than 20% less for the *long range quad*. The reduced suction system mass is due to a smaller wing area and reduced leading edge sweep on the latter.

The net DOC change for both aircraft was very small ($<1\%$). However, for the LR300 the introduction of an HLFC upper surface caused a DOC penalty whereas a small benefit was observed for the *long range quad*. This is principally due to the greater drag reductions for the latter aircraft. Other DOC terms used for the *long range quad*, namely crew costs and landing fees, are not included as they were unchanged. Whether these are included in the total DOC for the LR300 calculations is unclear, although they probably are, as they are included in most DOC methods.

7.3.2 NASA Study [2]

A NASA study considered a long range 300 seat twin-engine aircraft [2] with HLFC applied to the wing upper surface, and on both surfaces of the fin and tailplane. A turbulent baseline was defined from which the aircraft was re-sized based on three sets of assumptions.

The first two of these, termed HLFC-1 and HLFC-2, considered laminar flow throughout the cruise phase of flight with suction system mass and cost penalties only included in the second case. These are represented by a fixed suction system mass of 1,361kg (3,000lb) costing \$1.3 million and an increase in airframe maintenance of about 2.8% (corresponds to a 0.6% increase in total maintenance costs). The suction system was assumed to require 224kW (300hp) power off-take resulting in an 0.3% increase in specific fuel consumption.

For both cases, failure of the suction system would result in diversion to an alternative airport for refuelling or use reserve fuel to complete the mission. A third case, HLFC-3, sized the aircraft to include the suction system mass and cost penalties and to carry sufficient fuel reserves to complete its design mission subsequent to failure of the suction system at the beginning of cruise without using any reserves.

The aircraft were re-sized to retain the 6,500nm design range of the turbulent baseline, with constant wing loading and thrust/weight ratio. The wing aspect ratio, quarter chord sweep and taper ratio for the turbulent aircraft is retained for all HLFC configurations.

The HLFC-1 configuration, which achieved the greatest benefits, achieved a block fuel reduction by 16.84% on a 6,500nm mission. As the mass penalties or fuel reserves are not included in this configuration, the drag reduction will be closely related to the block fuel reduction, although this will be partially reduced because of a smaller aircraft. The drag reduction will be due entirely to profile drag as the

principal factors, wing-loading and aspect ratio, in the lift-dependent drag are unaltered.

The drag reduction for the HLFC-1 case is close to the cumulative profile drag reductions of the individual HLFC wing, fin and tailplane cases for the optimised configurations, Figure 41. These were approximately 10% for the HLFC wing, 2% for the fin, and 3-4% for the tailplane. However, the total drag reductions for the *medium range twin* and *long range quad* will be greater as the lift-dependent drag is also reduced due to lower wing loading and increased aspect ratio.

For the more realistic HLFC-2, the block fuel saving is reduced to 15.14% due to the suction system mass and specific fuel consumption penalty. The wing area, maximum take-off mass and engine thrust are reduced by just over 8%, and aircraft cost by approximately 2%. For a 3,000nm mission, with a fuel price equivalent to £0.19 per kilogramme (85-90c per USG), the DOC is reduced by approximately 9%. Comparison with the optimised *long range quad* which for the 3,000nm mission achieved a 5% DOC reduction for the HLFC wing, 1% for the HLFC fin and 2% for the HLFC tailplane. This combined total of 8% is slightly less than that for the HLFC-2 configuration. This is possibly due to a greater combined HLFC system mass 1787kg for the *long range quad* resulting in a system cost in excess of \$2.3 million. Thus, it appears that the cost and mass assumptions used in this study appear to be conservative, at least relative to the NASA study [2].

Limited comparisons can be made between the HLFC-3 case and the *long range quad* configuration considered in the fuel reserves sensitivity study, section 6.3.2.2, in particular where the aircraft was optimised to fly the entire mission without laminar flow, despite carrying an HLFC suction system. Both configurations are sized to carry enough fuel to perform the entire mission without laminar flow. The effect on the maximum take-off mass, wing area and sea-level static thrust, relative to the turbulent baseline, is shown in Figure 55.

	<i>Long Range Quad</i>	HLFC-3
Δ Maximum Take-Off Mass	+2.5%	+2.15
Δ Wing Area	+3.5%	+2.15
Δ SLS Thrust per Engine	+2.5%	+2.15

Figure 55: Comparison of HLFC-3 with Long Range Quad (Maximum Fuel Reserves)

All three parameters for the HLFC-3 were increased by the same amount due to fixed wing loading and thrust/weight ratio. The same trends were observed for the *long range quad* although somewhat greater, due to higher suction system mass and cost penalties.

The HLFC-3 design showed that DOC benefits were possible, although marginal for a wide range of fuel prices. It is not possible to compare the DOC benefits of the two aircraft due to a fundamental difference in the assumptions. This is that for the *long range quad*, the additional fuel reserves are assumed to be used during cruise whereas the HLFC-3 design is assumed complete the mission with all the additional fuel reserves remaining. This will result in lower fuel costs, relative to the *long range quad*, although it is likely that the aircraft maximum landing mass will be increased.

This will require an increased approach speed, more powerful high-lift system or increased wing area, all of which would increase aircraft empty mass.

7.3.3 Boeing Study [21]

Boeing studied the implications of retro-fitting HLFC to the wing, fin and tailplane of a 757-200 aircraft. This does not closely match any of the aircraft types included in this study, preventing any direct comparisons. However, the reductions in profile drag associated with the various HLFC applications are provided. These are compared with the corresponding drag reductions for the derivative *short range twin* aircraft with an HLFC upper wing surface and the optimised HLFC fin and tailplane configurations operating on its design mission.

	Reduction in Profile Drag of Individual Surface		Reduction in Total Profile Drag		Reduction in Total Aircraft Drag (assuming turbulent profile drag is approximately half of the total)	
	757	SR Twin	757	SR Twin	757	SR Twin
Wing Upper Surface	35.5%	29.1%	13.0%	12.5%	6.50%	6.9%
Wing Lower Surface	17.5%	--	6.5%	--	3.25%	--
Fin (Both Surfaces)	39.2%	47.2%	2.7%	3.4%	1.35%	1.9%
Tailplane (Both Surfaces)	44.4%	41.3%	4.3%	3.0%	2.15%	1.7%

Figure 56: Comparison of HLFC Drag Benefits for 757 and Short Range Twin

Although the 757 was larger than the *short range twin* the magnitude of the drag reductions of the two aircraft were similar in all cases. It is noticeable that the drag reduction for the upper surface is twice that for the lower surface despite similar extents of laminar flow on both surfaces. This suggests that the upper surface was assumed to be responsible for 2/3 of the total wing drag, agreeing with the assumption used for this study. The block fuel for the 757 aircraft was reduced by 8.2% on a 2128nm mission with HLFC applied to the upper and lower wing surfaces, as well as on both fin and tailplane surfaces.

7.4 Sensitivity Studies

The sensitivity of the DOC to variation in fuel price and the amount of fuel reserves loaded has been investigated in addition to the effect of increased suction system maintenance and production costs. Satisfactory results were achieved for the majority of the cases without the need to repeat cases, despite the wide ranging issues addressed.

The sensitivity of the optimum DOC was investigated for a range of fuel prices ranging from £0.05-£0.40 per kilogramme (\$0.25-\$2.00 per USG). For all aircraft types, DOC benefits were observed for even the lowest fuel prices on both average and design missions. In such cases the fuel cost savings are minimal compared to

reductions in aircraft finance charges resulting from decreased aircraft price associated with the smaller aircraft. As fuel prices were increased, greater fuel costs savings add to the benefits associated with finance charges.

In operation, laminar flow will not be achievable at all times during cruise, due to cloud encounter and surface imperfections. The sensitivity of the optimum aircraft configuration and DOC to variation in the percentage of cruise flown without laminar flow was investigated. For all aircraft types, on both average and design missions, the net DOC benefits were seen to reduce significantly as the percentage of cruise flown turbulent was increased. Net penalties were observed in all cases where aircraft were optimised to fly the mission without laminar flow for more than 60% of the mission. Long range aircraft were seen to be more sensitive as the fuel fraction is greater.

The maintenance costs per unit mass of the HLFC suction system and the modified leading edge structure were initially assumed to be the same as the rest of the airframe. However, the likely impact of these factors is still not clear. Therefore, the suction system maintenance and purchase costs per unit mass were factored relative to the value used for the rest of the airframe. The DOC was observed to be substantially more sensitive to increases in purchase costs than maintenance costs. The larger aircraft were more sensitive to increases in purchase costs as the suction system mass represented a greater proportion of the aircraft empty mass, due to increased suction requirements resulting from higher Reynolds numbers.

8. CONCLUSIONS

A methodology (described in section 5) has been developed to model the direct implications of introducing Natural Laminar Flow (NLF) or Hybrid Laminar Flow Control (HLFC) to subsonic transport aircraft. For both, the benefit associated with reduced profile drag is determined as a function of the aircraft configuration and cruise conditions, as are the suction system mass, purchase cost, maintenance cost and specific fuel consumption penalty associated with HLFC only.

The algorithms and mathematical relationships developed were based on the results of an extensive survey of published literature (presented in section 3) which defined the current state of the art in laminar flow technology.

The methodology was introduced into an existing numerical design synthesis for subsonic transport aircraft, supplied by the DRA. This permitted the indirect implications, namely aircraft re-sizing and configurational changes, to be assessed, as well as the 'snowballing' effects.

Design synthesis codes can never be truly regarded as finished as the methods can be improved as results from current and future research activities become available. However, they can be developed to a point where it can be used to conduct studies whose results reflect the current level of understanding. As such, the modified design synthesis was used to perform a number of studies considering the impact of laminar flow technology. These also provided an opportunity to check and validate the modified design synthesis.

Studies were performed to investigate the potential impact of HLFC on five aircraft types, ranging from a 100 seat regional jet to a long range 600 seat *super jumbo*. The principal conclusions from these studies were:

Turbulent baseline aircraft

- Five optimised turbulent baseline aircraft were generated using the design synthesis demonstrating its original capabilities had been retained. These represented a wide range of payload range capabilities, namely a *regional jet*, *short range twin*, *medium range twin*, *long range quad* and a *super jumbo*.

Minimum change derivative

- Increased range capabilities were observed for minimum change derivatives of all five aircraft types with three HLFC applications, wing upper surface, nacelles, and a combined fin, tailplane and nacelle case.
- Small (<2%) DOC benefits were achieved for the medium and long range aircraft with all three HLFC applications. Only marginal DOC benefits were achieved for the shorter range and *super jumbo* aircraft and in some cases a small penalty resulted. However, the DOC methods used may be conservative for assessing minimum change derivatives as development costs are likely to be less than for a new aircraft type.
- The DOC benefits were greater for the HLFC upper wing relative to the nacelle cases. The benefits for the combined fin, tailplane and nacelle were on a par with the wing case and some cases greater.

Optimised configurations

- For the optimised configurations, the DOC benefits were seen to be at least double, and in some cases triple those for the minimum change derivative. As the optimised configurations retained the turbulent baseline design mission length, no range increases were considered.
- The greatest benefits for an individual surface were for the HLFC upper wing case. These were typically more than two and a half times greater than either of the fin, tailplane or nacelle cases. A combined wing, fin, tailplane and nacelle case demonstrated even larger benefits, increased by a factor of at least 1.5 relative to the wing case.
- Substantial differences were observed between aircraft types on both minimum change derivative and optimised configurations. Generally, the benefits increased with the design and average mission stage length, primarily due to the increasing importance of fuel costs in the total DOC. This, however, is not true for the HLFC wing *super jumbo* which achieved less than half of the DOC of the *long range quad* despite having a similar design stage length. This is due to Reynolds number limits reducing the extent of laminar flow (expressed as percentage chord) on the larger aircraft.

Sensitivity studies

- Increasing the fuel price used for optimisation of both HLFC and turbulent was seen to increase net benefit of the laminar aircraft. The reduced fuel load for the HLFC configuration makes it less sensitive to changes in the fuel price. The aspect ratio on both laminar and turbulent optimum configurations was seen to increase, and wing loading decrease, with fuel price. This is due to the aerodynamic efficiency becoming more important, as drag reductions have a greater beneficial impact on the DOC.
- The project studies assumed that laminar flow was achievable uninterrupted throughout the cruise sector. However, cloud encounter and surface defects will typically result in localised permanent and global temporary losses of laminar flow. Therefore the five HLFC wing aircraft types were optimised with varying degrees of the cruise sector assumed to be flown without laminar flow. This required additional fuel to ensure that the design mission could be completed with some loss of laminar flow. This resulted substantial reductions in the net DOC benefit. For most aircraft types, DOC penalties were observed where laminar flow was assumed to be possible for less than 40% of cruise. The longer range aircraft were seen to be more sensitive due to the high fuel fraction for these aircraft.
- The DOC benefits were seen to be substantially more sensitive to changes to the HLFC suction system production costs than maintenance costs. Again, the longer range aircraft were more sensitive, due to increased suction system mass and power requirements.

These results show that HLFC applied to the wing, fin, tailplane or nacelle of a wide range of aircraft types can achieve DOC benefits. However, for practical applications the magnitude of these benefits will be eroded due to a number of factors. In

particular, airlines, and possibly certification authorities, would require that some degree of redundancy is incorporated to permit uninterrupted operation of the HLFC system subsequent to the failure of a suction unit. This results in increased suction system mass and production cost penalties.

In the operational environment, local losses of laminar flow will occur due to surface mismatches and accumulated impact damage to the airframe surfaces between maintenance visits. These factors will induce turbulent wedges to form, reducing the mean extent of laminar flow on the surface, thus limiting the block fuel reductions relative to those observed within this study. Furthermore, temporary, but total, losses of laminar flow associated with cloud encounter will increase the profile drag coefficients while the condition persists, again reducing the block fuel benefits.

The assumptions used in this study to define HLFC suction system maintenance and production cost penalties are pessimistic relative to other studies [2],[20],[121]. However, the actual penalties remain unknown and may be even greater.

These various factors all reduce the net DOC benefit of practical laminar flow applications. Clearly where the DOC benefits have been shown to be marginal by this study, the additional penalty factors may result in a net DOC penalty, making HLFC economically unviable. Thus, the most suitable aircraft types for HLFC are those with the most substantial DOC benefits, such that after taking account of the additional penalty factors, significant DOC benefits would still be possible.

For all applications, the *long range quad* achieved substantially greater DOC benefits relative to the shorter range aircraft, making it the most suitable for practical HLFC applications. The *super jumbo* is also suitable for HLFC fin, tailplane and nacelle cases, with DOC benefits that are comparable with the *long range jet*. However, benefits were limited for the wing and WFTN case due to the very large wing. The high sensitivity of the DOC to HLFC system costs and increased fuel reserves identifies them as critical areas in the success of any practical application.

It is likely that the initial HLFC applications would be to nacelle surfaces where the flow is largely 2D, the Reynolds numbers are moderate, and the leading edge is relatively simple. If successful, HLFC empennage surfaces would be added due to moderate Reynolds numbers, relative to the wing, and simpler leading edges (no high lift devices). Although the potential block fuel and DOC benefits are smaller than that possible for the wing, the technical risk and complexity is significantly less. This approach would also allow in-service experience to be gained in the operation and maintenance of HLFC systems. This could ultimately result in the development of HLFC wings, to be used in conjunction with the other HLFC surfaces.

These studies have also demonstrated the integrity and robustness of the design synthesis, with only a small number of cases requiring more than one run of the design synthesis to achieve an optimum solution.

8.1 Suggestions for Future Work

As stated above, a design synthesis can never be regarded as ‘finished’. As further research is performed by the numerous organisations around the world, data will

become available that will permit the methods and assumptions to be updated to reflect the increased level of understanding and the latest approaches.

Certain aspects of the design synthesis could benefit from attention to enhance the operation of the code. In particular, the input and output data files need to be re-formatted to clarify presentation. Additionally, modularisation of the code would greatly simplify the design synthesis code structure and facilitate further modifications to the code.

The use of weight based cost factors is sometimes questioned as structural and system mass reductions typically result in higher costs per unit mass. This is an issue that requires consideration when conducting studies on aircraft with differing levels of structural and systems technology. However, if this is assumed constant across all aircraft in a study, constant weight based cost factors can be used.

The methods used within this study consider all of the principal, and many of the secondary, issues associated with laminar flow technology. However, the assumptions used for a number of the secondary issues could benefit from further attention. These are listed below:

- The impact of replacing the typical hot air de-icing system with a liquid anti-icing/cleaning system must be considered. Although the latter will represent additional operational costs, due to replenishment of fluid, engine performance will not be degraded due to significant extraction of bleed air.
- The local skin friction of laminar boundary layers on suction surface increases as the suction rates are increased. This effect is not included within this study, although it is likely to be minor.
- The transition position on a wing section is dependent on the aerofoil pressure distribution, in particular the rooftop pressure gradient. This effect has been quantified for a number of pressure gradients for a range of chord Reynolds number [160]. Inclusion of this within the methodology would improve the transition prediction method, although it may complicate the methodology.
- To date, the use of Krüger flaps, in place of slats, has been assumed to have no net impact on the high-lift performance, leading edge mass and cost. The most significant of these is likely to be the high-lift performance, particularly if a sharper leading edge is used.

Within this study laminar flow was assumed to be achievable on the whole upper wing surface. Laminar flow might be considered on only part of the wing to avoid the problems associated with root and tip effects, the high chord Reynolds number on the inboard wing and the limited volume in the outer wing leading edge. This would require a more complex method to integrate the profile drag along the semi-span, namely a strip method, which would increase the time taken to run the code.

9. REFERENCES

- 1 **Ahmed, A; Wentz, W.H. & Nyenhuis, R:** In-Flight Boundary Layer Transition Measurements on a Swept Wing. *Journal of Aircraft*, Nov 1989.
- 2 **Arcara, P.C. Jr; Bartlett, D.W. & McCullers, L.A:** Analysis for the application of Hybrid Laminar Flow Control to a Long-Range Subsonic Transport Aircraft. SAE Paper 912113
- 3 **Arnal, D. & Jacques, J-J:** Le Controle de L'Ecoulement Laminaire. *L'Aéronautique et L'Astronautique & Nouvelle Revue Aéronautique et Astronautique*, Mar/Apr 1991.
- 4 **Arnal, D:** Boundary Layer Transition: Prediction, Application to Drag Reduction. AGARD-R-786 'Skin Friction Drag Reduction' course, 1992.
- 5 **Arnold, F:** Numerical Flow Simulation on High-Lift Configurations at Daimler-Benz Aerospace Airbus. European Forum on High Lift and Separation Control, Bath, U.K. 29-31 March 1995.
- 6 **Ashill, P.R; Fulker, J.L & Shires, A:** A Novel Technique for Controlling Shock Strength of Laminar Flow Airfoil Sections. 92-01-022, 1st European Forum on Laminar Flow Technology, March 1992.
- 7 **Aviation International News, 1994 May 01, p6:** Laminar Flow Falcon 900 Begins Test Flying..
- 8 **Aviation Week & Space Technology, 1986, Oct 27, p41:** Lockheed to Study Airlifter Laminar Flow Control Use.
- 9 **Aviation Week & Space Technology, 1994, April 25, p26:** Airbus Transport Concept Relies on Radical Design.
- 10 **Aviation Week & Space Technology, 1996, April 15, p37:** NASA Sends Test Data Via Web.
- 11 **Avmark Inc:** AVMARK's Estimated Jet Transport Prices as of July 1, 1994. Avmark Newsletter, July 1994.
- 12 **Avmark Inc:** Quarterly Aircraft Operating Costs and Statistics. 1st Quarter 1993.
- 13 **Barrett, R.V; Rickards, J. & Eustace, R:** Alleviation of the drag Penalty Incurred by Insect Contamination Using the Existing Suction System of a Hybrid Laminar Flow Nacelle. Paper 8.3, 2nd European Forum for Laminar Flow Technology, Bordeaux, June 1996.
- 14 **Barry, B:** Improving Fuel Economy through Laminar Flow. *The Rolls-Royce Magazine*, No 62, Sep 1994.
- 15 **Beasley, J.A:** Some Notes on the Design of Swept Wings for Laminar Flow Aircraft. Royal Aircraft Establishment Technical Report TR67169, July 1967.
- 16 **Bennett, J.A. et al (Lockheed-Georgia):** Evaluation of Laminar Flow Control Systems Concepts for Subsonic Commercial Transport Aircraft. NASA-CR-159254, 1980.

- 17 **Bieler, H. & Priest, J:** HLFC for Commercial Aircraft: First ELFIN Test Results. 92-01-035 , 1st European Forum on Laminar Flow Technology, March 1992.
- 18 **Bieler, H; Pfennig, J. & Herrmann, R:** A320 Fin: Interdisciplinary Approach to a Boundary Layer Suction System. Paper 7.6, 2nd European Forum for Laminar Flow Technology, Bordeaux, June 1996.
- 19 **Bobbitt, P.J; Ferris, J.C; Harvey, W.D. & Goradia, S.H:** Results for the Hybrid Laminar Flow Control Experiment Conducted in the NASA Langley 8 foot Transonic Tunnel on a 7 foot chord Model. NASA-TM-107582, 1992.
- 20 **Boeing Preliminary Design Dept:** F-111 Natural Laminar Flow Glove Flight Test Data Analysis and Boundary Layer Stability Analysis. NASA-CR-166051, 1984.
- 21 **Boeing:** Hybrid Laminar Flow Control Study: Final Technical report. NASA-CR-165930, 1982.
- 22 **Bolsunovsky, A; Buzoverya, N; Shkadov, L, Kotscheev, A; Cheryemukhin, G; Shapiro, A; Zavershnev, Y, Tabolov, M & Turitshev, V:** The Tu-22M Flying Testbed for Laminar Flow Studies. Paper 2.2, 2nd European Forum for Laminar Flow Technology, Bordeaux, June 1996.
- 23 **Bulgubure, C & Arnal, D** Dassault Falcon 50: Laminar Flow Flight Demonstrator. 92-01-003, 1st European Forum on Laminar Flow Technology, March 1992.
- 24 **Callaghan, J.T. & Liebeck, R.H:** Some Thoughts on the Design of Subsonic Transport Aircraft for the 21st Century. SAE 901987
- 25 **Capbern, P:** Theoretical and Experimental Study of High-Lift Device for a Natural Flow Airfoil. 92-01-032, 1st European Forum on Laminar Flow Technology, March 1992.
- 26 **Collier, F.S. Jr:** An Overview of Recent Subsonic Laminar Flow Control Flight Experiments. AIAA-93-2987.
- 27 **Collingbourne, J:** MultiVariate Optimization Applied to the Initial Design of Transport Aircraft. TR84044, 1984.
- 28 **Cousteix, J; Arnal, D. & Coustols, E:** La Réduction de Traînée de Frottement Aérodynamique. L'Aéronautique et L'Astronautique & Nouvelle Revue Aéronautique et Astronautique, 1st April 1993, p23-31.
- 29 **Croom, C.C. & Holmes, B.J:** Flight Evaluation of an Insect Contamination Protection System for Laminar Flow Wings. SAE 850860.
- 30 **Dalyell, T:** Villians of the Air and Sea. New Scientist, 12 October 1996.
- 31 **Davis, R.E; Maddalon, D.V; Wagner, R.D; Fisher, D.F. & Young, R:** Evaluation of Cloud Detection Instruments and Performance of Laminar Flow Leading Edge Test Articles during NASA Leading-Edge Flight Test Program. NASA-TP-2888, 1989.

- 32 **de Bruin, A.C:** Experiments and Theoretical Considerations Regarding the Allowable Surface Roughness Height in Laminar Flow. 92-01-008, 1st European Forum on Laminar Flow Technology, March 1992.
- 33 **Denning, R.M; Allen, J. & Armstrong, F:** Future Large Civil Airliner -- Design Revolution Rather than Evolution. Draft Aeronautical Journal Paper, 1995.
- 34 **Department of Trade and Industry:** Potential World Market Demand for Passenger Aircraft 1996-2015. A Discussion note by the Department of Trade and Industry, February 1996.
- 35 **Dodbele, S.S:** Effects of Forebody Geometry on Subsonic Boundary-Layer Stability. NASA-CR-4314, 1990.
- 36 **Dodbele, S.S; Van Dam, C.P. & Vijgen, P.M.H.W:** Design of Fuselage Shapes for Natural Laminar Flow. NASA-CP-3970, 1986.
- 37 **Duncan, W.J; Thom, A.S. & Young, A.D:** Mechanics of Fluids, 1970.
- 38 **Dziomba, B:** European Laminar Flow Projects. Aeroday 93: 2nd Community Aeronautics R&D Conference, Naples Oct' 93.
- 39 **Ellis, J.E. & Poll, D.I.A:** Laminar and Laminarising Boundary Layers by Suction Through Perforated Plates. Paper 8.2, 2nd European Forum for Laminar Flow Technology, Bordeaux, June 1996.
- 40 **Elsenaar, A & Haasnoot, H.N:** A Survey on Schiphol Airport of the Contamination of Wing Leading Edges of Three Different Aircraft Types under Operating Conditions. 92-01-025, 1st European Forum on Laminar Flow Technology, March 1992.
- 41 **ESDU:** Geometrical properties of cranked and straight tapered wing planforms. ESDU item number 76003, January 1976.
- 42 **Faust, G.K; Mungur, P; Obara, C.R. & Dodbele, S.S:** Nacelle Design & Aerodynamic Performance. NASA-CP-2487 Research in Natural Laminar Flow and Laminar Flow Control Symposium, Washington D.C. 1987, p891-913.
- 43 **Fischer, B:** Configurational Repercussions of New Technologies in the Design of a Regional Airliner. AIAA-89-2022.
- 44 **Fischler, J.E; Jerstad, N.M; Gallimore, F.H. Jr & Pollard, T.J:** Structural development of Laminar Flow Control Aircraft Chordwise Wing Joint Designs. NASA-CR-181888. April 1989
- 45 **Fisher, D.F. & Fisher, M.C:** Development Flight Tests of Jetstar LFC Leading Edge Flight Test Experiment. NASA-CP-2487 Research in Natural Laminar Flow and Laminar Flow Control Symposium, Washington D.C. 1987, p117-140.
- 46 **Flaig, A & Hilbie, R:** High Lift System for Large Transport Aircraft. AGARD CP-515 High Lift System Aerodynamics ch31, 1992.

- 47 **Flight International, 1962, July 12:** Laminar Report: Handley Page Progress in the Field of Boundary Layer Research..
- 48 **Flight International, 1993, Oct 6, p21:** Laminar Flow tests for Falcon 900 wing.
- 49 **Flight International, 1994, Jan 04:** Citation JPATS contender maiden flight.
- 50 **Flight International, 1994, Jan 19, p11:** NASA works to eliminate glycol.
- 51 **Flight International, 1996, November 6:** Fuel surcharge fears increase.
- 52 **Flight International, 1996, November 6:** US airlines break record again, but fear for the future.
- 53 **George-Falvy, D:** In Quest of the Laminar Flow Airliner: Flight Experiments on a T-33 Jet Trainer. 9th Hungarian Aeronautical Science Conference Budapest, Hungary 10-12 Nov 1988.
- 54 **Gratzer, L.B et al (Boeing Commercial Airplane Company):** Evaluation of Laminar Flow Control Systems Concepts for Subsonic Commercial Transport Aircraft. NASA-CR-158976, 1978.
- 55 **Gratzer, L.B. & George-Falvy, D:** Application of Laminar Flow Control Technology to Long Range Transport Design. NASA-CP-2036 CTOL Transport Technology, NASA Langley Feb/March 1978, p409-447.
- 56 **Greff, E:** Aerodynamic Design for a New Regional Aircraft. ICAS-90-2.7.1, ICAS '90 conference Stockholm.
- 57 **Hahne, D.H. & Jordan, F.L:** Full-Scale Semispan Tests of a Business Jet Wing with a Natural Laminar Flow Airfoil. NASA-TP-3133, 1991.
- 58 **Hall, P:** The Görtler Vortex Instability Mechanism in Three Dimensional Boudary Layer. ICASE Report p84-17, NASA-CR 172370, June 1984.
- 59 **Hansen, H:** The Effect of Suction on Transition - Lessons learnt from the ELFIN i Wind Tunnel Test. Paper 8.4, 2nd European Forum for Laminar Flow Technology, Bordeaux, June 1996.
- 60 **Henke, R; Bieler, H; Garcon, F. & Priest, J:** Hybrid Laminar Flow Control: The ELFIN Wind Tunnel Test Campaign. Aerodays 93: 2nd Community Aeronautics R&D Conference, Naples Oct' 93.
- 61 **Henke, R; Munch, F.X. & Quast, A:** Natural Laminar Flow: A Wind Tunnel test campaign and Comparison with Flight Test Data. AIAA-90-3045.
- 62 **Henke, R; Capbern, P; Davies, A, Hinslinger, R. & Santana, J:** The "A320 HLF Fin Programme": Objectives and Challenges. Paper 12.1, 2nd European Forum for Laminar Flow Technology, Bordeaux, June 1996.
- 63 **Holmes, B.J. & Obara, C.J:** Flight Research on Natural Laminar Flow Applications. IN Natural Laminar Flow and Laminar Flow Control (1992). Edited R.W.Barnwell & M.Y.Hussaini.
- 64 **Holmes, B.J. & Obara, C.J:** Observations and Implications of Natural Laminar Flow on Practical Airplane Surfaces. ICAS-82-5.1.1

- 65 **Horstmann, K.H; Redeker, G; Quast, A; Bressler, U & Bieler, H:** Flight Tests with a Natural Laminar Flow Glove on a transport aircraft. AIAA-90-3044.
- 66 **Houghton, E.L. & Carruthers, N.B:** Aerodynamics for Engineering Students, 1982.
- 67 **Humphreys, B:** Contamination Avoidance for Laminar Flow Surfaces. 92-01-026, 1st European Forum on Laminar Flow Technology, March 1992.
- 68 **Jagger, D.H. & Davies, A.J:** Design and engineering Issues of a Hybrid Laminar flow Wing. Paper 12.3, 2nd European Forum for Laminar Flow Technology, Bordeaux, June 1996.
- 69 **Jasperson, W.H; Nastrom, G.D; Davis, R.E. & Holdeman, J.D:** GASP Cloud Encounter Statistics: Implications for Laminar Flow Control Flight. Journal of Aircraft, Nov 1984.
- 70 **Jobe, C.E; Kulfan, R.M. & Vachal, J.D:** Application of Laminar Flow Control to Large Military Transports. Journal of Aircraft, 1978.
- 71 **Jones, R.I:** The Implications of Laminar Flow Control for Long Range Transport Aircraft. Cranfield Institute of technology PhD Thesis 1985.
- 72 **Keith, T.G. Jr & De Witt, K.J:** Analysis and Evaluation of an Integrated Laminar Flow Control Propulsion System, NASA-CR-192162, 1993.
- 73 **Khalid, M. & Jones, D.J:** A Summary of Transonic Natural Laminar Flow Airfoil Development at NAE. NAE-AN-65, 1990.
- 74 **Krogmann, P & Stanewsky, E:** Effects of Local Suction in Shock-Boundary Layer Interaction and Shock-Induced Separation. AIAA-84-0098.
- 75 **Lamb, M; Abeyounis, W.K. & Patterson, J.C. jr:** Nacelle/Pylon/Wing Integration on a Transport Model with a Natural Laminar Flow Nacelle, NASA-TP-2439, 1985.
- 76 **Lange, R.H:** Design Integration of Laminar Flow Control for Transport Aircraft. AIAA-83-2440.
- 77 **Lange, R.H:** Lockheed Laminar Flow Control Systems Development and Applications. NASA-CP-2487 Research in Natural Laminar Flow and Laminar Flow Control Symposium, Washihngton D.C. 1987, p53-77.
- 78 **Lee, C.C; Wusk, M.S. & Obara, C.J:** Flight Experiments Studying the Growth of Disturbances in the Laminar Boundary Layer. SAE 901979
- 79 **Levy, H:** Lockheed Pushes Stol Technology. Flight International, 24 Nov 1984 p1370.
- 80 **Lynch, F.T. & Klinge, M.D:** Some Practical Aspects of Viscous Drag Reduction Concepts. SAE 912129
- 81 **Maddalon, D. & Poppen, W.A. Jr** Design and Fabrication of Large Suction Panels with Perforated Surfaces for Laminar Flow Control Testing. NASA-TM-89011, 1986.

- 82 Maddalon, D.V. & Braslow, A.L: Simulated-Airline-Service Flight Tests of Laminar Flow Control with Perforated Suction System. NASA-TP-2966, 1990.
- 83 Maddalon, D.V. & Wagner, R.D: Operational Considerations for Laminar Flow Aircraft. NASA-CP-2413 Laminar Flow Aircraft Certification Workshop.
- 84 Meifarth, K.U. & Heinrich, S: The Environment for Aircraft with Laminar Flow Technology within Airline Service. 92-01-024, 1st European Forum on Laminar Flow Technology, March 1992.
- 85 Meister, J; Herrmann, Davies, H; Freke, S; et al: An On-board Suction System - System, Structure and Manufacture Aspects. Paper 3.2, 2nd European Forum for Laminar Flow Technology, Bordeaux, June 1996.
- 86 Meyer, R.R; Trujillo, B.M. & Bartlett, D.W: F-14 VSTFE and Results of the Cleanup Flight Test Program. NASA). NASA-CP-2487 Research in Natural Laminar Flow and Laminar Flow Control Symposium, Washihngton D.C. 1987, p819-844.
- 87 Moeken, B; Wohlrath, W. & Horstmann, K.H: Dornier 228 Experimental with Laminar Wing. NLF flight test with propeller aircraft. Dornier Post No.4 1992 p38-39.
- 88 Moens, F: Influence d'une aspiration de bord d'attaque sur C_{zmax} de profils hypersustentés. L'Aéronautique et L'Astronautique & Nouvelle Revue Aéronautique et Astronautique, September 1994 p50-51
- 89 Moens, F. & Capbern, P: Design and Testing of Leading-Edge Devices for Laminar Flow Wing Applications. European Forum on High Lift and Separation Control, Bath, U.K. 29-31 March 1995.
- 90 Mowbray, G.H. & Gebhard, J.W: Man's Senses as Information Channels. Report CM-936, the John Hopkins University Applied Physical Laboratory, 1958.
- 91 Mullender, A.J. & Poll, D.I.A: Natural and Hybrid Laminar Flow Control for Aero-Engine Nacelles. SAE 952016, SAE Aerotech '95, Los Angeles September 19-21 1995.
- 92 Mullender, A.J. & Riedel, H: A Laminar Flow Nacelle Flight test Programme. Paper 2.4, 2nd European Forum for Laminar Flow Technology, Bordeaux, June 1996.
- 93 Mullender, A.J; Lecordix, J.L; Lecossais, E; Godard, J.L. & Hepperle, M: The ELFIN II and LARA HLF Nacelles: Design, Manufacture & Test. Paper 5.3, 2nd European Forum for Laminar Flow Technology, Bordeaux, June 1996.
- 94 Mullender, A.J. & Rodgers, L.J: Porous Surface for HLF Nacelle. Patent Application No. 94222858, November 1994.

- 95 **Muraca, R.J:** Laminar Flow Control Overview. NASA-CP-2036 CTOL Transport Technology, NASA Langley Feb/March 1978 p349-356.
- 96 **Nangia, R.K. & Galpin, S.A:** Towards Design of High-Lift Krueger Flap Systems with Mach & Reynolds Number Effects for Conventional and Laminar Flow Wings. European Forum on High Lift and Separation Control, Bath, U.K. 29-31 March 1995.
- 97 **Nastrom, G.D; Holdeman, J.D. & Davis, R.E:** Cloud-Encounter and Particle-Concentration Variabilities from GASP Data. NASA-TP-1886, 1981.
- 98 **Nelson, P.A; Wright, M.C.M; Allan, W; Tutty, O.R. & Rogers, E:** Strategies for the Automatic Control of Laminar Boundary Layer Transition. Paper 6.2, 2nd European Forum for Laminar Flow Technology, Bordeaux, June 1996.
- 99 **Overbergh, C.:** Design Integration of the Hybrid Laminar Flow System on a Transport Aircraft Leading Edge. Paper 3.3, 2nd European Forum for Laminar Flow Technology, Bordeaux, June 1996.
- 100 **Palmer, J.R:** The TURBOMATCH scheme for Gas Turbine Performance Calculations. October 1983.
- 101 **Parikh, P.G; Lund, D.W; George-Falvy, D. & Nagel, A.L:** Hybrid Laminar Flow Control Tests in the Boeing Research Wind Tunnel. SAE 901978.
- 102 **Pearce, W.E:** Evaluation of Laminar Flow Control Systems Concepts for Subsonic Commercial Transport Aircraft. NASA-CR-159251, 1983.
- 103 **Pfenninger, W; Vemuru, C.S & Viken, J:** About the Design Philosophy of Long Range LFC Transports with Advanced Supercritical LFC Airfoils. AIAA-87-1284
- 104 **Pfenninger, W; Viken, J.K; Vemuru, C.S & Volpe, G:** All Laminar SC LFC Airfoils with Natural Laminar Flow over Main Wing Structure. AIAA-86-2625
- 105 **Poll, D.I.A. & Danks, M:** Relaminarisation of the Swept Wing Attachment line by Surface Suction. IUTAM Symposium on Laminar-Turbulent Transition, Sendai, Japan 5-9 Sep 1994.
- 106 **Poll, D.I.A; Danks, M & Davies, A.J:** The Effect of Surface Suction Near the Leading Edge of a Swept-Back Wing. 92-01-029, 1st European Forum on Laminar Flow Technology, March 1992.
- 107 **Poll, D.I.A; Danks, M. & Humphreys, B.E:** The Aerodynamic Performance of Laser Drilled Sheets. 92-01-028, 1st European Forum on Laminar Flow Technology, March 1992.
- 108 **Poll, D.I.A:** Some Observations of the Transition Process on the Windward Face of a Long Yawed Cylinder. Journal of Fluid Mechanics, Volume 150 pp329-356, 1985.

- 109 **Preist, J. & Paluch, B:** Design Specification and Inspection of Perforated Panels for HLF Suction Systems. Paper 6.3, 2nd European Forum for Laminar Flow Technology, Bordeaux, June 1996.
- 110 **Rawls, J.W:** Near Field Noise Predictions of an Aircraft in Cruise. NASA-CP-2487 Research in Natural Laminar Flow and Laminar Flow Control Symposium, Washington D.C. 1987, p617-636.
- 111 **Redeker, G & Wichmann, G:** Forward Sweep-A Favourable Concept for a Laminar Flow Wing. *Journal of Aircraft*, Feb. 1991 p97.
- 112 **Redeker, G; Müller, R; Blanchard, A. & Reneaux, J:** Evaluation of Transonic Laminar airfoil Tests under Cryogenic Conditions Including Stability Results and Computational Results. 92-01-019, 1st European Forum on Laminar Flow Technology, March 1992.
- 113 **Redeker, G; Horstmann, K; Köster, H. & Quast, A:** Investigation on High Reynolds Number Laminar Flow Airfoils. ICAS-86-1.1.3.
- 114 **Reneaux, J & Blanchard, A:** The Design and Testing of an Airfoil with Hybrid Laminar Flow Control. 92-01-021, 1st European Forum on Laminar Flow Technology, March 1992.
- 115 **Resthotko, E:** Boundary Layer Instability, Transition & Control. AIAA-94-0001.
- 116 **Riedel, H & Sitzmann, M:** Flight Investigation of the Effect of Yaw on the Intake and Fan Nacelle Flow of a Natural Laminar Flow Nacelle. RAeS Paper, Aircraft-Engine Integration Conference, October 1996.
- 117 **Runyan, L.J; Bielak, G.W; Behbehani, R; Chen, A.W. & Rozendaal, R.A:** 757 NLF Glove Flight Test Result. (Boeing). NASA-CP-2487 Research in Natural Laminar Flow and Laminar Flow Control Symposium, Washington D.C. 1987, p795-818.
- 118 **Sacco, G; Cinquetti, P & Martini, S:** P.180: Natural Laminar Flow Test, In-Flight Visualisation. AGARD CP-519-ch21, 1992.
- 119 **Sawyers, D.M. & Wilson, R.A.L:** An Assessment of the Impact of Hybrid Laminar Flow on a Large Subsonic Aircraft. Paper 3.1, 2nd European Forum for Laminar Flow Technology, Bordeaux, June 1996.
- 120 **Schallaböck, K:** Air Traffic and the Climate - A Key Problem. Air Traffic and Climate Forum, Berlin Climate Summit, March 1995.
- 121 **Schmitt, D, & Vahle, K.H:** The Impact of Hybrid Laminar Flow Control on the Performance of a Commercial Transport Aircraft. 1st European Forum on Laminar Flow Technology, March 1992.
- 122 **Schmitt, D:** Advanced Technology: Constant Challenge and Evolutionary Process. 3rd European Aerospace Conference 1994 London.
- 123 **Schmitt, V; Reneaux, J. & Thibert, J.J:** Design and Experimental Investigation of a Laminar Horizontal Tail. AIAA-90-3042.

- 124 **Scmitt, V; Quast, A. & Hinsinger, R:** Wind Tunnel Investigation of the A320 Fin. Paper 5.2, 2nd European Forum for Laminar Flow Technology, Bordeaux, June 1996.
- 125 **Schwab, U:** Electron Beam Drilled Holes for Laminar Flow Control. 92-01-027, 1st European Forum on Laminar Flow Technology, March 1992.
- 126 **Sedin, Y; Larrson, T; Olafsson, H; Lorentzen, L; Tysell, L; Agrell, N. & Hennington, D:** Aerodynamic Flow Calculation with Reference to Laminar Flow Wings. Paper 5.1, 2nd European Forum for Laminar Flow Technology, Bordeaux, June 1996.
- 127 **Sewell, W.G; McGhee, R.J; Hahne, D.E. & Jordan, F.L. jr:** Wind Tunnel Tests of the High Speed NLF(1)-0213 Airfoil. NASA-CP-2487 Research in Natural Laminar Flow and Laminar Flow Control Symposium, Washington D.C. 1987, p697-725.
- 128 **Shipley, P.P; Birch, N.T; Reidel, H; Horstmann, K.H. & Lücking, P:** A European Collaborative NLF Nacelle Flight Demonstrator. 92-01-005, 1st European Forum on Laminar Flow Technology, March 1992.
- 129 **Skrobanski, J.J:** RQPMIN Version 3.2, The Constrained Optimisation Program User Guide. The MVA Consultancy for the DRA, 1996.
- 130 **Stuke, H; Dressler, U; Priest, J. & Capbern, P:** Principles of Aerodynamic Layout and Design of a Suction System. Paper 6.4, 2nd European Forum for Laminar Flow Technology, Bordeaux, June 1996.
- 131 **Sturgeon, R.F:** Toward a Laminar Flow Control Transport for the 1990's. NASA-CP-2036 CTOL Transport Technology, NASA Langley Feb/March 1978, p449-495.
- 132 **Swinford, G.R:** A Preliminary Design Study of a Laminar Flow Wing of Composite Materials for Long Range Transport Aircraft. NASA-CR-144950, 1976.
- 133 **Swoboda, M. & Nitsche, W:** Shock Boundary-Layer Interaction on Transonic Airfoils for Laminar and Turbulent Flow. Journal of Aircraft, Jan-Feb 1996.
- 134 **Szodruch, J:** Viscous Drag Reduction on Transport Aircraft. AIAA-91-0685.
- 135 **Tamigniaux, T.L.B; Stark, S.E. & Brune, G.W:** An Experimental Investigation of the Insect Shielding Effectiveness of a Krüger Flap/Wing Airfoil Configuration. AIAA-87-2615.
- 136 **Tardif, C:** p45 Laminarité: Place aux Essais Grande Echelle. L'Aéronautique et L'Astronautique & Nouvelle Revue Aéronautique et Astronautique, 23 December 1994
- 137 **Tegarden, F.W:** Hybrid Laminar Flow Nacelles - A Test Success for the Future. RAeS Paper, Airframe-Engine Integration Conference, October 1996.
- 138 **The Engineer, 1993, March 4, p25:** Shorts find Thermoplastic fuel saver.

- 139 **Thibert, J.J; Quast, A. & Robert, J.P:** The A320 Laminar Fin Programme. 92-01-004, 1st European Forum on Laminar Flow Technology, March 1992.
- 140 **Thibert, J; Reneaux, J. & Schmitt, V:** ONERA activities on Drag Reduction. ICAS-90-3.6.1, ICAS '90 conference Stockholm.
- 141 **Thiede, P:** 1st Euro Forum Conclusions and Future. 1st European Forum on Laminar Flow Technology, March 1992.
- 142 **Torenbeek, E:** Synthesis of Subsonic Airplane design, 1982.
- 143 **Torenbeek, E:** The Propulsion of Aircraft with Laminar Flow Control, 1968.
- 144 **Viken, J & Wagner, R.D.** Design Limits of Compressible NLF Airfoils. AIAA-91-0067.
- 145 **Viken, J.K; Viken, S.A; Pfenninger, W; Morgan, H.L. & Campbell, R.L:** Design of Low Speed NLF(1)-414F and the High Speed HSNLF(1)-0213 Airfoils with High Lift Systems. NASA-CP-2487 Research in Natural Laminar Flow and Laminar Flow Control Symposium, Washihngton D.C. 1987, p637.
- 146 **Von Doenhoff, A.E. & Braslow, A.L:** The Effect of Isolated Surface Roughness on Laminar Flow. IN **Lachmann, G.V:** Boundary Layer and Flow Control Vol. II, 1961.
- 147 **Voogt, N:** Flight Testing of a Fokker 100 Test Aircraft with Laminar Flow Glove. Paper 2.1, 2nd European Forum for Laminar Flow Technology, Bordeaux, June 1996
- 148 **Wagner, R.D; Bartlett, D.W. & Collier, F.S. Jr:** Laminar Flow- The Past, Present and Prospects. AIAA-89-0989.
- 149 **Wagner, R.D; Maddalon, D.V. & Fisher, D.F:** Laminar Flow Control Leading Edge Systems in Simulated Airline Service. Journal of Aircraft, March 1990.
- 150 **Wagner, R.D; Maddalon, D.V; Bartlett, D.W; Collier, F.S. Jr & Braslow, A.L:** Laminar Flow Flight Experiments - A Review. IN Natural Laminar Flow and Laminar Flow Control (1992). Edited **R.W.Barnwell & M.Y.Hussaini.**
- 151 **Waters, M.H.L:** A Brief Comparative Study of the Effects of Advances in Technology on the Performance of Laminar-Flow and Conventional Subsonic Transport Aircraft. Royal Aircraft Establishment Technical Report TR 67094, April 1967.
- 152 **Waters, M.H.L:** Additional Notes on Cost Assumptions for Laminar-Flow and Subsonic Transport Aircraft. Royal Aircraft Establishment Technical Report TR68020, January 1968.
- 153 **Wie, Y.S; Collier, F.S. Jr; Wagner, R.D; Viken, J.K. & Pfenninger, W:** Design of a Hybrid Laminar Flow Control Engine Nacelle. AIAA-92-0400.

- 154 **Williams, N.R:** SPF/DB Titanium LFC Porous Panel Concept. NASA-CP-2218 Laminar Flow Control: 1981 Research and Technology Studies, NASA Dryden September 1981, p111.
- 155 **Williams, S.W. & Marsden, P.J:** New Laser drilling Techniques for Porous Surfaces. Paper 9.2, 2nd European Forum for Laminar Flow Technology, Bordeaux, June 1996.
- 156 **Wilson, R.A.L. & Jones, R.I:** Project Design Studies on Aircraft Employing Natural and Assisted Laminar Flow Technologies. SAE 952038, SAE Aerotech '95, Los Angeles September 19-21 1995.
- 157 **Wilson, R.A.L. & Jones, R.I:** Operational and Certification Considerations for Subsonic transport Aircraft with Hybrid Laminar Flow Control. Paper 11.3, 2nd European Forum for Laminar Flow Technology, Bordeaux, June 1996.
- 158 **Wilson, R.A.L:** CIVIL Version 2.0: User Guide. DRA working paper DERA/AS/PTD/WP97001, January 1997.
- 159 **Wong, P.W.C & Maina, M:** An Investigation of Hybrid Laminar Flow Aerofoil Pressure distributions and Performance Characteristics. Paper 7.4, 2nd European Forum for Laminar Flow Technology, Bordeaux, June 1996.
- 160 **Wong, P.W.C & Maina, M:** Study of Methods and Philosophies for Designing Laminar Flow Wings: Interim Report M275/1, 1995.
- 161 **Wylie, D.P. & Menzel, W.P:** Two years of Cloud Cover Statistics Using VAS. Journal of Climate, Volume 2, p380, 1988.
- 162 **Zuniga, F.A; Drake, A; Kenelly, R.A. Jr; Koga, D.J. & Westphal, R.V:** Transonic Flight Test of a Laminar Flow Leading Edge with Surface Excrescences. NASA-TM-4597, August 1994.

APPENDICES

A. TECHNOLOGY REVIEW

This technology review describes the current state of the art of laminar flow technology. A literature survey was conducted throughout the three year study to gather published information on NLF and HLFC. Overviews of recent major laminar flow research programs are provided in chapter 3. This appendix provides more detailed information on the observations and findings of these research programs. It is divided into three principal sections:

- Section A1 contains issues important to both NLF and HLFC, in particular issues related to structural tolerances, surface contamination, climate and noise.
- Section A2 contains issues related NLF, namely NLF section design and cruise performance.
- Section A3 contains HLFC issues such as section design, cruise and high lift performance, as well as suction system technology.

A.1 General Considerations

A.1.1 Structural Considerations

If laminar flow technology is to be applied to commercial transport aircraft, all structural considerations must be met. Of primary importance is the surface quality, as any imperfections can destabilise the boundary layer. Structural waviness, steps and gaps modify the local pressure field creating small areas of adverse pressure gradients which may amplify existing TS disturbances. Three dimensional roughness elements, such as rivet or screw heads, produce streamwise vortices which may cause a wedge of turbulent flow downstream.

Many laminar flow flight tests have overcome this problem by using a glove, a high quality non-structural surface attached over the outer surface of the airframe. As surface imperfections are unavoidable for current airframe production techniques, extensive research has been conducted to establish acceptable limits of various types of imperfection.

A.1.1.1 Surface Tolerances

A number of empirical expressions have been developed to define the maximum permissible degree of surface waviness assuming sinusoidal form. This limit, typically defined as the ratio of waviness amplitude and length, is a function of leading edge sweep, streamwise chord, and the Reynolds number based on streamwise chord.

The plot of allowable height and wavelength combinations for a large transport aircraft in cruise conditions, at $M=0.8$ and 38,000ft, with 25° leading edge sweep can be seen in Figure A-1. For these conditions the allowable waviness is 10% less than for an unswept wing.

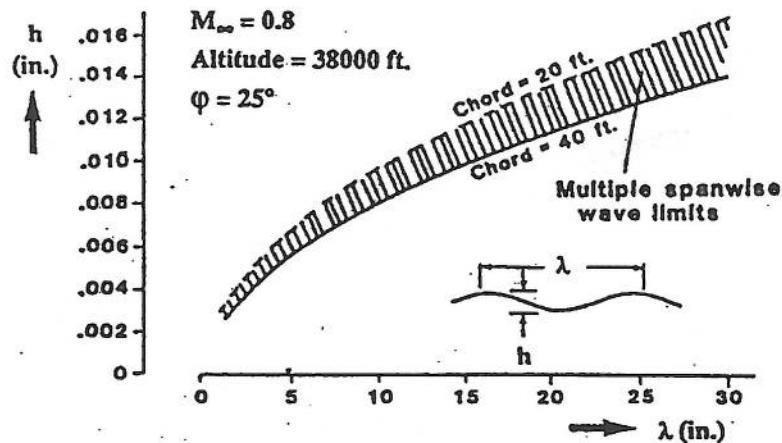


Figure A-1: Allowable Surface Waviness, from [4]

Where steps and gaps are concerned, Reynolds number criteria based on the roughness element dimensions have been determined for the various different surface discontinuities where, the transition location will start to move upstream. Research into this field is reviewed in [4], with the major points high-lighted in Figure A-2.

	Maximum Reynolds Number	Maximum Tolerance for Laminar Flow $M=0.8, 35,000\text{ft}$
Gap: Width 'b'	15,000	2.4mm
Rear Facing Step: Height 'h'	900	0.143mm
Forward Facing Step: Height 'h'	1,800	0.286mm
Forward Facing Rounded Step: Height 'h'	2,700	0.430mm
Inclined Surfaces: Height 'h'	> 4,000	> 0.636mm

Figure A-2: Limitations for Surface Imperfections, [4]

However, it should be noted that the above values are for low Reynolds number flow, and as such are only valid for flow close to the leading edge. Furthermore, a recent NASA study has investigated the influence of steps and gaps, in isolation and combinations, at transonic speeds. Although only preliminary results have been published for $M=0.7$, these suggest "that step and gap combinations may not be as alarming as may have been expected" [162].

The nature of isolated 3D roughness elements, variation in height 'k' and diameter 'd', complicate the definition of a limits. Early experimental work [146] provided Reynolds number (based on roughness height) limits, defined as the point at which the turbulent wedge apex reaches the roughness location, as a function of roughness diameter/height, d/k , ratios in 2D flow. More recent work [32] agrees with the earlier experiments, Figure A-3 shaded area represents earlier experiments, while error bars are for the more recent results.

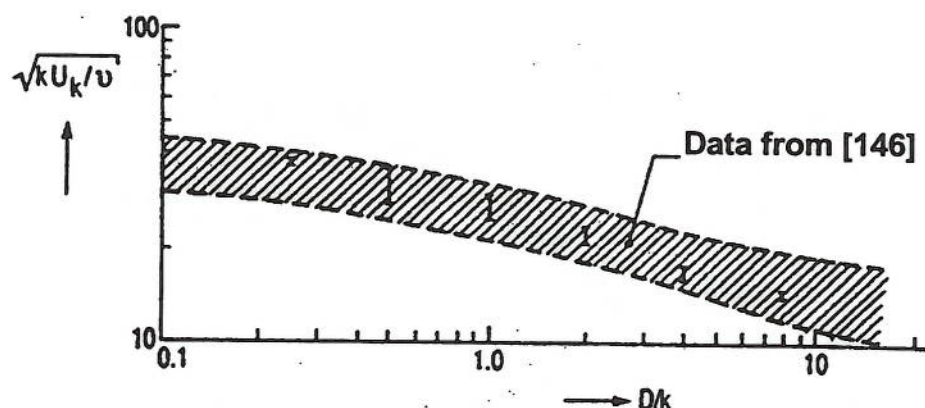


Figure A-3: Allowable 3D Roughness, from [32]

This shows that for $d/k=1$, representative of rivet and screw heads, the limiting Reynolds number was approximately 600. This varies from 1500 for $d/k=0.15$ and to 150 for $d/k=10$.

If rivets, ($d/k=1$) are considered, typical permissible heights for 3D roughness at 30,000ft and $M=0.8$ are in excess of 0.17mm when they are located 1m from the leading edge rising to 0.29mm at 5m from the leading edge.

A.1.1.1.1 Influence of Roughness Location on Boundary Layer Transition

NLF flight tests on a small transport aircraft [65], investigated the impact of the chordwise location of 2D and 3D roughness elements over the forward regions of the wing surface. Laminar flow was observed to be most sensitive to disturbances located between 5-20% chord with transition moved forward by up to 25% chord. A summary of the results from [65], for a forward/backward step disturbance, is shown in Figure A-4.

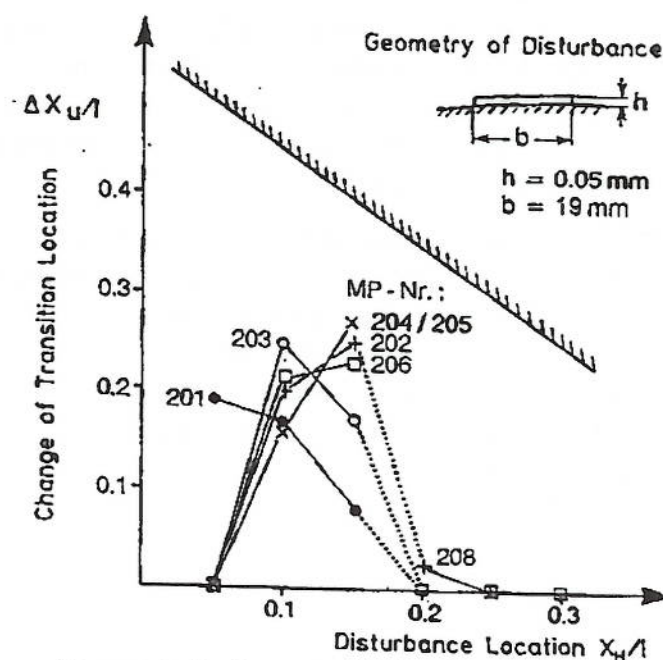


Figure A-4: Impact of Disturbance Location

Disturbances are damped by the stabilising influence of the strongly favourable pressure gradient ahead of 5% chord and aft of 20% the boundary layer thickness is large compared to the disturbance height.

Analytical investigation of the roughness limits on a family of ellipses [32] concluded that the location of minimum allowable roughness height is less than $1.7 \times R$ (R was leading edge radius) from the stagnation point.

The effect of chordwise location of three-dimensional roughness limits has also been addressed. Taking a pessimistic limiting Reynolds number of 200 and a Mach number of 0.8 for a range of cruise altitudes, Figure A-5 shows that the limiting height increases with distance from the leading edge, and also with altitude as unit Reynolds numbers are reduced.

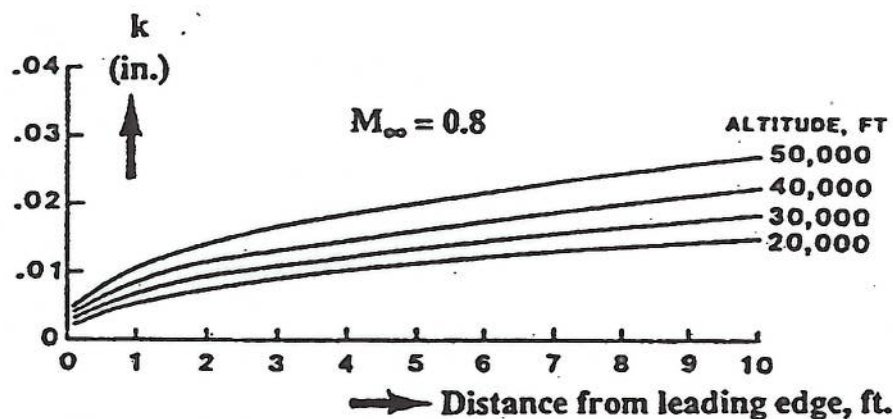


Figure A-5: Impact of 3D Disturbance Location, from [4]

A.1.2 Roughness due to Environmental Factors

If an aircraft's surface is fabricated to the tolerances described above, it will not give rise. However, the operating environment for transport aircraft contains numerous other factors that may degrade the extent of laminar flow. This environment includes a temperatures range exceeding -60°C to 40°C (-76°F to 100°F), in addition to the factors summarised in Figure A-6.

	Potential Threat to:	
	NLF Surface	Surface with Suction
Aircraft Parked on the Ground		
Particle matter - dust, soot, sand salt etc.	Minor - addressed by periodic cleaning.	Minor - some concern with blockage of porous surface if contamination level are high.
Rain	None, if no freezing.	May collect and freeze in porous surface and ducts.
Wax and greases from servicing activities	Minor - addressed by periodic cleaning.	May block porous surface.
Damage from servicing activities	Moderate - improved standards of care required.	
Frost, Snow, Freezing rain	Similar problems to existing aircraft - ground de-icing will be required - deposits from thickened ground de-icing fluids may be a problem.	Similar problems to existing aircraft - ground de-icing will be required - in addition potential blockage threat to surface and system and from thickened ground de-icing fluids.
Taxi and Low Altitude Flight (below 1,000ft to 2,000ft)		
Particle matter - dust, soot, sand salt etc.	Long term erosion threat.	Long term erosion threat. Minimal short term threat, assuming suction system inactive.
Rain	Minor - will cause transition only whilst condition prevails.	May collect and freeze in porous surface and ducts.
Insects	Major - Protection will be required if laminar flow to be guaranteed.	
Impact icing/freezing rain	Major - Protection will be required if laminar flow to be guaranteed.	
Snow	Minor - will cause transition only whilst condition prevails.	None, assuming suction system inactive.
Medium Altitude Flight (up to 22,000ft)		
Particle matter - dust, soot, sand salt etc.	Long term erosion threat.	Long term erosion threat. Possible blockage of porous surface may inhibit use of suction system in heavily polluted areas.
Rain	Minor - will cause transition only whilst condition prevails.	May collect and freeze in porous surface and ducts.
Impact icing/freezing rain	Major - Protection will be required if laminar flow to be guaranteed.	
Snow	Minor - will cause transition only whilst condition prevails.	May block suction system if active.
High Altitude Flight (above 22,000ft)		
Particle matter - dust, soot, sand salt etc.	Long term erosion threat.	Long term erosion threat. Particles generally too small to block porous surfaces, but a threat may exist for a short period after volcanic activity.
Ice crystals	Minor - may cause transition only whilst condition prevails.	Minor - may cause transition only whilst condition prevails. May block suction surface.

Figure A-6: Environmental Threats to Laminar Flow (from [67])

In many instances the threats are minor or long term, but it must be noted that transport aircraft are in service for in excess of 20 years and that laminar flow must be as achievable throughout this period.

A.1.2.1 Insect Contamination

The problem of insect contamination of airframe surfaces is often regarded as one of the major obstacles to practical applications of laminar flow technology. At air speeds greater than the critical speed, 20-30 knots depending on insect type, an insect

will rupture on impact. The protein content of the body, acting as a glue, fixes the solid debris to the surface forming a three-dimensional roughness element.

Insect impingement occurs where surfaces are largely normal to the airflow, such as leading edges. This region is also where a laminar boundary layer is most susceptible to roughness, see section .

The exact nature, size and location of insect debris is highly dependent on insect size, surface incidence and profile, normal impact velocity, and boundary layer characteristics.

The number and type of insects likely to be encountered by an aircraft can vary greatly with geographical location, season, altitude and local atmospheric conditions. Thus on some occasions no insect protection is necessary, whilst sometimes it is critical.

Numerous studies have investigated the insect distribution as a function of altitude and atmospheric conditions. Although these were performed at diverse geographic locations, South-East England, Virginia and Louisiana in U.S.A, many of the results concurred, reviewed in [29].

It was found that the insect density rapidly decreases from ground level to 500ft with extremely low densities above 1,000ft, as shown in Figure A-7. A combination of climatic conditions, namely 25°C (77°F) and 4-8mph wind-speed, were associated with the highest insect density. As either of these conditions is varied from this optimum state insect density was seen to decrease significantly. Below 21°C (70°F) the insect density was seen to decrease rapidly.

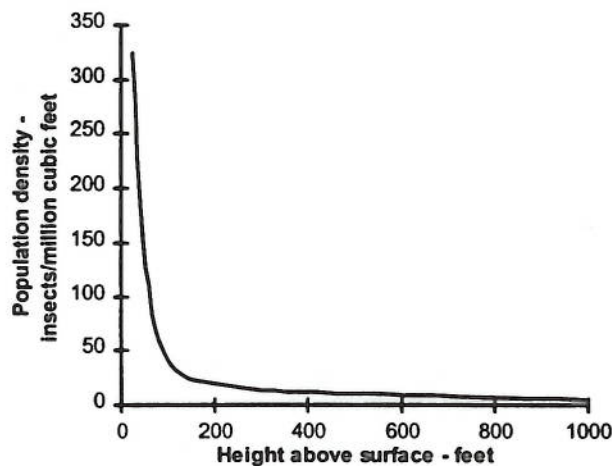


Figure A-7: Insect Distribution, from [29]

The accumulation rate rises with increased airspeed, as the surface sweeps through a larger volume of air in a set period. Higher speeds also result in more compact remains that are more resilient to erosion [67]. Increased climb rates after take-off reduce the time for which an aircraft is exposed to the risk of insect contamination.

Insect size and mass, which can vary greatly, will influence the characteristics of the impact site debris. Clearly, impingement of large heavy insects is more likely to

disrupt the laminar boundary layer. The vast majority of insects are very small (0.2mg) with a rapid reduction in numbers as mass increases [67].

Wind-tunnel tests to investigate the use of a Krüger flap as a shield [135], also analysed insect trajectory around a wing. Heavier insects, 0.6-0.8mg, impacted on the upper surface when the model attitude was representative of ground runs, whereas lighter insects, 0.2mg, tended to follow streamlines around the wing. The small size of the majority of insects will have less influence on laminar flow as the debris remaining after impact will not be of critical height to cause transition.

A study of insect accumulation on the leading edge of 3 short haul aircraft (Boeing 737, Douglas DC9 and a Fokker F-28) operating throughout Europe analysed the seasonal variation of insect density [40]. The number of insect impact sites on the leading edge, counted weekly during 1988, was similar for all aircraft. The proportion of the impacts that were deemed to be supercritical, >0.3mm in height (capable of disrupting laminar flow) was seen to be 10-20% of the total.

As expected, a clear seasonal variation in insect activity was observed with greatly increased activity during the summer with two large peaks in early and late summer, possibly due to climatic reasons or times of pollination and fruit. Towards the beginning and end of the year the insect impacts observed reduced dramatically

This study concluded that laminar flow would be achievable on large parts of a wing during the winter months, without cleaning or an anti-contamination system. However, substantial disruptions to any laminar flow were predicted during the summer.

The extent of insect contamination is also a function of an aircraft's operating schedule, with longer missions requiring fewer take-offs/landings, and hence less exposure to contamination. Insect contamination is a potential problem throughout the year for long-range aircraft, where climatic conditions may vary greatly between the departure and destination locations, especially for intercontinental flights across the equator with the resulting changes in season.

A.1.2.1.1 Contamination Avoidance

The aircraft types already employing laminar flow, gliders and a small number of business aircraft, require manual leading edge cleaning. It is reported that several flights are possible before sufficient contamination has been accumulated to prevent significant amounts of laminar flow on an NLF wing on a business aircraft [118]. Typical operation of these aircraft is less intensive than commercial transports, and not driven by airline schedules, allowing time for the crew or maintenance staff to clean the leading edge areas as required.

If extensive laminar flow is to be routinely achievable on transport aircraft, some method is needed to prevent insect contamination. This would only be required when the aircraft is traveling at air-speeds in excess of the insect rupture speed (20-40kts) and below the 500-1000ft ceiling of normal insect flight. This includes ground manoeuvring, such as taxiing, take-off and landing runs, and low level flight such as

initial climb and final approach. The typical duration for each of these are presented, for two classes of aircraft, in Figure A-8.

	Time Regional Turboprop	(minutes) Long Range Jet
Taxi	4.8	4.8
Take-off and Climb	1.5	1.0
Descent and Land	2.5	1.5
Taxi	4.8	4.8
Total	13.6	12.1

Figure A-8: Typical Duration for Ground Operations and Low-Level Flight ([67])

Most notable of these is taxiing, representing approximately 80% of the total. Low speeds are usually associated with this, although aircraft are quite capable of taxiing at speeds in excess of the insect rupture speeds. If the airspeed is limited to 20 knots, the lowest insect rupture speed, insect impingement can be avoided during taxi.

Various protective devices and systems have been utilised (summarised in Figure A-9) in numerous wind-tunnel and flight tests.

Insect Protection Concept	Comments
Paper covering	Successful for experimental work but impractical for airline service.
Soluble films (e.g. Ice, Gelatine)	Successful for experimental work but impractical for airline service.
Resilient surface	Successful at low speeds. Poor resistance to rain erosion. Not feasible with suction surface.
Scrapers, Wipers	Successful for experimental work. Used on sailplanes. Impractical for airline service. Likely to abrade and score surface.
Re-laminarisation by suction	Not applicable to NLF surfaces. May require excessive suction flow rates and may not be effective under all circumstances. May require sensing of boundary layer state to permit active control of suction rate to minimise mass flow.
Deflector e.g. Krüger slat	Successful. Attractive if high lift device required. Limits laminar flow to upper surface only. Not attractive if high lift not required. e.g. stabilisers and engine cowlings.
Liquid discharge. Spray nozzles	Successful at high rates of flow. Can also provide ice protection.
Liquid discharge. Porous surface	Successful at reasonable rates of flow. Can also provide ice protection.

Figure A-9: Concepts for Leading Edge Contamination Protection (From 67)

Of these the most appropriate concepts for commercial transport aircraft are fluid discharge systems and Krüger flaps/shields, which are further discussed below.

A.1.2.1.2 Fluid Discharge Systems

Fluid discharge systems have been used extensively on many recent research programs ranging from low speed NLF applications on small General Aviation Aircraft, through to LFC flight tests representative of a small commercial transport.

This is a preventative system deterring adherence rather than removing existing debris. A fluid is placed onto the leading edge of the surface as a thin film. As an insect ruptures upon impact, the body and the proteins are trapped within the fluid, where the adhesive proteins are diluted, thus preventing the solid debris adhering to the surface. The airflow causes the fluid to flow aft and off the trailing edge. This

requires a continuous application of fluid to the leading edge whilst the possibility of insect contamination persists.

Although water has also been used, most tests have used a glycol or glycol/water based solution as this offers improved protection through higher viscosity, better wetting qualities and lower evaporation rates and it can act as a solvent to insect proteins. [67]. Flight tests evaluating the effectiveness of various glycol/water solutions, found that a 80/20 (glycol/water) was four times as effective as a 20/80 solution, and a hundred time more effective than water.

The glycol/water solution also acts a freezing point suppressant, and as such is used on existing fluid anti-icing systems on a number of existing general aviation and business aircraft. Therefore one system could provide contamination and ice protection, although it is probable that only one of these threats will exist at any given time.

The widespread use of glycol poses an environmental problem, although NASA have investigated an environmentally friendly fluid that can be used as a direct substitute for glycol [50].

The fluid film can be placed onto the surface using one of two methods, by excreting it through a perforated surface or spraying from the leading edge high lift device, if one is used.

Excretion through a porous skin allows the surface to be continually wetted using minimal amounts of fluid, full explanation of the system in [67]. A number of studies have evaluated the system performance. Tests using a Cessna 206 aircraft [29] conducted at 130kts at an altitude of 50ft report that the system reduced the number of insects adhering to the leading edge by over 75%, Figure A-10. Although this aircraft is not representative of large transport aircraft, the test speed is typical of transport aircraft high speed ground runs just prior to take-off and after landing. The same system used on the Dornier 228 NLF flight tests [87] was reported to be 90% effective.

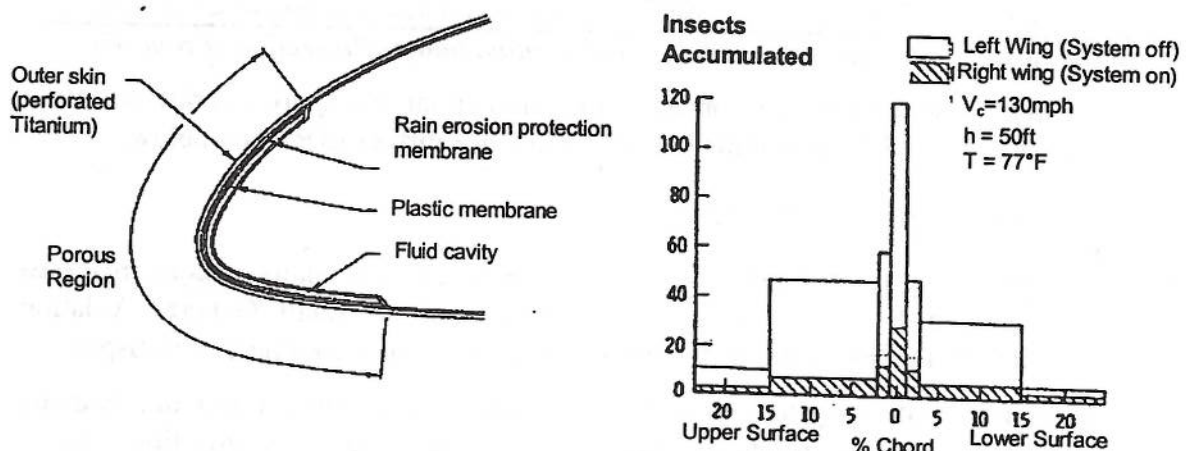


Figure A-10: Fluid Discharge System and Effectiveness, from [67] and [29]

Flow rates of 1.5 l/min (0.6 U.S. gal/min) and 49 l/min (8.1 U.S. Gal/min) were reported for the wings of a 19m span regional turboprop transport and a 747 type aircraft, respectively [67]. Figure A-11 presents the fluid requirement per flight for differing surfaces, with and without system operation during taxi (based on exposure times defined in Figure A-8) for the regional and large aircraft. Note that the values in brackets are for the system not operating during taxi.

	Fluid usage (l)			
	Regional Turboprop		Long range jet	
	per min	per flight	per min	per flight
Wing	1.5	20 (6)	49	595 (148)
Empen.	0.8	10 (3)	21	253 (64)
Nacelle	-	-	6	71 (15)
Total	2.3	30 (9)	76	918 (228)

Figure A-11: Fluid Usage for Two Aircraft Types, from [67]

A project study for a 100 passenger regional jet aircraft with NLF [43] estimated a 10kg fluid requirement per flight. This value is consistent with the above data for case where no fluid is used in taxi.

Spray nozzles can be attached to the rear surface of a Krüger flap, where one is used, such that it can discharge the fluid directly onto the wing leading edge. Such a system was used in the Jetstar Leading Edge Flight Tests (LEFT) program in conjunction with a shield [45]. The combination was reported to be successful.

A.1.2.1.3 Krüger Flap/Shield

Many LFC and HLFC concepts have used Krüger flaps in place of slats for a number of practical reasons. A Krüger flap is a section of the lower surface of the leading edge which can be hinged to allow it to be deployed to a position similar to that of a slat (full description in section 1). The Krüger flap can also be configured to shield the leading edge and forward parts of the upper wing surface during ground manoeuvring and low-level flight. Insects impact on the shield, which is then retracted into the lower surface after an initial climb, leaving the wing leading edge free of debris. However, the insect debris on the stowed Krüger flap and the spanwise step along its aft edge prevents any laminar flow on the lower wing surface.

Flight tests and wind-tunnel experiments have investigated the shielding effectiveness of a Krüger flap. Douglas installed a shield as part of its test article for NASA's Jetstar LEFT program [82]. An important phase of these tests was the Simulated Airline Service program where the aircraft was operated in a manner representative of commercial airline aircraft. The Krüger flap was deployed during take off and landing, i.e. below 4,000ft, greatly reducing the measured insect accumulation relative to an unprotected leading edge. The only two insect impacts detected were in the unprotected region close to the inboard end of shield. It was reported to be very rare for an insect, of sufficient size to cause premature transition to impact on the protected upper surface.

Boeing have conducted wind tunnel tests to investigate the effectiveness of the Krüger flap as a leading edge shield [135] on a 2 foot chord model in typical take-off and approach attitudes and configurations at $M=0.142$ and chord Reynolds number

$Re_c = 2 \times 10^6$. This investigated the impact characteristics of different size insects at a range of attitudes representative of taxi, take-off, and landing. No insect impacts reported were capable of causing transition on the upper surface. This work concluded that the Krüger flap provided a very effective means of contamination protection for Laminar flow applications to the upper surface.

A.1.2.2 Ice Formation, Freezing rain, Frost & Snow

During climb to, and descent from, cruise altitudes, supercooled water droplets ($< 0^\circ$ but still liquid) impinge on the forward facing surfaces, freezing on impact. This can alter the surface profile, significantly changing the aerodynamic characteristics of the surface. In some circumstances, large formations of ice can jeopardise aircraft safety.

However, even relatively minor ice accumulation can seriously effect the performance of an aircraft employing laminar flow technology. Clearly, any changes to the surface profile may cause disturbances to the pressure distribution and possibly produce adverse pressure gradients. Additionally the ice will form roughness elements. All of which will seriously degrade the extent of laminar flow. Where suction systems with perforated surfaces are used the ice formation will block the suction surface preventing any suppression of boundary layer disturbances.

Where freezing rain is encountered, the problems faced are similar, although ice formation may occur over a much greater area, resulting in roughness elements some distance from the leading edge.

If no action is taken to remove ice accumulated during climb, the low temperatures at cruise altitudes will ensure that the ice remains and that the holes stay blocked.

A.1.2.2.1 Ice Protection

There are two basic approaches for ice protection, “de-icing” and “anti-icing”. De-icing does not prevent ice formation but operates periodically to remove any ice accumulation before it becomes critical, whereas anti-icing operates continually during periods of icing to prevent any formation on the wing [99].

A common de-icing system is elastomeric inflatable boots installed on the leading edge surface which are periodically inflated to break and remove the ice. However, the implications on surface quality preclude the use of such systems. The use of hot bleed air blown onto the internal leading edge surface can be used continually for anti-icing, or periodically at greater flow rates for de-icing. Such systems may be used on NLF applications, although the substructure associated with a HLFC suction system would add complexity if adequate circulation is to be achieved.

It is likely that anti-icing systems will be required to prevent any ice formation within the suction perforations or on the internal face of the skin. One possibility is to operate a fluid discharge system, such as that required to prevent insect contamination (section 2). The fluid which acts a freezing point suppressant will mix with any atmospheric water encountered and run-off the rear of the surface.

On current transport aircraft ice protection is generally only applied to the outboard sections of the wing, as the impact of sectional changes due to ice formation is reduced

with increasing Reynolds number, and to reduce the possibility of wing tip stall. However, where laminar flow is required anti-icing will be required across the entire span to prevent surface roughness and widespread blockage of suction holes.

If HLFC engine nacelles are used, existing hot-air ice protection systems can be used as the suction is generally located away from the leading edge. Ice protection is not usually installed on fin and tailplane leading edges, although full span anti-icing would be essential if laminar flow was required on these surfaces.

A.1.2.3 Cloud Encounter

High altitude cirrus cloud is comprised of ice-crystals. When an aircraft with laminar flow enters such a cloud, the ice-crystals penetrate the boundary layer and can cause transition, although this is dependent on crystal size and concentration, and unit Reynolds number [31]. Numerous flight tests have demonstrated that even low concentrations of crystals significantly degrade the extent of laminar flow, with transition occurring close to the leading edge. Upon exiting the cloud, laminar flow is immediately re-established, with no long-term effects.

The primary benefit of laminar flow is reduced fuel burn. Time spent in cloud represents periods of higher fuel burn, which reduces the net operating cost benefits. For revenue earning laminar flow aircraft to be feasible, the penalties associated with time spent in clouds must not outweigh the benefits of laminar flow.

The NASA Global Atmospheric Sampling Program (GASP) evaluated the probability of cloud encounter on airline routes (above 20,000ft), and its variation with altitude, season and location [69] [97]. During 1975-1979, four commercial Boeing 747 aircraft were fitted with cloud detection instruments and flown in routine commercial service.

This program provided the most complete set of cloud encounter data available at aircraft flight altitudes to date. Approximately 88,000 cloud detector observations were made between a latitude range of 65°N and 35°S. These were classified into seven long range airline routes and three altitude bands. The resulting data, summarised in Figure A-12 overleaf, showed that for all routes/altitudes the probability of cloud encounter on more than 10% of a flight was less than 33%, the probability of cloud encounter on more than 25% of the flight is less than 10%, and the probability of encountering clouds on more than 50% of a flight is less than 1.5%.

The above data was further divided to investigate the effect of season, latitude, height above/below the tropopause, and the type of weather system [69].

In all cases the average time spent in clouds is less than 10% of the total cruise time, with this value decreasing with increased altitude in most cases. The figure of 90% time in clear air implies that cloud is not a major obstacle to the application of laminar flow to transport aircraft.

These tests were conducted at high cruise altitudes (>28,000ft). The regional aircraft considered as candidates for NLF may spend the majority of their time cruising at altitudes lower than this, due to short stage lengths. No data exists on the probability

of cloud encounter at these lower altitudes which are likely to be close to or below the tropopause.

The distribution of cloud on a specified route can also effect the fuel load required. If the cloud is concentrated in the latter stages of a mission, the fuel required to overcome the increased drag must be carried until required, further increasing the fuel load.

Code: No. of flights
 TIC_R % P(TIC < 10%), % TIC - Time in Cloud
 P(TIC < 1%), % P(TIC < 25%), % P(TIC) - Probability of Time in Cloud
 P(TIC < 5%), % P(TIC < 50%), %

Altitude band	28,500-33,500ft		33,000-38,500ft		38,500-43,500ft	
California-Hawaii	22		177		2	-
	9.4	67.8	5.5	82.6	-	-
	17.3	91.1	24.7	97.9	-	-
	47.6	98.8	62.8	100.0	-	-
East Coast-W Coast (US)	3	-	58		13	
	-	-	7.5	74.1	2.4	97.2
	-	-	20.1	94.7	41.3	100.0
	-	-	53.8	99.6	86.0	100.0
W Coast - N.W. Europe	6		26		26	
	9.9	66.0	2.7	96.0	2.8	95.6
	16.7	90.1	38.6	99.9	37.7	99.9
	46.2	98.6	83.1	100.0	82.2	100.0
E. Coast - N.W. Europe	38		99		24	
	9.3	67.8	7.9	72.6	3.4	92.9
	17.5	91.3	19.5	94.0	33.5	99.7
	47.8	98.9	52.3	99.4	76.9	100.0
Australia - S.E. Asia	16		20		-	-
	8.4	70.8	8.9	69.1	-	-
	18.7	93.0	18.0	92.1	-	-
	50.6	99.3	49.0	99.1	-	-
W. Coast - Japan	4	-	30	73.8	14	
	-	-	3.8	90.9	2.2	97.9
	-	-	31.3	99.5	43.5	100.0
	-	-	73.8	100.0	87.9	100.0
Japan - W. Coast	-	-	12		29	
	-	-	8.9	69.1	3.6	91.9
	-	-	18.0	92.1	32.2	99.7
	-	-	49.0	99.1	75.3	100.0

Figure A-12: Summary of GASP Data (from [69])

A.1.2.4 Cloud Detection

The need for cloud detection is twofold. Primarily to forecast the position and altitude of cloud along an intended flight path for fuel load planning purposes. Secondly, to automatically inform the flight crew and flight management system when the aircraft is actually encountering cloud, particularly thin cirrus cloud or during night flights. Although this does not aid fuel planning, it would allow data to be established for use on subsequent flights on the same route.

A.1.2.4.1 Remote Detection of Cirrus Cloud Formations

The most suitable platform for meteorological observations are satellites due to their large area of coverage. At the end of the 1980s, however, reliable detection, by standard meteorological satellite based sensors, of cirrus clouds was difficult because

they often form thin, broken layers and which are optically transparent [161] and hence susceptible to the effects of background conditions. They are often mistaken for lower altitude clouds or completely missed.

More recently, a satellite based method has been developed that is capable of detecting cirrus cloud, even thin broken layers, and determining their altitude. This is the VISSR (Visible and Infrared Spin Scan Radiometer) Atmospheric Sounder (VAS) installed on the GOES geo-stationary satellite in the mid-1980's. Fully described in [161], detection is achieved by measuring the extent of infrared radiation across a range of wavelengths with a spatial resolution of 7-14km. Analysis of this data allows the cloud top pressure to be specified in 50mb steps, from which the altitude can be estimated. If this shows that cloud is present within the scan area, the effective cloud concentration can be determined.

A.1.2.4.2 Aircraft based Cloud Detection Sensors

The installation of cloud detection instruments on aircraft will allow the flight management system to recognise conditions that are likely to degrade the drag reductions made possible by laminar flow technology. Such a sensor must be simple, and reliable such that it does not represent a significant cost or a major maintenance item.

As part of the Simulated Airline Service (SAS) test series within the Leading Edge Flight Tests (LEFT) program, two cloud detection instruments were evaluated along with the effect of particle size/density on the extent of Laminar Flow achievable [31].

The two instruments used, a Cloud Particle Spectrometer (Knollenberg Probe) and a Charging Patch, were able to detect the presence of cloud or haze. A Charging Patch is the simpler of the two, which is basically an electrically isolated patch of the aircraft surface, close to a leading edge. Particles impinging on this area generate a charge which can be measured. Calibration permits a level to be set which laminar flow will be adversely affected.

A Spectrometer was also mounted as this was capable of counting and sizing any particles encountered. This provided data with which the charging patch results could be calibrated.

The time in clear/unclear air measured by the two sensors was generally close (within 5%). However, in some cases the difference was as large as 60%, with more cloud detected by the charging patch. This is probably due to a higher percentage of time encountering smaller particles ($<60\mu\text{m}$) which were only detectable using this instrument. It was also noted that the total time spent in cloud was in the region of 6% of cruise time, which agrees with the GASP findings.

The Learjet flight tests [78] also included an investigation into the effectiveness of the charging patch for cloud detection. This concluded that this device was capable, not only of detecting cloud, but also of distinguishing the type of cloud formation encountered (i.e. stratus or cumulus).

A.1.3 Acoustic Disturbances

Acoustic disturbances, originating from sources external to the boundary layer, can amplify natural disturbances possibly causing premature transition. These external sources can be split into two categories, engine noise and vibration, and aerodynamic noise [115].

A.1.3.1 Aerodynamic Noise

As an airframe is moved through the air, noise is generated by steps, gaps, and cavities in the aircraft skin as well as within the boundary layer, Figure A-13. At transonic speeds, shock waves add substantially to aerodynamic noise.

The influence of shock wave location on noise was investigated during the 757 NLF flight tests [117]. The shock wave was found to move rearwards across the wing as the Mach number was increased toward its design values. Sound Pressure Levels (SPL) were recorded at two locations, close to the leading edge and at approx. 60% chord. In both cases the highest SPL was recorded when the microphone was immediately downstream of the shock wave, although it is noticeable that the SPL for the rear microphone at $M=0.8$ is greater than that for the forward microphone at $M=0.7$. The results for $M=0.75$ show that ahead of the shock the SPL is significantly less than that downstream even though the forward microphone is much closer to the shock wave. This is due to the local Mach numbers ahead of the shock being supersonic, preventing upstream noise propagation.

A.1.3.2 Engine Noise

This subject has been perceived as a major threat to the achievement of laminar flow over an aircraft's wing where wing mounted engines are considered. The engine noise can amplify TS instabilities within the boundary layer leading to premature transition. The composition of engine noise is very complex with many different spatially separated noise sources Figure A-13, with varying frequencies and intensities. This composition also varies between different engines, altitude and power settings as well as the position of a reference point with respect to the noise source.

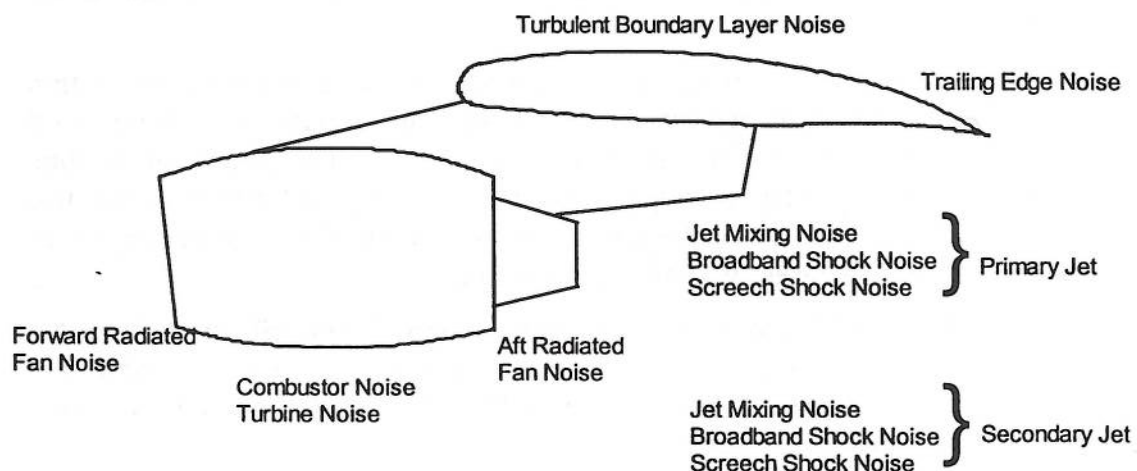


Figure A-13: Noise Sources, from [110]

However, projects conducted over the last ten years appear to conclude that the influence of engine noise from wing mounted engines is minor. The most relevant to laminar flow wings was the 757 NLF flight tests where a NLF glove, covering both surfaces, was attached to the wing just outboard of the engine location. At low engine settings NLF was achieved to 25%-30% on the upper surface and 15%-20% on the lower surface. These tests, with a 165kN (37,000lb) take-off static thrust PW2037 turbofan engine, found that the transition location on the upper surface was unaffected by power setting whereas a 2%-3% chord reduction in the extent of laminar flow was observed on the lower surface at high power settings, Figure A-14. It is believed that the wing structure shields the upper surface flow from the noise.

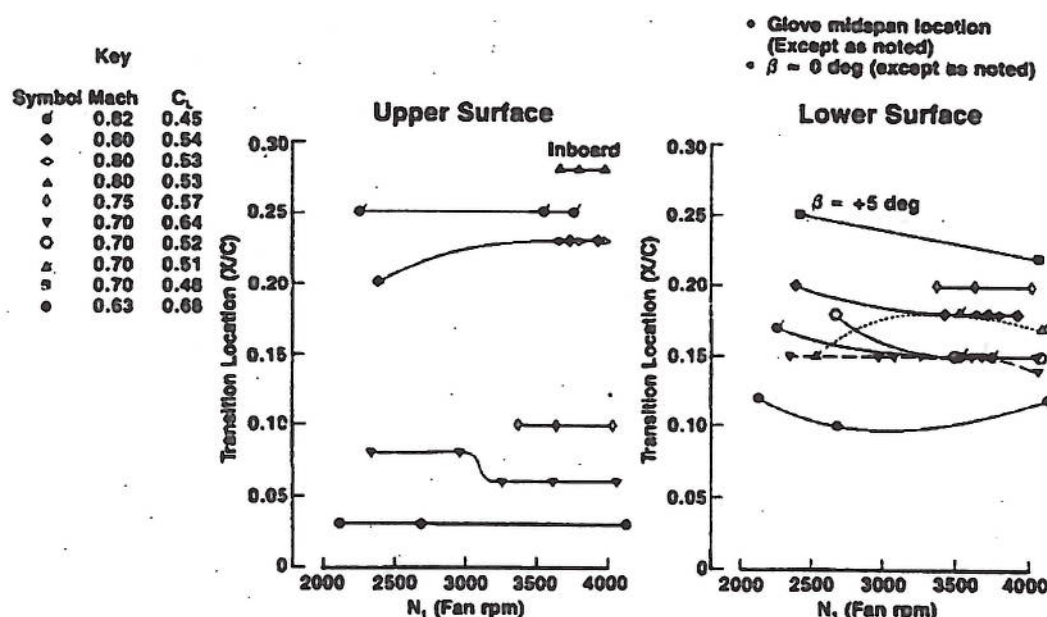


Figure A-14: Impact of Throttle Setting on Transition Location, from [117]

The DLR NLF flight tests, using the VFW-614 [65] with overwing mounted engines, also investigated this subject. Under most conditions no change in transition location was measured on the upper surface. However, when the sweep angle was increased by yawing the aircraft, the transition location moved from approximately 50% chord to 40% chord, when the power setting was increased from 50% to 92%.

During the NASA F-111 NLF flight tests [20], engine noise was also considered. No effect was reported, which is not surprising as the engines on this aircraft are buried in the aft fuselage, and therefore shrouded by the structure. The only possible noise would be aerodynamic and intake noise.

The threat of engine noise is very significant where laminar flow engine nacelles are considered due to their proximity to the noise source. General Electric [42] found that if a noise source is of a similar frequency to that of the TS instabilities, the extent of laminar flow was reduced by 3%-5% of the chord length. Clearly, if care is taken to ensure that no major components of engine noise are of a similar frequency to TS instabilities the impact of engine noise can be limited.

A.2 Natural Laminar Flow

A.2.1 NLF Aerofoil Section Design

As the extent of NLF over an aerofoil is highly dependent on the pressure distribution, the design of NLF aerofoil sections has formed a crucial part of all recent NLF projects. Considerable work has been conducted on NLF aerofoils for general aviation and business jet aircraft, with low lift coefficients, in the range of 0.2-0.25, [118] [145] [127] [57]. As the main aim of this research is to consider transport aircraft, only studies considering sections whose design conditions exceed $M=0.7$ and $2D C_L=0.4$ are included.

The issues that must be addressed when designing a NLF aerofoil section are discussed in [144]. A comparison of the upper surface pressure distributions for typical NLF and conventional turbulent aerofoil sections is made in Figure A-15. The most obvious difference is the lack of a pressure peak on the NLF section to achieve a favourable (negative) pressure gradient over the forward part of the section. This requires a sharper leading edge, along with a gradually thickening forward section resulting in lower local Mach numbers, and hence lift, over the forward region. The favourable pressure gradient extends to approximately 50-60% chord, where the shock occurs. This tends to move the aerodynamic centre aft increasing section pitching moments.

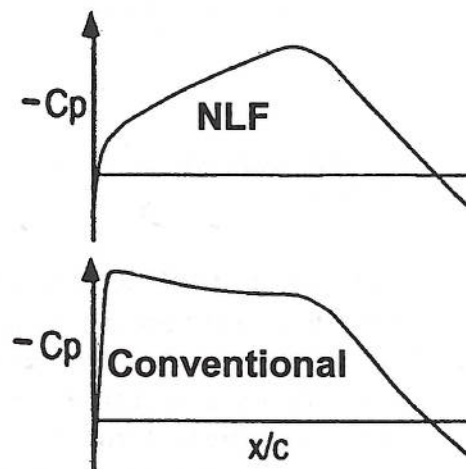


Figure A-15: Typical NLF Pressure Distribution, from [26]

Reduced nose radius also reduces the maximum lift coefficient, which for wings with symmetrical sections is approximately proportional to the square root of the leading edge radius. This is because of earlier formation of leading edge separation bubbles, as incidence is increased, resulting in an undesirable sharp stall onset. For practical wing sections increased camber may partially offset the reduction in maximum lift coefficient, this is restricted by cruise considerations such as suitable positioning of the attachment line for laminar flow [15].

Another important consideration with a sharper leading edge is the movement of the attachment line location with incidence during cruise. Movement to regions of increased radius may cause local ALT or pressure peaks, thus destabilising the laminar boundary layer

Typically the maximum thickness of a NLF section occurs further aft, relative to a turbulent equivalent, possibly resulting in increased height for the rear spar which can improve structural efficiency and the available fuel volume, although a sharper leading edge may reduce the height of the front spar.

A number of approaches have been considered to produce satisfactory NLF sections with higher lift coefficients. Increasing the rear loading by appropriately shaping the mid- to rear surfaces of the aerofoil. This increases the upper surface Mach numbers, reducing upper surface pressure, thus increasing lift, although increased shock development may occur if they are increased excessively. An alternative is to alter the lower surface to reduce the local Mach numbers, creating a thinner aerofoil, which leads to reduced structural efficiency and fuel volume. A compromise is to create a concave lower surface close to the trailing edge which decelerates the flow, decreasing the local Mach number, again increasing lift. However, increased pitching moments are inherent with rear loading as the aerodynamic centre is moved even further aft.

A sharp leading edge along with slight undercutting of the forward section of the aerofoil can lead to forward loading, i.e. reducing the lower surface flow velocity over the forward 20% of the aerofoil. This has the effect of moving the aerodynamic centre forward, although pitching moments due to aft loading will not be totally removed as the moment arm associated with the aft loading is greater. Problems associated with reduced nose radius are discussed earlier.

In order to design optimum NLF sections for transport aircraft, a compromise must be made between all of the above issues. To achieve this, computational methods have been developed based on flight and wind tunnel test data.

Some of the earliest designs for NLF aerofoil sections are those forming the NACA 6 series of sections which were designed in the 1940s, for low profile drag over the limited range of lift coefficients encountered during cruise. Typical drag polars for both an unswept and swept laminar flow wing are shown in Figure A-16. The reduction in drag, the "drag bucket", at cruise lift coefficients, is clear, with the additional impact of 3-dimensional cross flow instabilities evident on the swept wing.

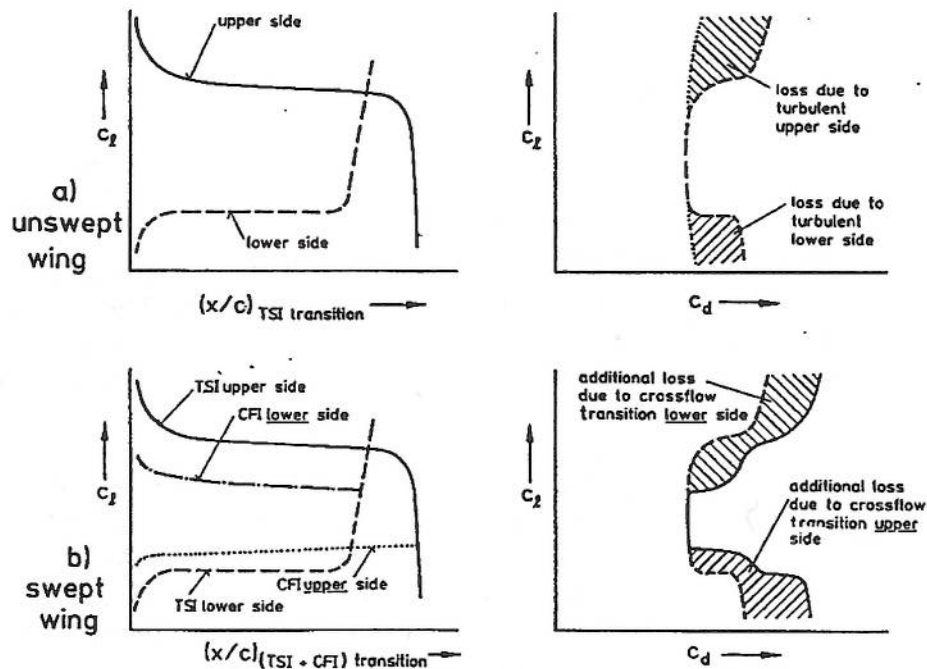


Figure A-16: Typical Drag Polar for Laminar Flow Aerofoils, from [113]

The drag bucket occurs over a limited range of lift coefficients, within which the pressure distribution is suitable for laminar flow. Laminar flow aerofoils need to be designed to ensure that all cruise conditions occur within the drag bucket to achieve the required extent of laminar flow.

More recent studies, conducted during the since the early 1980s, has considered NLF aerofoils for high sub-sonic transport aircraft. The Canadian National Aeronautic Establishment (NAE) have developed and tested a family of four transonic supercritical NLF aerofoils, with design $C_L=0.6$, for $M=0.68-0.8$. A number of European institutions, DRA, ONERA and DLR, have designed and tested their own transport aircraft sections. NASA conducted a theoretical study [144] to design a variety of NLF sections, including one for transport aircraft, to operate at $M=0.8$, $2D C_L=0.45-0.5$ and a chord Reynolds number of 30 million.

A.2.1.1 Cruise Performance

NLF aerofoils are optimised to achieve the greatest extent of laminar flow during cruise where flight conditions are steady, Reynolds numbers are lower, and most of the fuel is burnt

The results from a selection of wind-tunnel and computational studies are summarised in Figure A-17. Further details are available in the references shown.

	Ref.	Thickness / Chord Ratio	Lift Coefficient	Reynolds Number (million)	Mach Number	Transition		Drag Reduction
						Upper Surface (% chord)	Lower Surface	
NASA	144	11.1%	0.45-0.50	30.0	0.8	70%	60%	55%
NAE	73	21%	0.6	14.5	0.68	70%	50%	~50%
NAE	73	16%	0.6	14.5	0.72	70%	50%	~50%
NAE	73	13%	0.6	14.5	0.76	70%	50%	~50%
NAE	73	10%	0.6	14.5	0.80	70%	50%	~50%
DLR	112	12%	0.6	11.0	0.74	70%	60%	

Figure A-17: Summary of NLF Aerofoil Studies.

For the Mach 0.8 NAE section, the total drag was found to decrease gradually with increasing Mach number up to the design value of 0.80-0.81 and then increase sharply at 0.82 as the effects of wave drag increase. At the design conditions shown in Figure A-17, all of the aerofoils show reductions in drag of about 50% compared to the fully turbulent values.

The drag rise Mach numbers for all the sections was typically only 0.01-0.02 greater than the cruise Mach number. For turbulent flow, it was noticeable that the margin between cruise and drag rise Mach numbers was even less than that for laminar cases.

As part of their transport aircraft studies [43] [140], ONERA, Aérospatiale and DLR have conducted a number of wind tunnel tests for NLF sections. The French participants conducted wind tunnel tests on a infinite yawed (14.9° sweep) NLF section during the late 1980s [140] [3]. At the design conditions of $M=0.76$, $0.36 < C_L < 0.55$ and $Re_C = 22 \times 10^6$, laminar flow was achieved to 60% chord on both surfaces. When the drag polar results for this test are compared with fixed transition results, Figure A-18, the drag reduction is clear.

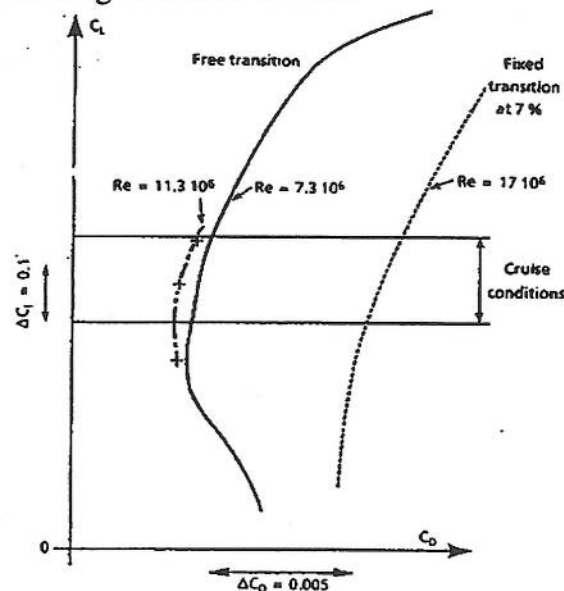


Figure A-18: Drag Polar for French NLF Study, from [140]

DLR have conducted wind tunnel tests [112], in conjunction with ONERA, on the DLR-LV2 aerofoil. This section was a 12% thick transonic aerofoil, intended for use on a transport aircraft with a 20° swept wing at design conditions of $M=0.74$,

$C_L=0.6$ and $Re_C=26 \times 10^6$. The design pressure distribution is typical for NLF aerofoils, with no leading edge velocity peak and a favourable pressure gradient, giving laminar flow to 65% and 60% chord on the upper and lower surfaces respectively.

A summary of the results, on an unswept model, at $M=0.74$ and streamwise chord Reynolds numbers of 6.8×10^6 , showed that the laminar drag bucket included all typical cruise lift coefficients. No results are published for the turbulent cases are available for comparison, although an interruption in the smooth curves for $C_L=0.7$ (transition is forward of 20% chord) implies that a 25% section drag reduction may be achievable. Computational studies of the NLF section, used for the ELFIN Fokker 100 flight tests, also showed the a distinct drag bucket due to laminar flow for cruise lift coefficients [126].

Details on the glove section used for the NASA 757 NLF flight tests are not available. However, results are available for the variation of laminar flow with 3D lift coefficient and Mach number, Figure A-19. The mid-span results are more important as they are not likely to be influenced by the effects of the glove edge. These results show only minor variation of upper surface transition location with typical values for cruise. The lower surface shows an increase in NLF extent with increasing C_L , agreeing with other aerofoil results.

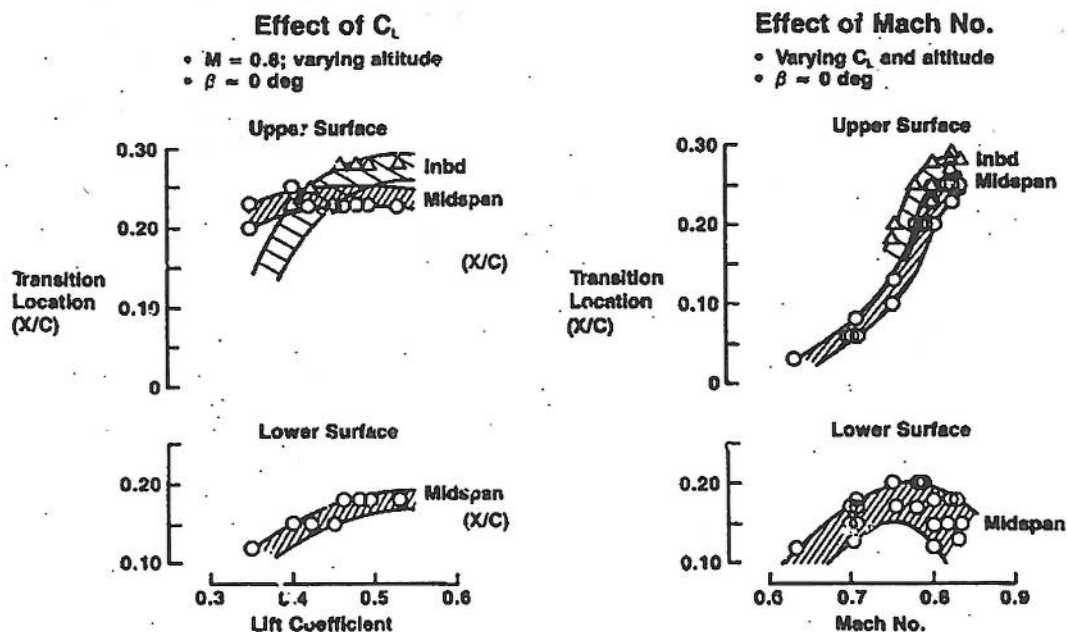


Figure A-19: Variation of Laminar Extent with C_L and Mach Number, from [117]

The effect of Mach number on the upper surface transition location is more marked, with a dramatic increase from 5% chord to almost 30% as the Mach number increases from 0.6 to 0.82. Again this is a characteristic found on many of the NLF aerofoils described above. For the lower surface, the transition location moves aft with increasing Mach number up to 0.78, after which it moves forward. This is due to changes in the pressure distribution with Mach number.

A recurring feature of NLF experiments is the small difference between the design cruise Mach number and the drag rise Mach number. This is typically less (0.01-0.02) than on turbulent aerofoils (typically 0.04). As a result of the upper surface pressure distribution, a rapid increase in shock strength occurs when Mach number or lift coefficient are increased above the design condition.

A.2.1.1.1 Laminar Boundary Layer-Shock Interaction

Where aircraft are designed for operation at high-subsonic conditions, the local flow velocity over parts of the airframe surface are supersonic, causing compressibility effects to occur, in particular shock formation. Modern transonic (supercritical) turbulent aerofoils, used for transport aircraft wings, are designed to achieve extensive regions of supersonic upper surface flow terminating in a shock along with an associated rapid flow deceleration. The strength of the shock and its effect on the boundary layer determines the extent of compressibility (wave) drag.

A wind tunnel study was conducted to investigate the boundary layer-shock interaction for turbulent and laminar flows [133] on a common aerofoil. Over a range of freestream conditions, stronger shocks were observed with laminar flow conditions, relative to turbulent flows. A separation bubble extending up to 20% of the chord was observed compared with a much smaller separation bubble for the turbulent flow. Both observations indicate that the high-speed performance of the aerofoil was superior with turbulent flows.

A number of systems have been proposed to reduce the shock strength. A passive system, described in detail in [140] [149], involves placing a cavity, covered by a porous surface, in the upper surface below the shock location during cruise. This recirculates air from the downstream to the upstream side of the shock, thus spreading the deceleration. An active system, [6] involves a small deployable bump at the shock location. This is extended during cruise causing compression waves ahead of the shock wave which reduces the Mach number immediately upstream of the shock, thus reducing the shock strength.

Both passive and active systems require further work to allow a better understanding of the processes involved and their potential benefits.

A.2.1.2 High Lift Performance

Leading edge slats can not be used on NLF configurations as its rear edges will form steps when the slat is stowed during cruise. The sharper leading edge gives a higher suction peak for a given lift coefficient, and hence a lower $C_{L_{max}}$. This may also limit the maximum incidence achievable, an important consideration for take-off and approach to ensure safe operation. The rear spar depth of NLF sections tends to larger, compared to turbulent sections, resulting in a thicker flap and an improved flap pressure distribution improving the maximum lift to a value close to that for a conventional wing with no slat.

This issue was addressed for a regional jet aircraft [56] which concluded that the limited nose-up attitude would prevent significant flaring prior to touchdown increasing landing speed and the risk of nose landing gear damage.

This concurs with 1990 Aérospatiale wind tunnel tests [25] where a double slotted trailing edge flap was considered on an OAS100 aerofoil. For a clean wing, 2D C_{Lmax} was achieved at 12° angle of attack Figure A-20, whereas at full flap deflection C_{Lmax} has greatly increased with the section stalling at -2° angle of attack.

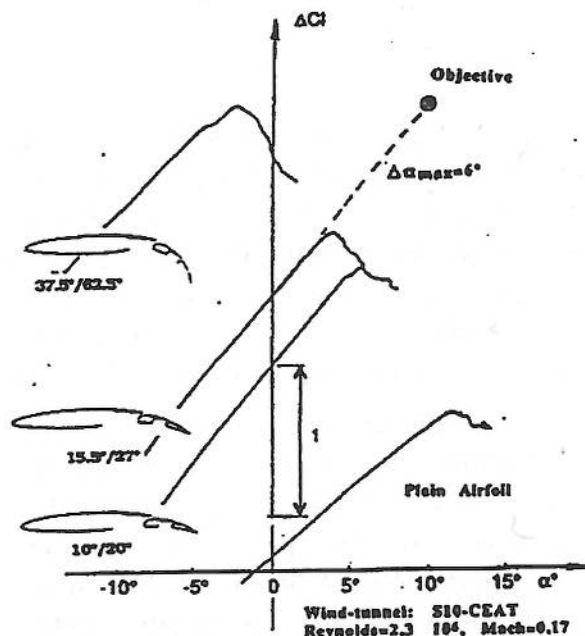


Figure A-20: High lift Performance of OAS100 Aerofoil, from [25]

Tests were also conducted to investigate the feasibility of using a leading edge suction system to prevent flow separation at the leading edge in high α conditions. Although this resulted in an increase in the maximum angle of attack, it remained significantly below the limit required for normal operation. If the penalties associated with a suction system used for high lift alone are also considered, this approach appears unfeasible.

No data is available for the performance of the Canadian aerofoils with high lift devices although in a clean configuration the three thicker sections achieve C_{Lmax} close to $\alpha = 15^\circ$ and the thinnest aerofoil, 10% thickness/chord, stalls at $\alpha = 9^\circ$.

All of these tests, wind tunnel or in flight, were conducted at chord Reynolds numbers in the region of $4-5 \times 10^6$, primarily due to short chords. This is representative of small business aircraft only, with no published data yet available for higher Reynolds numbers. Clearly, the choice of leading edge radius for an NLF aircraft is a compromise between the conflicting requirements of the cruise pressure distribution or the attachment line transition and the low speed performance.

The solution, for large and small aircraft alike, may well be to use the maximum allowable leading edge radius that does not create a leading edge pressure peak and avoiding attachment line transition during cruise.

A.2.2 NLF Nacelles

Rolls-Royce Aero-Engines and General Electric Aircraft Engines led research programs have performed flight tests that have demonstrated that significant extents of

NLF could be achieved. These required suitable shaping of the nacelle surface to produce favourable pressure gradients over the forward regions. A typical NLF nacelle pressure distribution is shown in Figure A-21 along with a typical conventional pressure distribution for comparison.

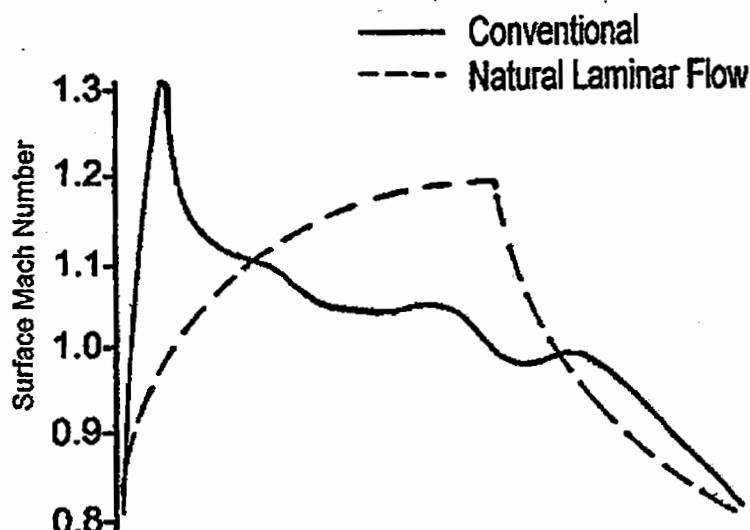


Figure A-21 Pressure Distribution on NLF Nacelle, from [91]

The influence of the engine noise on laminar flow extent was a major consideration in these tests. Only minor, 3-5% nacelle length, movements in transition were recorded during the G.E. flight tests, when a range of frequencies and intensities were generated within the nacelle. These tests were not representative, as engine noise is more complex than the discrete tones used. The Rolls-Royce tests provided a more realistic situation with the original nacelle replaced by an NLF replacement about the M45 engine.

Off-design considerations are of primary importance. The sharper leading edge lip, required to prevent a lip velocity peak (section A.2.1), degrades low-speed, high incidence performance due to increased likelihood of flow separation on the internal surface [38]. This is undesirable and could result in an unacceptable flow quality at the engine face. G.E. considered several techniques to improve the situation [42], although all were found to be impractical. At cruise conditions, the impact of limited aircraft yaw on the Rolls-Royce/DLR NLF nacelle was shown to be minimal [116], although low speed conditions were not investigated.

A further problem with NLF nacelles is that the engine suction, during ground and low level operations, would draw insects and debris towards the engine at high velocity, leading to higher probability of impingement on the nacelle lip.

The G.E. wind tunnel tests also considered the effect of Nacelle/Pylon/Wing integration for a NLF nacelle [75] at cruise conditions of $M=0.80$ and wing 3D $C_L=0.45$. This concluded that the interference drag is either the same, or less, when the NLF configuration is compared with that for a turbulent equivalent.

In general, it is concluded that it would be unlikely for NLF nacelles to be considered for aircraft any larger than executive jets where the small size of the engine allows a smaller lip radius necessary for NLF.

A.3 Hybrid Laminar Flow Control

A.3.1 Cruise Performance

The aerofoil sections used on existing turbulent transport aircraft are the result of an ongoing development process that has steadily increased the aerodynamic efficiency of wings, during the last 40 years. These wings are designed to be operated efficiently close to limits imposed by significant increases in wave drag, and buffet criteria ([142] p245).

The introduction of laminar flow represents an additional design criterion that must be satisfied along with all existing considerations. The issues raised for NLF section design are also relevant to HLFC sections although leading edge suction reduces the severity of the constraints imposed for NLF, as explained in section 1

Typically transonic HLFC aerofoil sections have been designed with pressure distributions having a small peak close to the leading edge, followed by a region of increasing pressure (an adverse pressure gradient) over the suction region, after which the 'roof-top' has a mildly favourable pressure gradient [19] [160] [21]. Such a pressure distribution has been found to maximise the extent of laminar flow.

However, aerofoils of this type are often are prone to increased shock growth which result in earlier occurrence of drag rise conditions, relative to an aerofoil with an adverse 'roof-top' pressure gradient [160]. In fundamental wing design terms this implies increased sweep, reduced thickness/chord ratio, and/or reduced wing loading, all of which reduce the aerodynamic and/or structural efficiency of the wing for a specified design condition.

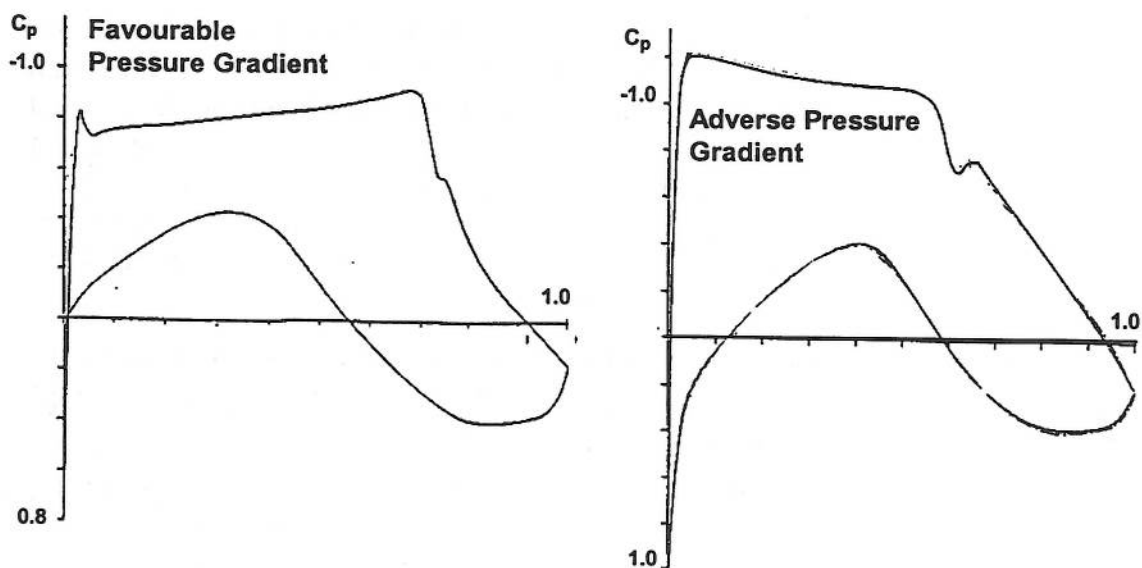


Figure A-22: Typical HLFC Pressure Distributions

An alternative approach may be to use an aerofoil with a mildly adverse 'roof-top' pressure gradient to improve wave drag and lift capabilities, albeit with a reduced extent of laminar flow. Careful consideration would be required to select an aerofoil section to achieve maximum aircraft efficiency and minimum operating economics with laminar flow and a suitable off-design performance. In addition, it is necessary to ensure adequate efficiency and economics with turbulent boundary layers.

Boeing have conducted successful HLFC flight tests in 1990 on a Boeing 757, where laminar flow was routinely achieved to 65% chord at cruise conditions on a 22ft span wing section [26]. This represents transition Reynolds numbers in the order of 20 million, much greater than any achieved during NLF flight tests. Indeed, the extent of laminar flow may have been limited by adverse pressure gradients related to the shock wave, or surface discontinuities resulting from the forward edge of the spoilers, rather than the Reynolds number.

As part of the ELFIN program, a 1.2m span HLFC suction system and glove was installed on a half scale 3D wing model of the VFW-614, with 28° leading edge sweep, model used for NLF studies [61]. When tested in the ONERA S1MA facility at 'realistic transonic conditions', laminar flow was achieved up to the aft extent of the HLFC glove at 55% chord [60]. The effect of suction rate and wing incidence on transition position and the predominant transition mechanism [59], summarised in Figure A-23.

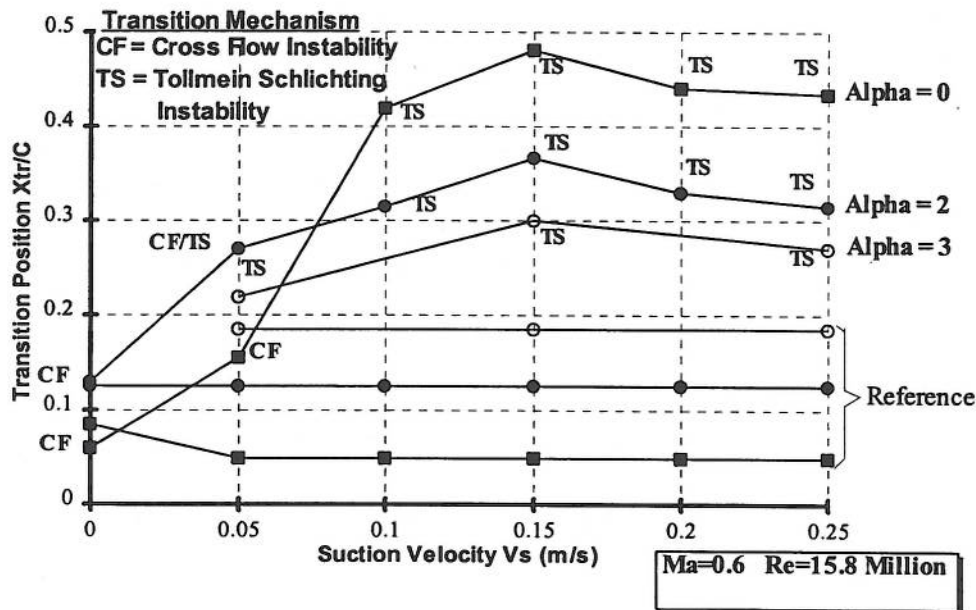


Figure A-23: Effect of Suction and Incidence, from [59]

At low suction rates (relatively constant suction rates around leading edge) transition occurs close to the leading edge due to the 3-dimensional cross-flow mechanism. As the suction rates were increased transition moved aft and was due to 2-dimensional Tollmein-Schlichting mechanism. It is also noticeable that the extent of laminar flow was reduced as the wing incidence was increased, probably due a more pronounced pressure peak increasing the amplification of disturbances.

NASA performed HLFC wind tunnel tests using an infinite yawed wing model. The 7ft chord model spanning NASA Langley's 8ft transonic pressure tunnel was swept to 23° , using the Pfenninger supercritical LFC section described in [104]. Experiments were performed for Reynolds numbers from 8-24 million, for three cases at Mach numbers between 0.805 and 0.826. In all but the highest Mach number cases laminar flow was achieved to 60%, where transition was probably due to adverse pressure gradients associated with the pressure recovery. For a Mach number of 0.826, significant adverse pressure gradients were not present until aft of 80% chord and transition occurred at 90% chord at low Reynolds numbers, reducing to 50% chord as the Reynolds number was increased to 24 million. Further detail is presented in detail in [19].

A.3.1.1 Prevention of Attachment Line Contamination

As discussed in section 2.1.3.1, the turbulent fuselage boundary layer can propagate onto the wing root attachment line, contaminating the boundary layer flow. A number of approaches have been investigated to prevent this since it was first identified during the 1950s.

For forward swept surfaces (section 3.1.3.1) the attachment line boundary layer propagates from the tip to the root, and hence is not prone to contamination from the fuselage, although extensive 3D flow at the tip may pose some problems. Other concerns currently preclude such configurations on transport size aircraft, although this approach may be suitable for smaller aircraft, such as business jets, provided the cruise Mach number is not too high, and hence only low sweep is required.

If it is assumed that rear swept wings are to be used then some means is required to remove the influence of the turbulent fuselage boundary layer. One such method is a "Gaster" bump, where a small fairing is attached to the inboard leading edge covering all possible positions of the attachment line during cruise. This creates stagnation conditions which deflect the contaminated upstream boundary layer over the wing. Downstream a new laminar attachment line boundary layer begins to develop, devoid of contamination. An similar approach is to use a leading edge notch, which acts in the same way as the "Gaster" bump.

The introduction of "Gaster" bumps, notches, and a combined notch-bumps to the Douglas LEFT test article, for the Jetstar tests [77] [82] [45], Figure A-24, resulted in dramatic improvements in the extent of achievable laminar flow across a range of conditions, Figure A-25. The range of attachment line positions for which a "Gaster" bump is effective is limited, although notches can be effective over a wider range.

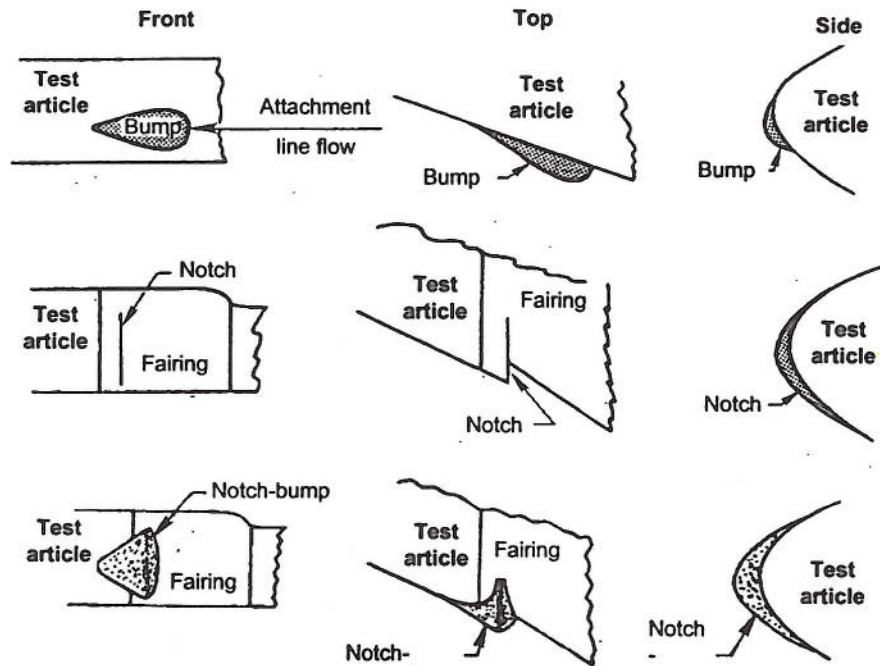


Figure A-24: Bump, Notch and Notch-Bump Configuration, from [82]

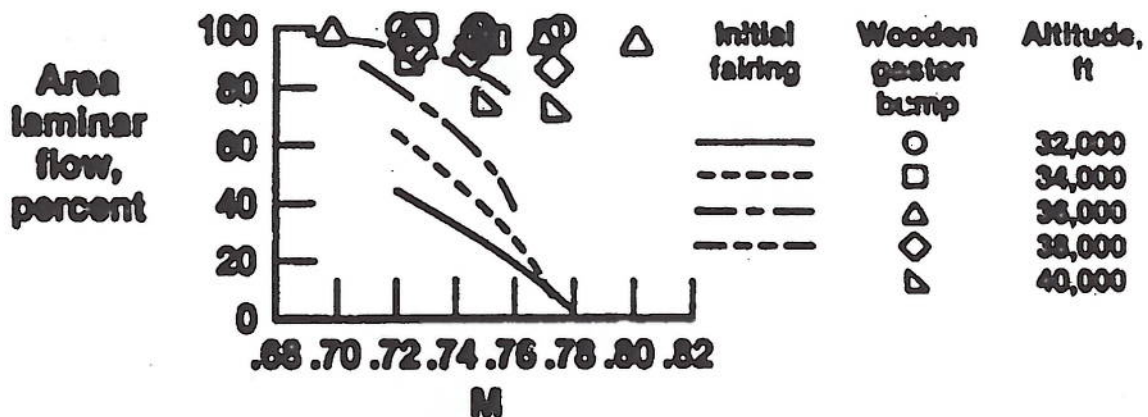


Figure A-25: Impact of Gaster Bump on Extent of Laminar Flow, from [45]

Careful consideration is required when locating the bump or notch along the span. It needs to be located far enough outboard to be outside the turbulent fuselage boundary layer. However, as laminar flow is not possible inboard of the bump, the distance from the root must be minimised. The optimum distance is therefore a function of the aircraft geometry and the worst case cruise conditions.

Suction of the attachment line region has been shown to be capable of reducing attachment line contamination thus preventing transition to turbulent flow. If the suction intensity is great enough it may relaminarise a turbulent boundary layer [105].

A.3.2 High Lift

Any transport aircraft employing HLFC must operate within the same airport/runway limits as those of current aircraft. Therefore, the off-design performance of HLFC configurations must also be taken into account to ensure the resulting aircraft is feasible. For laminar flow wings, the most important consideration will be the high lift performance. Any high lift devices must not interfere with the laminar flow system

during cruise. Clearly the leading edge devices, located in the area where a laminar flow is present are of most interest.

A.3.2.1 Leading Edge

The use of conventional leading edge slats with HLFC poses a number of practical problems, namely that much of the suction surface will be located on the moveable slat and that a rear facing step will be formed on the upper surface at the rear of the retracted slat in a region where the laminar boundary layers are most sensitive to disturbances. During cruise, wing bending may accentuate step size at points between the discrete supports. The suction surface and plenum chambers would have to be installed within the confined space in the slat structure, with some means to transfer the air into the fixed leading edge structure, such as flexible hoses or a socket that seals when the slat is retracted.

For many previous HLFC studies, Krüger flaps have been proposed in place of slats as these overcome many of the difficulties, although other solutions include increased leading edge suction to delay leading edge separation, or simply to delete all leading edge high lift devices. Generic configurations for leading edges equipped with slats or Krüger flaps are shown in Figure A-26.

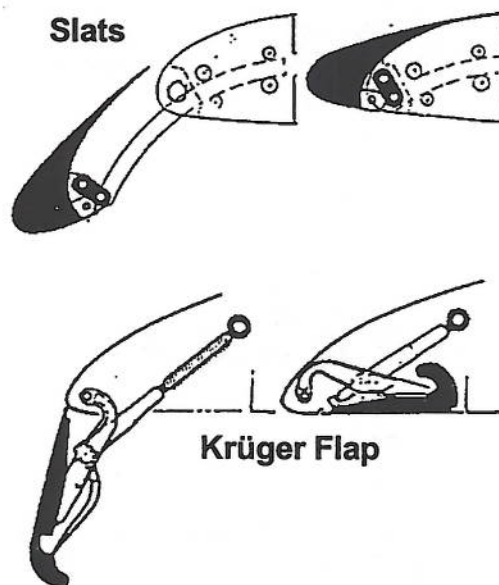


Figure A-26: Generic Leading Edges equipped with Slats or Krüger, from [99]

A.3.2.1.1 Krüger Flap

Krüger flaps act in a similar manner to a conventional slat when deployed ahead of the main aerofoil, effectively extending the chord and drooping the leading edge (increasing effective camber) of the wing. The fundamental difference between the two is that the stored slat forms the nose of the wing, whereas the Krüger flap is stored within the lower leading edge structure, with its outer surface forming the lower leading edge surface (Figure A-27). Krüger flap location and setting definition is similar to that used for slats, although the datum used for deflection can vary.

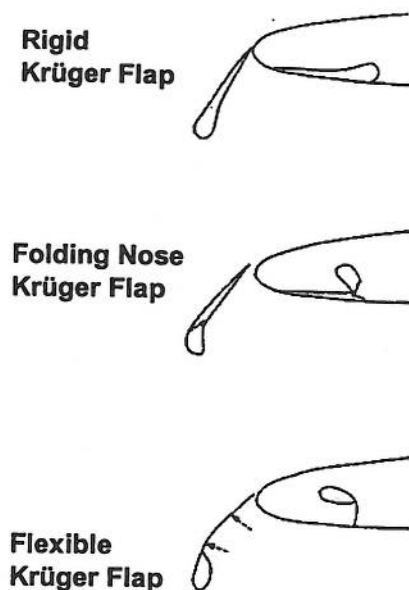


Figure A-27: Krüger Flap Configurations, from fig.2 [89]

Simple Krüger flaps, as used for inboard regions of Boeing 747 aircraft, hinge about a point close to the wing leading edge effectively drooping the aerofoil nose. For laminar flow applications, however, Krüger flaps have a secondary role to shield the leading edge region from damage and contamination during ground operation and low-altitude flight. Hence, the deployed surface must be positioned such that it shields the fixed leading edge in the line of flight, which necessitates a more complicated linkage system.

Wind-tunnel investigations of a slotted Krüger flap configuration [89] showed that a high-lift performance similar to a conventional slat is possible. Slotted configurations generally allow a higher $C_{L_{max}}$, due to increased incidence, than a sealed equivalent. The design of wings with Krüger flaps is discussed in [96]. Wind-tunnel and numerical studies [5] conclude that the 'high position' of a Krüger flap required for maximum shielding effectiveness results in early leading edge stall, relative a 'low position' with a more exposed upper surface. Conversely, a 'high position' Krüger, whose position was optimised, was reported to achieve 'maximum lift comparable with that of the same aerofoil model equipped with a leading edge slat' [135]. As a shield, it was shown to be very effective against insect contamination. Achieving adequate high lift performance with high position Krüger flap is important as this configuration provides the greatest shielding effectiveness.

The use of Krüger flaps can permit a slightly increased cruise L/D and $C_{L_{max}}$ to be achieved through increased optimisation of the forward upper surface, although Airbus trade studies have concluded that more complex and heavier support structure required outweighs the advantages [46]. However, a Boeing study [21], concluded that employing slotted Krüger flaps, instead of slats, on a HLFC 757 wing would provide 150kg (13.4%) leading edge mass saving.

Slat deployment results in a smooth increase in section lift, as the leading edge is moved forward and down. This permits an optimum slat position to be selected for each flight phase, such as take-off, hold, approach, and landing. The positions of Krüger flaps are

limited due to the kinematics required to ensure that all desired settings are included on the deployment path, and the need to lock the linkage system at each setting. Flexible Krüger flaps overcome some, but not all, of these problems, as the surface profile can be altered to provide more than one configuration.

Additionally, increases in lift do not occur until late in the deployment movement, indeed significant disturbances to the leading edge flow during early movement may increase drag. This may necessitate the use of sequential deployment across the wing, which would have the added advantage of lower power requirements. Any adjustments to deployed settings would require modification to the linkage system, which may pose problems if changes are required to correct any undesirable characteristics encountered during flight tests [80].

The slat acts as the wing leading edge when it is retracted, allowing the fixed structure leading edge to be optimised for high lift operation, which results in increased bluntness relative to the slat leading edge to delay separation at high incidence. For slotted Krüger flap configurations, the fixed structure leading edge is sharper due to cruise performance requirements. This is compounded by the sharper leading edges typically used on HLFC sections, relative to turbulent equivalents, section 1. These factors may limit the incidence at which maximum lift occurs for a clean wing. Bird-strike requirements may apply to the fixed leading edge structure as well as to the Krüger flap, whereas a slat covers much of the fixed structure at all times. The icing requirement is doubled as protection is required for the Krüger flap and fixed leading edge [80].

Laminar flow will prove difficult to maintain on the lower surface as the gaps at the front and rear of the stowed Krüger flaps are likely to trip the boundary layer. Wind tunnel experiments conducted under the ELFIN program [17], demonstrated the use of increased suction in and behind these gaps to achieve significant laminar flow, although very high suction rates were required.

A possible alternative solution proposed by Sonaca [99], uses a Krüger flap type device that can be deployed to cover the leading edge suction surface during ground operation, to prevent collision damage, and during icing flight, where a hot-air anti-icing system is activated. During normal cruise it is stored in the lower surface and in a conventional position for high lift operation. This is shown in Figure A-28

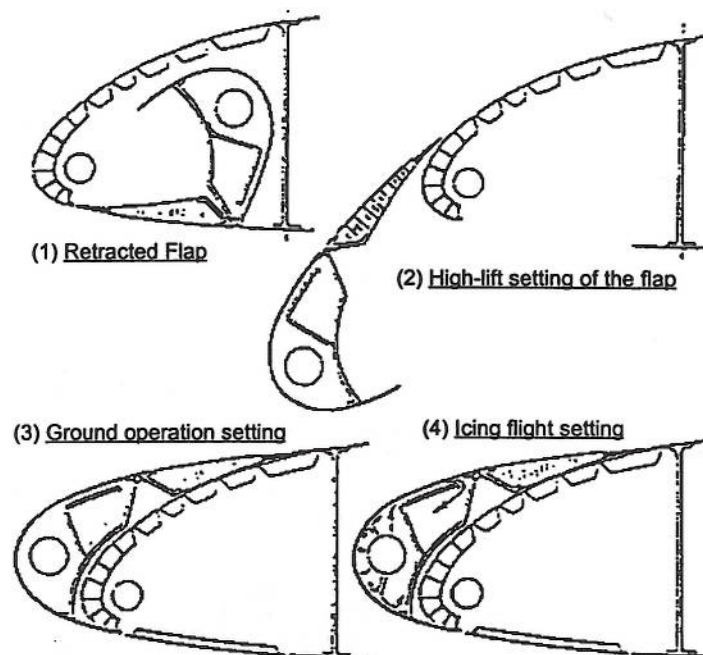


Figure A-28: Possible Configuration for Enhanced Krüger Flap, from [99]

A.3.2.1.2 Increased Leading Edge Suction

As discussed above, sharper leading edges are required for laminar flow aerofoils, which can result in separation bubbles and ultimately early leading edge stall. Slats or Krüger devices modify the leading edge configuration such that the high leading edge suction, associated with high incidence, are located on the devices. This reduces the suction on the basic aerofoil, delaying flow separation and increasing incidence at the stall and improving maximum lift capabilities.

The disadvantages of slats and Krüger flaps, with regard HLFC applications are discussed in sections 1 and 1, respectively. One possible alternative solution is to use increased suction rates [88] of 0.5-1m/s compared with typical cruise values of 0.15m/s, to reduce upper surface pressure coefficients thus delaying separation to improve high lift characteristics. However, the improvements were small, $\Delta C_{L_{max}} = 0.3$ and a 1° - 2° increase in stall angle. Similar results were achieved in previous studies [25].

Such an approach used in conjunction with a Krüger may be beneficial, although a full feasibility study would be required to assess whether the benefits would justify a more powerful suction system to achieve the higher mass flow requirements due to increased suction intensity and higher air density at low altitude. This system would also be classified as a powered lift system, leading to concerns within the civil certification authorities about asymmetry or shortfalls in required lift, should part of the system fail during final approach.

A.3.2.2 Trailing Edge

The impact of HLFC on the trailing edge flaps will be limited, in some studies [21] the flaps for the turbulent baseline aircraft have been maintained, although this, and other reports [26] have suggested that the rear element be capable of $\pm 5^\circ$ movement during

cruise to modify the attitude and pressure distribution. This, however, would introduce increased complexity into the flight control system. An increase in flap area may also be required to reduce the dependence on any leading edge devices. Increased section thickness at the rear spar on HLFC sections may allow thicker, stiffer, flaps leading to a reduction in the mass and complexity of the support structure.

A.3.3 Suction System Technology

Central to any HLFC application is the suction system. Clearly this must be capable of suppressing any boundary layer disturbances over the forward part of the surface, such that the flow remains laminar for some distance downstream of the suction surface. A typical arrangement for a HLFC upper surface suction system installed within the wing leading edge is shown in Figure A-29.

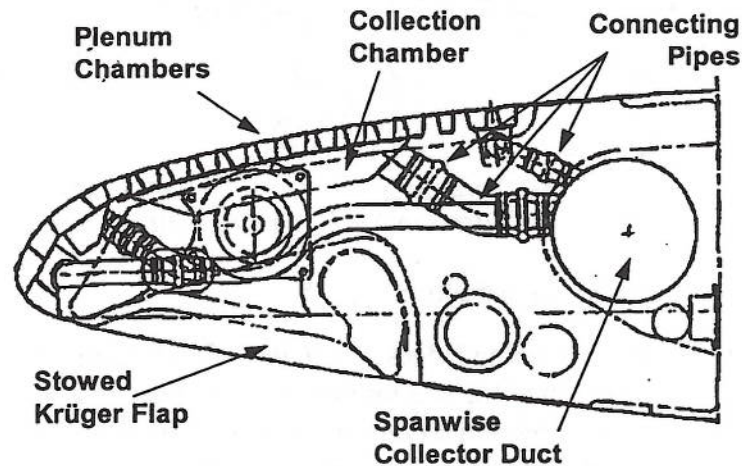


Figure A-29: HLFC Wing Leading Edge for a Transport Aircraft, from [68]

Air is drawn through the surface into the suction plenum chambers, where in this case it is gathered into a smaller number of collection chambers via metering holes. These chambers are connected by pipes to a main spanwise collector duct which transports the air to the suction unit (compressor). Downstream of the suction unit the air is exhausted to the atmosphere. The pressure variation through part of a proposed 757 HLFC wing suction system is shown in Figure A-30.

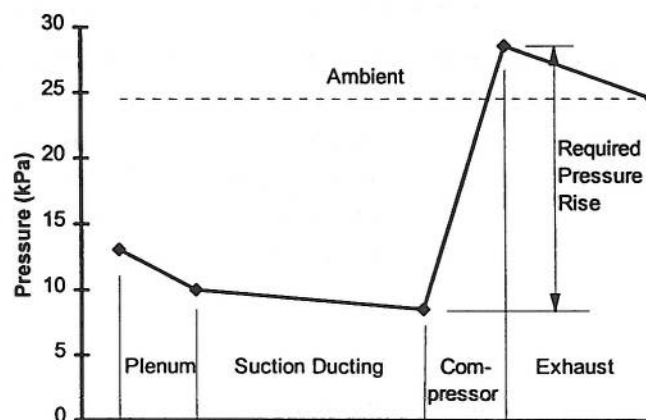


Figure A-30: Pressure Variation Through Suction System, from [21]

The use of a suction system will increase aircraft mass and complexity, and hence production costs, due to complicated, and sometimes novel, production techniques. Once in service, the suction system will add to the maintenance costs, considered in this study as a function of the system size and complexity.

The primary advantage of HLFC, over LFC, is that a smaller suction system is required. This can be housed in the leading edge structure ahead of the front spar, so that a conventional primary structural box can be employed, free from any disruptions. In cases where attachment line Reynolds numbers are greater than the critical values, suction must cover all possible cruise attachment line locations.

Where the leading edge Reynolds number does not exceed the limit for ALT, suction is only required in areas of high cross-flow and adverse pressure gradients, typically aft of 2% chord. Forward of this, a rapid flow acceleration prevents significant cross flow instability.

The aft extent of the suction is dependent on the pressure distribution and 3D geometry in the leading edge region, and as such must be determined for each application. Clearly if the suction surface area can be minimised then costs associated with surface drilling and ducting can be reduced, although the mass flows for the aft suction region are minor compared to those further forward.

The Falcon 50 flight test program [23] installed suction in the leading 10% wing chord of the upper surface only. When sweep was reduced, the extent of laminar flow was observed to increase, suggesting that three-dimensional disturbances had not been sufficiently suppressed, or that adverse pressure gradients were present.

ELFIN wind-tunnel tests used a suction system extending to 12% chord on the upper surface, behind which significant extents of laminar flow were achieved. Information on sweep angles other than 28° has not been published.

A suction surface extending to 25.7% chord was installed in the upper surface for the NASA HLFC wing wind-tunnel tests [19]. This was used to investigate transition position as a function of suction extent. Suction was required to 20% chord to delay transition to approximately 60%, with a rapid reduction to 30% chord as suction extent was reduced to 15% chord. Suction applied after 20% did not result in any further improvements, although this may be due to adverse pressure gradients at this location. It should be noted that the suction distribution was not published.

Conversely, BAe (Airbus) [119] and ARA [160] studies conclude that extending the suction from 15% chord to 20% only moves transition aft by 5%.

The suction surface for Airbus A320 fin wind-tunnel model extended up to 21% chord on both surfaces [139]. Suction to 15% chord was selected for a British Aerospace (Airbus) structural and systems demonstrator representing the mid-span section of a Airbus A340 wing [68]. This value was also selected for Boeing and NASA project studies, [21] and [2], respectively.

Suction requirements for HLFC engine nacelles differ from other surfaces, in that the flow is primarily 2D. Hence, the suction is required to suppress the growth of 2D instabilities resulting from adverse pressure gradients, natural disturbances and

roughness elements over the forward part of the nacelle. Therefore, suction is only applied in regions of adverse pressure gradients. Although dependent on nacelle shape this is typically between 10% and 20% chord. This approach was followed by both General Electric, suction from 8% to 23% [137] and Rolls-Royce, suction from 8% to 28%, [91] for flight tests.

To define a suction system for a specified application, the aerodynamic requirements must first be assessed, resulting in a suction rate distribution capable of suppressing all boundary layer disturbances over the forward regions of the surface, allowing laminar flow to some point downstream of the suction surface. From this the suction system components can be defined and sized.

A.3.3.1 Suction Distribution

Airbus A320 fin and ELFIN wing wind-tunnel tests both reported that a mean through-surface velocity (total volume flow/area of suction) of $0.1\text{--}0.15\text{ms}^{-1}$ was required at typical cruise speeds.

However, the level of suction required at any given point on the suction surface is primarily a function of the predominant type of local boundary layer instability, TSI, CFI or ALT. Other factors are the 3D surface geometry, pressure distributions, and the flight conditions.

To compare suction rates at different flight conditions, a suction coefficient, C_q can be defined to provide a non-dimensional suction term [101]:

$$C_q = \frac{\rho_o v_o}{\rho_\infty v_\infty}$$

Where v and ρ denote velocity and density, and the o and ∞ subscripts refer to the sucked air and freestream conditions, respectively.

This can be approximated as the ratio of the mean through wall suction velocity to freestream velocity [107], as differences in density will be minor compared to that between the velocities. The $0.1\text{--}0.15\text{ms}^{-1}$ mean suction rates mentioned above correspond to a suction coefficient of $C_q \approx 0.0003\text{--}0.0005$.

This should not be confused with U.S. references [21] [45], which although still non-dimensional defines the suction coefficient as:

$$C_Q = \frac{Q}{V \cdot S_{\text{Ref}}}$$

While [21] denotes "Q" as volume flow (m^3/s), [45] uses kg/s and subsequently multiplies the lower part of the above expression with a density term. "V" and " S_{ref} " are defined as freestream velocity and gross wing area, respectively. If the " S_{ref} " term is defined as the suction surface area, the two terms will agree.

To minimise the volume, or mass, flow of sucked air, the minimum suction coefficient required to maintain laminar flow would need to be defined for each point. However, practical suction systems divide the suction surface into separate chordwise and spanwise regions, to each of which a fixed suction coefficient is applied.

The suction surface is typically divided into three chordwise zones, reflecting the dominant boundary layer instability in that zone. Within each zone, a number of narrow spanwise suction chambers are used to allow limited variation in suction coefficient. These are necessary to prevent outflow, and to provide support to the suction surface. Outflow can occur where significant pressure gradients exist across a suction panel. The suction pressure required for areas of high external pressure may be greater than the external pressure in other areas of the surface, causing air to be injected into the external flow from the suction ducting. Outflow must be prevented as even small amounts are believed to de-stabilise the boundary layer causing premature transition [105].

The spanwise suction chambers are attached to the internal face of the suction surface, resulting in a series of suction strips interspersed with blanked strips at the attachment locations. Clearly it is desirable that the chordwise extent of these suction interruptions are minimal to achieve a surface that can be considered continuously porous.

For all reported HLFC applications on swept surfaces, it is noticeable that higher suction coefficients are used in the forward sections of the suction surfaces (Figure A-31), to suppress attachment line transition and contamination, as well as cross flow instabilities in the first 5-10% chord. The C_q values reduce to approximately a quarter of the maximum value over the rear sections of the suction panel.

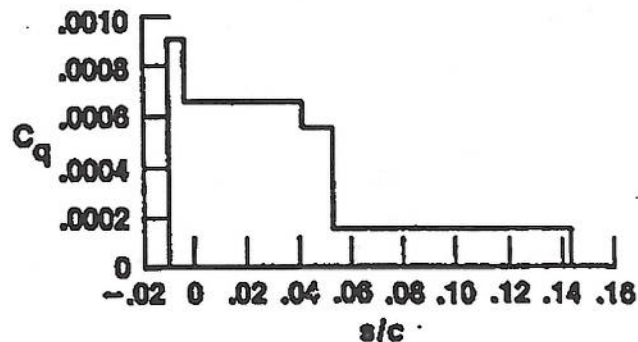


Figure A-31: Summary of Suction Distributions, from [45]

During cruise, the wing attachment line Reynolds number, R , for transonic transport aircraft typically exceeds the critical value (section 2.1.3) across all or part of the span. Hence, disturbances within the boundary layer will be naturally amplified to a point where transition occurs. R is a function of leading edge sweep, attachment line radius and flight conditions.

Suction along the attachment line can be used to stabilise the boundary layer. The suction thins the boundary layer which results in a more stable flow [4]. Suction has the effect of increasing critical R values, or reducing the $R\theta$ value of the flow [139], to a point where any disturbances in this flow are suppressed.

Experimental results [105] have shown that the attachment line boundary layer can be stabilised or laminarised using suction, for R values in excess of 600. The R value for the inboard region of an large transport aircraft (A340 class) wing is reported to be in the order of 700 [114], and is likely to be nearer 1,000 for an aircraft in the

‘super-jumbo’ class. This is primarily due to the increased size, and hence leading edge radius, for the larger aircraft.

Although the leading edge radius for a fin is less than that for a wing, the increased leading edge sweep leads to possibility of ALT at some locations at cruise conditions. The R value across an A320 fin [139], a small transport aircraft, is in excess of the critical value of 250 along almost its entire height.

It is clear that the level of suction required to suppress CFI is primarily dependent on leading edge sweep, the chord Reynolds number and leading edge geometry. Examination of the results from NLF flight tests (section 3.1.1) shows a reduction in transition Reynolds number with increasing leading edge sweep. This is due to greater CFI intensity increasing the overall level of boundary layer disturbances.

Provided all 3D disturbances are removed in the attachment line and cross-flow regions, the suction rates required in the Tollmein-Schlichting region are generally dependent on the pressure gradient and Reynolds number, with higher suction coefficients required for increased adverse pressure gradients.

If a tapered surface is considered, attachment line and cross-flow suction coefficients will both decrease with distance from the inboard end due to Reynolds number effects, resulting in spanwise variation of the optimum suction coefficients. To provide this spanwise variation, the suction surface is divided into panels. For each panel the suction coefficients are approximately constant in a spanwise direction, and are determined by the higher Reynolds numbers at their inboard end. Away from this, the suction coefficients will be greater than the required value. Clearly, shorter panels will result in reduced excess suction across the span, although the increased number of discontinuities in suction rates and the panel joints, and associated turbulent wedges will reduce the laminar area. The effect of panel length on the area of laminar flow lost, assuming a turbulent wedge of 10° half angle at each panel joint, increases as the panel is shortened. If an A340 size wing is considered, the area of laminar flow, based on transition data presented in [160], rapidly reduces for panel lengths less than 3m, Figure A-32.

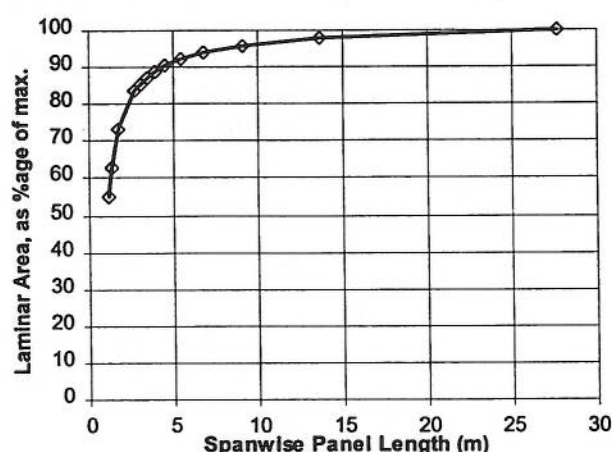


Figure A-32: Impact of Panel Length on Laminar Area on an A340 size Wing

If part of the leading edge is damaged or defective, replacing a short panel will be simpler and reduce costs. Manufacturing constraints limited the length of suction panels to less than 3m for the BAe systems demonstrator [68], for which 2.2m panels were selected due to structural considerations. The A320 HLFC fin flight test article uses two suction panels, each approximately 2m in length [85], Figure A-33.

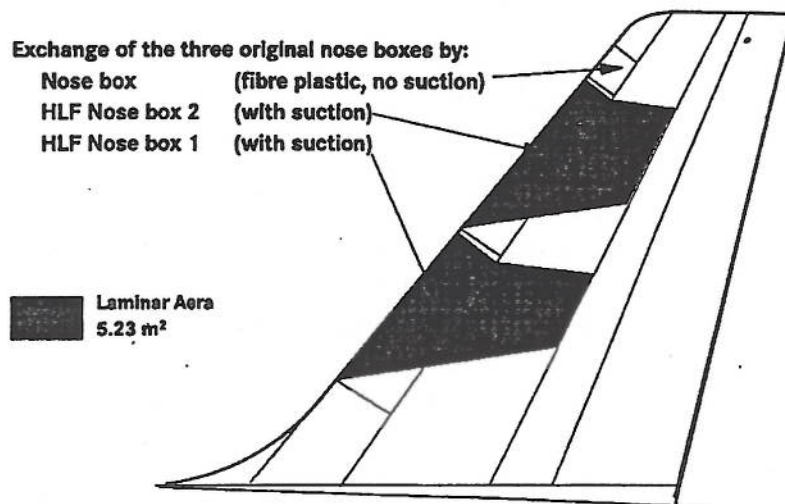


Figure A-33: A320 Fin Suction System Configuration

A.3.3.2 Structural Design of Laminar Flow Surfaces

Given the destabilising effects of even small surface mismatches or imperfections, particularly in the leading edge region (section 1), considerable attention must be paid to the structural design of the suction surface to ensure that the stringent surface requirements are met. The structure must be easily removable to permit inspection and repair/replacement of the leading edge structure, high-lift system, cabling and suction ducting. Processes must be developed to ensure that subsequent to maintenance, the surface finish is within the required tolerances for laminar flow.

The surface tolerances for current structural repair procedures, defined by aerodynamic criteria, are approximately 0.8mm (0.031 in.) for a step normal to, and 1.0mm (0.039 in.) parallel to the airflow [84]. A comparison of these values with the limits for allowable step sizes, Figure A-2 Section 1, shows that maintenance procedures would have to be modified significantly in the leading edge region to ensure that laminar flow is possible throughout the service life of an aircraft.

The current structural tolerance for rivets after repair is 0.15mm protuberance above the external skin. The limit required for a laminar flow surface is dependent on the final shape (diameter/height) of the rivet head after finishing. However, it is probable that additional care will be required to ensure that the laminar flow is not disrupted by rivet heads.

The allowable limits for laminar flow on the main structural box are not clear, although only minor filling and smoothing of the original Boeing 757 wing box structure was needed to produce a surface capable of sustaining extensive laminar flow during HLFC flight tests [26]. Earlier NLF tests on the same aircraft achieved 30% chord laminar flow with a composite glove [117], whose surface quality was

similar to that of the original wing surface. However, it should be noted that this is a research aircraft and may have lower utilisation rates, and less exposure to the operational hazards associated with commercial operation and maintenance.

For wing, fin and tailplane structures, the principal surface imperfections are the spanwise attachments of the leading and trailing edge assemblies to the main structural box. Of these, the leading edge joint is the more critical as it is within the 5%-20% chord region where laminar flow is particularly sensitive to disturbances. On turbulent aircraft, this joint is usually designed such that only limited bending loads are transferred into the leading edge assembly. This results in a discontinuity which may cause transition. The possibility of integrating the leading edge and main wing box structure has been investigated for an NLF 100 seat regional aircraft [43], which although eliminating the leading edge/wing-box joint, impedes easy replacement of any damaged leading edge structure. The leading edge/wing-box discontinuity may be accentuated by the increased spanwise stiffness of the HLFC leading edge panels, due to suction plenums acting as stringers. A possible design solution is described in [68]. Conventional trailing edge joints are acceptable as transition will usually occur forward of this point

Although located away from the sensitive leading edge area, skin joints on the main structural box may also cause transition. Improved manufacturing practices have allowed larger skin panels to be processed, thus reducing the number of panels. On smaller aircraft (less than 100 seats), it may be possible to produce single piece wing-box skins. For larger aircraft, where this is not possible, the panels could be arranged so that any joints are located as far aft as possible. Of more concern are chordwise joints across the wing box which may need to be located within the turbulent wedges developing from leading edge due to the chordwise suction panel joints.

The chordwise joints within the leading edge structure are of critical importance as they are located within the sensitive region for the laminar boundary layer, the primary considerations being external smoothness and waviness, minimal hole blockage between panels, fabrication, installation and panel removal, weight and stiffness and panel life.

The design difficulties of these joints are compounded by the flexible nature of surfaces under consideration. A gap is required between panels to provide clearance for installation. This must then be sealed such that under operating conditions, principally compressive loading or cold temperatures, it does not bulge or distort causing transition. Six preliminary concepts, meeting the above considerations, are described in [44]. Two of these were selected for detailed structural evaluation, including compression and tension load in temperatures ranging from -54°C (-65°F) to 71°C (160°F). The chordwise joints used on the BAe systems demonstrator are described in [68].

Suction is not possible at the chordwise joints, which often results in a turbulent wedge at each junction. The orientation of the chordwise joints relative to the flow can be varied depending on the requirements, Figure A-34. Each of these has potential benefits and disadvantages that must be assessed for each application.

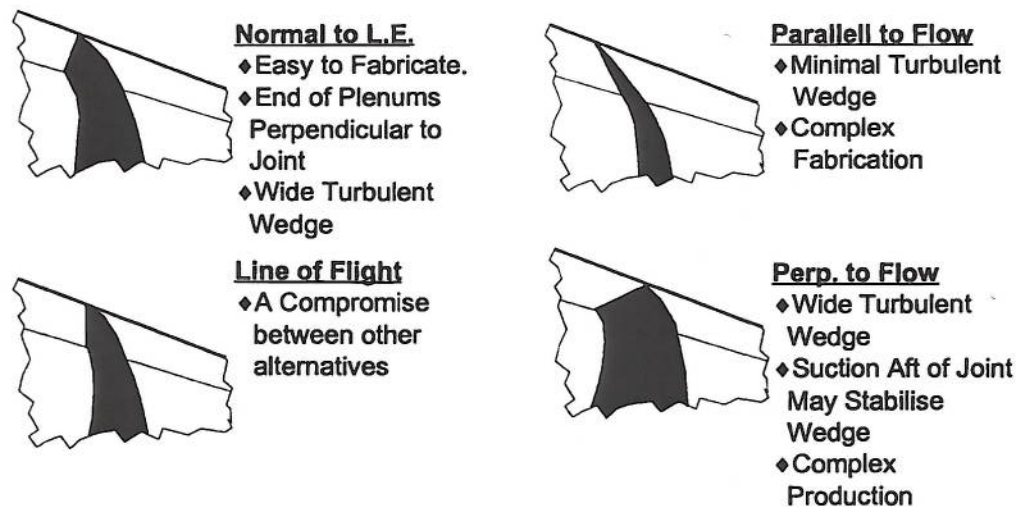


Figure A-34: Orientation of Chordwise Joints

A possible alternative to mechanical fasteners would be to bond the skin to the substructure although there are concerns about bond failure, or reactions between the adhesive and fuel or hydraulic fluids. Bonding can increase production costs and cause problems during deep maintenance where removal of structure is required.

For engine nacelles, the fan cowl doors, inspection ports, and thrust reversers are responsible for the major surface imperfections.

Although forward facing steps are preferable to rear facing steps for laminar flow surfaces, they increase drag in turbulent conditions. In addition rear facing steps help to prevent fluid ingress into the structure, which may be important if a fluid de-icing/anti-contamination system is used.

A.3.3.3 Effect of Roughness on Suction Rates

The use of suction to relaminarise a laminar boundary layer after encountering a 3D roughness element has been investigated for engine nacelles, with a view to replacing insect contamination protection systems with increased suction rates [13]. As suction rates were increased from the normal values, the half angle of the turbulent wedge downstream of the disturbance narrowed, although it reverted to its original value aft of the suction surface. As suction rates were increased further the flow downstream of the disturbance was relaminarised and remained laminar aft of the suction. However, the high suction rates required degrade the benefits (in terms of total energy balance) of maintaining laminar flow.

A.3.3.4 Suction surfaces

The most effective suction surface, aerodynamically, would be a continuously porous one, such as woven metal cloth or sintered bronze, as used on early experiments, including the Vampire full chord LFC flight tests. However, these materials lacked structural strength and produced poor surface finish, making them unsuitable for LFC. All subsequent LFC suction surfaces have employed one of two basic concepts to provide a practical surface, continuous spanwise suction slots or distributed suction through a perforated skin.

Until the 1970s LFC experiments, including the X-21 flight tests, favoured the use of suction slots. Perforated surfaces were unattractive due to the minimum possible drilling diameter of 0.25mm, which is larger than aerodynamic requirements, using slow and costly processes [107]. However, the introduction of electron beam and laser drilling processes has meant that perforated surfaces, with very fine holes, $<100\mu\text{m}$, can now be produced quickly, using automated processes. For both processes, the beam impinges on the surface of the work piece, causing local melting and vapourisation [125]. Hole diameter is dependent on beam thickness, although both processes result in generally conical (approx. 3° half angle) hole profiles, with the large diameter on the surface facing the beam source, due to increased exposure to the beam. The smaller diameter defines the suction hole size. In operation, the smaller diameters are placed on the external surface as any particles capable of passing through will pass through the larger internal diameter. If the hole is blocked by a particle it will remain on the outer surface facilitating removal by the airflow or a cleaning process.

The minimum hole diameter, for these processes is dependent on the material thickness, with smaller diameters possible in thinner material. A German Electron Beam drilling system [125] was limited to holes larger than $40\mu\text{m}$ in 0.5mm and $60\mu\text{m}$ in 1.0mm thick stainless steel. A U.S. system was capable of drilling $63\mu\text{m}$ holes in 0.635mm thick titanium [81]. The Laser drilling process used thus far on flight tests, Nd-Yag laser, is capable of holes as small as $30\mu\text{m}$ [107], although material thickness is not quoted.

The hole diameters quoted above are nominal values, as the holes resulting from these techniques are not perfectly round or of uniform size or cross-section [130]. The smallest diameter can vary by up to $\pm 10\mu\text{m}$ from a nominal value regardless of the required diameter. If practical HLFC systems are to be manufactured, it must be possible to routinely produce suction surfaces with consistent suction characteristics.

An ONERA study investigated the uniformity of suction performance, measured as pressure drop against mass flow. Samples of surfaces with a nominal hole diameters ranging from less than $50\mu\text{m}$ up to $80\mu\text{m}$ were tested for scatter in both hole diameter and suction performance. The degree of scatter was observed to reduce substantially as the hole size was increased [109]. Clearly the optimum hole size will be the result of some compromise between the aerodynamic and production considerations.

The drilling rate for both electron beam and laser processes is a function of the required hole diameter and material thickness, with smaller holes in thinner material resulting in increased drilling rates [81]. A typical laser drilling rate of 40 holes per second is reported in [155], while a figure of approximately 1,000 holes per second for electron beam drilling of $63\mu\text{m}$ holes in 0.635mm titanium is reported in [81]. Drilling rates in excess of this are possible where thinner material is used. A figure of up to 3,000 holes per minute is reported for the system, although hole details are unavailable.

Fatigue tests on a micro-perforated surface drilled with a Nd-Yag laser showed that the design life of such materials is substantially less than a similar undrilled surface. This is primarily a concern for HLFC fin or tailplane cases, where tensile loads can

frequently occur on both surfaces. For wing cases, where suction is only applied to the upper surface, it is not of primary importance as the surface in question is generally under compressive loading during flight, with tensile loading limited to dynamic loading during gust encounters or landing and static loading during ground manoeuvres.

Drilling with an Eximer laser is a possible alternative process currently under development. This allows very high quality holes, with reduced taper, to be produced as small as 10µm at drilling rates of 40-400 holes per second, although the cost per hole is increased by a factor of three. The variation in hole size was much smaller, with nominal 38µm holes showing much less than 1% variation. The mechanical properties of the perforated material may also be improved as Heat Affected Zones (HAZ), which form around each hole, during Nd-Yag laser drilling, do not develop when the Eximer laser process is used [155]. The improved hole quality may also benefit the fatigue characteristics of the drilled material, relative to the Nd-Yag drilled surface.

The performance characteristics of a suction surface are a function of the porosity, which is dependent on hole spacing in addition to hole size. Clearly, with greater spacing fewer holes are required, reducing production costs. However, as spacing is increased the mass flow through each hole must increase, necessitating larger holes or higher suction velocities, both of which have aerodynamic limitations. For many applications, a hole spacing in the order of 10 diameters is used to prevent roughness effects from individual holes combining to de-stabilise the boundary layer. This results in surfaces with porosity of less than 1%, although reduced hole separation can be used to increase porosity where higher mass flows are required. In particular, the suction rates for attachment line suction require increased porosity - 1.2% for wind-tunnel tests at Manchester University [105] [106] and 3.14% for ELFIN wind-tunnel tests [60]. Where increased porosity is required, the hole separation along a streamline can be increased by skewing the hole pattern relative to the flow [107].

Titanium is currently the preferred suction surface material due to its high strength, low weight and corrosion resistance, the last of which precludes aluminium as oxidation would cause widespread hole blockage during operation. Composite materials are a possibility for HLFC nacelles, although its use for suction surfaces in the leading edge region is questionable due to impact damage concerns. General Electric successfully utilised a drilled composite surface for HLFC nacelle flight tests.

Other possible future surfaces are resin starved plastics which have lower production costs, as no drilling is required. A thermoplastic material was proposed by Shorts [138], and a carbon-fibre reinforced sintered thermoplastic has also been proposed as a porous material for use on HLFC nacelles [94]. Doubts about the use of such materials may arise concerning surface roughness, their environmental resilience and absorption of standing water.

An important aspect of the drilling processes is the workpiece handling capability of the plant, in terms of sheet size. As the size of the workpieces increases, the number of joints will be reduced. The U.S. Electron Beam process was capable of drilling

sheets up to $0.43 \times 1.37\text{m}$. A more recent report on suction systems suggests that laser drilled panels up to 3m in length might be possible [68].

A.3.3.4.1 Suction Surface Resilience

While wind tunnel and flight tests suggest that laminar flow is possible, it must be remembered that these tests are typically conducted over short time periods, relative to the 20-25 year life of transport aircraft, in conditions often unrepresentative of the operational environment. The possibility of large scale hole blockage and surface resilience are frequently raised concerns where porous suction surfaces are proposed.

The Simulated Airline Service (SAS) program [82], part of the LEFT program, flew seventy flights, resembling typical airline mission profiles throughout the continental USA. Almost half of these flights were winter operations with maximum daytime temperatures routinely below 0°C (32°F) and frequent exposure to snow, frost and freezing rain. In these conditions rain water penetrating the surface and atmospheric water vapour condensing within the suction system would be expected to freeze and block the duct

To combat this during the SAS tests, filtered pressurised air was passed through the suction ducting and blown through the suction surface to expel residual de-icing fluid, or standing water. However, water expelled during flight in icing conditions was believed to have frozen on the external surface preventing laminar flow. Care should be taken to avoid expelled water re-freezing on the control surfaces which may compromise aircraft safety. A alternative solution would be to draw the standing water through the suction system exhausting it overboard or design the suction ducting such that water will collect in traps from which drainage is possible.

Ground tests investigated the influence of purging pressure on the time taken to clear the suction surface of a glycol/water mixture [83]. The time required to clear the system was observed to reduce with increasing purge pressure. However, increased purging pressure places higher power requirement on the suction system, and hence a fuel consumption penalty. This may be a minor consideration as the purge time involved is short, although excessive purging requirements may have a bearing on the required suction system sizing.

Rain presents different problems as it may deform the suction surface, in extreme cases. The short term effect of rain erosion on electron beam drilled surfaces, with varying sub-structures, was examined by Douglas [102]. At typical flight speeds, no deformations were recorded, although one sample was deformed at high speed (500mph).

No data has been published comparing the effect of large hailstones on NLF or perforated HLFC surfaces with that on conventional surfaces. However, the implications on surface quality for laminar flow aircraft are more critical as any widespread deformation will result in reduced payload/range performance.

After four years operation of an electron beam perforated ($63.5\mu\text{m}$ holes) suction surface, in the LEFT experiments, no measurable degradation in surface quality or suction performance was detected. Although this is only a fraction of a transport

aircraft's operational life, it is encouraging. Dassault are currently assessing the operation of an HLFC suction system on a Falcon 900 in charter service.

When operating at busy airports it is likely that the suction surfaces will be exposed to the exhaust gases of other aircraft, i.e. hot and gritty gases. This situation was encountered during the SAS program [82] with no reported problems.

As mentioned in section 4, the hole on the external suction surface is smaller than the internal to ensure that any particle capable of entering the external surface will not become trapped within the surface. However, particles too large to pass through the hole may lodge in the external hole. This will not significantly effect the suction quality provided the number of blocked holes remains relatively small. Much of the blockage may be removed during purging. In certain circumstances additional purging during cruise may be capable of clearing widespread blockage due to severe atmospheric pollution, such as volcanic particles.

Periodically, the suction surfaces may require cleaning to remove accumulated debris. One potential process is steam cleaning, which could be used between flights or at routine servicing with the surface in place on the aircraft. This process was observed to return the performance of contaminated laminar flow test surfaces to that of a specimen cleaned using ultra-sonics, Figure A-35.

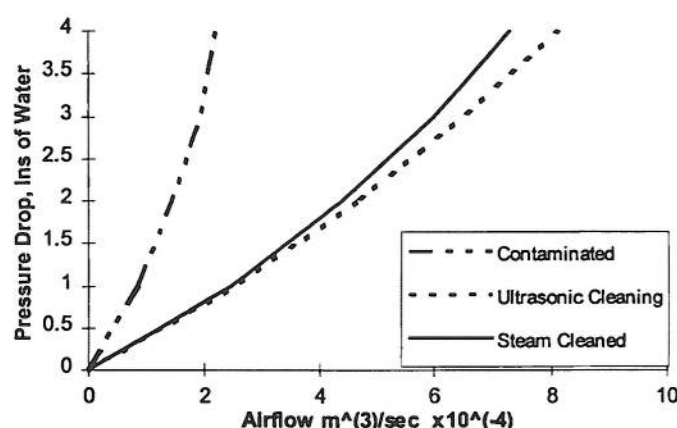


Figure A-35: Comparison of Steam Cleaning Process, from figure 12 [81]

A.3.3.5 Suction Surface Substructure

To prevent outflow and to allow chordwise variation in the suction coefficient, spanwise plenum chambers are mounted on the internal face of the suction surface. These also act as stringers supporting the perforated suction surface whose thickness may be limited by drilling requirements, as the skin for the A320 HLFC fin [130].

Three basic substructure concepts have been proposed for flight tests. Firstly, plenum chambers resembling top-hat stringers have been used on numerous laminar flow suction system studies, such as the Jetstar LEFT program [82], the Falcon 50 flight test [23], the NASA wind-tunnel model [19], the aft regions of the suction surface on the Boeing HLFC 757 project study [21] and the BAe HLFC wing demonstrator [68] (in Figure A-29). In some cases, a corrugated configuration is used to produce multiple plenum chambers from a single sheet of material, with backing material used

to stiffen the structure. This concept often results in significant areas between the plenum chambers where suction is not possible. These, in the order of 10mm for the BAe systems demonstrator, provide a suitable surface to attach the suction surface.

The second option is to use a monolithic configuration, which used in areas of high curvature such as the nose regions of the A320 fin suction surface [18], BAe systems demonstrator [68] and the Boeing 757 project study [21]. The Boeing HLFC wing [101] and Airbus A320 fin (shown in Figure A-36) wind tunnel models, and Rolls-Royce-led HLFC nacelle flight tests [92] used this concept throughout the suction region. The plenum chambers are can be machined out of solid metal leaving narrow walls between the plenum chambers, and a base to the chamber. Alternatively, formed composite structures can attached to suction surface. A wall thickness of 5mm was used for the BAe demonstrator (forward facing surfaces in Figure A-29), while the ELFIN HLFC wing wind-tunnel model, with reduced loads, used 1.5mm walls. The Boeing wind tunnel model chamber width was 17.8mm (0.7in) and a much thicker wall width of 12.7mm (0.5in), which possibly is configured to produce low cost substructure representative of a corrugated configuration. Excessive wall thickness would result in a very heavy substructure, which would be unacceptable for installation on an aircraft.

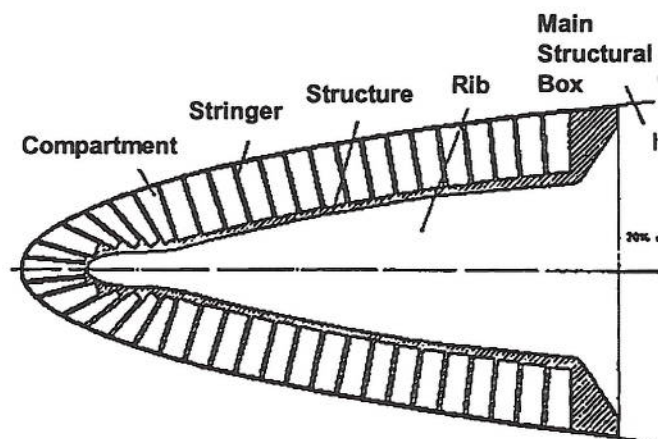


Figure A-36: Monolithic Substructure, from [139]

The suction surface is placed over the substructure and joined on the exposed edge of the walls. The principal advantage of this concept is reduced width of lost suction between plenum chambers, although this complicates the process of fixing the suction surface to the substructure.

The third type of substructure is honeycomb as used on the rear parts of A320 HLFC fin suction surface. Presumably, air is drawn through the suction surface, passed through the honeycomb, and passes through a further surface into the some collector chamber. This minimises the structural hole blockage, although it is only suitable for regions of low curvature.

To simplify the ducting arrangement for all three types of substructure, sucked air from a number of adjacent plenum chambers is gathered in a collecting chamber. This is only possible where the suction coefficients for a group of plenum chambers are of a similar value. Tuning the metering holes, between the plenum and collecting chambers, will allow the desired suction coefficient to be set for each plenum. Many

HLFC suction systems use three collecting chambers, one each for attachment line, cross-flow and Tollmein-Schlichting areas, as in Figure A-29.

Airbus A320 fin and ELFIN wing wind tunnel models both used fifteen plenum chambers each connected directly to the suction unit. This permits freedom to investigate the impact of various suction distributions. For A320 flight tests, the number of collection chambers has been reduced to nine [85], which still allows some freedom to experiment, although it is probable that a production system would reduce the number further.

For primarily 2-dimensional applications, namely nacelles, it may be possible to use only one collecting chamber as the variation in suction coefficients across the suction surface is minor. In such cases, this chamber may be connected directly to the suction unit, a configuration used for the Rolls-Royce HLFC nacelle

If thermoplastic suction surfaces were used, the continuously porous surface could be bonded to a shaped structural surface, such that no discontinuities were formed. Sucked air would be drawn through holes within the structural surfaces into a collecting chamber. The layout of such a concept for a nacelle application is presented in [94].

Within the plenum and collection chambers, the Boeing 757 study [21] suggested flow Mach numbers of 0.05 and 0.1, respectively. These low speeds limit pressure losses in the ducting.

Although a titanium substructure would be beneficial in terms of material compatibility, for structural reasons (reduced joint loads) [68] it is advisable to minimise its use. The BAe demonstrator uses a titanium substructure close to the attachment line, with glass-reinforced plastic further aft, which is joined to the skin by welding and bonding, respectively. Super Plastic Forming/Diffusion Bonding processes may also be feasible for titanium substructures [154].

A.3.3.6 Collection Ducts

On many wind-tunnel and small scale flight tests the plenum or collecting chambers are linked directly to the compressor. However, this is not feasible for HLFC systems of significant length as these chambers are limited to 3-5 metres in length (section 2). Therefore the chambers are connected to a spanwise duct that collects the sucked air from all the collecting chambers, transporting it to the compressor. The diameter of the pipes connecting the collection chamber to the spanwise duct can be used as a simple means to meter the flow. This also serves to simplify the ducting system as all the sucked air is collected into one spanwise duct. This reduces duct mass and minimises the cross sectional area required for ducting. The cross sectional area of the duct is driven by the mass flow of air and flow Mach number. For an outboard LFC panel on a 200 seat aircraft at cruise conditions, the duct pressure loss was seen to increase as a function of the square of the duct Mach number [132]. Conversely, increasing duct Mach number results in smaller duct diameters, thus facilitating installation in the limited leading edge volume and producing mass savings. Clearly, a compromise between these two conflicting considerations is required. A Boeing project study set the flow Mach number as 0.2 [21].

As the duct runs towards the compressor, the mass flow in the pipe will increase as air is introduced from collection chambers. To maintain a desired Mach number, the duct would need to increase in cross sectional area with reduced distance from the compressor. Thus flow direction for wing and empennage surface should be inboard as the available volume, despite being limited, will increase in this direction.

A.3.3.7 Suction Unit

The suction unit, or pump, comprises a compressor and some form of drive system, which is required to generate a pressure differential between the compressor face and the external boundary layer such that the desired quantity of air is drawn through the suction surface to achieve laminar flow. The compressor is required to raise the pressure of the sucked air such that it can be exhausted to the atmosphere at conditions close to freestream pressure and velocity, to minimise losses associated with the suction process.

Two types of compressor are typically proposed for HLFC applications, namely radial and axial. Other types are available, although the two mentioned are most suitable given the limited pressure rise required. When the characteristics of these types are compared for low mass flow HLFC applications, the radial compressor is generally the more efficient, as well as being the more rugged of the two. The radial variety also has a wider range of design mass flows, along with a greater pressure ratio for each stage [102].

The number and location of suction units varies with each application. Typically suction system layout for an HLFC wing involves the installation of a suction unit in the port and starboard wing root fillets or within the cargo hold. To consider a practical system, the probability, and implications, of suction unit failure must be considered. One option is to install a third suction unit and size these such that they operate at two-thirds of their maximum mass flow rates for normal operation [68]. Subsequent to the failure of one unit, the speed of the remaining two is increased to maintain the desired suction coefficients. It is likely that the third unit would have to be located within the fuselage and connected via ducting and control valves to the two units in the wing root.

An alternative approach is to size two units such that either is capable of sustaining the required suction coefficients following the failure of one unit. This would require a cross-link for the power supply and sucked air along with some form of control system. To compensate the greater volume flow in the failure case, the speed of the remaining unit would have to be increased. However, the doubling of mass flow through the nozzle may cause it to choke, and would therefore require an increase in the nozzle area for efficient operation. Both approaches will increase the power requirement due to reduced efficiency and increased pressure ratios.

The suction units can be driven by a number of methods, almost all of which use energy extracted directly from the aircraft powerplant, through either bleed air or shaft power off-take.

A.3.3.7.1 Bleed Air Systems

High pressure air can be extracted from the compressors in the main propulsion units. The energy within this air can then be used in a number of ways to drive a laminar flow suction system. The primary attraction of bleed air systems is their simplicity, with relatively few moving parts, although the need for high pressure ducting imposes mass penalties and hence may limit choice of location.

The simplest bleed air system is an ejector system, where high pressure air is introduced at high velocity into the exhaust section of the suction surface collector duct. The venturi effect draws the sucked air into the high speed duct, thus creating a suction force. Their simplicity and ease of operation have led to their use on numerous wind tunnel studies, such as the Boeing wing, A320 fin, ELFIN wing, and experimental flight tests, namely the Rolls Royce HLFC nacelle (Figure A-37). However, these systems are very inefficient and only suitable for limited mass flows.

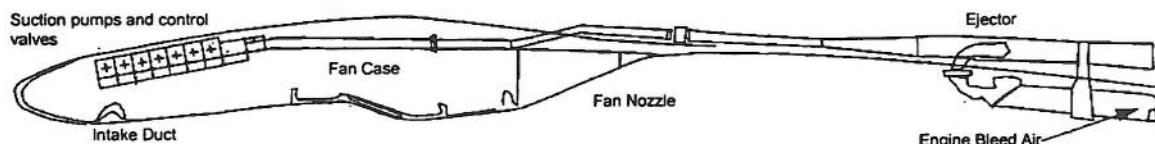


Figure A-37: Ejector System on Rolls-Royce HLFC Nacelle Flight Test [14]

A Bleed Air Drive (Figure A-38), or Turbo-Compressor, uses the high pressure bleed air to drive a small turbine which drives, via a shaft, a compressor. Compared to the ejector, a bleed air drive offers improved efficiency, greater mass flow capabilities and increased suction control, although it introduces increased complexity. Such drives have been used on several flight tests, namely the Jetstar LEFT experiments [149] and the General Electric HLF Nacelle Demonstration [137].

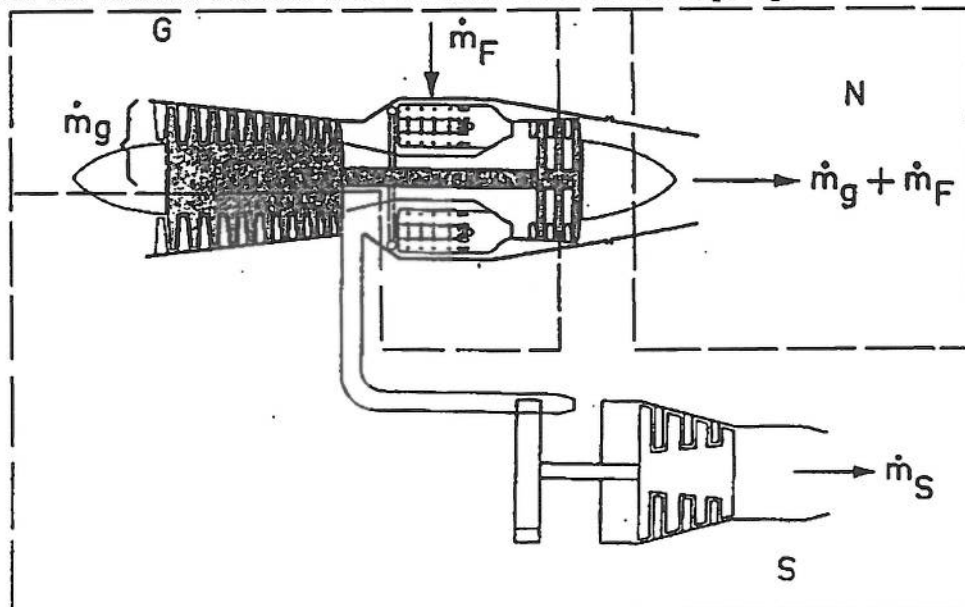


Figure A-38: Bleed Air Drive, from [143]

A variation on the Bleed Air drive is a Bleed and Burn Cycle, where fuel is added to the bleed air and ignited close to the suction unit. The resulting gases drive a turbine, connected to the compressor, and exit to the atmosphere, Figure A-39. This is

suitable where the suction unit is located some distance from the engines. However, the additional combustion chamber, external to the engine, may raise safety concerns, and complicate to the fuel system, substantially increasing maintenance costs.

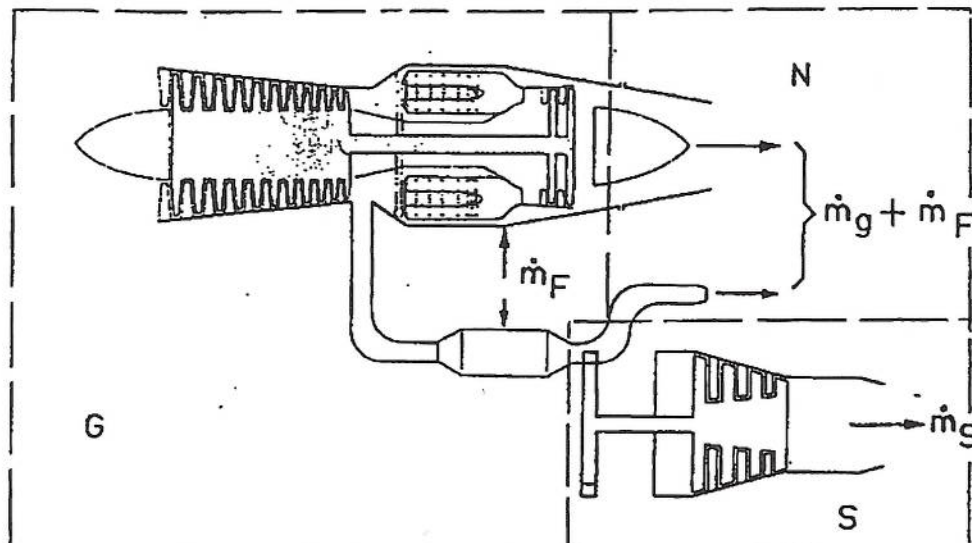


Figure A-39: Bleed and Burn System, from [143]

The implications of bleeding air from the powerplant, and its effectiveness at providing suction, is highly dependent on the amount removed and the position of the extraction point in the compressor. Where the bleed air requirements are excessive, engine performance can be significantly degraded. Therefore bleed and burn drive systems were often proposed for full chord LFC applications where the substantial power requirements were in excess of the power extraction limits on the main propulsion units.

A.3.3.7.2 Mechanical Power Off-Take

The energy required to drive the suction units can be extracted directly from the engine by mechanical means from one of the turbine/compressor shafts within the main propulsion units. This removes the need for high pressure ducting of bleed air systems, but introduces the need for mechanical linkages. The engine performance penalties associated with mechanical power off-takes are typically half those for conventional bleed systems for the same power, Appendix E.

A Direct Drive system is the simplest of these methods is (fig 78 2), in that the suction compressor is driven from one of the drive shafts for the main propulsion unit compressors, Figure A-40. Suction unit location is restricted as it must be in line with the gas turbine, which may disturb the inlet flow into the main engine. Furthermore, the turbines would have to be capable of driving the suction unit in addition to the main compressors.

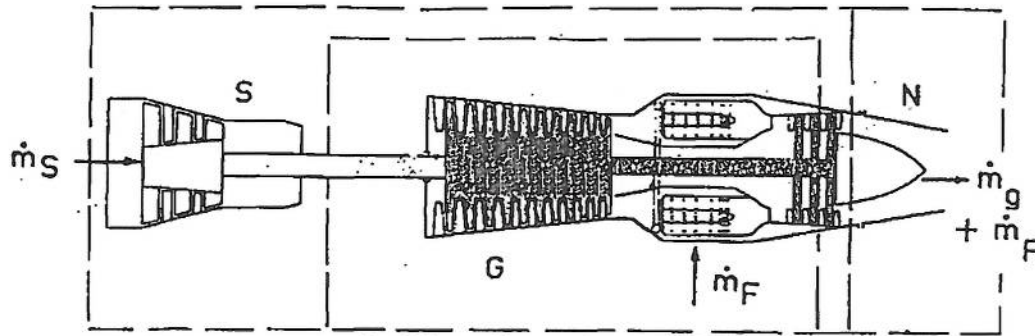


Figure A-40: Direct Drive System, from [143]

A full comparison between direct drive and bleed and burn systems, for an LFC application [102] showed that, for a 140kN turbo-fan engine, the bleed and burn system requires 30% more fuel than the turbo-shaft system.

A more practical solution is a free turbine system. The suction unit is offset from the centre line of the gas turbine with power transmission via a geared shaft, permitting increased freedom in suction unit location (Figure A-41).

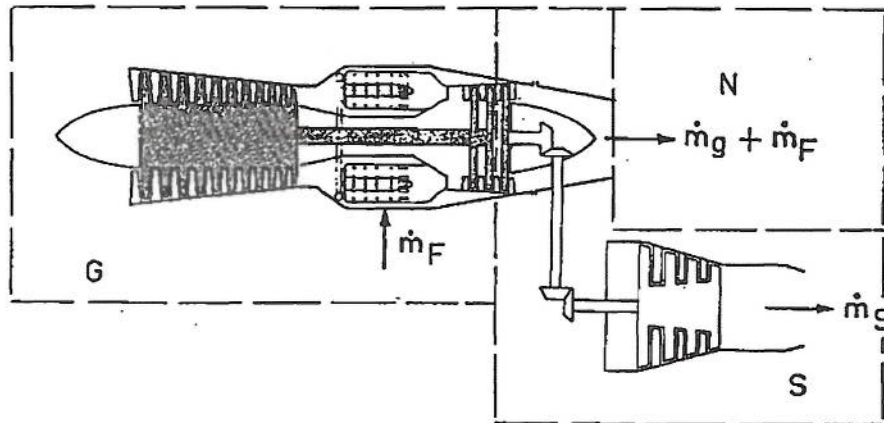


Figure A-41: Free Turbine Drive System, from [143]

Both systems offer high efficiencies, although shaft mass, safety and reliability considerations require that the drive shaft length be minimised, implying that suction units must be located within the engine nacelle. The underwing mounting of engines in pods limits the size of suction units of suction unit that can be used, although such a drive would be suitable for nacelle applications.

A.3.3.7.3 Electrical Power Off-Take

If the off-take shaft is used to drive an electrical generator, this can supply electrical energy to the suction units, where electric motors are used to drive the compressors, Figure A-42. The principal advantage of this drive is in a greater freedom to locate the suction units, as electrical cabling is easier to route than high pressure ducting and lengthy mechanical links. Therefore, electrical drives are particularly useful for high mass flow applications where the necessary large suction units can be suitably located and not constrained by the drive system. They are also appropriate for applications some distance from the engines, such as the empennage, as energy losses in cables are small compared to those in bleed air ducts.

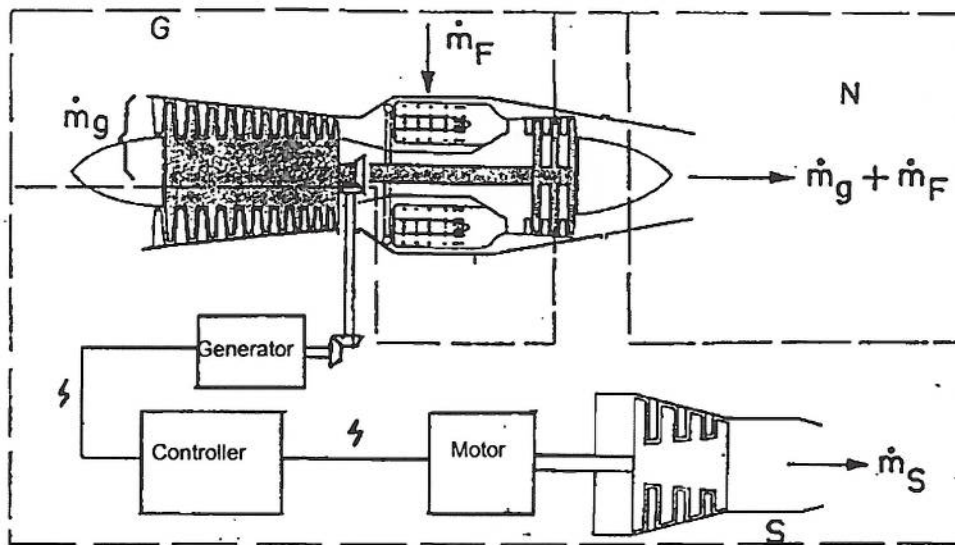


Figure A-42: Electrical Drive System, Based on Figure in [143]

The pylon/engine interface represents the boundary between the responsibilities of the airframe and engine manufacturers. Connection of electrical supply across this boundary would be simpler than for bleed ducts or mechanical linkages. The main disadvantage of this system is the multiple conversion of energy types which can cause significant losses. In addition, the power requirement of the suction system would mean considerably larger, or additional, generators being driven by the engines, representing additional mass, and possibly complexity.

A.3.3.7.4 Miscellaneous Systems

Direct Ingestion was proposed [143] for LFC applications, where sucked boundary layer air represents the total inlet mass flow for the main engines, Figure A-43. A number of LFC studies in the 1970's included a number of small suction engines installed in the rear wing [102]. The mass flows associated with HLFC may be too small for such a system. Additional engines would significantly increase maintenance costs and complicate the fuel system.

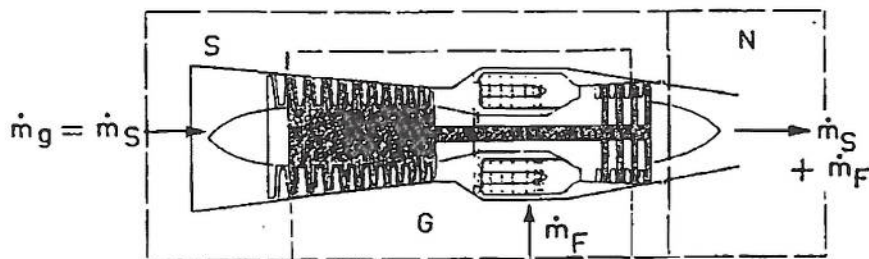


Figure A-43: Direct Ingestion, from [143]

Another possibility is to use air turbines located on the wing tips to turn small generators. These may also reduce tip vortices, reducing induced drag [122]. The main disadvantages of such a system are their vulnerability to damage and installation difficulties in the limited volume of the wing tip.

A.3.3.8 HLFC Nacelles

Much of the above description is applicable to HLFC wing, empennage and nacelle applications. However, the requirements for engine nacelles are somewhat different from the other surfaces, in particular those related to powerplant performance.

The concerns discussed for NLF nacelles, section A.2.2, are also relevant for HLFC nacelles, in particular the off-design cases. However, the use of boundary layer suction overcomes many of the limitations imposed by NLF. In particular, the suction suppresses TSI, permitting limited adverse pressure gradients associated with a blunter leading edge, Figure A-44.

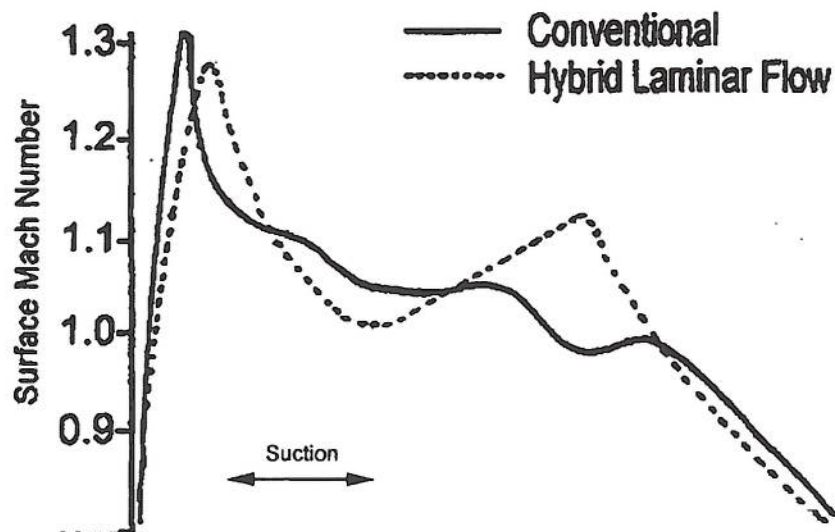


Figure A-44: HLFC Nacelle Pressure Distribution

As part of the European ELFIN and LARA programmes, the performance of an HLFC nacelle at cruise and low-speed conditions was investigated, respectively [93]. The high speed (ELFIN) wind tunnel experiments evaluated suction system performance and the drag reduction over a range of cruise Mach numbers and nacelle attitude. For the zero incidence case, transition occurred as far aft as 50-60%, which corresponded to a 42% drag reduction. This was achieved at $M = 0.78$, beyond which the maximum extent of laminar flow reduced very sharply to the beginning of an adverse pressure gradient at 10% of the nacelle length.

These tests were repeated with a nacelle incidence of 2° , which increased the magnitude of the peak suction around the upper half of the nacelle and reduced them on the lower half. At the top and bottom of the nacelle where these effects largest, the extent of laminar flow was zero and 70%, respectively. The maximum extent of laminar flow was achieved at $M=0.82$ although significant extents were still possible at $M=0.845$, the maximum Mach number investigated.

The cruise thrust requirements vary as a function of aircraft mass, cruise speed and altitude. In addition, to maintain constant cruise speed and altitude the engine throttle setting must be gradually reduced, as aircraft mass reduces due to fuel burn. As the engine flow rate was increased, reduced nacelle drag was observed, probably due to reduced local flow incidence to the inlet lip, resulting in a less severe leading edge

pressure peaks. Although this trend is also observed for conventional nacelles the effect is more pronounced for the HLFC nacelle. These tests also encountered drag rise conditions at high Mach numbers.

At low speeds, nacelle performance in cross-wind conditions and at high incidence are the primary considerations. Although the HLFC system is not used during these phases of flight, distortion of flow entering the engine is an important consideration. The LARA low-speed wind tunnel tests showed that the nacelle performance met all requirements.

B. OPERATIONAL AND CERTIFICATION CONSIDERATIONS FOR SUBSONIC TRANSPORT AIRCRAFT WITH HLFC

Conference paper presented by the author at *2nd European Forum on Laminar Flow Technology*, Bordeaux, June 10-12 1996.

Operational and Certification Considerations for Subsonic Transport Aircraft with Hybrid Laminar Flow Control.

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ABSTRACT

The use of laminar flow technology to reduce drag, and hence fuel burn, is currently receiving considerable attention. If Hybrid Laminar Flow Control is to be applied to commercial transport aircraft, the certification authorities must first be satisfied that it will not jeopardise safety. In addition, the airlines must be satisfied that the benefits outweigh the mass and cost penalties before any commitment is made to introduce HLFC to this class of aircraft. This paper addresses operational and certification issues relevant to HLFC and samples current airline opinion.

INTRODUCTION

The potential for significant fuel burn reductions through the use of laminar flow technology has been demonstrated in numerous flight tests [1]. In addition, many of the aerodynamic phenomena and practical obstacles are becoming sufficiently understood to permit serious consideration to be given to the introduction of Hybrid Laminar flow Control (HLFC) on practical aerospace surfaces.

When contemplating the introduction of laminar flow technology to commercial transport aircraft, the views of the regulatory authorities and potential operators must be considered, and where necessary, measures taken to satisfy any demands that they impose.

The principal concern of the regulatory authorities is the airworthiness of transport aircraft, ensuring that they will not jeopardise the safety of the aircraft, passengers, or public. This is regulated by the issuing of certification and operational requirements.

The certification requirements define a standard against which a new, or significantly modified, aircraft type must demonstrate compliance before approval is granted for the aircraft to be operated in commercial service. Operational requirements lay down the manner in which a commercial transport aircraft must be operated in routine service.

These organisations are generally national institutions that have each historically issued their own regulations. However, many of these now subscribe to either the European Joint Aviation Authorities Committee (JAA) or the Federal Aviation Administration (FAA) in the United States, although even these two are converging towards a common set of regulations.

In addition to overriding safety considerations, the primary concern of airlines, as commercial interests, is to transport people and goods in such a way as to generate profit for their owners. Many of the requirements laid down by the regulatory authorities have a direct cost impact on aircraft operation.

If the safety concerns of the regulatory authorities, or economic viability requirements of the airlines can not be met, the introduction of HLFC to transport aircraft can be no more than a research exercise.

This paper firstly reviews previously published material concerning the certification and operational aspects of laminar flow, including airline attitudes and opinions. Issues raised by the introduction of laminar flow are discussed, bearing in mind existing certification and operational requirements, namely JAR-25 and JAR-OPS 1, respectively. Finally, a sample of current airline opinions with regard to laminar flow technology is discussed based on communications with representatives from three European airlines, British Airways, Lufthansa German Airways & Virgin Atlantic Airways.

The paper is intended to highlight some of the principal areas and concern, and not to be a definitive set of requirements to which all aircraft employing HLFC would have to adhere.

REVIEW OF PREVIOUS MATERIAL

A number of previous studies have considered the opinions of regulatory authorities and airlines with regard to the application of laminar flow technologies to transport aircraft. These have addressed both full chord LFC, and HLFC applications, although only the latter can be considered as technically feasible.

As part of the studies resulting from NASA's Aircraft Energy Efficient (ACEE) program, Boeing Commercial Airplane Company, Douglas Aircraft Company and Lockheed-Georgia Company each produced an evaluation of LFC systems applied to various subsonic transport aircraft. Each of these consulted airlines, during the late 1970's, to assess their opinions to, and requirements for, a practical LFC concept.

The Douglas Aircraft Company held discussions with United Air Lines and Flying Tigers (Freight) Air Lines, during the late 1970's [2], regarding the

application of LFC to a 300 seat aircraft, with a range of 9,180km (5000nm). The main points raised were:

- i) Both airlines viewed LFC favourably, with fuel saving advantages outweighing system maintenance costs and added cleaning.
- ii) LFC was seen as an attractive protective measure against Fuel Allocation.
- iii) LFC was acceptable at the same DOC as a turbulent aircraft, although the DOC must be evaluated for average trip length, rather than at design range.
- iv) The cost of the LFC system was assumed to depreciate over an aircraft's lifetime, by United, while the Flying Tigers considered it a modification and as such should be depreciated over five years.
- v) High interest in porous materials.
- vi) Laminar Flow on upper surface only
 - Maintenance ease and efficiency.
 - Elimination of leakage problem.
 - Elimination of under-wing frost problem.
- vii) LFC suction system should have the same reliability as main propulsion system.
- viii) LFC system must not be required for despatch.
- ix) Maintaining surface cleanliness a major concern.

This study also considered certification issues. In particular, it suggested that "Special Conditions" would be imposed by the FAA defining additional requirements for the certification of an aircraft employing laminar flow technology. These would cover the additional reserve fuel required to counteract failure of the LFC system at the most critical time. The aircraft would also have to be capable of dispatch with all or part of the suction system inoperative.

Boeing also consulted United Air Lines with regard to their proposals for LFC applied to a 200 seat aircraft capable of operating over 10,190km (5,550nm) at a Mach number of 0.8 [3]. The main points are summarised below:

- i) Reliability and justifiable total life cycle costs were seen as the major obstacles to a practical commercial LFC system.
- ii) Maintainability, durability, and cost were recognised as important considerations.
- iii) Low speed, and stability and control must not be compromised to achieve LFC.
- iv) Surface tolerances. Manufacturing tolerances and maintenance requirements must be compatible. Surface quality must include a margin to allow a reasonable degree of degradation and possibly defacement before action is required. Maintenance procedures should be relatively simple and economical.
- v) Definition required of maintenance requirements, and the effects of repair action pertaining to corrosion, physical damage and quality control in field repair.

Lockheed-Georgia liaised with Delta Air Lines with regard to their proposal for LFC applied to a 400 seat aircraft with a range of 12,000km (6,500nm) [4]. Again, the points raised are reviewed below:

- i) LFC aircraft must be maintained within the framework of existing maintenance programs.
- ii) LFC surfaces with integral slots and ducting require the development of new maintenance procedures.
- iii) Increased inspection of leading edge required, due to increased sensitivity of laminar flow to discontinuities and the higher risk of damage to this region.
- iv) Operational differences, such as Air traffic procedures, between LFC and turbulent aircraft must be minimised.

It must be remembered that while these studies consider full chord LFC, many of the above points are also valid for HLFC applications, although a simpler suction system will lessen the impact of some. At that time, late 1970's, fuel prices were forecast to greatly increase toward the end of the century, as the world oil stocks diminished, with the possible introduction of fuel allocations. In reality this has not happened with current (1996) fuel costs representing a smaller proportion of the operating costs than in the late 1970's, a situation that is expected to continue for the foreseeable future.

Operational considerations for an LFC aircraft were addressed in [5]. The principal issues of concern were surface quality, contamination, clogging, and corrosion of the suction surface, noise induced transition, and cloud encounter. A 20% range reduction, with design payload, was reported for the Lockheed-Georgia aircraft presented in [4], although it should be noted that laminar flow was assumed to be possible to 75% on upper and lower wing surfaces, and 65% on all empennage surfaces.

More recently (1992) Lufthansa German Airlines considered the practical implications of employing NLF and HLFC technology within the operating environment [6]. The drag reductions, and lower fuel consumption, were reported to offer increased range or decreased fuel costs and to be "ecologically beneficial" (reduce the impact of air transport on the environment).

The practical concerns for laminar flow technology fell into three main categories:

- i) Ambient conditions.
 - Contamination of leading edge, in particular suction hole blockage.
- ii) System failure.
 - HLFC monitoring system needed for pilot and maintenance information.
 - Failure resulting in asymmetric flight conditions must be avoided.

- Aircraft performance during, and subsequent to failure must not challenge basic pilot skills or the automatic flight control system.
 - Intermediate re-fuelling stops unacceptable.
 - HLFC system must not be despatch critical.
 - Fuel flow performance monitoring to allow precise fuel planning.
 - Additional fuel for unknown laminar flow degradation, presumably cloud encounter, is unacceptable
- iii) Airline technical aspects.
- Additional resources required for technical support. Additional training of airline personnel required due to HLFC system and the modified leading edge high-lift devices.
 - HLFC system must be compatible with existing maintenance program.
 - Stringent surface quality requirements may necessitate increased attention, requiring new tools and test equipment.

Many of the above points represent additional costs to an airline, which must be included in an evaluation of the economic benefits afforded by laminar flow technology.

CERTIFICATION CONSIDERATIONS

Little information has been published defining any additional regulations that may be imposed on aircraft utilising laminar flow technology, although existing regulations may be applicable in their current form, or slightly modified, for many issues.

All existing requirements would have to be met independent of whether laminar flow can be achieved. The principal requirement covering the design of all 'Equipment, Systems and Installations' is JAR 25.1309. This comprehensive requirement can be summarised as:

All systems must be capable of operating under any foreseeable operating conditions [JAR 25.1309(a)].

All possible failure modes must be considered, along with their likely cascade effects on other essential services, the probability of multiple failures, the resulting effect on the aeroplane and occupants at any stage of flight, and the required crew warning cues [JAR 25 1309(a), (b), (c), and (d)].

Each installation whose functioning is required for certification and that requires a power supply, is an 'essential load' on the power supply. The power sources and the system must be able to supply the following power loads in probable operating combinations and for probable durations [JAR 25.1309(e)]:

In addition to the loads for normal operating conditions, essential loads must be supplied

after failure of any one component in the power system, the failure of one engine on two-engined aeroplanes or two engines on three- or more engined aeroplane.

Loads not required for controlled flight need not be considered for two-engine-inoperative condition on three- or more engined aeroplanes [JAR 25.1309(f)].

Critical environmental conditions, such as vibration, acceleration, handling and fluid pressure effects must be considered [JAR 25.1309(g)]

The consequences, on the aeroplane and occupants, of any failure condition described above determines the allowable probability of occurrence as defined in Figure 1.

	Event Probability per flight hour	Class	Effect on Aircraft and Occupants
Frequent	$>10^{-2}$		Normal
Frequent	$>10^{-3}$	Minor	Nuisance
Reasonably Probable	$>10^{-5}$	Minor	Operating limitations; emergency procedures
Remote	$>10^{-7}$	Major	Significant reduction in safety margins; difficult for crew to cope with adverse conditions; passenger injuries.
Extremely Remote	$>10^{-9}$	Hazardous	Large reduction in safety margins; crew extended because of workload or environmental conditions; serious or fatal injury to a small number of passengers.
Extremely Improbable	$<10^{-9}$	Catastrophic	Multiple deaths, usually with loss of aircraft

Figure 1: Product Integrity, from AMJ 25.1309

Other certification issues are described below. These must be considered in addition to JAR 25.1309.

Loss of Laminar Flow

In the aircraft operating environment, laminar boundary layers can be disrupted by numerous disturbances creating turbulent boundary layers in their place, thus increasing aircraft drag. Where suction is employed to stabilise the boundary layer, such as for HLFC, malfunction of the suction system will also result in a loss of laminar flow. This represents a change in flight condition, and as such is subject to existing regulations:

JAR 25.143(a) The aeroplane must be safely controllable and manoeuvrable during: (1) Take-off; (2) Climb; (3) Level flight; (4) Descent; and (5) Landing.

JAR 25.143(b) It must be possible to make a transition from one flight condition to any other flight condition without exceptional piloting skill, alertness, or strength, and without danger of exceeding the aeroplane limit-load factor under any probable operating conditions.

As laminar flow is only achievable at altitude, the impact of losing laminar flow need only be considered during final stages of climb, cruise, and the initial stages of descent.

The principal performance implications of losing laminar flow is a step increase in aircraft drag causing a deceleration. In order to evaluate the extent of this deceleration, a large twin-engined transport aircraft, similar to an Airbus A330, is considered flying at cruise altitudes, with a lift/drag ratio of 15, a conservative value for modern transport aircraft. The introduction of HLFC to the upper wing surface is assumed to give a profile drag reduction of 14%, corresponding to approximately 7% of the total aircraft drag at the beginning of cruise. Aircraft mass is assumed to be at the Operators Mass Empty condition (zero fuel and payload) of 115 tonnes, as the greatest deceleration will occur for low mass cases. This results in a deceleration of 0.046m/s^2 (0.0047g) which is an order of magnitude smaller than the human threshold at which linear acceleration becomes perceivable (0.02g for acceleration, 0.08g for deceleration [7]). This suggests that this consideration has no impact of passenger comfort or aircraft safety.

Numerous wind-tunnel tests of aerofoil sections have shown that the nose-down (negative) pitching moments are greater when laminar flow is present [8]. This implies that aircraft trim condition will alter as a function of the degree of laminar flow achieved on the wing, and the margin between turbulent and laminar pitching moments. This must not compromise aircraft safety.

If transition from laminar to turbulent boundary layers occurs on the wing of a trimmed aircraft, the aircraft nose will pitch up. If an aerofoil section is considered separately with laminar and turbulent flow, a higher incidence is required to achieve a specified lift coefficient when turbulent flow is present. This suggests that any pitch-up caused by transition will increase the aerofoil incidence towards that required to maintain the desired cruise lift-coefficient. However, the drag increment caused by the turbulent boundary layers and increased incidence will require additional thrust to maintain speed.

If the failure occurred on only one wing, the drag imbalance between the wings would result in an asymmetric flight condition. Furthermore, the increased incidence required for the turbulent wing would increase the asymmetry, although it would probably still be minor compared to the effects of a failed engine. To maintain trimmed flight, either the control surfaces would need to be deflected increasing aircraft drag further, or the rest of the HLFC system would have to be de-activated. This would be dependent on the degree of asymmetry.

The deployment and retraction of Krüger flaps, used in place of conventional slats for HLFC wing applications, would have to comply with JAR 25.143.

For HLFC applications on fin, tailplane and nacelle surfaces, the impact of the above issues is much reduced, relative to the wing. Clearly loss of laminar flow on a fin will not result in asymmetry, or require significant changes in incidence. Tailplane applications will be subject to asymmetry if only one side fails, and incidence will have to be increased once laminar flow is lost to achieve the same necessary trim force. Nacelles, designed to generate little net lift force, are not subject to pitch or incidence changes, although asymmetry can occur where the engine is located on the wing.

Use of Purging System during Take-off and Climb

Many suction system concepts have included the ability to purge the suction system by blowing filtered air through suction surface. This is used on the ground and during climb to remove any residual fluid (water, ground de-icing fluid, integral anti-insect fluid) from the surface perforations and ducting [9].

If this purging has any effect on aircraft climb performance, the climb gradient requirements defined in JAR 25.117, .119, and .121 would have to be satisfied for the worst case. In addition, the aircraft must remain controllable after initiation or termination of purging system [JAR 25.111 see previous section].

While operating in the purging mode, the suction system can be assumed to be a low pressure pneumatic system, similar in configuration to a hot air ice-protection system, and as such comply with:

JAR 25.1438 Pneumatic systems (ducting and components) served by bleed air such as ... hot air ice-protection systems which are essential for the safe operation of the aeroplane or whose failure may adversely effect any critical part of the aeroplane or the safety of the occupants, must be so designed and installed to comply with JAR 25.1309 (General system design requirement). In particular, account must be taken of bursting or excessive leakage.

OPERATIONAL REGULATIONS

As with certification requirements, it is probable that any aircraft employing HLFC would have to comply with all existing operational requirements along with any additional regulations.

Many of the issues included within the operational regulations were highlighted in the previous studies reviewed earlier in this paper. These are discussed below in greater detail.

Turbulent Cruise Performance

JAR-OPS 1.540 & 1.575 (depending on aircraft class) both require an aircraft to be capable of achieving a climb rate of 91.4m/min (300ft/min) at any point on its route or diversion, in the expected meteorological conditions. This is most relevant at the top of climb or after a step climb, where the aircraft mass will be close to the maximum for that flight condition. It is likely that an aircraft employing

laminar flow would have to be capable of meeting this requirement with no laminar flow possible, to allow for cloud encounter at the top of climb.

Fuel Reserves

Once laminar flow has been lost, completely or partially, aircraft fuel consumption will be increased until laminar flow has been restored. This will increase the quantity of fuel required to complete a specified mission. If this additional fuel is not included in the flight planning additional re-fuelling stops will be required. Such stops are undesirable to airlines as they would incur additional landing fees and fuel costs, and place an extra cycle on the airframe and engines. In addition, the extra time involved may disrupt the operating schedule and in some cases cause flight crew and cabin crew to exceed their permitted work hours causing an excessive delay or overnight stop imposing even greater cost penalties. Any delay for the passengers would also be unpopular, particularly when they must connect with other flights at the destination.

In order to assess the likely additional fuel reserves required for aircraft employing laminar flow technology, all categories of laminar flow losses must be addressed with respect to existing operational requirements, specified in JAR-OPS 1.255 Fuel Policy. Relevant sections have been included below:

JAR-OPS 1.255(a) *An operator must establish a fuel policy for the purpose of flight planning and in-flight replanning to ensure that every flight carries sufficient fuel for the planned operation and reserves to cover deviations from the planned operation.*

JAR-OPS 1.255(b) *An operator shall ensure that the planning of flights is only based upon:*

(2)(i) *Realistic aeroplane fuel consumption data;*

(2)(iii) *Expected meteorological conditions;*

JAR-OPS 1.255(c) *An operator shall ensure that the pre-flight calculation of usable fuel required for the flight includes:*

(3)(i) *Contingency fuel (specified in IEM OPS 1.255(c)(3)(i) as the fuel required to compensate for deviations of an individual aeroplane from the expected fuel consumption data, from the forecast meteorological conditions, and planned routings and altitudes).*

(3)(iv) *Additional fuel, if required by the type of operation (e.g. ETOPS).*

(Note: It is likely that for ETOPS operations, all flight subsequent to an engine failure will have to be assumed to be turbulent. This will reduce the off-take power load on the remaining engine. In addition, operation at off-design conditions may prevent significant extents of laminar flow. It is unclear how this will tie up with JAR 25.1309(e) described earlier)

The extent of additional fuel reserves that will be required is dependent on the above regulations and the

failure mode, whether the losses are permanent or temporary, at what point during the mission the losses occur, and if the disturbances are localised or global. From these, four categories of failure can be defined, which can be used to determine the fuel reserve requirement.

Permanent global failures - This is the most critical case where laminar flow is lost across the entire wing for the remainder of the mission and from thereafter until the disruption is rectified. This is predominantly a concern for HLFC applications resulting from complete failure of the suction system at some point during flight. This will result in higher fuel consumption for the remainder of the mission. However, if the failure occurs at the start of cruise the additional fuel required will be greater than that needed when failure occurs at the end of cruise.

A project study of a long-range large twin-engined aircraft employing HLFC, considered the question of fuel reserves [2]. This demonstrated the significant penalty effect of excessive fuel reserves. It also concluded that the aircraft could complete its 6,500nm mission, with a 450nm margin, after a complete failure of the HLFC system provided the conventional reserves were used. However, under the FAA regulations, pertinent for the early 1980's, the additional fuel reserves would have to be determined assuming failure of the suction system at the most critical time, and that the conventional fuel reserves could not be used to overcome any range shortfall [2].

Let us consider a commercial transport required to perform a mission from 'A' to 'B' whose fuel load has been calculated assuming that laminar flow is possible throughout the flight (Figure 2). The principal implication of permanently losing some degree of laminar flow will be a range shortfall. This shortfall is a function of the drag reduction due to the laminar flow technology, typically 5-10% of the total aircraft drag for an HLFC wing application. This results in a range shortfalls in the order of 5-15%.

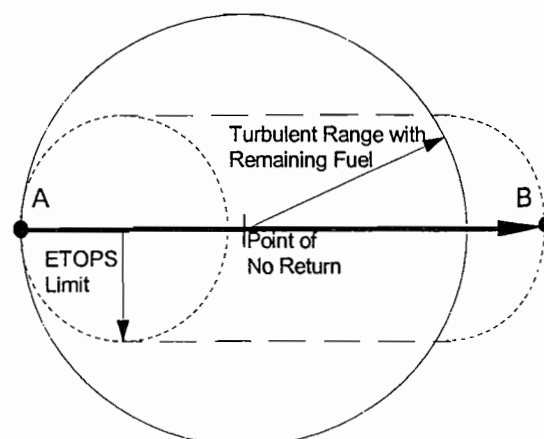


Figure 2: Schematic Representation of Laminar Flow Mission

If no suitable airports for a re-fuelling stop are located along this route the aircraft would have to

either return to its point of departure, or continue to its destination subsequent to a complete loss of laminar flow. A 'point of no return' can be defined as the position along the flight path after which the aircraft will no longer be capable of returning to its point of departure with fully turbulent flow. Furthermore, with the increased fuel consumption, it would not be capable of reaching its destination. Therefore some degree of contingency fuel would be required to ensure that the aircraft is capable of reaching its destination from the point of no return [JAR-OPS 1.255(c)(3)(i) & iv)]. These additional reserves will have the secondary effects of increasing the fuel consumption rates due to the increased rates, and push the 'point of no return' further along the flight path. These aspects would have to be included in the flight planning to achieve the correct fuel load. This approach was adopted in [3] which proposed that the fuel on board must permit flight from the mid-point to the intended destination, for the most critical of four failure cases, based on combinations of engine and LFC system failures.

However, if complete loss of laminar flow occurs on a route along which suitable airports are available, the aircraft has the added option of diverting to an alternative airport to take on the fuel required to complete the mission with fully turbulent flow. These airports would have to be within the turbulent range capabilities at the point of complete loss of laminar flow. This turbulent range is proportional to the fuel remaining when all laminar flow is lost, in that it reduces with the distance from the departure point.

This is clearly an option for over-land, and ETOPS missions. Indeed in most cases, the ETOPS requirement for suitable airports along the route will be more than adequate for a laminar flow failure case. The extent of this would be highly dependent on the mission length and the level of ETOPS approval (90-, 120-, or 180-minute flying time with one-engine failed). Some additional fuel reserve may be required to ensure that the aircraft can reach its destination after failure during the final stages of the mission where the turbulent range would be small, as there is little fuel remaining, limiting diversion distance.

The frequency of permanent global failures would be significantly reduced if the HLFC systems for the port and starboard wing were cross-linked and sized to permit suction across both wings with only one suction unit operating. If the probability of a complete HLFC system failure can be demonstrated to be sufficiently remote, there may be a scenario where the existing fuel reserves can be used to complete a mission, negating the requirement for additional fuel reserves.

A variation on this theme would be a modified 're-clearance' procedure as proposed in [2]. This flight would be planned to fly laminar from 'A' to 'B', and fully turbulent to a secondary destination, where one is available, short of the desired destination that can be

reached assuming no laminar flow is possible during the flight. At some defined 're-clearance point', a decision is taken, to either continue to the desired destination, or divert to the secondary, based on the remaining fuel load.

Permanent Partial Losses - These losses are predominantly due to leakage, or blockage of the ducting system transferring air from the suction surface to the compressors. This ducting system would be subjected to extensive bending due to the flexible nature of aircraft structures, in particular high aspect ratio wings. The duct material would need to be resistant to corrosive substances, such as hydraulic fluid. Water within the suction ducting could lead to internal corrosion, particularly as the aircraft ages. The expansive nature of freezing water may also cause leakages, in addition to the blockage it will cause.

Any leakage would cause air within the leading edge to be drawn into the low pressure ducts. This would reduce the pressure drop across all suction surfaces, located upstream from the leak, as a function of the degree of leakage. Where only minor leakage is present, the suction units could be operated at higher speeds to maintain the required suction coefficients, although the system power requirement will be increased. Where leakage is more substantial, the suction system would not be capable of stabilising the boundary layer instabilities.

Blockage of ducts, with ice or accumulated debris, will prevent any pressure drop across suction surfaces upstream from the obstruction, again preventing laminar flow across part of the surface.

The impact on aircraft performance of these failure modes is a function of blockage or leak location. Clearly if this occurs close to the compressor, laminar flow will be lost over a much greater area than for an obstruction or leak at the extremity of the ducting.

For HLFC wing applications, significant duct leakage, or blockage, will generally result in an asymmetric flight condition (see certification), possibly requiring the entire suction system to be de-activated. Therefore, it is likely that the fuel reserve requirements for this type of failure would be similar to that for a global failure.

Permanent localised losses - Wedges of turbulent flow can occur on laminar flow surfaces originating from local disturbances. These are unavoidable within the transport aircraft operating environment where damage can be inflicted by impact (bird-strike, stones during take-off and landing runs, hail, lightning, and collisions with service vehicles), or surface contamination, such as insect debris and corrosion.

All will result in surface flaws, which may not be noticed without detailed inspection. In many of these cases a conventional aircraft would be unaffected and hence no action would be required. For laminar flow surfaces, however, these flaws may cause a local

disruption to the boundary layer causing transition, and a small increase in drag that is proportional to the area of laminar flow lost. These disturbances will be predominantly close to the leading edge, where the boundary layer is particularly susceptible to disturbances and may contaminate the attachment line flow causing more extensive loss of laminar flow.

Detailed inspections of the laminar flow surface would probably be conducted at periodic maintenance checks, where any corrective action can be performed. Once the aircraft is returned to service, it will accumulate damage leading to a gradual deterioration in the drag reduction from laminar flow, and hence an increase in the fuel required to complete a mission. To inspect the leading edge in detail before each flight would be impractical.

A solution may be to continuously monitor the extent of laminar flow across the wing span [3], and/or the fuel consumption required to attain specified performance parameters. While the first of these would assist maintenance operations by identifying the disturbance locations, the second would provide realistic fuel consumption data for fuel load planning [JAR-OPS 1.255(b)(2)(i)]. This may be similar in nature to the continuous monitoring of engine performance that is currently performed by the airlines.

The suction surface may be divided into a number of panels to allow a more optimum spanwise suction distribution. In addition, shorter panels facilitate maintenance as a damaged section can be replaced individually, reducing the cost of the repair.

Temporary global failures - These occur as a result of cloud encounter where the ice crystals, forming the cloud, penetrate the boundary layer and cause transition to turbulent flow. The percentage of cruise time spent in cloud can vary from zero to over 50%, although the global average is less than 10% [10]. This represents a major problem to flight planning as sufficient fuel must be carried to ensure that the mission can routinely be completed without having to use any of the conventional reserves. On the other hand, excessive fuel loads will restrict the economic benefits of laminar flow technology.

Current flight planning takes no account of high altitude cirrus cloud as it has no measurable impact on turbulent aircraft. A satellite based method capable of detecting cirrus cloud, including sub-visible formations, and determining its altitude and density was being developed for climate research purposes during the late 1980's [11]. If determination of the location, altitude and density of cirrus clouds were possible on a global scale it may be possible to forecast, with some degree of confidence, the additional fuel reserves required to overcome loss of laminar flow due to cloud encounter [JAR-OPS 1.255(b)(2)(iii)]. Furthermore, it may be possible to include this method into that used to optimise a flight

path for minimum fuel burn, in a manner similar to that used for high altitude wind.

Inclement Weather

A commercial transport aircraft must be capable of operating in all but the most extreme weather conditions. Any practical HLFC system would have to be capable of operating within the existing conditions specified for the rest of the aircraft. Minimum and maximum temperatures limits are established by the manufacturer to which the aircraft is certificated. Of particular concern to HLFC systems is operation in cold wet climates, where heavy rain, freezing rain, hail, snow and frost are likely.

Freezing rain - This can cause widespread hole blockage as the rain will freeze on contact with the suction surface. If this occurs on the ground, during the take-off run or climb, the air temperatures at cruise altitude, in the order of -55°C, will ensure that the holes remain blocked preventing suction, and hence laminar flow. If suction is possible the attached ice will represent a roughness element possibly causing transition to turbulent flow. Suction system operation with widespread hole blockage would also increase the pressure differential across the duct walls which may lead to damage to the duct.

Current ice protection is only installed on the outboard sections of wings. For HLFC applications, it may be necessary to install leading edge anti-icing across the entire span to prevent hole blockage.

Heavy rain - Rain may penetrate the suction surface on the ground or during low-level flight, and accumulate in the ducting system. This may reduce suction system effectiveness, damage the compressors, and possibly freeze, causing duct blockages. Drainage holes will prevent any substantial build up of standing water, although care will be required to limit any in-flow of air into the ducting during suction. A number of proposals for suction systems have suggested a purging system where air is blown out of the suction surface either by 'reversing' the suction system, or using bleed- or ram air [2]. This has been shown to remove significant amounts of standing water and de-icing fluid when used during the initial part of the flight.

AIRLINE CONSIDERATIONS

Airlines are commercial organisations, and as such are required to generate profits for their share-holders. On all routes air travel competes for custom with other modes of transport, such as high-speed railways, shipping, and road travel. The extent of this competition is dependent on many factors, such as distance, availability of each mode, type of custom (passenger or freight), volume of traffic, and cost.

Generally, the advantages of air travel increase with greater distance, or where natural barriers, such as large bodies of water or mountain ranges, hinder other transport types. In such cases the airlines must

compete among themselves for the available custom. The major factors in this competition are the service offered and cost. These two are related as enhanced standards of service generally increase costs. Obviously, any opportunity to reduce costs for an airline permits reduced fares or an improved service, thus enhancing the airlines competitiveness.

Three European airlines, British Airways, Lufthansa German Airlines, and Virgin Atlantic Airways, were approached with regard to the application of HLFC to subsonic transport aircraft. The first two of these represent major carriers with extensive established global networks, while Virgin Atlantic are a smaller, expanding operator with a developing route network.

The aspects raised by previous studies were used as a basis for a questionnaire that was provided to each of the airlines, to which they all responded. Further discussions were consequently conducted with regard to their responses.

The prominent points from these consultations are summarised below, after which further detail is provided:

- i) All airlines expressed interest in HLFC as a means to reduce costs.
- ii) Fuel prices not expected to increase significantly in the near future, although environmental taxes may be a long term issue.
- iii) Airlines were interested in Life Cycle Cost rather than Direct Operating Cost savings.
 - Initial costs for establishing of maintenance support for HLFC must be considered along with operating costs.
 - Significant DOC savings needed to sustain benefit of HLFC after changes to operating costs, such as reduced fuel price or increased maintenance rates.
 - Operating cost savings must be achievable throughout the service life of an aircraft.
- iv) HLFC represents an additional system, increasing aircraft complexity, resulting in higher maintenance costs, and possibly more operational disturbances.
 - Failure modes, and their respective probability of occurrence, important. Failures corrected during turn-round are of less concern than those requiring extensive maintenance actions.
- v) HLFC system must not be despatch critical:
 - Aircraft must be capable of normal operation with turbulent flow.
 - Airlines would not want to withdraw aircraft with defective HLFC system from service. Increased fuel load, or payload (freight) reductions, required.
 - If mission exceeds turbulent payload/range limit, the aircraft could be exchanged with another operating on a non-limiting sector.

However, this would be an unlikely option for smaller operators.

- vi) Altitude and speed losses are unacceptable in airspace with reduced "in-trail" and vertical separation criteria.
- vii) Unscheduled re-fuelling stops due to range shortfall resulting from HLFC failure are extremely expensive, and unpopular with passengers.
- viii) Random nature of losing laminar flow due to cloud encounter poses problems for fuel planning, and range capabilities.
 - Monitoring system to report status of laminar flow to aid flight management.
- ix) Surface contamination and inclement weather are concerns for parked aircraft.
 - Ground de-icing fluid a particular concern.
 - Surface cleaning between each flight unpopular.

Economic Background

Laminar flow technology has the potential to produce significant fuel cost savings as a consequence of improved aerodynamic efficiency. To consider the operating economics of a commercial transport aircraft, the costs associated with a number of factors must be analysed, of which fuel costs are only one.

The numerous factors that contribute towards transport aircraft operating economics can be divided into two general categories, Indirect and Direct Operating Costs (Figure 3). The first includes cost terms that are independent of aircraft type, whilst Direct Operating Costs (DOC) are those related to aircraft operation, and are therefore used to assess the economic performance of an aircraft.

A number of methods have been developed, by various organisations, to evaluate aircraft DOC. All of these include certain cost terms such as finance charges, depreciation, insurance, flight crew, fuel, and maintenance. Other terms, detailed in Figure 3, are considered by some methods but omitted in others. For the above reasons, any comparison between aircraft types must be performed using only one DOC method.

Indirect Operating Costs (IOC)	IOC or DOC Dependent on Method	Direct Operating Costs (DOC)
Passenger Reservations	Landing fees	Flight crew salary & allowances
Passenger Handling	Cabin Crew salary & allowances	Fuel
Baggage Handling	Aircraft Handling	Maintenance
Commissions	Navigation Fees	Depreciation
Ground Property & Equipment	Food and In-Flight Services	Finance charges
Advertising and Publicity		Insurance
General and Administrative		

Figure 3: Operating Cost Terms, from [12] and [13]

The relative importance of these factors within the total DOC for a new long-range aircraft is shown in

Figure 4, although these are subject to extensive variation, as a function of the design mission. The combined finance related charges, ie. depreciation, interest, and insurance, are shown as the largest constituent at almost 50%. However, the importance of fuel costs in the total DOC, typically over 25%, suggests that significant DOC benefits are possible through fuel burn reductions alone.

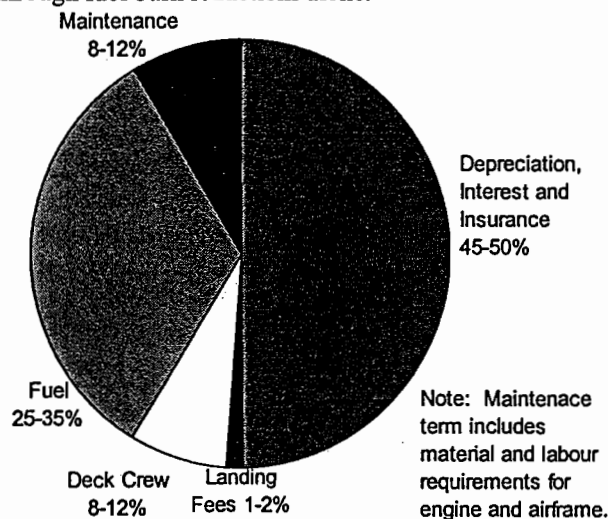


Figure 4: Typical breakdown of Direct Operating Costs for turbulent long-range aircraft.

DOC information can be presented in various forms, such as DOC per flight (fixed stage length), per block hour, per air-kilometre (or alternative unit length), or per Air-Seat Kilometre (or alternative unit length). The last of these is the most flexible as comparisons can be made between varying aircraft types, operating over different stage lengths, with different payload capacities.

DOC methods are used during the preliminary design phase of a transport aircraft to provide a standard method for evaluating the implications of design decisions or, as in this study, the impact of a new technology. When the economic viability of laminar flow technology is assessed, the net DOC change is typically used to compare the mass, cost, and maintenance penalty effects against the performance benefits.

The actual in-service operating costs of one aircraft type can vary greatly between operators through variation in numerous factors, such as aircraft age, whether the aircraft is owned or leased, utilisation rates, the airline's route structure, maintenance policy (in-house or sub-contract), crew salaries, etc. Provided suitable factors are available, DOC methods can be used to assess an aircraft's economic performance at any time during its operational life, in the service of any airline, on a selected route. However, this only provides a snapshot.

When airlines consider the acquisition of new aircraft, Life-Cycle-Costs (LCC), rather than DOC, are typically used to assess the relative economic performance of different aircraft types. LCC includes

the sum of all aircraft operating costs (Indirect and Direct) throughout the aircraft's life in addition to acquisition costs, establishment of maintenance support, and disposal costs. This approach, however, is highly airline specific, dependent on issues such as fleet size of a particular aircraft type, commonality with other aircraft types within the fleet, and local economic conditions.

Although these methods require excessive information to be widely employed during the design process, the likely impact of design decisions on the LCC needs to be considered in general terms.

Cost Benefits

To be acceptable, HLFC must offer significant long-term cost savings over a turbulent equivalent as airlines may be a reluctant to accept a technically advanced aircraft in place of one employing familiar technology.

Moreover, the introduction of a first aircraft type employing laminar flow, into an airline's fleet, would require additional investment to acquire test equipment, tools and ground equipment, to develop maintenance procedures, and to conduct personnel training. This would represent a significant cost to the operator that is not usually included within DOC calculations. This would have to be offset against the operating cost benefits during the aircraft's period of service, although care is required when using the expression 'period of service'. This can be defined as the 20-25 year service life of an aircraft, the 10-12 year duration of the finance period, or less than 10 years where airline policy is to retain a modern fleet. Again this implies that significant DOC benefits are required for HLFC to be acceptable.

It should be noted that this additional investment can be divided into system, and aircraft specific items. For all subsequent aircraft types employing HLFC introduced to the fleet, only aircraft specific items would be required, reducing the initial investment pertaining to the suction system. However, the development of subsequent aircraft types employing HLFC may be dependent on the success of the first.

The maintenance policy adopted by the airlines will also have a bearing on the financial burden of establishing support for the HLFC system. An independent company maintaining the aircraft from a number of airlines must also invest in the items described above, if it is to maintain aircraft employing laminar flow technology. Although these costs would be passed onto the airlines through higher maintenance fees, the set-up costs for each airline would be less than those for an airline maintaining its own aircraft.

Airlines operating leased aircraft may also have different attitudes to HLFC, although these will depend on the size of the airline, commonality with other aircraft in the fleet, and the period of lease.

Direct Operating Costs or Life Cycle Costs?

Where DOC is used as a measure of economic viability of HLFC, the finance charges, depreciation rate and insurance are usually taken as those applicable to the beginning of the aircraft service life.

Throughout a commercial transport aircraft's 20-25 year service life, many of the factors (described in the previous section) are subject to variation as a result of economic conditions, although it is probable that there will be an underlying upward inflationary trend. However, any variation in the finance charges will be a function of interest rate changes on a fixed, or reducing, capital lump sum. Therefore, its importance in the overall DOC will be reduced with time, increasing the importance of all other terms. After 10-12 years, the duration of a typical aircraft finance deal, no further payments are required, although depreciation and insurance must still be considered.

This can be illustrated by comparing reported in-service operating costs for the -200 and -400 series of the Boeing 747 aircraft, [12]: the first of each series entering service in 1971 and 1990, respectively. The main improvements on the later model (full comparison given in [14]) are an increased seating capacity, and a 10-12% fuel burn reduction through more efficient wings and engines.

Average operating costs per block hour of the two aircraft types, in service with United Air Lines, for the year ending 31 March 1993, are presented in Figure 5.

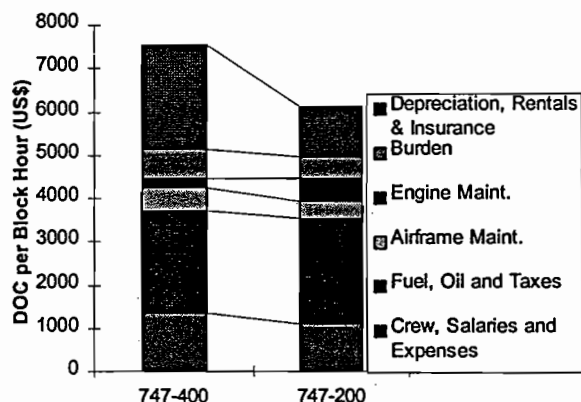


Figure 5: In-Service DOC data for 2 versions of the Boeing 747

As expected, the maintenance costs for the older aircraft are noticeably greater than the -400 aircraft. Despite the reduced fuel consumption of the -400, the fuel costs are similar due to higher average cruise speeds and higher seat numbers. It is clear that the older aircraft costs less to operate, primarily due to the difference in "depreciation and rentals" values which are greatly reduced for the older aircraft.

The fuel contribution to the DOC per block hour increases from 31.6% for the -400 to 39.6% in the older aircraft. Therefore, as an aircraft ages it seems clear that any fuel reductions will have a greater impact when compared to a turbulent aircraft of equivalent

age. This suggests that the benefits offered by HLFC are likely to increase with time, provided the effectiveness of the HLFC system does not degrade through the aircraft's service life.

HLFC System Reliability

It would be impossible to produce a practical system that is 100% reliable, although they are designed to be as close to this as is possible, within cost and weight constraints which are highly conditional on the consequences of the failure.

The safety implications of losing laminar flow, discussed earlier, appear to be minor. However, there are commercial considerations that must be addressed.

The prolonged loss of all laminar flow during cruise should not lead to a reduction in speed or altitude, due to stringent separation rules imposed by current Air Traffic Control (ATC). This implies that the high-speed performance of the wing, with fully turbulent boundary layers must be similar to that with laminar boundary layers, and that the engines must be sized to produce sufficient thrust to meet this condition when the aircraft is at maximum mass.

The margin between maximum continuous cruise thrust and maximum climb thrust should not be used to counter the increased drag of turbulent flow as this is required to meet the en-route climb requirement discussed earlier in the operational requirements. In addition, extended use at the maximum climb setting will have serious consequences on the engine life. Take-off, climb, descent and approach performance are unaffected as the HLFC system is inoperative during these phases.

Upon arrival at the destination, repairs could be performed during the 'turn-round', in which case the aircraft can return to operation with no interruption. If repairs could not be completed within the time permitted, the departure could be delayed, causing an interruption.

All airlines indicated that the HLFC system must not be despatch critical: the aircraft can be despatched with no laminar flow possible. They would not want to remove the aircraft from service for repairs after a complete failure of the suction system

However, it is clear that the aircraft will no longer be capable of achieving its design payload/range combination. This may not matter in many cases as the average stage lengths flown by transport aircraft in airline service are considerably less than the design range, although this can vary greatly between operators. Therefore, if the suction system was known to be unserviceable before despatch, it would be possible to increase the fuel load, permitting the aircraft to cover the vast majority of its payload/range envelope.

It is at the extremes of this envelope that limitations are imposed, in particular for longer range missions, as the maximum payload capability is

unaffected (Figure 6). For a specified payload, the fuel load can be increased until maximum take-off weight is reached, after which payload mass must be directly exchanged for fuel mass to increase the aircraft's range capability. However, fuel tank volume constraints may also be met, requiring an even more severe rate of payload reduction per unit range increase. The severity of this range shortfall is proportional to the margin between aircraft drag with, and without, laminar flow.

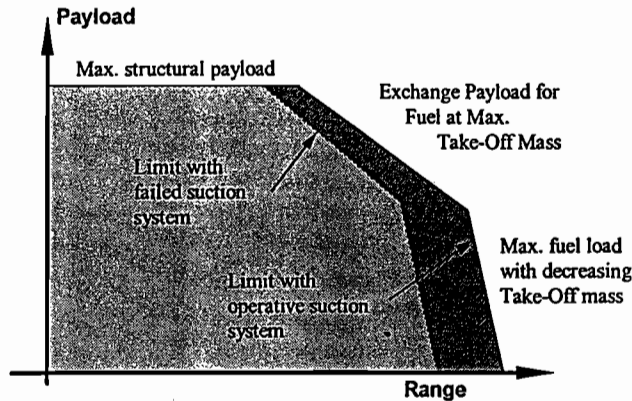


Figure 6: Payload/Range Envelope for HLFC Aircraft

Where an aircraft with a failed HLFC system is required to fly a mission close to the payload/range boundary, it may also be possible to exchange it for another that is scheduled to operate on an alternative route, within the turbulent range of the aircraft. This possibility is conditional on the availability of an alternative aircraft, which in turn is a function of fleet size, route structure and schedules. Clearly, major airlines operating large fleets from large hubs are more likely to be in a position to take this option.

For practical HLFC applications to the upper surface of the wing, a separate suction system is often proposed for port and starboard, with one or more suction units for each. To achieve a standard of reliability acceptable to operators, either of the two suction systems must need to be capable of providing the necessary suction to permit laminar flow across both wings following an in-flight failure of a critical component in one suction system. This will preserve the drag savings thus permitting completion of the mission with no range shortfall.

This system configuration would also permit the aircraft to remain in operation, retaining the benefits of laminar flow, until repair of the defective unit is possible. Despatch of the aircraft would be possible with only one suction unit operative, although additional fuel may be required due to operation of the suction system at off-design conditions, and hence reduced efficiency. The fuel reserves would have to be calculated to ensure that the aircraft would be capable of reaching a suitable airport after a malfunction of the second system, resulting in a complete loss of laminar flow.

System reliability can be assessed using various measures. PIREP's (Pilot REports) are, as the name

suggests, defects reported to maintenance staff by the flight crew, however minor. While each of these would require some form of maintenance action, imposing a cost on the airline, the probability of individual failure modes would determine the degree of operational reliability.

Where possible, corrective action 'on-aircraft' is performed whilst the aircraft is being 'turned-round' for its next flight. Where the failure mode is more severe requiring additional time, major components and/or complex ground equipment, departure of the next flight may be delayed and in some cases cancelled. In other cases, the PIREP can occur during flight, where a defect of certain components may force the aircraft to return to its point of departure or divert to an alternative airport. In each of these cases, the airline schedule is interrupted (15 minute delay constitutes an interrupt). The interrupt rate, often expressed as interruptions per 100 take-offs, relating to a particular system can also be used to assess reliability.

HLFC suction systems have often been compared with the air-conditioning system due to commonality of some components, such as a power supply from the powerplant, compressors, flow control system and extensive ducting. Other aspects differ between the two systems such as the heat exchangers and thermal control units for air-conditioning units, and purging and de-contamination systems for HLFC suction systems. The mode of power supply, bleed or electric, for each system may also differ, along with the power requirement.

It is difficult to forecast the reliability for a HLFC system based on the reported interrupt rate for existing air-conditioning systems without a detailed breakdown of the failure modes and the component at fault.

However, in-service air-conditioning reliability data may provide an initial estimate. Air-conditioning PIREP data and interrupt rates for existing Airbus Industrie and Boeing transport aircraft showed 5-10 PIREP's per 1,000 hours of operation, and less than 0.1 interruptions per 100 take-offs. To consider the interrupt rate in terms of flight hours, the flight time for the average stage length would be required.

This assumption is complicated by the nature and demands placed on the air-conditioning system. Complete failure of all air-conditioning will jeopardise occupant safety and prevent continued normal operation of the aircraft. Current commercial transport aircraft generally carry two air-conditioning units. Each must be capable of supplying sufficient cabin ventilation subsequent to a reasonably probable (defined in Figure 1) failure of one unit, permitting the aircraft to complete its mission uninterrupted [JAR 25.831]. This defect must be corrected before the aircraft can be despatched as it will no longer comply with the above requirement.

Surface cleaning

Surface cleaning is one of the most commonly raised issues when considering laminar flow technology, with the principle concerns being the cleaning methods, and the frequency at which cleaning is necessary. Steam-cleaning is one process that has been shown to be effective for cleaning a contaminated surface [15]. The equipment required for this is relatively simple compared to other cleaning processes, such as ultra-sonic cleaning, and the method can be used without removing the surface from the aircraft.

Cleaning the surface between each flight will clearly minimise the loss of laminar flow due to surface contamination. However, the level of contamination for each flight might be low, with only periodic cleaning necessary to maintain an adequate degree of laminar flow. Another option is to clean the surface as required, once a specified level of contamination occurs, although this would involve some form of continuous monitoring.

FLIGHT TEST EVALUATION OF CERTIFICATION AND OPERATIONAL FACTORS.

A number of recent flight test programs have investigated the impact of laminar flow technology, many of which are summarised in [1] and [16]. Of these, two in particular have evaluated the operation of a suction system in airline service. The NASA Simulated Airline Service (SAS) program, part of the LEFT program, assessed the performance of a porous and a slotted LFC suction leading edges, on a Jetstar business jet

A preliminary flight test program to verify suction system performance [17], was followed by seventy flights [9], resembling typical airline mission profiles, made through various seasons between various city-pairs within the continental USA. Almost half of these flights were winter operations centred on Cleveland, Ohio, where the daytime temperature was routinely below 0°C (32°F) with frequent exposure to snow, frost and freezing rain. Others were flown from Atlanta, Georgia, where temperatures were routinely in excess of 27°C (80°F) and thus conducive for high insect activity.

The main conclusions from this program as reported in [9] are as follows:

- i) LFC systems performed as intended during routine airline service.
- ii) No schedule delays were caused by LFC systems.
- iii) No pilot control of suction system required, other than on-off commands.
- iv) No measurable degradation of the perforated titanium suction surface after four years of flight testing.
- v) Surface cleaning between flights not required when the LFC systems were operated.

- vi) No special care was required for the suction surface and ducting when they were exposed to inclement weather on the ground or in the air.
- vii) Snow and ice were removed on the ground with conventional equipment.

A similar program is currently being conducted by Dassault, who have installed suction systems into the inboard wing leading edges of a Falcon 900 business jet from the Dassault Falcon charter service [18 and 19]. Initial flight tests will validate the system and quantify the achievable drag reductions. Upon completion of these, the aircraft will be returned to charter service, where the system performance will be assessed in a truly operational environment.

CONCLUSIONS

Any aircraft employing HLFC will have to demonstrate compliance with all existing certification and operational requirements, in addition to any further special conditions that may be imposed.

The principal additional certification issue will be aircraft controllability and manoeuvrability, during transition from laminar to turbulent boundary layers resulting from any failure modes. The same concern may also apply for low altitude climb performance when using a purging system to clear contaminants from the porous surface.

Operational issues include flight planning, in particular fuel reserves, cruise performance with no laminar flow, and operation in inclement meteorological conditions.

The airlines consulted were all interested in laminar flow technology, although significant long term cost benefits, relative to equivalent turbulent aircraft, would have to be possible before they would accept an aircraft employing HLFC, a technology that is unfamiliar to them. Questions concerning surface cleaning and system reliability must also be answered as these have a direct impact on the extent of operating cost benefits.

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REFERENCES

- 1 Collier, F.S. Jr: An Overview of Recent Subsonic Laminar Flow Control Flight Experiments. AIAA-93-2987.
- 2 Pearce, W.E: Evaluation of Laminar Flow Control Systems Concepts for Subsonic Commercial Transport Aircraft. NASA-CR-159251, 1983.
- 3 Gratzner, L.B et al (Boeing Commercial Airplane Company): Evaluation of Laminar Flow Control Systems Concepts for Subsonic Commercial Transport Aircraft. NASA-CR-158976, 1978.
- 4 Bennett, J.A. et al (Lockheed-Georgia): Evaluation of Laminar Flow Control Systems Concepts for Subsonic Commercial Transport Aircraft. NASA-CR-159254, 1980.
- 5 Maddalon, D.V. & Wagner, R.D: Operational Considerations for Laminar Flow Aircraft. NASA-CP-2413 Laminar Flow Aircraft Certification Workshop.
- 6 Meifarth, K.U. & Heinrich, S: The Environment for Aircraft with Laminar Flow Technology within Airline Service. 92-01-024, 1st European Forum on Laminar Flow Technology, March 1992.
- 7 Mowbray, G.H. & Gebhard, J.W: Man's Senses as Information Channels. Report CM-936, the John Hopkins University Applied Physical Laboratory, 1958.
- 8 Chan, Y.Y: Analysis of experimental data for CAST 10-2/DOA2 Supercritical at High Reynolds Numbers. NAE-AN-49, 1988.
- 9 Maddalon, D.V. & Braslow, A.L: Simulated-Airline-Service Flight Tests of Laminar Flow Control with Perforated Suction System. NASA-TP-2966, 1990.
- 10 Nastrom, G.D; Holdeman, J.D. & Davis, R.E: Cloud-Encounter and Particle-Concentration Variabilities from GASP Data. NASA-TP-1886, 1981.
- 11 Wylie, D.P. & Menzel, W.P: Two years of Cloud Cover Statistics Using VAS. Journal of Climate, Volume 2, p380, 1988.
- 12 Avmark Inc: Quarterly Aircraft Operating Costs and Statistics. 1st Quarter 1993.
- 13 Van Bodegraven, G: Commercial Aircraft DOC Methods. AIAA-90-3224.
- 14 Aircraft Economics, Jan/Feb 1994: 747-400 Fights for its Share of the -200B Market.
- 15 Maddalon, D. & Peppen, W.A. Jr Design and Fabrication of Large Suction Panels with Perforated Surfaces for Laminar Flow Control Testing. NASA-TM-89011, 1986.
- 16 Dziomba, B: European Laminar Flow Projects. Aerodays 93: 2nd Community Aeronautics R&D Conference, Naples Oct' 93.
- 17 Fisher, D.F. & Fisher, M.C: Development Flight Tests of Jetstar LFC Leading Edge Flight Test Experiment. NASA-CP-2487 Research in Natural Laminar Flow and Laminar Flow Control Symposium, Washington D.C. 1987, p117-140.
- 18 Flight International, 1993, Oct 6, p21: Laminar Flow tests for Falcon 900 wing.
- 19 Aviation International News, 1994 May 01, p6: Laminar Flow Falcon 900 Begins Test Flying..

C. CHANGES TO THE DESIGN SYNTHESIS

C.1 Introduction of Laminar Flow

The introduction of laminar flow to the CIVIL design synthesis has required considerable change to the design synthesis. All of the modifications described below are valid for both NLF and HLFC, bar those pertaining to suction systems which are only relevant for HLFC.

New variables and any of those from [27] used in the method described below are defined in the variable listing in Appendix C.3. New variables are also defined within the text where they are first used. Note that all **VARIABLES** are denoted by bold upper case text, and "**SUBROUTINES**" as bold upper case text within quotation marks.

If laminar flow is to be considered on airframe surfaces, a number of factors need to be considered. The primary direct benefit is the reduction in profile drag, **CD0WL** due to reduced skin friction and form factor values. Other indirect issues requiring attention are wing high-speed aerodynamic performance, namely wave drag, **CDWDR**, and any additional mass and cost due to additional systems.

Fully turbulent flow is assumed on all surfaces unless transition criteria are specified for one or more surfaces. As a safeguard an appropriate setting of the input switch **LFLOW** is also required to model laminar flow - failure to do so will reset all surfaces to fully turbulent flow. Where HLFC, rather than NLF, is required the input switch, **HLFC**, must also be set to the correct value.

The methods used to model laminar flow on wing, empennage and nacelle surfaces are all very similar, although the level of complexity is somewhat higher for wing cases. Therefore, the modelling of laminar flow on wings is discussed in detail below, after which the differences between these and other applications are detailed.

C.1.1 Laminar Flow Wings

The same basic method is used to evaluate profile drag for both NLF and HLFC cases, the primary difference being the definition of the maximum extent of laminar flow on the wing. For NLF, the maximum transition Reynolds number is considered as a function of leading edge sweep, whilst for HLFC a maximum transition Reynolds number is set within the input data, which is irrespective of the leading edge sweep as the suction is assumed to suppress all 3D instabilities.

In the original code, the profile drag was calculated within the "**SUB2**" subroutine. These calculations are now conducted within three new subroutines "**PDRAG1**", "**PDRAG2**" & "**FRICITION**" which are called by "**SUB2**" as they are required for the design, additional and alternative cruise conditions. The first subroutine sets up the limits of the laminar flow, the second calculates the area of laminar flow and the third determines the mean skin friction coefficients.

C.1.1.1 Wing Planform Geometry

The extent of NLF over the wing is dependent on a number of factors, such as the geometry, surface smoothness, pressure distribution, free-stream Reynolds number and disturbance environment. Wing geometry such as span, taper ratio, aspect ratio, geometric mean chord, and quarter chord sweep, (SPAN, TR, A, SWP, GMC, respectively) were already calculated within the original code. However values for centreline, root and tip chords (CCL, CR & CT) are now required along with the leading edge sweep of the wing (SWPLE). These are calculated within "SUB2" due to their independence from the various cruise conditions. The expressions used are as follows:

$$CCL = \frac{2 * GMC}{(1 + TR)} \quad (1)$$

$$CT = TR * CCL \quad (2)$$

$$CR = CCL - \frac{FUSD}{2} * \frac{(CCL - CT)}{(SPAN / 2)} \quad (3)$$

$$SWPLE = \frac{180}{\pi} * \tan^{-1} \left(\tan \left(SWP * \frac{\pi}{180} \right) + \frac{(0.25 * (CCL - CT))}{\frac{SPAN}{2}} \right) \quad (4)$$

C.1.1.2 Transition Prediction

Once the geometric parameters have been evaluated, the subroutine "PDRAG1" is called where the upper and lower surfaces are considered separately with the last letter ,U or B, in the variable name denoting upper or lower surface. The process described below is for the upper surface, although the same process is used for the lower surface. The rear end of the favourable pressure gradients is denoted by RTP and LMLT (set within "PDRAG1") for the upper and lower surface, respectively. LMLT is set to 0 to where laminar flow is on the upper surface only. Note that for HLFC, only upper surface applications can be considered

It is here that the effects of leading edge sweep on the maximum transition Reynolds number are considered. The results from many of the major NLF flight tests conducted over the last fifty years, Figure C-1, show an decrease in the maximum streamwise transition Reynolds number with an increase in leading edge sweep.

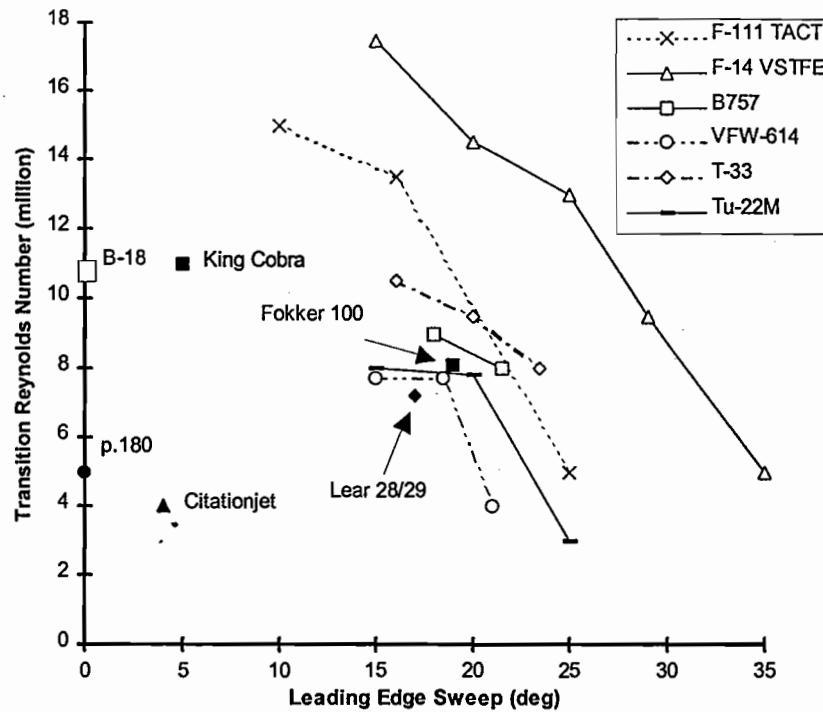


Figure C-1: Summary of NLF Flight Tests, based on Figure 16 [148]

For all these tests, the surfaces considered have been shaped to create large areas of favourable pressure gradients (reducing pressure), and hence accelerating flow to delay transition to turbulent flow.

Therefore, within the MVO code, the maximum transition Reynolds number, **RET**, is calculated as a function of leading edge sweep:

$$RET = RET1 - \frac{RET1}{RET2} * SWPLE, \quad (5)$$

where **RET1** is the maximum value of **RET** at 0° leading edge sweep and **RET2** is the sweep angle at which **RET** will become zero.

For realistic results: **RET1=20e06** & **RET2=35°**

These values provide a function which passes close to results achieved on transonic transport aircraft, namely the Fokker 100 in the ELFIN tests and the Boeing 757 NLF tests. It is unclear from Figure C-1 whether the variation for transport aircraft is linear as results are only available for a small range of sweep. It is quite possible that below a certain sweep angle the **RET** may become constant and at higher sweep angles rapid decrease in **RET** will occur due to 3-D mechanisms.

If required, it is possible to fix **RET** to a specific value by setting the **RETIN** variable, within the input file, to the negative value of the required **RET**. If this is used for NLF applications, it is advisable that the quarter chord sweep angle, **SWP**, is fixed, as transition Reynolds numbers are generally associated with particular sweep conditions.

Detailed HLFC flight test data is not currently available, although an overview of the Boeing/NASA 757 HLFC flight tests showed a transition position of 65% at mid-span during cruise at $M=0.82$ and 38,600ft [26]. This indicates a chord Reynolds Number in the region of 30 million, suggesting transition Reynolds numbers in excess of 20 million are possible at transonic conditions. Therefore a typical value for **RETIN** may be -25,000,000.

To determine the mean extent of laminar flow on the wing, the maximum transition Reynolds number is first used to define the maximum physical distance, **CTRAN**, at which transition can occur from the leading edge. This results in a transition front parallel to the leading edge. Thus,

$$CTRAN = \frac{RET * NUC * 3.6}{VC}, \quad (6)$$

where **NUC** & **VC** are the relevant values of **NUCR**, **WNUCR** or **XNUCR** and **VCR**, **WVCR** & **XVCR** passed from "SUB2".

This is then compared to the tip and root chords to obtain values of **TPTU** & **TPRU**, the fraction of tip and root chords with laminar flow.

$$TPTU = \frac{CTRAN}{CT} \quad (7)$$

$$TPRU = \frac{CTRAN}{CR} \quad (8)$$

Subroutine "PDRAG11" is then called where **TPTU** & **TPRU** are compared with the chordwise location of the rear end of the roof-top pressure distribution, **RTP** (expressed as a fraction of the chord which is constant across the span). As transition cannot occur aft of the end of the roof-top, if **TPTU** and/or **TPRU** are greater than **RTP**, the relevant variable(s) are set to the value of **RTP**, which can be fixed to a desired value, if **RTPC** is set to the negative value of the required chordwise position, or be left free to vary, within the code.

This provides the physical distance covered by laminar flow at the tip and root, **LFTU** & **LFRU**.

$$LFTU = TPTU * CT \quad (9)$$

$$LFRU = TPRU * CR \quad (10)$$

C.1.1.3 Area of Laminar Flow

Where **TPTU** & **TPRU** are both less than **RTP**, the transition front is parallel to the leading edge at a chordwise distance of **CTRAN**. When both are greater, the transition point is at a constant fraction of the chord (based on **RTP**) forming a trapezoidal area of laminar flow. In these cases, the area covered by laminar flow on each semi-span, **SLAMU**, is defined by:

$$SLAMU = 0.95 * ((LFTU + LFRU) * (SPAN - FUSD)) \quad (11)$$

The factor 0.95 represents an allowance for the loss of laminar flow at the wing root due to interference from the fuselage.

However, where **TPRU** is less than **RTP** and **TPTU** greater (Figure C-2), the transition front parallel to the leading edge (inboard section) will coincide with the rear end of the pressure roof-top (at constant percentage chord) at some point along the semi-span.

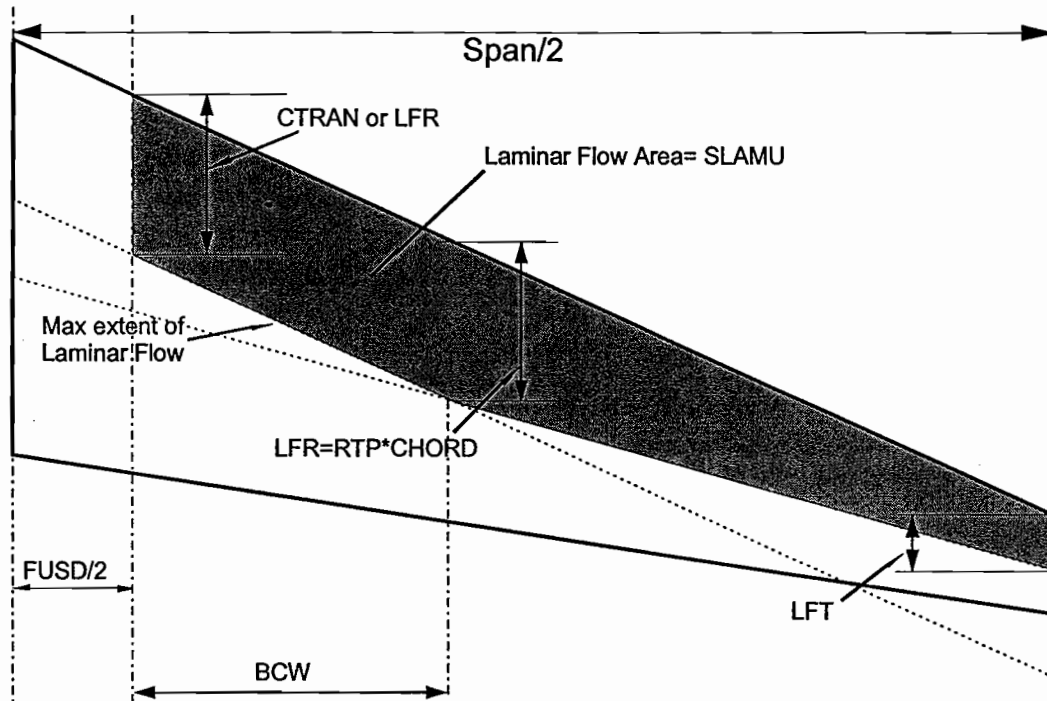


Figure C-2: Derivation of Laminar Flow Extent

This point will occur where:

$$LFRU = RTP * CHORD, \quad (12)$$

where **CHORD** is the streamwise chord at some point **BCWU** metres along the wing. As the design synthesis considers the wing to be trapezoidal, the wing chord will decrease linearly from the root to tip permitting the following expression to be derived:

$$LFRU = RTP * CR - BCWU * \left(\frac{RTP * (CR - CT)}{\frac{SPAN}{2} - \frac{FUSD}{2}} \right) \quad (13)$$

This can be manipulated to find **BCWU**.

$$BCWU = \left(\frac{SPAN - FUSD}{2 * RTP * (CR - CT)} \right) * (RTP * CR - LFRU) \quad (14)$$

Inboard of this point, a parallelogram is formed with **LFRU** as the length of two sides and **BCWU** as the height. Outboard of this point a trapezium is formed with the parallel sides of lengths **LFTU** & **LFRU** with a height being the remainder of the span. In such cases, the laminar area, **SLAMU**, is determined using the following expression:

$$SLAMU = 2 * 0.95 * \left((LFRU * BCWU) + \frac{LFRU + LFTU}{2} * \left(\frac{SPAN}{2} - BCWU - \frac{FUSD}{2} \right) \right) \quad (15)$$

The proportion of laminar flow over exposed wing area, **LPU**, is then calculated:

$$LPU = \frac{SLAMU}{NWA * S} \quad (16)$$

Note, this value should not exceed $0.95 * RTP$.

The process is repeated, if required, to define the area of laminar flow on the lower surface, **SLAMB**. The entire process repeated for the alternative mission, **XSLAMU** & **XSLAMB**, and the high speed cruise case, **WSLAMU** & **WSLAMB**.

C.1.2 Drag Prediction

The method within the MVO for evaluating turbulent profile drag of wings uses a mean skin friction coefficient based on the geometric mean chord (GMC). This has been retained for laminar flow applications, although comparisons were made with a strip method to ensure that this approach was valid for laminar flow cases. The extent of laminar flow and hence the resulting profile drag were defined for each strip. The strip profile drag coefficients were totalled and compared with the result using a mean skin friction coefficient applied to the GMC. Typical wing planforms for an executive jet, regional jet and a long range aircraft were used to ensure that aircraft size was not a factor. The results, summarised in Figure C-3, show that the differences between the strip and mean methods were less than 1% for all cases, which suggests that using a mean skin friction coefficient is satisfactory.

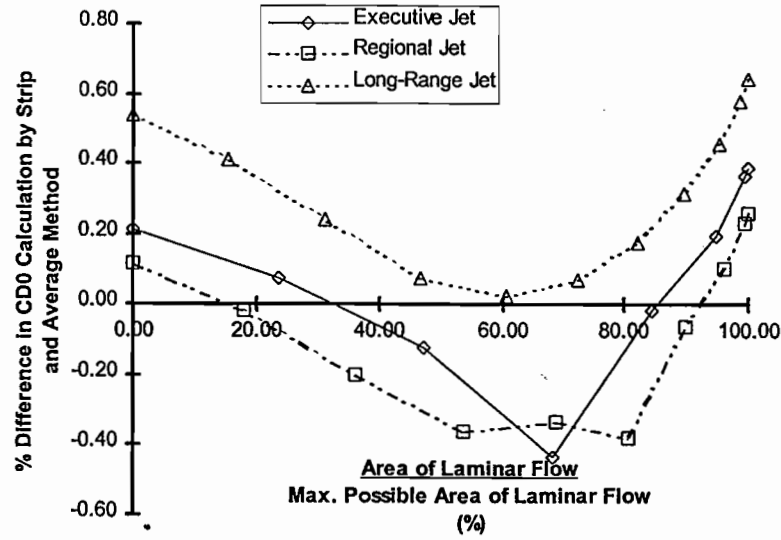


Figure C-3: Comparison of Strip and Mean Methods for Profile Drag Prediction

C.1.2.1 Skin Friction

A mean point of transition is then assumed to be at a distance **TPMU** from the leading edge on the GMC.

$$TPMU = LPU * GMC \quad (17)$$

At this point subroutine "**FRICITION**" is called, where a mean transition Reynolds number for the wing, **RETW**, is calculated based on **TPMU**.

This is then used to calculate the wing skin friction coefficient using the method for defining the mean skin friction on a flat plate with some degree of laminar flow [37] where:

$$CF = \frac{0.49}{\log(RE)^{2.625}} * [1 + (LP - X0C)]^{6/5}, \quad (18)$$

where **LP** is the transition position, expressed as a fraction of the chord, **RE** is the chord Reynolds number, and **X0C** is defined as :

$$X0C = \left[\frac{0.664 * \sqrt{LP} * RE^{-0.5}}{0.0225} \right]^{6/5} \quad (19)$$

The code then returns to "**PDRAG1**" where the flat plate (no form factor) turbulent and laminar profile drag coefficients for the wings, **ACDT** & **ACDL**, are calculated (**ACD0WT** & **ACD0WL** in "**SUB2**"):

For the turbulent case:

$$ACDT = \left(\frac{1.15 * N WAF}{\log_{10}(REC)^{2.625}} \right), \quad (20)$$

where the "1.15" is the product of 2 (upper and lower surface)*0.49 (term in skin friction calculation) and 1.17 (factor representing additional drag due to steps, gaps and excrescences)

The upper surface contributes 2/3 of the total profile drag for the wing [119]. As the extent of laminar flow can differ on each surface, the profile drag for each surface must be determined separately and weighted to represent the 2/3 - 1/3 split. Thus for the laminar case:

$$ACDL = NWA F * ((1.526 * CFLU) + (0.821 * CFLB)) \quad (21)$$

The "1.526" & "0.821" values are derived from the "1.15" in the turbulent definition with 0.49 removed, as they are included in the CFLU and CFLB terms.

Surface quality is not considered in detail within the MVO, a factor of 1.17, in equation (20), is applied to the wing skin friction to represent increased drag due to gaps, steps and. It is possible that this could be lowered because of the reduction in allowable step and gap sizes for laminar flow. The lack of leading edge high lift devices on NLF applications, with the inherent rearward slat/leading edge step represents a further argument for reducing this factor. However, in the absence of any further evidence the original value has been retained.

The same process is used to define the corresponding values for the high speed, WACDWT & WACDWL, and alternative cruise cases, XACDWT & XACDWL.

C.1.2.2 Form Factor

ACD0WT & ACD0WL are then used, within subroutine "CLCRUISE", to produce values of CD0WT & CD0WL, the total profile drag for the wings in a turbulent and laminar case respectively. These CD0* expressions include a form factor, $(1 + \psi)$, to convert the flat plate friction drag values, ACD0*, to those representative of a wing. Within the original design synthesis this form factor was defined as:

$$Form_Factor = 1 + 3 * TC * \cos^2(SWPA), \quad (22)$$

where TC is wing thickness/chord, and SWPA is the effective aerodynamic sweepback.

Using information, supplied by BAe Airbus Ltd, for representative NLF and HLFC sections, the aerodynamic performance of aerofoil sections with some degree of laminar flow present was investigated. Results from this study have been used derive expressions for the form factor with laminar flow on the upper wing surface only (NLF and HLFC):

$$Form_Factor = 1 + 3 * TC * \cos^2(SWPA) * [(-1.3281 * LPUC^2 - 0.02311 * LPUC) + 1] \quad (23)$$

Where laminar flow is present on upper and lower surfaces (NLF only):

$$Form_Factor = 1 + 3 * TC * \cos^2(SWPA) * [(-2.3532 * LPUC^2 - 0.13647 * LPUC) + 1] \quad (24)$$

C.1.2.3 Clouds

The influence of cloud encounter has also been taken into account using the input term, **PENFUL**, which is a weighting factor between the turbulent and laminar profile drag coefficients. When equal to **0.0**, this defines the mean profile drag as being laminar throughout the cruise sector. When equal to **1.0** no laminar flow is possible at any time in cruise.

The resulting profile drag coefficient **CD0AV** is defined as:

$$CD0AV = (1 - PENFUL) * CD0L + PENFUL * CD0T \quad (25)$$

This is subsequently used within the cruise drag, **CD0CR**, term.

C.1.3 HLFC Wing Suction System Sizing

The suction system sizing occurs subsequent to the aerodynamic routines in the subroutine "SUCTION" which is called from "SUB2".

The preliminary task is to calculate the suction area, which is achieved by setting, within the input file, a chordwise extent of suction from the leading edge, **CTS**, and inboard and outboard extremities of suction as a fraction of a half-span, **BSUCKI** & **BSUCKO**. The chords at each extremity, **CSUCKI** & **CSUCKO**, are then calculated:

$$CSUCKI = CR - BSUCKI * (CR - CT) \quad (26)$$

$$CSUCKO = CT + BSUCKO * (CR - CT) \quad (27)$$

From these the suction area, **SSUCK**, can be defined:

$$SSUCK = 2 * \left(CTS * \left(\frac{CSUCKI + CSUCKO}{2} \right) * \left(\frac{SPAN - FUSD}{2} \right) * (1 - (BSUCKI + BSUCKO)) \right) \quad (28)$$

C.1.3.1 Suction Coefficients

To evaluate the suction coefficients, subroutine "SUCK", called from "SUCTION", defines the suction panel geometry. "SUCK2" is then called to define the suction coefficients for various cases.

The suction coefficient required at any position on the suction surface to maintain laminar flow is dependent on the principal boundary layer disturbances at that location, and the flight conditions. To simplify matters, in suction system design and for this study, the suction surface around the leading edge of a wing is considered as three distinct zones denoted by the dominant transition mechanism in that region: attachment line, cross-flow, and Tollmein-Schlichting zones, Figure C-4. Tollmein-Schlichting instabilities are 2-D in nature, while attachment line transition and cross-flow instabilities are 3-D mechanisms. On 3-D swept wings, attachment line transition dominate on the leading edge, and cross-flow instabilities in the forward 6-10% chord where the flow is highly 3-D. Tollmein-Schlichting instabilities become dominant downstream of the cross-flow region where the flow is largely 2-D. Full descriptions of these are provided in [4].

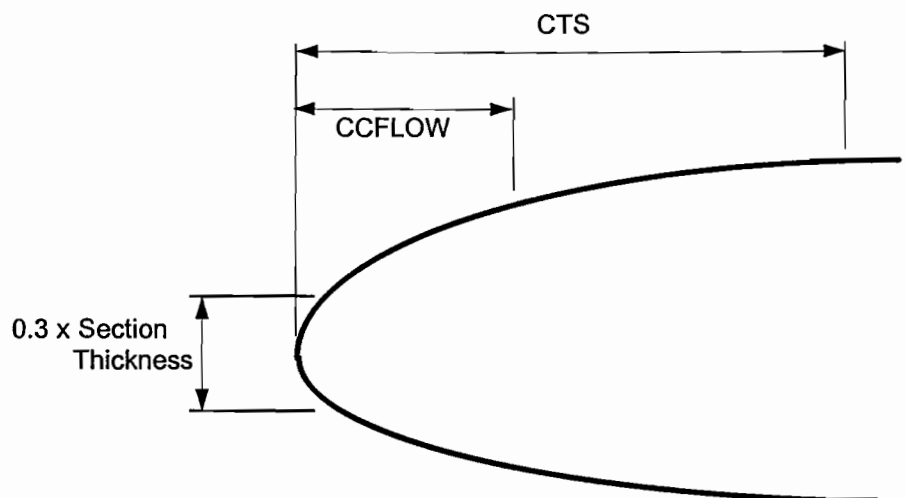


Figure C-4: Suction Surface Definitions

As the surface in the attachment line zone is primarily normal to the line-of-flight, it is regarded as a vertical flat plate within the design synthesis extending over 30% of the maximum section thickness covering all possible attachment line locations during cruise and for reasonable climb gradients. The aft extent of the cross-flow is defined within the input data as **CCFLOW** (expressed as % chord). For simplicity this zone is approximated using a horizontal flat plate extending from the leading edge, although in reality it commences at approximately 2% chord where the attachment line zone ends. This does not imply that the cross-flow suction area is too large as the actual surface is neither horizontal nor flat.

The rear extent of the Tollmein-Schlichting zone is defined in the input data as **CTS** (defined as % chord). As the surface is almost parallel to the line of flight, this zone is also considered as a horizontal flat plate, whose forward extent is defined by the rear extent of the cross-flow suction surface.

Suction coefficients are derived for each zone, allowing the volume flow of sucked air through each zone to be determined. The process is repeated for cruise conditions representative of the alternative mission.

A design case for HLFC suction system is set at a low cruise altitude, 30,000ft, and at the design cruise Mach number, (highest cruise Reynolds numbers). The high suction velocity requirements for this condition ensure that the suction system will be capable of normal operation at all cruise conditions.

This design case is used to derive suction system masses, with cruise flight conditions determining the specific fuel consumption penalty during cruise. For the 30,000ft design case, all variables end with a 'D'

C.1.3.1.1 Attachment line zone

The suction coefficient for the attachment line zone is a function of the leading edge Reynolds number, R_{bar} , which is itself dependent on the attachment line pressure distribution, sweep and flight conditions [4]. The leading edge Reynolds number can be written as:

$$Rbar = \sqrt{(REC / U1)} * \sin(SWPLE), \quad (29)$$

where REC is the streamwise chord Reynolds number, U1 is the attachment line velocity gradient. Data supplied for the modern representative aerofoil types used in [160] detailed values of U1 corresponding to various initial pressure gradients, DCPDSI, which can be represented as follows:

$$U1 = -.0032 * DCPDSI^2 + 1.3048 * DCPDSI + 38.799 \quad (30)$$

This value of R_{bar} is then used in the expression below, from [105] to derive the attachment-line suction coefficient, CQAL:

$$CQAL = \frac{-CQALB - \sqrt{CQALB^2 - 4 * CQALA * CQALC}}{2 * CQALA}, \quad (31)$$

where:

$$CQALA = 64226.75 * Rbar^2 \quad (32)$$

$$CQALB = -28812 * Rbar \quad (33)$$

$$CQALC = 60025 - Rbar^2 \quad (34)$$

This value represents the minimum suction coefficient that is required to suppress any boundary layer disturbances in the attachment-line flow, and if necessary relaminarise a turbulent boundary layer. If Rbar is less than 245, suction of the attachment line is not required as any boundary layer disturbances are naturally damped. In such cases, the suction coefficient is set to zero.

C.1.3.1.2 Cross-Flow Zone

A cross-flow Reynolds number, χ , can be defined for a yawed ellipse [108] as:

$$\chi_{max} = A \left(\frac{Q_{\infty} r}{\nu} \right)^{1/2}, \quad (35)$$

where Q_{∞} is the free-stream velocity, r is the leading edge radius, A is a function of sweep angle and thickness/chord ratio, and ν is the kinematic viscosity. It was found that A was strongly dependent on sweep, but only weakly dependent on the thickness/chord ratio. As detailed aerofoil geometry is not included within the design synthesis, results from an analytical study [160] have been used to define the minimum suction coefficients required to prevent cross-flow induced transition, as a function of streamwise chord Reynolds number and leading edge sweep.

Results are presented for two values of the initial pressure gradient, (DCPDSI=40 & 100), shown as the solid lines in Figure C-5 & Figure C-6. Each of these was modelled such that one expression defines the minimum suction coefficient for each case. Interpolation between these two results is used to define the suction coefficient, CQCF, corresponding to the initial pressure gradient, DCPDSI, specified in the input data.

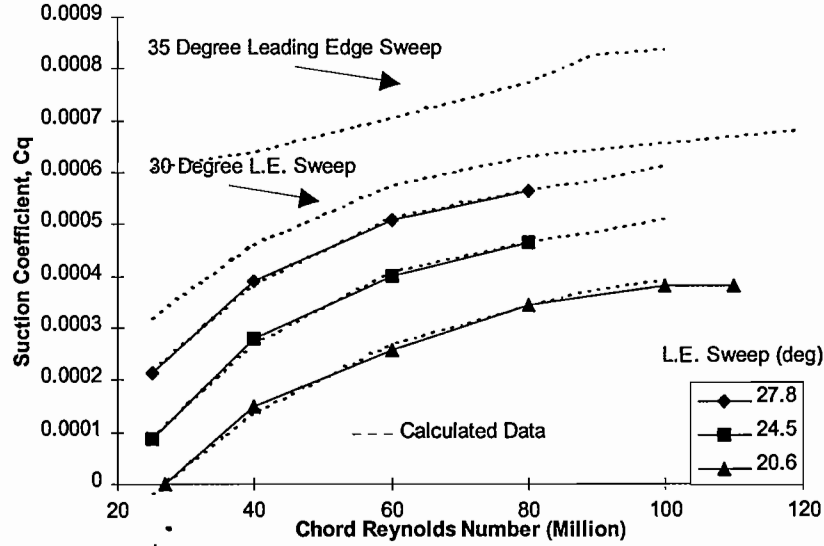


Figure C-5: Minimum Suction Coefficients for DCPDSI=100

The above data, for an initial pressure gradient of 100, was modelled using the following expression:

$$CF100 = CF10001 * REC1^3 + CF1002 * REC1^2 + CF1003 * REC1 + CF1004, \quad (36)$$

where

$$CF1001 = -1.561e^{-11} * SWPLE^2 + 8.029e^{-10} * SWPLE - 9.429e^{-9} \quad (37)$$

$$CF1002 = 3.894e^{-9} * SWPLE^2 - 1.991e^{-7} * SWPLE + 2.284e^{-6} \quad (38)$$

$$CF1003 = -2.985e^{-7} * SWPLE^2 + 1.511e^{-5} * SWPLE - 1.651e^{-4} \quad (39)$$

$$CF1004 = 6.790e^{-6} * SWPLE^2 - 3.067e^{-4} * SWPLE + 3.026e^{-3} \quad (40)$$

Good agreement was achieved for the original range of data, which was limited to chord Reynolds numbers less than 80 million. However, all cases approach an asymptote at high Reynolds numbers [159]. Therefore where the chord Reynolds number exceeds 100 million, the suction coefficient is set to the value that corresponds with 100 million.

Reference [160] only provided data for leading edge sweep angles up to 27.8°. When the above expression was used for 30° and 35° sweep cases, the trend observed for the lower sweep cases was maintained.

Similarly, the following expression was used to model the minimum suction coefficient for an initial pressure gradient of 40:

$$CF40 = CF401 * REC1^3 + CF402 * REC1^2 + CF403 * REC1 + CF404$$

Where:

$$CF401 = 2.687e^{-13} * SWPLE^2 + 6.352e^{-10} * SWPLE - 1.031e^{-9} \quad (42)$$

$$CF402 = -6.151e^{-11} * SWPLE^2 - 1.133e^{-8} * SWPLE + 1.385e^{-7} \quad (43)$$

$$CF403 = -2.914e^{-9} * SWPLE^2 + 8.494e^{-7} * SWPLE - 3.960e^{-6} \quad (44)$$

$$CF404 = -1.777e^{-7} * SWPLE^2 + 3.081e^{-5} * SWPLE - 4.972e^{-4} \quad (45)$$

As for the previous case, good agreement was achieved for chord Reynolds numbers up to 100 million, Figure C-6, after which the suction coefficient is assumed to be fixed at the value for 100 million. Again the extrapolated results for the 30° and 35° leading edge sweep cases look plausible.

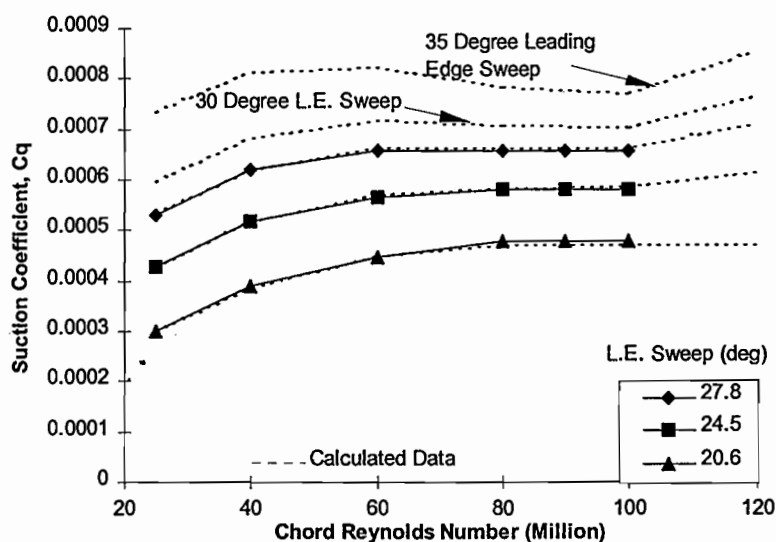


Figure C-6: Minimum Suction Coefficients for DCPDSI=40

C.1.3.1.3 Tollmein-Schlichting Zone

The suction coefficients in this zone are generally very small and are independent of leading edge geometry and flight condition. A constant value is therefore used and is set within the input data file typically at $C_{QTS}=0.0002$

C.1.3.2 Volume Flow

When defining the suction coefficients for the attachment-line and cross-flow zones, the chord Reynolds number is of primary importance. Obviously, where a tapered wing is considered, the chord Reynolds number, and thus the suction coefficients, will reduce with distance from the root as the chord decreases across the span.

Practical suction surfaces are often considered as 3-4m spanwise panels, to allow changes in suction coefficients along the span, in addition to maintenance considerations. Thus the distance from the wing/fuselage junction to the tip, parallel to the exposed leading edge, **LESPAN**, is divided by 3 (minimum panel length). The resulting real number is truncated to form an integer representing the number of panels required across one wing. **LESPAN** is then divided by this to get the panel length, **PANLEN**. For each panel, the inboard and outboard chord of the panel to be defined as, **CHORDI** & **CHORDO** (Figure C-7).

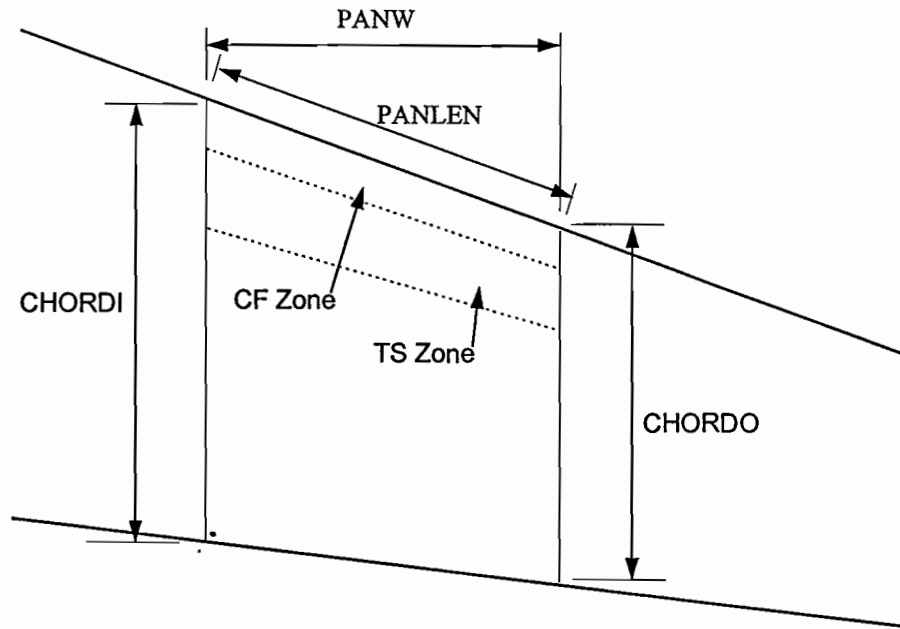


Figure C-7: Schematic of Suction Panel

The inboard chord, being the greatest, is used to determine the suction coefficients across the whole panel. Given that the suction coefficient can be considered as the ratio of mean suction velocity to the free-stream velocity, the mean suction velocity for each zone on the panel can be defined.

The depth of the attachment-line zone is determined by taking 30% of the section maximum thickness. For the outer wing this is simply derived from the thickness/chord ratio in the design synthesis and the inboard and outboard panel chords. To represent the increased thickness/chord ratio on the inboard section of transport aircraft wings, implying increased suction area, the thickness/chord ratio is assumed to increase linearly from the outer wing value, at 40% span, to 140% of the outer wing thickness/chord ratio at the fuselage side. The product of the average suction depth and panel length, **PANLEN**, are used to define the attachment line suction area.

The area of suction for the cross-flow and Tollmein-Schlichting zones can be determined from the panel geometry and the definition of the suction extent, **CCFLOW** & **CTS**. For each zone, the volume flow rate is the product of the mean flow velocity and the suction area.

The volume flow from all three zones on all panels is combined to give the total volume flow of sucked air for one wing, which is then doubled to represent the sucked air for the whole wing, **WMFSUK**.

C.1.3.3 Suction Power

The minimum value of C_p , **CPMIN**, in the suction region, which is set within the input data, is used to determine the minimum pressure, **PMIN**:

$$P_{MIN} = C_{P_{MIN}} * \left(\frac{RO * (VCR / 3.6)^2}{2} \right) + RO * 287 * TA, \quad (46)$$

where **RO** & **TA** are the ambient density and temperature at the cruise altitude.

The loss in pressure from the external face of the suction surface to the compressor face, as a fraction of the external pressure, **PLOSS**, is an input term and is used to determine the pressure at the compressor face, **PCOMPF**:

$$P_{COMPF} = (1 - P_{LOSS}) * P_{MIN} \quad (47)$$

The power required by the electrically driven compressor to return the sucked air to ambient conditions (assuming exhaust produces no net drag or thrust), **POWCOM**, is defined as:

$$POWCOM = 1.1 * MFSUCK * \left(\frac{RO * 287 * TA - P_{COMPF}}{ETAC} \right) \quad (48)$$

Where **ETAC** is the compressor efficiency (input value) and the '1.1' factor provides a small power reserve.

Further energy losses during transmission and generation are considered in the expression for the electrical power off-take from the engine, **POWENG**:

$$POWENG = \left(\frac{POWCOM}{ETAT} \right) / ETAG, \quad (49)$$

where **ETAT** & **ETAG** are transmission and generating efficiencies.

The effect of this energy off-take from the engine can be measured in terms of increased fuel consumption to maintain net thrust. The increase in fuel consumption, although it does not exceed 1% for the majority of expected HLFC power requirement/engine combinations, will represent an increment in fuel mass. This in turn may lead to a heavier structure, or even a larger and/or thicker wing if its geometry is driven by fuel volume, and to a DOC penalty.

This effect is represented by a fuel consumption penalty factor, **CFCPEN**, based on an off take power/net cruise thrust ratio:

$$CFCPEN = \left(P_{ENCF} * \frac{POWENG}{TREQ} \right) + 1 \quad (50)$$

TREQ & **PENCF** are the net thrust requirement at cruise, and an engine independent factor, derived from a study using the 'Turbomatch' gas turbine modelling code [

100] (typically **PENCF**=0.001773). **CFCPEN** is then returned to the "SUB2" subroutine where the specific fuel consumption, **CFC**, is factored by this value.

The specific fuel consumption penalty for the alternative mission cruise is calculated within the same subroutine. The power requirements are determined using terms based on equations (28) to (48) after which the penalty is defined as:

$$XCFCPN = \left(PENC F * \frac{XPOWENG}{XTREQ} \right) \quad (51)$$

C.1.4 Suction System Mass

The “SUCTION” subroutine calls an HLFC suction system mass estimation routine, “SUKMAS”. The suction system mass, **MSUCK**, is the sum of the component masses, which becomes **WMSUCK** (denoting wing suction mass) when returned to the “SUCTION” and “SUB2” subroutines.

For this study the suction system components are considered as plenum and collection chambers, spanwise collector ducts, compressors, electric motors, cabling, and generators. Each of these are expressed as the product of a specific-mass value, in the input data, and some aircraft or suction system related term. Plenum and collection chamber mass, **MCHAN**, is considered as a function of the area of suction:

$$MCHAN = MCHANI * SSUCK \quad (52)$$

Spanwise collector duct mass, **MDUCT**, is defined as a function of the total volume flow of sucked air in the suction system design case:

$$MDUCT = MDUCTI * MFSUCKD$$

Compressor mass, **MCOMP**, and electric motor mass, **MMOTO**, are defined as functions of the compressor power requirement for the suction system design case:

$$MCOMP = POWCOMD / MCOMPI \quad (54)$$

$$MMOTO = POWCOMD / MMOTOI \quad (55)$$

The cable mass, **MCAB**, is a function of aircraft configuration and engine number and location. For aircraft with two engines located under the wing or on the rear fuselage, the following expression is used:

$$MCAB = 3 * MCABI * \frac{POWENG D}{2} * [MCAB2 + FUSD + 2] \quad (56)$$

The relative maximum power loading is defined by the normal operation of the suction system. If the top-left illustration in Figure C-8 is considered, the cable length from point ‘a’ to ‘b’ is represented by **MCAB2**, ‘b’ to ‘d’ by **FUSD**, with a 1m length of cable assumed between each wing root leading edge and suction unit (‘b’ to ‘c’).

The other terms in equation (56), **MCABI** and **POWENG D/2** are, respectively, the cable mass per metre per watt and the power extracted from the propulsion system for each suction unit. The whole expression is factored by three to represent a three-phase electrical system.

A similar approach is taken for aircraft with four engines mounted under the wing and two suction units, resulting in the following expression:

$$MCAB = 3 * MCABI * \frac{POWENG D}{2} * [MCAB1 + FUSD + MCAB2 + 2] \quad (57)$$

Where **MCAB1** represents the cable length from inboard engine to the wing root, and **MCAB2** is the cable length from outboard engine to wing root, and where relevant the cable length from rear mounted engines to the suction units:

$$MCAB1 = NEIW * \left[NACL + \frac{\frac{SPIENG * SPAN}{2} - \frac{FUSD}{2}}{\cos(SWPLE)} \right] \quad (58)$$

$$MCAB2 = NEOW * \left[NACL + \frac{\frac{SPOENG * SPAN}{2} - \frac{FUSD}{2}}{\cos(SWPLE)} \right] + NER * [NACL + (KENG - CGPOSN) * FUSL] \quad (59)$$

Generator mass, **MGEN**, is defined as a function of the power off-take from the engine for the design case:

$$MGEN = \frac{POWENG D}{MGEN1} \quad (60)$$

Electrical power for the suction system can be supplied either by the main electrical supply, requiring increased capacity generators, or installing additional generators dedicated for the suction system. Either option can be selected for wing cases, using a switch within the input data, **MGEN2**, which is set to '0' for using the main supply, and '1' for additional dedicated generators. Where **MGEN2**=1, generator mass determined using **MGEN2** is increased by 38kg per engine to represent the fixed mass penalty of using additional generators.

Once the suction system masses for wing, fin, tailpane and nacelle surfaces have also been determined they are totalled, within subroutine "**CG_POSITION**" (sections 1 and 2) to provide the total mass of suction system on the aircraft, **TOTSUM**.

Typical values for the input data are:

$$\begin{aligned} MCHANI &= 6.82 \text{ kg/m}^2 \text{ of suction surface} & MDUCTI &= 13.14 \text{ kg/m}^3 \text{ of sucked air} \\ MCOMPI &= 2000 \text{ W/kg (compressor power)} & MMOTOI &= 2200 \text{ W/kg (Comp. power)} \\ MCABI &= 3.2075 \times 10^{-6} \text{ kg/m/W} & MGEN1 &= 2980 \text{ W/kg (Off-take power)} \end{aligned}$$

It is not known with any certainty whether data from which the above coefficients are derived made any allowance for operation after failure of selected components within the suction system. There is, however, evidence that the values are appropriate to the no-failure case, thus it is assumed that all the above values correspond to this case. This is therefore assumed to be the default case.

C.1.4.1 Suction System Redundancy

If desired, some form of suction system redundancy can be modelled by selecting an appropriate value for the **MODEF** input switch. For example, in the case where suction is provided by two compressors, failure of one would require the mass flow of the other to double requiring increased compressor speed to achieve the desired

compression ratio. If the compressor is sized to achieve maximum efficiency during the normal mode of operation the efficiency during the failure case will be significantly reduced.

The electric motor for each suction unit would have to be capable of delivering sufficient power to drive the compressor with twice the mass flow at reduced efficiencies. If sensible assumptions are made, the power capability of each motor must be increased by a factor of 3.6 from the normal mode of operation, although a typical 50% excess capacity in a motor will permit this factor to be reduced to 2.4 which must be applied to **MMOTOI**. Additionally, the power generating capability, namely **MGEN1**, would have to be doubled to provide sufficient power for both suction units after failure of one of the generators.

The additional power requirements will call for the maximum power loading in certain sections of the cabling to be increased. This is considered for suction unit or generator failure in Figure C-8, where P_1 represents the power requirement for one suction unit.

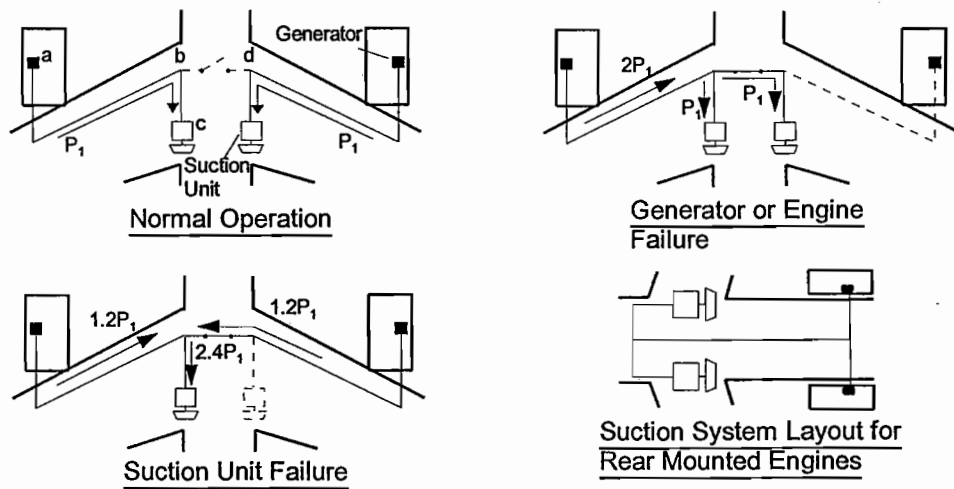


Figure C-8: Cable Layout for Two-Engined Aircraft

Taking the highest power loading for each section of cabling, the following expression, derived from equation 56, can be used for twin-engined aircraft, provided $MCAB2 = 2$.

$$MCAB = 3 * MCAB1 * \frac{POWENG D}{2} * [2 * MCAB2 + 1.2 * FUSD + 2.4 * 2] \quad (61)$$

A similar approach for four engine aircraft results in the following expression, derived from equation 57.

$$MCAB = 3 * MCAB1 * \frac{POWENG D}{2} * [1333 * MCAB1 + 1.2 * FUSD + 0.667 * MCAB2 + 24 * 2] \quad (62)$$

This approach is modelled by setting **MODEF** to '2', which factors the motor and generator by the appropriate values and evaluates the corresponding cable mass.

An alternative method to overcome failure of part of the suction system is to install a third suction unit to provide a degree of redundancy. Each of the three suction units

are sized such that normal operation requires only two to be functioning. To model this, the compressor and motor mass need to be increased by a factor of 50%. In this case, all three suction units could either be operated with reduced mass flow, relative to the design condition, or two could be operated at design conditions with the third acting as a standby. This approach is modelled by setting **MODEF** to '3', which factors the compressor, motor and generator mass by the appropriate value.

Again, failure of certain components will require increased power loading on the electrical cables. A similar approach to that in Figure C-8 was used to define equation 63 for twin-engine aircraft. The principal difference, from the previous case, being the deletion of the factor applied to the last two terms.

$$MCAB = 3 * MCAB1 * \frac{POWENG D}{2} * [2 * MCAB2 + FUSD + 3] \quad (63)$$

Similarly, for four engine aircraft:

$$MCAB = 3 * MCAB1 * \frac{POWENG D}{2} * [1.333 * MCAB1 + FUSD + 0.667 * MCAB2 + 3] \quad (64)$$

C.1.5 Suction System Sizing for HLFC Empennage and Nacelles

The method used to size the suction systems for empennage and nacelle applications follows the same approach as that for the wing, although a number of simplifications and modifications are necessary.

C.1.5.1 HLFC Engine Nacelle Applications

Within the "**CG_POSITION**" subroutine, total nacelle suction area, **NSSUCK**, is defined as a fraction, **SUCKL**, of the nacelle wetted area, **SCOWL**. **SUCKL**, set within the design synthesis, is assumed to be 0.12. A mean suction velocity, **VWALL**, is used in place of suction coefficients and is set within the input data (Typical value **VWALL** = 0.15m/s)

Volume flow, **NMF**, is defined as:

$$NMF = NSSUCK * VWALL \quad (65)$$

The "**SUKMAS**" subroutine is called and the energy requirements at the 30,000ft design case are determined, assuming a minimum pressure coefficient of **NCPMIN** = -0.8. This in turn defines the nacelle suction system mass, returned as **NMSUCK**, using the mass coefficients specified for the wing case. Subsequently, the masses for the electric motor, cabling and generators are set to zero as a direct drive is assumed, due to the compressor's proximity to the engine.

C.1.5.2 HLFC Empennage Applications

Like the nacelle cases, the fin and tailplane suction areas, **FSSUCK** and **TSSUCK** respectively, are defined within "**CG_POSITION**":

$$FSSUCK = 0.2 * 0.8 * 2 * SFIN \quad (66)$$

$$TSSUCK = 0.2 * 0.8 * 2 * STP \quad (67)$$

Where “0.2” represents suction to 20% chord, “2” represents suction on both surfaces, “0.8” limits suction to 80% of the span or height. Each of these is multiplied by **VWALL** to determine the volume flows, **FMF** and **TMF**, for the 30,000ft design case, assuming **FCPMIN** and **TCPMIN** are -0.8 (set within the design synthesis).

The “**SUKMAS**” subroutine is called to define the energy requirements and suction system mass, returned as **FMSUCK** and **TMSUCK** for the fin and tailplane, respectively. As these items are located some distance from wing mounted engines additional cable is required and is defined as (not used if fuselage mounted engines selected):

$$MCAB = MCAB + 3 * FPOWENG * MCABI * (KFIN - CGPOSN) * FUSL \quad (68)$$

Where **MCAB** is the cable mass determined for the wing case, **FPOWENG** is the engine power off-take requirement for the fin, “3” represents a 3 phase system, and no failure cases are considered. The same approach is taken for tailplane cases, substituting **TPOWENG** and **KTP** for **FPOWENG** and **KFIN**.

C.1.6 HLFC System Maintenance and Production Costs

The DOC terms for standing charges and maintenance costs are functions of airframe mass and production cost, which is itself a function of airframe and system mass. The extent of additional maintenance due to HLFC is not clear. Therefore, to permit variation of the HLFC suction system and leading edge structure maintenance costs relative the rest of the airframe, a factor, **MFAC**, has been introduced. The same procedure is used to increase the maintenance of the fin and tailplane structures where HLFC is present on these surfaces. This creates an artificial airframe mass, **MAFCST**, and production cost, **PAFCST**, for use only in the airframe maintenance cost term (function of mass and production cost).

The airframe mass and production cost used to assess performance and other DOC terms is unaffected by the **MFAC**.

Where an HLFC system mass is detected, the artificial airframe mass is incremented using the following term:

$$MAFCST = MAF + (MFAC - 1) * TOTSUM \quad (69)$$

If HLFC is applied to either the wing, fin or tailplane the following terms increase the airframe mass accordingly:

$$MAFCST = MAF + (MFAC - 1) * MWLE \quad (70)$$

$$MAFCST = MAF + (MFAC - 1) * 0.1 * MFIN \quad (71)$$

$$MAFCST = MAF + (MFAC - 1) * 0.1 * MTP \quad (72)$$

For fin and tailplane cases, the leading edge, main box and trailing edge structural mass are not considered separately. Therefore, the leading edge is assumed to represent 10% of the total mass for each surface, hence the 0.1 term in the fin and tailplane terms.

Similarly, an artificial production cost is defined for use only to evaluate the airframe maintenance costs:

$$PAFCST = PAF + (MFAC - 1) * KPSYS * TOTSUM \quad (73)$$

The artificial cost of structure associated with HLFC wing, fin or tailplane is incremented using the following terms:

$$PAFCST = PAF + (MFAC - 1) * KPWLE * MWLE \quad (74)$$

$$PAFCST = PAF + (MFAC - 1) * 0.1 * KPFIN * MFIN \quad (75)$$

$$PAFCST = PAF + (MFAC - 1) * 0.1 * KPTP * MTP \quad (76)$$

The production cost per unit mass of the suction system is also an unknown. In order to consider the impact of increased HLFC system production costs, relative to the rest of the airframe systems, a factor, **PFAC**, has been introduced:

$$PAF = PAF + (PFAC - 1) * KPSYS * TOTSUM \quad (77)$$

In order to isolate the impact of increased HLFC suction system cost, the artificial airframe production cost, **PAFCST**, must be set for **PFAC** = 1 to prevent an increment in airframe maintenance costs. This is performed by subtracting the second term in equation (73).

C.1.7 Turbulent Cruise Requirement

It is probable that at some point during cruise the drag reductions associated with laminar flow may be lost through cloud encounter or system failure. To meet air traffic and certification requirements, some limit may be imposed to ensure that the aircraft is capable maintaining a reasonable cruise altitude and Mach number, when laminar flow is not possible. Values for these are set in data file as **YHCR** and **YVCR** respectively along with term, **YTHCR**, defining the temperature variation from the ISA conditions. **YHCR** can be set as a minimum altitude, **YHCR** > 5000, or as an altitude reduction, **YHCR** < 5000, from the cruise values (Note: positive values represent reduced altitudes). The latter option being particularly useful when altitude is being optimised. The input value for **YVCR** is more complex, allowing absolute values or reductions in cruise speed or Mach number to be selected as follows.

$YVCR > 400$	Absolute cruise speed.
$400 > YVCR > 1$	Cruise speed reduction.
$1 > YVCR > 0.5$	Absolute Mach number.
$0.5 > YVCR$	Mach number reduction.

All expressions associated with this condition are denoted with a 'Y' prefix.

The method used is similar to that employed for the extended, 'W' prefix cruise performance ([27] Section 12.10), resulting in constraint 5. In the turbulent cruise case, the engine thrust is evaluated for the turbulent value of profile drag at the true start of the required cruise. Thus, the engine mass required to achieve this performance, **YMENG3**, is derived and compared with **MENG**, forming a new constraint:

$$c(21) = MENG - YMENG3 \quad (78)$$

A second constraint (No. 13), concerning wave drag during extended performance, is described in [27] section 12.10. This is not considered in the turbulent cruise case as the cruise Mach number-altitude combination is unlikely to be exceed those for the design and extended cruise.

C.2 General Changes to MVO code

Whilst introducing the ability to consider laminar flow applications to the MVO code, other changes and improvements have been introduced. These include:

- the input of skin friction coefficients for the nacelle, empennage and fuselage has been replaced by a method to calculate these as a function of Reynolds number;
- ability to select either speeds or Mach numbers as independent variables to facilitate studies requiring changing altitude/constant Mach number;
- introduction of the capability to consider ovoid fuselages associated with double-deck configurations being considered for aircraft in the “super-jumbo” category;
- modification of wing-box structure design case to include most recent gust velocity certification requirements in addition to previous requirements, and improved consideration of the manoeuvre case;
- introduction of a factor to increase structural thickness/chord ratio relative to aerodynamic thickness/chord ratio;
- introduction of geometrical output data to provide a graphical representation of the optimised configuration.

C.2.1 Nacelle, Empennage and Fuselage Profile Drag Prediction

In the design synthesis described in [27], the nacelle, empennage and fuselage profile drag was calculated as the product of the calculated wetted area for each surface and a skin friction coefficient specified within the input data for each. Clearly, the specified skin friction coefficients should be altered for cases at different cruise conditions or for surfaces whose size varies during the course of optimisation.

To permit a more accurate prediction of the skin friction coefficients, the method has been modified using the flat plate analogy:

$$C_D = \frac{S_{\text{wet}}}{S_{\text{ref}}} \cdot C_f (1 + \psi), \quad (79)$$

where S_{wet} Wetted area in question.
 S_{ref} Reference area, typically gross wing area.
 C_f Mean skin friction coefficient.
 ψ Form factor.

The wetted areas for the empennage and fuselage are already defined within the design synthesis, although further geometrical data, namely the geometric mean chord, was required for the empennage surfaces to determine the mean skin friction coefficient. The engine nacelle wetted area was originally calculated as a function of the engine thrust. This has been replaced with a method that uses nacelle diameter and length, with the latter also used to define nacelle skin friction.

A study of existing empennage and nacelles was conducted to derive empirical relationships for the geometrical characteristics. These are evaluated in the "CG_POSITION" subroutine. The "PDRAG2" subroutine is then called to determine profile drag coefficients.

C.2.1.1 Nacelle Geometry

It was found that a strong correlation existed between the maximum sea-level static thrust per engine (TSTAT/NE) and maximum nacelle diameter (NACD), up to a by-pass ratio of about 7.0 for a variety of installations. This can be represented by the expression:

$$NACD = -0.00001588 * \left(\frac{TSTAT}{1000 * NE} \right)^2 + 0.01138 * \left(\frac{TSTAT}{1000 * NE} \right) + 0.9377 \quad (80)$$

For the nacelle length (NACL), three expressions are required due to the use of 3/4- or full length nacelles on wing mounted engines and long nacelles on fuselage mounted engines. A good correlation was achieved for each of the nacelle types, although only a small data set was available for fuselage mounted engines. Selection of the desired expression is achieved by setting NACTYP in the input data to an appropriate value.

For wing mounted engines with 3/4 length cowl (NACTYP = 1):

$$NACL = -0.00002635 * \left(\frac{TSTAT}{1000 * NE} \right)^2 + 0.01756 * \left(\frac{TSTAT}{1000 * NE} \right) + 1.549 \quad (81)$$

For wing mounted engines with full length cowl (NACTYP = 2):

$$NACL = -0.00003395 * \left(\frac{TSTAT}{1000 * NE} \right)^2 + 0.02693 * \left(\frac{TSTAT}{1000 * NE} \right) + 1.776 \quad (82)$$

For engines mounted on the rear fuselage with full length cowl (NACTYP = 3):

$$NACL = 0.04526 * \left(\frac{TSTAT}{1000 * NE} \right) + 2.272 \quad (83)$$

NACTYP is automatically set to 3, within the code, if fuselage mounted engines are used. There may be a case for considering fuselage mounted 3/4 length cowl engines in the near future although presently all fuselage mounted engines are assumed to have long cowls

The nacelle wetted area, SCOWL, is found by initially assuming that it is a cylinder, using nacelle length and diameter:

$$SCOWL = NACL * \left[\pi * \frac{NACD^2}{4} \right] \quad (84)$$

Based on measurements of actual nacelles, SCOWL is then factored by 0.95 for 3/4 length nacelles and by 0.92 for long nacelles to take account of fore- and aft-body tapering.

The pylon wetted area is derived using a simple expression derived from some existing installations for full length (mixed flow) nacelles:

$$SPYL = SCOWL * \left(0.1 + 0.3 * \frac{NACD}{NACL} \right) \quad (85)$$

For 3/4 length nacelles the same expression is used replacing the **0.3** term with **0.42**.

C.2.1.2 Empennage Geometry

Consideration of geometry data for existing transport aircraft empennage surfaces, demonstrated a good correlation between the geometric mean chords of tailplane, **TAPGMC**, and fin, **FINGMC**, surfaces and their respective plan areas:

$$TAPGMC = 1.201 + 0.0487 * STP - 0.0001 * STP^2 \quad (86)$$

$$FINGMC = 2.8439 + 0.0522 * SFIN \quad (87)$$

C.2.1.3 Profile Drag of Empennage, Nacelle and Fuselage

The geometry data for the empennage, nacelles and fuselage is passed to the “**PDRAG2**” subroutine where a chord Reynolds number for each, **RENAC**, **REFIN**, **RETAP** and **REFUS** are calculated. These, in addition to cruise condition data and a mean laminar-turbulent transition point for each surface, **FINLP** (fin), **TAPLP** (tailplane), and **NACLP** (nacelle), are then used within the “**FRICTION**” subroutine (fully described in section 1) to define a mean cruise skin friction coefficient for the nacelle, fin and tailplane surfaces (Note: Transition set to zero represents fully turbulent flow).

In all off-design conditions, such as take-off, climb out, descent, hold, diversion and approach, it is assumed that laminar flow is not possible. As the profile drag coefficients for these conditions are derived from the cruise value, it is necessary to define a turbulent skin friction coefficient, which requires a second call to the “**FRICTION**” subroutine for each surface.

This results in laminar and turbulent mean skin friction coefficients for the fin, **CFFINL** and **CFFINT**, the tailplane, **CFTAPL** and **CFTAPT**, and the nacelle, **CFNACL** and **CFNACT**.

The profile drag of the fin is defined as the product of the wetted area (twice the plan area), the skin friction coefficient and a form factor (**FFFINL** for laminar cases, **FFFINT** for turbulent cases):

$$CDSFL = 2 * SFIN * CFFINL * FFFINL \quad (88)$$

Similarly for the tailplane:

$$CDSTL = 2 * STP * CFTAPL * FFTAPL \quad (89)$$

and nacelles:

$$CDSNL = FFNACL * CFNACL * SCOWL + FFNACT * CFNACT * SPYL \quad (90)$$

The form factors used for fin and tailplane cases are defined in a similar way to that for the wing, although in a simplified manner. It is assumed that the fin and tailplane

have a thickness/chord ratio of 10% and effective sweeps of 44° and 35°, respectively. With these assumptions, the turbulent form factors become $(1+0.15)$ for the fin and $(1+0.201)$ for the tailplane as. Where laminar flow is present on either of these surfaces, the second term in the form factor is factored using the expression used for the wing case (for laminar flow on upper and lower surfaces), see section 3.

A typical nacelle form factor is quoted in [142] as 1.25. However, data for a large modern engine suggests a turbulent form factor of 1.363 reducing to 1.12 with laminar flow to 38% chord. Therefore, the nacelle form factor is assumed to reduce linearly between these two points such that the form factor is:

$$FFNACL = 1.363 - 0.63 * NACL P, \quad (91)$$

where $NACL P$ is the extent of laminar flow expressed as a fraction of nacelle length.

The method for calculating the fuselage profile drag has also been altered, such that the flat plate analogy is used within the "PDRAG2" subroutine:

$$CDSFUS = CFFUS * SFUS * (1 + FFFUS), \quad (92)$$

where $CFFUS$ is a turbulent skin friction coefficient determined in "FRICTION" (Reynolds number based on fuselage length) and $FFFUS$ is a form factor defined in [142] as:

$$FFFUS = \frac{2.2}{\left(\frac{FUSL}{FUSD}\right)^{1.5}} + \frac{3.8}{\left(\frac{FUSL}{FUSD}\right)^3} \quad (93)$$

C.2.2 Choice of Cruise Speed/Mach Number as Independent Variable

An independent variable has previously been used to define cruise speed, VCR . However, where cruise altitude is included in the optimisation process, a fixed value of cruise speed will result in Mach number variation with altitude. The design synthesis has been changed to permit either the cruise speed or Mach number to be selected as the independent variable.

If the starting point for the independent variable is <1 , the design synthesis recognises the selection of Mach number, and derives cruise speed at the beginning of the "SUB2" subroutine. Otherwise, the input value is assumed to be the cruise speed. The same procedure is followed for the alternative mission cruise speed and the high speed cruise requirement. Care must be taken in the input file to ensure that relevant upper and lower bounds, and scaling factors are set.

C.2.3 Ovoid Fuselage Cross Sections

A major area of interest in aircraft design, during the early 1990's, has concerned aircraft larger than the Boeing 747, i.e. greater than 400 seats. In order to achieve this it is likely that a double deck passenger cabin will be required, necessitating an ovoid fuselage cross section.

The design synthesis has been modified to allow such fuselage configurations to be considered, alongside the circular single deck fuselages already included within the

code. Central to this is the assumption that the cross section is in fact a true ellipse, the same curvature along the top and bottom.

The method used to calculate the fuselage diameter, **FUSD**, has been retained, although the result is now assumed to be the fuselage width. The definition of the passenger compartment length, however, has required minor changes as the not all the passengers are located on the main deck. By reducing the seat pitch, **PCH**, to an artificially low value, the correct cabin length can be forced to the required value.

The fuselage height, **FUSH**, is now defined using the input variable **FUSH1**, which is the ratio of fuselage height and width, i.e. **FUSH/FUSD**.

The expression for fuselage wetted area has also been modified. The expression for the circumference of an ellipse has replaced that for a circle, based the values for the fuselage height and width. An average of the height and width is used, in place of the fuselage diameter, is then used to calculate the loss in surface area due to fore- and aft-body tapering. This average value is also used in place of the fuselage diameter wherever it is used in the fuselage mass calculations in the "TOMASS" subroutine.

No account is taken of any mass increment due to the reduced efficiency of an elliptic pressure vessel, but the mass of the floor and related furnishings is increased by a factor of 1.8, based on assumption that second floor area is 80% of the main floor. This is achieved by using a term **FLOOR** which is set to 1.8 when **FUSH1** > 1. For all other cases, **FLOOR** = 1. Floor mass is represented by the last term in the expression for **AMFUS** (see [27] for full description of expression).

Despite these approximations and the fact that the effect of the second floor on the fuselage shell mass is not considered, the calculated mass for a double deck fuselage compared well with an independent project study.

C.2.4 Design Case for Wing-Box Structure

To determine wing-box mass, the design load case must be defined. This depends on the product of maximum load factor and an effective mass. This calculation is performed for a manoeuvre and a gust case, with the larger of the two taken as the design condition. Only the gust case is considered in detail in [27]. The manoeuvre case is detailed here, along with an update to the gust case to reflect current requirements.

C.2.4.1 Manoeuvre Case

For aircraft with maximum take-off mass greater than 22680kg (50,000lb), the limiting manoeuvre load factor will be $N = 2.5$ (JAR 25.337), to which a safety factor of 1.5 is applied to give the ultimate of 3.75, which is taken as the design value.

The aircraft is assumed to be at maximum take-off mass with maximum payload. Therefore the effective mass (taking into account bending relief from the wing structure, fuel, powerplant and part of the HLFC suction system where relevant) of the aircraft for this case, **BMEFF**, is defined as:

$$BMEFF = MTO - 0.56 * [MWBX1 + MWLE + MWTE + WMCHAN + WMDUCT + MFUEL - (HPAYF - 1) * MPAY] - 3.6 * WUNENG * (NEOW * SPOENG^2 + NEIW * SPIENG^2) \quad (94)$$

C.2.4.2 Gust Case

The gust load factor is determined using the methodology described in JAR 25.341 and ACJ 25.335(d). Recent changes to the gust velocity requirements are illustrated in Figure C-9. Prior to 1987, the design gust velocity was 50fps up to 20,000ft, above which it reduced linearly to 25fps at 50,000ft. In 1987, the design gust velocities were set to 90% of the previous values.

These were later superseded by the current regulations laid down in an 'orange paper', such that the reference design gust velocity, **UREF**, reduces linearly from 56fps at sea-level to 44fps at 15,000ft, and thereafter to 26fps at 50,000ft.

A flight profile alleviation factor, **FG**, is required to obtain design derived gust velocities, **UDE**, from the post-'orange paper' reference gust velocities.

$$UDE = UREF \left(FG + \frac{HTMVM}{ZMO} (1 - FG) \right), \quad (95)$$

where:

ZMO = Maximum operating altitude.

HTMVM = Altitude at which the maximum operating Mach number (M_{mo}) and speed (V_{mo}), **VG**, coincide. Results in highest gust load factors.

$$FG = 0.5(FGZ + FGM) \quad (96)$$

$$FGZ = 1 - \frac{ZMO * 3.2808}{250,000} \quad (97)$$

$$FGM = \left[R_2 \tan\left(\frac{\pi R_1}{4}\right) \right]^{0.5} \quad (98)$$

$$R_1 = \frac{HMLDG}{MTO} \quad (99)$$

$$R_2 = \frac{MTO - MFUEL + (HPAYF - 1) * MPAY}{MTO} \quad (100)$$

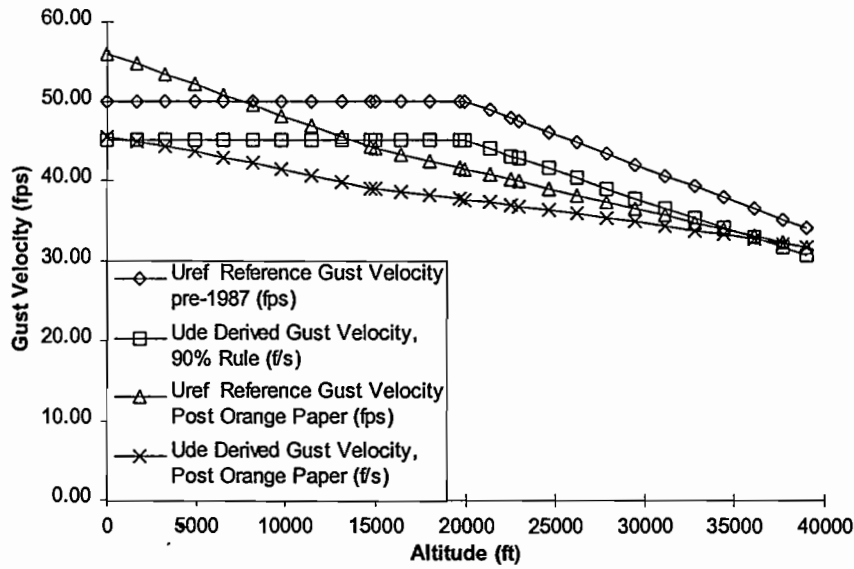


Figure C-9: Gust Velocity Variation with Altitude

The flight profile alleviation factor is applied to the reference gust velocity at sea-level to give the corresponding derived gust velocity. The value of this factor is then increased, toward 1 (less effect), linearly with altitude such that it is equal to 1.0 at the aircraft's maximum operating altitude. The derived gust velocities shown in Figure C-9 are typical for an aircraft similar to an A320

It is possible to select any of the three gust velocity requirements using the term, **GUST**, in the input file:

GUST=1 Pre-1987
GUST=2 90% Rule
GUST=3 Post 'Orange-Paper' (Current Requirements)

The maximum operating mach number is derived from **WVCR** (if **WVCR** < 1, the value is used for **WMCR**, from which a corresponding **WVCR** is calculated) and speed, **VG**, are input terms.

Calculation of the gust load factor, **N**, is as follows:

$$N = 1.5 \cdot \left[1 + \frac{GAF \cdot UDE \cdot (VG/0.516) \cdot DCLDA}{498 \cdot \left(\frac{MGUST \cdot 2.2046}{S \cdot 10.764} \right)} \right], \quad (101)$$

where:

$$GAF = \frac{0.88 \cdot MU}{5.3 + MU} \quad (102)$$

$$MU = \frac{2 \cdot MGUST / S}{ROVM \cdot GMC \cdot DCLDA} \quad (103)$$

$$MGUST = MTO - MFUEL + (HPAYF - 1) \cdot MPAY + MFUELD + MFUELH \quad (104)$$

ROVM = Density at **HTMVM**, GMC = geometric mean chord,

DCLDA = lift curve slope.

The effective mass for the gust case is defined as the maximum zero-fuel mass taking into account bending relief from the wing structure, engines and some suction system components.

$$MEFF = MTO - MFUEL - 0.56 * [MWBX1 + MWLE + MWTE + WMCHAN + WMDUCT] \\ + (HPAYF - 1) * MPAY - 3.6 * WUNENG * (NEOW * SPOENG^2 + NEIW * SPIENG^2) \quad (105)$$

C.2.5 Structural Thickness/Chord Factor

For almost all commercial transport aircraft, wing thickness/chord ratio varies across the span, with at least one trailing edge kink, and possibly kinks in the leading edge. It is possible to represent the aerodynamic characteristics of such wings with an equivalent constant thickness/chord straight-tapered planform wing, [41]. It is the equivalent planforms that the design synthesis uses to optimise the aircraft aerodynamic performance, using an constant equivalent thickness/chord ratio across the entire span.

Earlier versions of CIVIL have used one value of thickness/chord, TC, for both aerodynamic and structural expressions. An input data term, TCST, has been introduced to factor the aerodynamic thickness/chord ratio, TC, to provide a structural thickness/chord ratio, STRTC. This term directly replaces the TC term in expressions used for mass estimation of wing-box components, within the "MASSWBX" subroutine, described in detail in ([27] section 5.4.2).

This enables some account to be taken of the beneficial effects of a thicker wing, due to increased thickness to chord ratio and the larger chord (relative to a trapezoid planform), generally used on the inboard wing.

C.2.6 Graphics for the MVO

The output from the CIVIL MVO code, as described in [27] consists of a collection of variable names and values which the user must interpret to assess the aircraft's geometry. The user now has the option to create a graphical representation of the final configuration. A subroutine, "GROUT", has been included that utilises variables from the design synthesis to generate a set of co-ordinates which can then be plotted to create a two-dimensional planform image of the aircraft. This subroutine is called at the end of the "SUB2" subroutine on the final iteration of the optimisation. Thus, only the final design solution is included.

The "GROUT" subroutine is only called if a file name is included within the input data file as a character string GRAFIK. Leaving this blank results in no graphical output file.

The output file is simply two columns of numbers, representing the 'x' and 'y' co-ordinates, based on an origin located at the aircraft's nose, where blank lines denote the end of one line and the start of another. The subroutine is so arranged that the co-ordinates for the starboard half (positive 'y' values) of the aircraft are defined first and then mirrored about the x-axis to create the port side.

An example of the resulting graphical output can be seen, Figure C-10, for an aircraft, representative of the Airbus A330. This can be viewed using a number of applications on both UNIX and PC computer systems. Extensive use has been made of PC based spreadsheets, which permit simple post-processing and inclusion into reports.

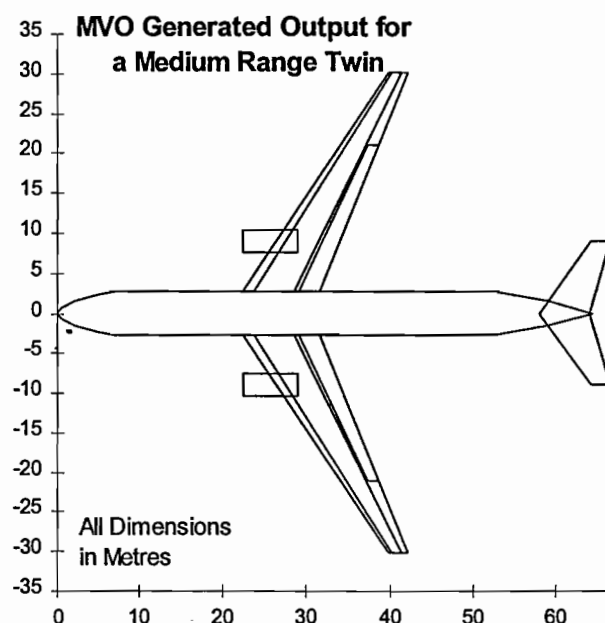


Figure C-10: Sample Graphical Output of A330 type Aircraft as Plotted in 'Excel'

The view includes the fuselage shape with the extent of fore- and aft-tapering based on empirical data, i.e. the distance from the nose to the beginning of the parallel section, **XFO**, is defined as:

$$\mathbf{XFO} = 4.8 + 0.04 * (\mathbf{FUSD} - 3.0) * \mathbf{FUSD}^2 \quad (106)$$

and the distance from the nose to the rear end of parallel section, **XAF**, can be determined using:

$$\mathbf{XAF} = \mathbf{FUSL} - (8.0 + 0.07 * (\mathbf{FUSD} - 2.5) * \mathbf{FUSD}^2) \quad (107)$$

It should be noted that **XAF** and **XFO** are not used elsewhere in the design synthesis and that the forward and rear contouring is merely cosmetic and intended to be representative of current transport aircraft.

The wing planform is defined within the MVO, with its longitudinal location fixed using the assumption that the aerodynamic centre (25% of the aerodynamic mean chord) and aircraft centre of gravity are at the same longitudinal position. Spar location and flap geometry are also taken directly from the design synthesis and plotted relative to the wing planform. The same is true for engine size and spanwise location, although the longitudinal position is nominal, to represent current mountings. Distinctions are made, based on information within the design synthesis, between full length and $\frac{3}{4}$ length wing mounted nacelles as well as fuselage mounted engines.

The tailplane area and a mean chord are calculated from an empirical fit (equation 86) within the design synthesis. The additional parameters required to define the planform are the taper ratio and leading edge sweep are included within the "GROUT" subroutine as nominal values, taper ratio **TTR**=0.38 and leading edge sweep **TSWPLE**=35°. These values can be changed at any time by the operator although the code will subsequently need to be re-compiled.

The above variables define the planform of the tailplane which is then longitudinally located using the **KTP** variable, i.e. distance of tailplane aerodynamic centre along fuselage as a fraction of the fuselage length and the position of the aerodynamic centre within the tailplane plan. To achieve this, the aerodynamic mean chord (AMC) is calculated along with its distance from the aircraft centreline, using the method employed within the design synthesis to define the corresponding values for the wing. The aerodynamic centre is assumed to be at 25% of the AMC, the position of which is then matched with that of **KTP**.

Any variables generated within the design synthesis, that are required to construct the view, must be contained within the **ALL.H** file.

C.3 Variable List

The list below, Figure C-11, is intended to provide a quick reference for variable names, with input variables shown as shaded entries. The first column contains the variable name, input variables shown in **bold**. Due to the use of common variable names with appropriate prefixes, where a variable name cannot be found as printed in the text, it is likely that it can be found elsewhere. Ignoring the first letter of a variable name, especially if X, W, F, T, or N, should allow a definition to be found.

Where relevant, units are shown in the second column. S.I. units are used for all except a few variables related to the gust criteria. The third column contains brief definitions of the variables, with further information provided in the section of text shown in column four.

The methods described in this study have been added to or modified an existing design synthesis, detailed in the Royal Aircraft Establishment Technical Report TR84044 [27]. Where variables defined in the earlier report are either used, replaced or modified, the corresponding variable name in [27] is given in the fifth column, entitled 'TR84044'. Typically variables, whose name and definition are unchanged from the previous report, have been used, whereas all others have been modified or replaced.

Variable	Unit	Definition	Section	TR84044
ACDOWT, ACDOWL		Wing profile drag coefficients (turbulent and laminar) without form factors for design cruise in "SUB2" subroutine	C1.2.1	
ACDT, ACDL		Wing profile drag coefficients (turbulent and laminar) without form factors in "PDRAG1" subroutine	C.1.2.1	
AMFUS		Coefficient used to calculate fuselage mass	C.2.3	AMFUS
BCWU, BCWB	m	Distance from fuselage side to cross over between max. transition Reynolds number and roof-top limited laminar flow	C.1.1.2	
BMEFF	kg	Effective aircraft mass for stressing in manoeuvre case	C.2.4.1	
BSUCKI, BSUCKO		Distance of inboard/outboard end of suction to wing root/tip	C.1.3	
CCFLOW	% chord	Chordwise position of rear end of cross-flow suction	C.1.3.1	
CCL	m	Wing chord at aircraft centre-line	C.1.1.1	
CD0AV		Profile drag weighted between laminar and turbulent cruise cases	C.1.2.3	CD0
CD0T, CD0L		Total profile drag (turbulent and laminar) for design cruise	C.1.2.2	CD0
CD0WT, CD0WL		Wing profile drag coefficient for design case	C.1.2.2	CD0W
CDCR		Drag coefficient at the true start of cruise	C.1.2.3	CDCR
CDSFL		Profile drag for laminar fin	C.2.1.3	CDOEW
CDSFT		Profile drag for turbulent fin	C.2.1.3	CDOEW
CDSFUS		Profile drag for fuselage	C.2.1.3	CDOEW
CDSNL		Profile drag for laminar nacelle	C.2.1.3	CDOEW
CDSNT		Profile drag for turbulent nacelle	C.2.1.3	CDOEW
CDSTL		Profile drag for laminar tailplane	C.2.1.3	CDOEW
CDSTT		Profile drag for turbulent tailplane	C.2.1.3	CDOEW
CF		Skin Friction Coefficient in "FRICTION" subroutine	C.1.2.1	
CF100		Suction coefficient for wing cross-flow region when DCPDSI = 100	C.1.3.1.2	
CF1001, CF1002, CF1003, CF1004		Coefficients in CF100	C.1.3.1.2	
CF40		Suction coefficient for wing cross-flow region when DCPDSI = 40	C.1.3.1.2	

Figure C-11: Variable Listing

Variable	Unit	Definition	Section	TR84044
CF401, CF402, CF403, CF404		Coefficients in CF40	C.1.3.1.2	
CFC	N/hr/N	Engine specific fuel consumption	C.1.3.3	CFC
CFCPN		SFC penalty [Pre-fixed by W = Wing F = Fin, T = Tailplane, N = Nacelle]	C.1.3.3	
CFFINL		Skin friction coefficient for laminar fin	C.2.1.3	KSFEMP
CFFINT		Skin friction coefficient for turbulent fin	C.2.1.3	KSFEMP
CFFUS		Skin friction coefficient for fuselage	C.2.1.3	KSFFUS
CFNACL		Skin friction coefficient for laminar nacelle	C.2.1.3	KSFNAC
CFNACT		Skin friction coefficient for turbulent nacelle	C.2.1.3	KSFNAC
CFTAPL		Skin friction coefficient for laminar tailplane	C.2.1.3	KSFEMP
CFTAPT		Skin friction coefficient for turbulent tailplane	C.2.1.3	KSFEMP
CGPOSN		Aircraft CG. position from fuselage nose / FUSL	C.1.5.2	CGPOSN
CHORDI, CHORDO	m	Chord at inboard and outboard ends of suction panel	C.1.3.2	
CPMIN		Minimum pressure coefficient on suction surface	C.1.3.3	
CQAL		Suction Coefficient for wing attachment line zone	C.1.3.1.1	
CQALA, CQALB, CQALC		Coefficients in CQAL, the attachment line suction coefficient	C.1.3.1.1	
CQCF		Suction coefficient for wing cross-flow zone	C.1.3.1.2	
CQTS		Suction coefficient for wing Tollmein-Schlichting zone	C.1.3.1.3	
CR	m	Wing Chord at Root (fuselage side)	C.1.1.1	
CSUCKI, CSUCKO		Wing Chord at inner/outer extremity of suction	C.1.3	
CT	m	Wing Tip Chord	C.1.1.1	
CTAN		Maximum physical distance at which transition can occur, based on RET	C.1.1.2	
CTS	chord	Chordwise position of rear end of Tollmein-Schlichting suction	C.1.3.1	
DCLDA		Lift curve slope for critical gust case	C.2.4.2	DCLDA
DCPDSI		Initial pressure gradient	C.1.3.1.2	
ETAC		Compressor efficiency	C.1.3.3	
ETAG		Generation efficiency	C.1.3.3	
ETAT		Transmission efficiency	C.1.3.3	
FCPMIN		Minimum pressure coefficient on fin suction area	C.1.5.2	
FFFINL		Form factor for laminar fin	C.2.1.3	
FFFINT		Form factor for turbulent fin	C.2.1.3	
FFFUS		Fuselage form factor	C.2.1.3	
FFNACL		Form factor for laminar nacelle	C.2.1.3	
FFNACT		Form factor for turbulent nacelle	C.2.1.3	
FFTAPL		Form factor for laminar tailplane	C.2.1.3	
FFTAPT		Form factor for turbulent tailplane	C.2.1.3	
FG		Flight profile alleviation factor for gust case	C.2.4.2	
FGZ, FGM		Coefficients in FG	C.2.4.2	
FINGMC	m	Geometric mean chord of tailplane	C.2.1.2	
FINLP		Extent of laminar flow / fin aerodynamic mean chord	C.2.1.3	
FLOOR		Factor applied to mass of cabin floors and related furnishings for double deck fuselage configurations. Total floor area (upper and main deck)/Main deck floor area.	C.2.3	
FPOWENG	W	Off-take power requirement for HLFC fin	C.1.5.2	
FUSD	m	Fuselage width	C.1.1.1	FUSD
FUSH	m	Maximum fuselage height	C.2.3	
FUSH1		Maximum fuselage height / maximum fuselage width	C.2.3	
FUSL	m	Fuselage length	C.2.3	FUSL
GAF		Gust alleviation factor	C.2.4.2	GAF
GMC	m	Wing geometric mean chord = sort S/A	C.1.1.1	GMC
GRAFIK		File name for optional graphics output file	C.2.6	
GUST		Switch for selecting gust criteria	C.2.4.2	
HLFC		Switch for selecting HLFC: set to 1 for HLFC, 0 for NLF	C.1	

Figure C-11: Variable Listing (Continued)

Variable	Unit	Definition	Section	TR84044
HMLDG	kg	Maximum landing mass	C.2.4.2	HMLDG
HPAYF		Maximum payload / Design payload	C.2.4.2	HPAYF
HTMVM	m	Altitude at which Mach number and speed limitation coincide	C.2.4.2	
KENG		Distance of CG. of rear-mounted engines from fuselage nose / FUSL		KENG
KFIN		Distance of CG. of fin from fuselage nose / FUSL	C.1.5.2	KFIN
KPPFIN	£ or \$ /kg	Cost coefficient for fin structure	C.1.6	KPPEN
KPSYS	£ or \$ /kg	Cost coefficient for systems	C.1.6	KPSYS
KPTP	£ or \$ /kg	Cost coefficient for tailplane structure	C.1.6	KPPEN
KPWLE	£ or \$ /kg	Cost coefficient for wing leading edge structure	C.1.6	KPWLE
KTP		Distance of CG. of tailplane from fuselage nose / FUSL	C.1.5.2	KTP
LESPAN	m	Distance along leading edge from wing root to tip	C.1.3.2	
LFLOW		Switch for selecting laminar flow: set to 1 for laminar flow, 0 for turbulent flow	C.1	
LFRU, LFRB		Physical distance of transition from leading edge at wing root [upper (u) and lower (b) surface]	C.1.1.2	
LFTU, LFTB		Physical distance of transition from leading edge at wing tip [upper (u) and lower (b) surface]	C.1.1.2	
LMLT		Chordwise position of the end of favourable pressure gradients on the lower surface	C.1.1.2	
LPU, LPB		Area of Laminar Flow / Net Wing Area	C.1.1.2	
MAF	kg	Airframe mass	C.1.6	MAF
MAFCST	kg	Virtual airframe mass for use with MFAC and PFAC	C.1.6	
MCAB	kg	Mass of electrical cables for HLFC [Pre-fixed by W = Wing F = Fin, T = Tailplane, N = Nacelle]	C.1.4	
MCAB1, MCAB2	m	Cable length from inboard engine, and outboard or fuselage mounted engines	C.1.4	
MCABI	kg/W/m	Specific mass of electrical cable per unit off-take power per unit length	C.1.4	
MCHAN	kg	Mass of suction plenum chambers and collection chambers [Pre-fixed by W = Wing F = Fin, T = Tailplane, N = Nacelle]	C.1.4	
MCHANI	kg/m ²	Specific mass of plenum and collection chambers per unit area	C.1.4	
MCOMP	kg	Mass of HLFC compressors [Pre-fixed by W = Wing F = Fin, T = Tailplane, N = Nacelle]	C.1.4	
MCOMPI	kg/W	Specific mass of HLFC compressors per unit of compressor power	C.1.4	
MDUCT	kg	Mass Collection Ducts [Pre-fixed by W = Wing F = Fin, T = Tailplane, N = Nacelle]	C.1.4	
MDUCTI	kg/m ³	Specific mass of collection ducts per unit volume flow	C.1.4	
MEFF	kg	Effective aircraft mass for wing stress	C.2.4.2	MEFF
MFAC		Maintenance cost factor for HLFC systems and leading edge structure	C.1.6	
MFSUK	m ³ /s	Mass flow of sucked air in SUKMAS routine [Pre-fixed by W = Wing F = Fin, T = Tailplane, N = Nacelle]	C.1.3.3	
MFSUKD	m ³ /s	Mass flow of sucked air at suction system design condition in SUKMAS routine [Pre-fixed by W = Wing F = Fin, T = Tailplane, N = Nacelle]	C.1.3.3	
MFUEL	kg	Mass of fuel	C.2.4.2	MFUEL
MFUELD	kg	Mass of fuel for diversion	C.2.4.2	MFUELD
MFUELH	kg	Mass of fuel for hold	C.2.4.2	MFUELH
MGEN	kg	Mass of generator for HLFC [Pre-fixed by W = Wing F = Fin, T = Tailplane, N = Nacelle]	C.1.4	
MGEN1	kg/W	Specific mass of HLFC generator per unit of off-take power	C.1.4	
MGEN2	kg	Increase in mass per engine to represent additional generator for HLFC	C.1.4	
MGUST	kg	Aircraft mass for gust case	C.2.4.2	
MMOTO	kg	Mass of electric HLFC motors [Pre-fixed by W = Wing F = Fin, T = Tailplane, N = Nacelle]	C.1.4	
MMOTOI	kg/W	Specific mass of electric HLFC motors per unit of compressor power	C.1.4	
MODEF		Switch for introducing redundancy into suction system	C.1.4.1	
MPAY	kg	Mass of Payload	C.2.4.2	MPAY

Figure C-11: Variable Listing (Continued)

Variable	Unit	Definition	Section	TR84044
MSUCK	kg	Mass of HLFC suction system [Pre-fixed by W = Wing F = Fin, T = Tailplane, N = Nacelle]	C.1.4	
MTO	kg	Maximum take-off mass	C.2.4.2	MTO
MU		Aircraft mass ratio for critical gust case	C.2.4.2	MU
MWBX	kg	Mass of wing-box	C.2.4.2	MWBX
MWLE	kg	Mass of wing leading edge	C.1.6	MWLE
MWTE	kg	Mass of wing trailing edge	C.2.4.2	MWTE
N		Wing loading factor	C.2.4.2	N
NACD	m	Nacelle diameter	C.2.1.1	
NACL	m	Nacelle length	C.2.1.1	
NACLP		Extent of laminar flow / nacelle length	C.2.1.3	
NACTYP		Switch to select long, 3/4 length wing mounted nacelles or fuselage mounted	C.2.1.1	
NCPMIN		Minimum pressure coefficient on nacelle suction area	C.1.5.1	
NEIW		Number of inboard engines	C.1.4	NEIW
NEOW		Number of outboard engines	C.1.4	NEOW
NUCR, XNUCR, WNUCR	m ² /s	Kinematic viscosity of air at design mission cruise, alternative mission cruise, and additional cruise requirement.	C.1.1.2	NUCR, XNUCR, WNUCR
NWAF		Net wing area factor	C.1.1.2	NWAF
PAF	£ or \$	Airframe price	C.1.6	PAF
PAFCST	£ or \$	Virtual airframe production cost for use with MFAC and PFAC	C.1.6	
PANLEN	m	Suction panel width along leading edge	C.1.3.2	
PANW	m	Suction panel spanwise width	C.1.3.2	
PCH	m	Seal Pitch	C.2.3	PCH
PCOMPF	Pa	Pressure at Compressor face	C.1.3.3	
PENCF	1/W/N	SFC penalty per unit of shaft power off-take per unit net cruise thrust	C.1.3.3	
PENFUL		Weighting factor between laminar and turbulent profile drag	C.1.2.3	
PFAC		Price factor for HLFC systems, relative to rest of aircraft systems	C.1.6	
PLOSS		Pressure loss from external suction surface to compressor face / min. pressure on external surface	C.1.3.3	
PMIN		Minimum pressure on suction surface	C.1.3.3	
POWCOM	W	Compressor power requirement at cruise condition [Pre-fixed by W = Wing F = Fin, T = Tailplane, N = Nacelle]	C.1.3.3	
POWCOMD	W	Compressor power requirement at suction system design condition [Pre-fixed by W = Wing F = Fin, T = Tailplane, N = Nacelle]	C.1.3.3	
POWENG	W	Power off-take requirement from propulsion units for HLFC at cruise condition [Pre-fixed by W = Wing F = Fin, T = Tailplane, N = Nacelle]	C.1.3.3	
POWENGD	W	Power off-take requirement from propulsion units for HLFC at suction system design condition [Pre-fixed by W = Wing F = Fin, T = Tailplane, N = Nacelle]	C.1.3.3	
R1, R2		Coefficients in FGM	C.2.4.2	
Rbar		Leading edge (Attachment Line) Reynolds number	C.1.3.1.1	
RE		Chord Reynolds number for surface in question in "FRICTION" subroutine	C.1.2.1	
REC		Streamwise chord Reynolds number used for LE Reynolds number	C.1.3.1.1	
REFIN		Fin Reynolds number, based on FINAMC	C.2.1.3	
RENAC		Nacelle length Reynolds number	C.2.1.3	
RET		Maximum transition Reynolds number	C.1.1.2	
RET1		Maximum transition Reynolds number with zero leading edge sweep	C.1.1.2	
RET2		LE sweep at which maximum transition Reynolds number is zero	C.1.1.2	
RETAP		Tailplane Reynolds number, based on TAPAMC	C.2.1.3	
RETIN		Fixed maximum transition Reynolds number, independent of sweep	C.1.1.2	
RO	kg/m ³	Air density in question for suction system performance analysis	C.1.3.3	
ROVM	kg/m ³	Air density for gust case	C.2.4.2	
RTP		Chordwise position of the end of roof-top pressure distribution	C.1.1.2	RTP
RTPC		Input value for RTP	C.1.1.2	RTPC
S	m ²	Gross Wing Area	C.1.1.2	S
SCOWL	m ²	Wetted area of nacelle (fan cowl)	C.2.1.1	
SFIN	m ²	Fin Area	C.1.5.2	SFIN
SFUS	m ²	Fuselage wetted area	C.2.1.3	SFUS

Figure C-11: Variable Listing (Continued)

Variable	Unit	Definition	Section	TR84044
SLAMU, SLAMB	m ²	Area of Laminar Flow on Wing [upper and lower (b) surface]	C.1.1.2	
SPAN	m	Wing span	C.1.1.1	SPAN
SPIENG		Spanwise location of inboard engine / (SPAN/2)	C.1.4	SPIENG
SPOENG		Spanwise location of outboard engine / (SPAN/2)	C.1.4	SPOENG
SPYL	m ²	Wetted area of engine pylons	C.2.1.1	
SSUCK	m ²	HLFC suction area [Pre-fixed by W = Wing F = Fin, T = Tailplane, N = Nacelle]	C.1.3	
STP	m ²	Tailplane Area	C.1.5.2	STP
STRTC		Structural thickness/chord ratio	C.2.5	TC
SUCKL		Length of nacelle suction / nacelle length	C.1.5.1	
SWP	deg	Wing quarter chord sweep	C.1.1.1	SWP
SWPA	deg	Effective aerodynamic sweepback of wing	C.1.2.2	SWPA
SWPLE	deg.	Wing leading edge sweep	C.1.1.1	
TA	K	Temperature at altitude for suction system performance analysis (also used as approach thrust)	C.1.3.3	
TAPGMC	m	Geometric mean chord of tailplane	C.2.1.2	
TAPLP		Extent of laminar flow / tailplane aerodynamic mean chord	C.2.1.3	
TC		Wing equivalent aerodynamic thickness/chord ratio	C.2.5	TC
TCST		Ratio of structural thickness/chord to aerodynamic thickness/chord (STRTC/TC)	C.2.5	
TOTSUM	kg	Total mass of aircraft suction systems	C.1.6	
TREQ	N	Required thrust at design cruise condition, includes 300ft/min climb rate	C.1.3.3	
TPOWENG	W	Off-take power requirement for HLFC tailplane	C.1.4.2	
TPMU, TPMB	m	Physical distance of transition from leading edge on the geometric mean chord [upper and lower (b) surface]	C.1.2.1	
TPRU, TPRB		Chordwise location of transition at wing root / wing root chord [upper (u) and lower (b) surface]	C.1.1.2	
TPTU, TPTB		Chordwise location of transition at wing tip / wing tip chord [upper (u) and lower (b) surface]	C.1.1.2	
TR		Wing taper ratio	C.1.1.1	TR
TSTAT	N	Sea-level static thrust for aircraft	C.2.1.1	TSTAT
UDE	ft/s	Derived gust velocity	C.2.4.2	
UREF	ft/s	Reference gust velocity	C.2.4.2	
VC	m/s	Aircraft forward speed at altitude in question within "PDRAG1"	C.1.1.2	
VCR, XVCR, WVCR	km/h	Aircraft cruise speed for design mission, alternative mission and high speed cruise requirement.	C.1.3.3	VCR, XVCR, WVCR
VG	m/s	Maximum cruise speed	C.2.4.2	
VWALL	m/s	Mean suction velocity for 'other than wing' cases	C.1.5.1	
WACDWT, WACDWL		Wing profile drag coefficients (turbulent and laminar) without form factors for high speed case in "SUB2" subroutine	C.1.2.1	
WCDOT, WCDOL		Total profile drag (turbulent and laminar) for high speed case	C.1.2.2	WCDOW
WCDOWT, WCDOWL		Wing profile drag coefficient for high speed case	C.1.2.2	WCDOW
WSLAMU, WSLAMB	m ²	Area of Laminar Flow on Wing [upper and lower (b) surface] for high speed cruise case	C.1.1.2	
WUNENG	kg	Mass of one engine	C.2.4.2	WUNENG
XOC		Chordwise distance from start of turbulent boundary layer to end of transition / wing chord	C.1.2.1	
XACDWT, XACDWL		Wing profile drag coefficients (turbulent and laminar) without form factors for alternative mission in "SUB2" subroutine	C.1.2.1	
XCDOT, XCDOL		Total profile drag (turbulent and laminar) for alternative cruise	C.1.2.2	XCDO
XCDOWT, XCDOWL		Wing profile drag coefficient for alternative cruise case	C.1.2.2	XDCOW
XCFCPN		Specific fuel consumption penalty for alternative mission	C.1.3.3	
XSLAMU, XSLAMB	m ²	Area of Laminar Flow on Wing [upper and lower (b) surface] for alternative mission case	C.1.1.2	
Y		All terms prefixed with 'Y' refer to the turbulent cruise case.	C.1.7	
ZMO	m	Maximum service ceiling of aircraft	C.2.4.2	

Figure C-11: Variable Listing (Continued)

D. FORM FACTOR, ψ

To assess the form factor variation with transition position, the BVGK code was used to investigate the performance of two 2D sections representative of transonic NLF and HLFC aerofoils. The effect of moving transition aft on the upper surface only on both sections was investigated. The NLF section was also used to analyse the impact of moving transition aft simultaneously on both upper and lower surfaces. The results from these studies are summarised below

Note: CDV Calc. Calculated Viscous Drag coefficient

Form Factor (Viscous drag coefficient/Calculated viscous drag coefficient) - 1
 % difference Form Factor / Form Factor for transition at 2% chord $\times 100-100$

NLF 2D Study

Transition on upper surface only

Transition Position	Lift Coefficient	Mach number	Incidence α	Reynolds number	Viscous Drag Coefficient	CDV calc.	Form Factor	% difference	CD(WAVE)
0.02	0.45	0.71	0.705	2.00E+07	0.00824	0.00616	0.34	0.00	0.00000
0.05	0.45	0.71	0.683	2.00E+07	0.00811	0.00607	0.34	-0.79	0.00000
0.10	0.45	0.71	0.643	2.00E+07	0.00786	0.00592	0.33	-3.26	0.00000
0.20	0.45	0.71	0.558	2.00E+07	0.00732	0.00561	0.31	-9.76	0.00000
0.30	0.45	0.71	0.468	2.00E+07	0.00677	0.00528	0.28	-16.73	0.00000
0.40	0.45	0.71	0.376	2.00E+07	0.00618	0.00495	0.25	-26.24	0.00000
0.45	0.45	0.71	0.328	2.00E+07	0.00588	0.00477	0.23	-31.51	0.00000
0.50	0.45	0.71	0.280	2.00E+07	0.00558	0.00460	0.21	-36.96	0.00000
0.55	0.45	0.71	0.234	2.00E+07	0.00527	0.00442	0.19	-43.26	0.00000

Transition on upper and lower surfaces

Transition Position	Lift Coefficient	Mach number	Incidence α	Reynolds number	Viscous Drag Coefficient	CDV calc.	Form Factor	% diff	CD(WAVE)
0.02	0.45	0.71	0.705	2.00E+07	0.00824	0.00616	0.34	0.00	0.00000
0.05	0.45	0.71	0.684	2.00E+07	0.00804	0.00603	0.33	-1.22	0.00000
0.10	0.45	0.71	0.646	2.00E+07	0.00768	0.00580	0.32	-3.87	0.00000
0.20	0.45	0.71	0.565	2.00E+07	0.00689	0.00531	0.30	-12.23	0.00000
0.30	0.45	0.71	0.484	2.00E+07	0.00603	0.00481	0.25	-25.13	0.00000
0.40	0.45	0.71	0.402	2.00E+07	0.00512	0.00429	0.19	-43.16	0.00000
0.45	0.45	0.71	0.324	2.00E+07	0.00440	0.00403	0.09		0.00000

HLFC 2D Study (Laminar Flow on Upper Surface Only)

Transition Position	Lift Coefficient	Mach number	Incidence α	Reynolds number	Viscous Drag Coefficient	CDV calc.	Form Factor	% diff	CD(WAVE)
0.02	0.55	0.7	-0.210	4.00E+07	0.00708	0.00553	0.28	0.00	0.00017
0.05	0.55	0.7	-0.219	4.00E+07	0.00698	0.00545	0.28	0.17	0.00018
0.10	0.55	0.7	-0.236	4.00E+07	0.00680	0.00531	0.28	0.09	0.00019
0.15	0.55	0.7	-0.254	4.00E+07	0.00660	0.00517	0.28	-1.05	0.00020
0.20	0.55	0.7	-0.272	4.00E+07	0.00639	0.00502	0.27	-2.71	0.00022
0.25	0.55	0.7	-0.292	4.00E+07	0.00616	0.00487	0.26	-5.72	0.00024
0.30	0.55	0.7	-0.311	4.00E+07	0.00592	0.00472	0.25	-9.46	0.00025
0.35	0.55	0.7	-0.332	4.00E+07	0.00568	0.00457	0.24	-13.23	0.00026
0.40	0.55	0.7	-0.356	4.00E+07	0.00543	0.00441	0.23	-17.84	0.00030
0.45	0.55	0.7	-0.383	4.00E+07	0.00517	0.00426	0.21	-23.40	0.00040
0.50	0.55	0.7	-0.406	4.00E+07	0.00490	0.00410	0.20	-29.99	0.00040
0.55	0.55	0.7	-0.429	4.00E+07	0.00461	0.00393	0.17	-38.64	0.00028
0.60	0.55	0.7	-0.454	4.00E+07	0.00432	0.00377	0.15	-47.72	0.00037
0.65	0.55	0.7	-0.481	4.00E+07	0.00400	0.00360	0.11	-60.25	0.00038

Figure D-1: Summary of Results from BVGK Study

The percentage change in the form factor from the turbulent (transition at 2% chord) form factor for all three cases are shown in Figure D-2.

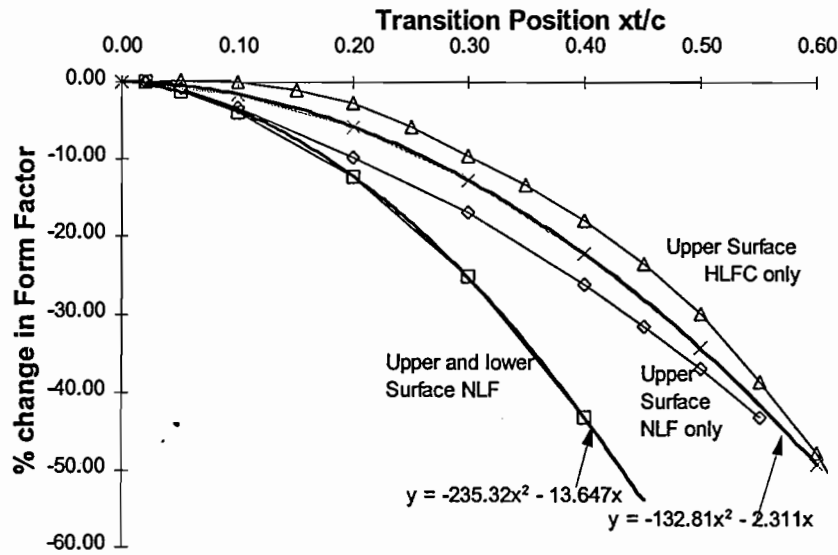


Figure D-2: Form Factor variation with Transition

For all cases the form factor was found to reduce with increasing transition position. The rate of reduction was also observed to increase as transition moved aft.

Although there were small differences between the NLF and HLFC 'upper surface only' cases, both plots following the same trend. For simplicity an averaged function has been defined for use in the design synthesis where laminar flow is on one surface only. Introducing NLF onto the lower surface resulting in even lower form factors. Given the satisfactory agreement between NLF and HLFC 'upper surface only' cases, the NLF function is used to evaluate the form factor where laminar flow is possible on both surfaces.

E. POWER OFFTAKE

The additional shaft power off-take required to drive the HLFC suction system will have a detrimental effect on the engine specific fuel consumption. To assess the magnitude of this, studies were performed using the 'Turbo-Match' code to model commercial turbofan engines. The increment in fuel flow to maintain the specified net thrust were noted for various power off-take settings. The resulting data was compared with real engine data from performance manuals, and performance data from Rolls-Royce. The results of this study are shown below in Figure E-1

Trent 775 (Turbo-Match)								
Power off-take (kW)	kW per kN net thrust	Gross Thrust (N)	Momentum Drag (N)	Net Thrust (N)	Fuel Flow (kg/s)	S.F.C. (mg/N/sec)	S.F.C. (N/hr/N)	S.F.C. % change
0	0.00000	132278.31	81126.97	51151.34	0.8372	16.36676	0.57802	0.00000
50	0.97774	132251.55	81113.12	51138.43	0.8386	16.39814	0.57913	0.19173
100	1.95644	132202.86	81089.64	51113.21	0.8399	16.43170	0.58032	0.39678
150	2.93307	132232.73	81091.50	51140.98	0.8421	16.46706	0.58152	0.61283
200	3.90877	132259.45	81092.45	51167.01	0.8444	16.50252	0.58281	0.82949
CF6-80C2-A2 (Turbo-Match)								
Power off-take (kW)	kW per kN net thrust	Gross Thrust (N)	Momentum Drag (N)	Net Thrust (N)	Fuel Flow (kg/s)	S.F.C. (mg/N/sec)	S.F.C. (N/hr/N)	S.F.C. % change
0	0.00000	138389.39	87926.49	50462.90	0.8820	17.47872	0.61726	0.00000
50	0.99071	138376.19	87907.55	50468.63	0.8838	17.51148	0.61845	0.18743
100	1.98083	138404.22	87920.03	50483.90	0.8855	17.53958	0.61945	0.34819
150	2.97094	138389.67	87900.69	50488.99	0.8872	17.57244	0.62058	0.53619
200	3.96025	138413.73	87911.85	50501.88	0.8889	17.60148	0.62161	0.70234
CFM56-5C-2 (Turbo-Match)								
Power off-take (kW)	kW per kN net thrust	Gross Thrust (N)	Momentum Drag (N)	Net Thrust (N)	Fuel Flow (kg/s)	S.F.C. (mg/N/sec)	S.F.C. (N/hr/N)	S.F.C. % change
0	0.00000	77290.56	46436.13	30854.44	0.5109	16.55706	0.58478	0.00000
50	1.61985	77302.09	46434.98	30867.00	0.5127	16.60877	0.58660	0.31231
100	3.24342	77246.12	46414.46	30831.65	0.5135	16.65500	0.58819	0.59153
150	4.86682	77224.47	46403.54	30820.92	0.5149	16.70458	0.59000	0.89098
200	6.48807	77224.48	46398.70	30825.79	0.5087	16.75604	0.58280	1.20178
RB211-535E4 (Performance Manual)								
Power off-take (kW)	kW per kN net thrust	Gross Thrust (N)	Momentum Drag (N)	Net Thrust (N)	Fuel Flow (kg/s)	S.F.C. (mg/N/sec)	S.F.C. (N/hr/N)	S.F.C. % change
0	0.00000			40159.60			0.64590	0.00000
149.2	3.71518			40159.60			0.65007	0.64560
RB211-22 (Performance Manual)								
Power off-take (kW)	kW per kN net thrust	Gross Thrust (N)	Momentum Drag (N)	Net Thrust (N)	Fuel Flow (kg/s)	S.F.C. (mg/N/sec)	S.F.C. (N/hr/N)	S.F.C. % change
0	0.00000			40968.80				0.00000
100	2.44088			40968.80				0.42080
Trent 700 (Rolls-Royce Data)								
Power off-take (kW)	kW per kN net thrust	Gross Thrust (N)	Momentum Drag (N)	Net Thrust (N)	Fuel Flow (kg/s)	S.F.C. (mg/N/sec)	S.F.C. (N/hr/N)	S.F.C. % change
0	0.00000			70250				0.00000
186.6	2.656228			70250				0.58
Tay (Rolls-Royce Data)								
Power off-take (kW)	kW per kN net thrust	Gross Thrust (N)	Momentum Drag (N)	Net Thrust (N)	Fuel Flow (kg/s)	S.F.C. (mg/N/sec)	S.F.C. (N/hr/N)	S.F.C. % change
0	0.00000			15574.				0.00000
37.3	2.395017			15574.				0.43000

Figure E-1: Engine Performance Variation with Power Off-Take

The percentage increase in specific fuel consumption is plotted in Figure E-2.

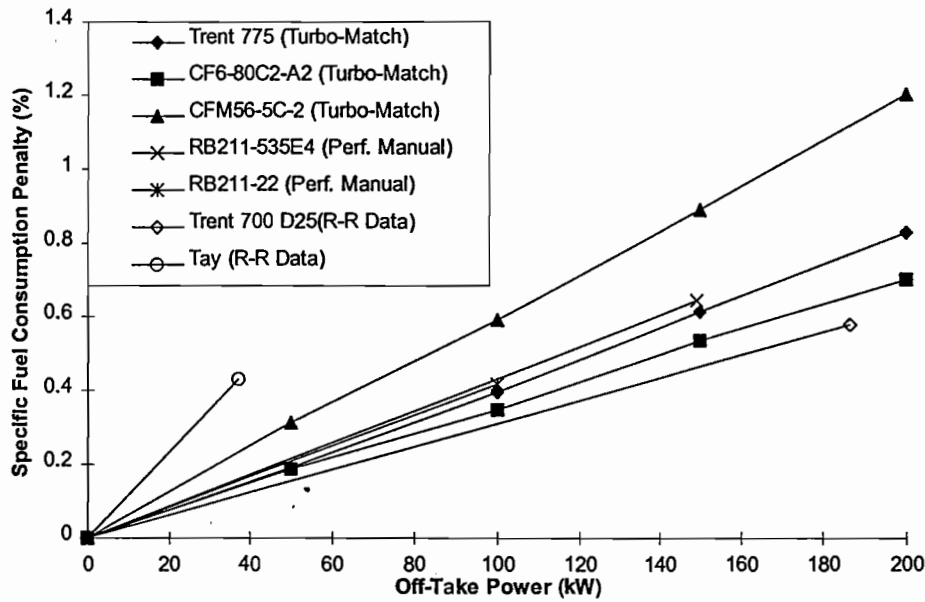


Figure E-2: SFC Penalty vs Off-Take Power

As expected, the gradient of these plots generally decrease with increases in the net cruise thrust. The only exception is the Turbo-Match Trent plot, whose penalty is greater than expected, possibly due to a low cruise thrust setting. The effect of engine size is removed from these plots by dividing the power off-take by the net cruise thrust, Figure E-3

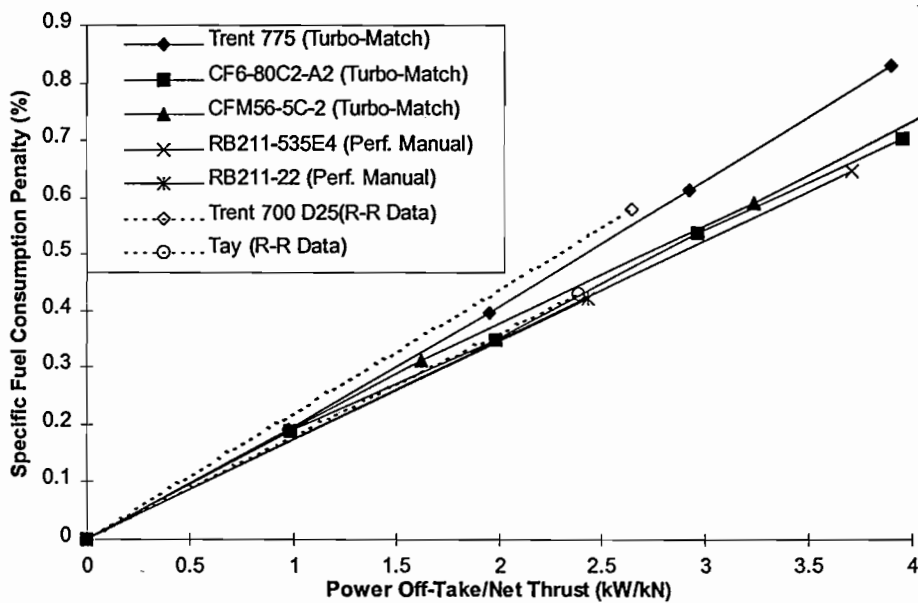


Figure E-3: SFC Penalty vs Power Off-take/Net Thrust

It is clear from this plot that engine size is the primary factor in defining the gradient of the specific fuel consumption penalties for power off-take, with all data, except

both sets of Trent data, following the same gradient such that the SFC penalty can be expressed as:

$$SFC_PENALTY = 0.1773 * \frac{SHAFT_OFF_TAKE_POWER}{NET_THRUST}$$

If consideration of the Trent engine required, the “0.1773” term can be replaced by “0.213”.

The data for the CFM56 extends linearly of this plot, suggesting that the relationship for all engines is linear for substantial power off-takes.

F. COMPARISON OF ELECTRICAL AND BLEED DRIVES FOR SUCTION UNIT

Engine Type: 140-150kN Sea-Level Static Thrust

Suction Power Requirement: 40kW

Electrical Drive

Generation and transmission efficiency of 0.8

Therefore Shaft Off-take power = 50kW

Using above figures for CFM56 type engine

sfc penalty = 0.31 %

Bleed Drive

Using data from [102]

Engine type: 140kN Total Air Flow (cruise): 36.25kg/s

The effect of bleeding air from different locations in the compressor is investigated in [102]. These same two cases are investigated here.

Bleed Temp	500°K	688°K
Power/Airflow (kW/(kg/s))	205.5	394.6
Δ sfc for 1 % bleed	1.07%	2%
Bleed Flow (kg/s)	0.195 (0.54%)	0.1013 (0.28%)
Δ sfc	0.576%	0.559%

The sfc penalty for the Electrical drive is approximately half that for the bleed drive.

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G. SUMMARY OF OPTIMISED AIRCRAFT DATA FROM PROJECT STUDIES

A summary of configuration, mass, performance and DOC data is provided for all optimised configurations for the *Regional Jet*, *Short-Range Twin*, *Medium range-Twin*, *Long-range Quad* and the *Super Jumbo* aircraft. These include:

- Turbulent baseline for all aircraft.
- Optimised HLFC wing upper surface for all aircraft, fin, tailplane, nacelle cases as well as a combined case with HLFC on all four surfaces.
- Baseline and HLFC wing case for all aircraft optimised for a range of fuel prices.
- HLFC wing case for all aircraft optimised assuming a reducing proportion of cruise with laminar flow achievable.
- HLFC wing case for all aircraft optimised assuming varying suction system and leading edge maintenance cost per kg, relative to an average value for the rest of the airframe.
- HLFC wing case for all aircraft optimised assuming varying suction system and production cost per kg, relative to an average value for the rest of the aircraft systems.
- HLFC wing case for *long range quad* and *super jumbo* with varying maximum transition Reynolds numbers.

Regional Jet

	Wing Area m ²	Aspect Ratio	1/4c Sweep (deg)	L.E. Sweep (deg)	Thick./Chord	Taper Ratio	Profile Drag	Design Mission			Average Mission			Thrust-Sea Level Static (N)	Thrust Cruise (N)	Thrust-Turbulent Cruise (N)	Engine Mass (kg)	HLFC System Mass (kg)	Max. Take-Off Mass (kg)	Design Mission		Alternative Mission	
								CL	CD		CL	CD								Mfuel (kg)	DOC/ASK (p/ask)	XMFLU (kg)	DOC/ASK (p/ask)
Turbulent Baseline	98.42	8.98	12.17	15.51	0.116	0.285	0.01737	0.41843	0.02504	0.37587	0.02352	0.02352	121,187	27,425	0	4,757	0	45,351	1,439	2,899	2,236		
HLFC Wing	95.54	8.86	7.28	10.73	0.113	0.293	0.01538	0.42710	0.02355	0.38729	0.02205	0.02205	119,796	25,186	27,231	4,718	123	44,822	1,406	2,702	2,209		
HLFC Fin	97.99	8.95	11.41	14.79	0.116	0.285	0.01704	0.41997	0.02482	0.37780	0.02330	0.02330	121,088	27,086	27,450	4,758	57	45,303	1,436	2,871	2,235		
HLFC Tailplane	96.70	8.82	9.24	12.71	0.114	0.287	0.01670	0.42528	0.02481	0.38318	0.02323	0.02323	121,443	26,739	27,524	4,772	108	45,246	1,431	2,838	2,231		
HLFC Nacelles	96.48	8.86	9.01	12.50	0.115	0.282	0.01683	0.42561	0.02495	0.38327	0.02337	0.02337	121,233	26,826	27,512	4,767	66	45,188	1,430	2,843	2,227		
HLFC WFTN	99.24	8.57	11.44	15.09	0.106	0.269	0.01311	0.41060	0.02068	0.37563	0.01943	0.01943	118,649	23,142	27,129	4,689	375	44,661	1,388	2,548	2,207		

Fuel Price - Laminar

	Wing Area m ²	Aspect Ratio	1/4c Sweep (deg)	L.E. Sweep (deg)	Thick./Chord	Taper Ratio	Profile Drag	Design Mission			Average Mission			Thrust-Sea Level Static (N)	Thrust Cruise (N)	Thrust-Turbulent Cruise (N)	Engine Mass (kg)	HLFC System Mass (kg)	Max. Take-Off Mass (kg)	Design Mission		Alternative Mission	
Fuel Price (£/kg)								CL	CD		CL	CD								Mfuel (kg)	DOC/ASK (p/ask)	XMFLU (kg)	DOC/ASK (p/ask)
0.05																							
0.1	97.04	8.41	10.22	13.92	0.117	0.275	0.01532	0.4207	0.02363	0.38076	0.02208	0.02208	123,719	25,628	27,710	4,827	133	44,825	1,208	2,730	1,965		
0.2	99.66	8.75	12.19	15.74	0.104	0.269	0.01494	0.41148	0.02238	0.37357	0.02105	0.02105	119,631	24,990	27,059	4,696	142	45,035	1,432	2,700	2,246		
0.3	97.76	9.57	10.81	13.91	0.12	0.296	0.0152	0.41725	0.02251	0.37912	0.02119	0.02119	117,185	24,676	26,837	4,638	136	44,808	1,643	2,675	2,506		
0.4	98.41	9.89	10.22	13.44	0.119	0.265	0.01511	0.41507	0.02215	0.37753	0.02089	0.02089	116,232	24,461	26,635	4,602	135	44,868	1,858	2,662	2,774		

Fuel Price - Turbulent

	Wing Area m ²	Aspect Ratio	1/4c Sweep (deg)	L.E. Sweep (deg)	Thick./Chord	Taper Ratio	Profile Drag	Design Mission			Average Mission			Thrust-Sea Level Static (N)	Thrust Cruise (N)	Thrust-Turbulent Cruise (N)	Engine Mass (kg)	HLFC System Mass (kg)	Max. Take-Off Mass (kg)	Design Mission		Alternative Mission	
Fuel Price (£/kg)								CL	CD		CL	CD								Mfuel (kg)	DOC/ASK (p/ask)	XMFLU (kg)	DOC/ASK (p/ask)
0.05																							
0.1	96.86	8.78	10.09	13.58	0.117	0.284	0.01753	0.42489	0.02568	0.38131	0.02405	0.02405	122,116	27,664	0	4,797	0	45,327	1,221	2,910	1,972		
0.2																							
0.3	97	9.32	9.15	12.5	0.115	0.279	0.0175	0.42496	0.02525	0.38205	0.02371	0.02371	120,474	27,267	0	4,730	0	45,397	1,704	2,888	2,556		
0.4	97.61	9.63	9.71	12.95	0.117	0.276	0.01746	0.42264	0.02492	0.38025	0.02345	0.02345	119,590	27,094	0	4,698	0	45,432	1,943	2,879	2,846		

Regional Jet (Continued)

Fuel Reserves

Frac. cruise without laminar flow	Wing Area m ²	Aspect Ratio	1/4c Sweep (deg)	L.E. Sweep (deg)	Thick./ Chord	Taper Ratio	Profile Drag	Design Mission			Average Mission			Thrust Cruise (N)	Thrust- Turbulent Cruise (N)	Engine Mass (kg)	HLFC System Mass (kg)	Max. Take-Off Mass (kg)	Design Mission		Alternative Mission	
								Cruise CL	Cruise CD	Profile Drag	Cruise CL	Cruise CD	Thrust- Sea Level Static (N)						Mfuel (kg)	DOC/ ASK (p/ask)	XMFLU (kg)	DOC/ ASK (p/ask)
0	95.82	8.83	7.75	11.25	0.113	0.286	0.01535	0.42565	0.02349	0.022	0.38593	0.022	119758	25199	27251	4720	125	44803	9296	1.406	2703	2.209
0.3333	97.24	8.98	9.9	13.32	0.117	0.283	0.016	0.42163	0.02388	0.0224	0.38116	0.0224	120091	25944	27325	4733	132	45079	9506	1.421	2772	2.226
0.6667																						
1																						

Maintenance Costs

LF Maint/ airframe maint (per kg)	Wing Area m ²	Aspect Ratio	1/4c Sweep (deg)	L.E. Sweep (deg)	Thick./ Chord	Taper Ratio	Profile Drag	Design Mission			Average Mission			Thrust Cruise (N)	Thrust- Turbulent Cruise (N)	Engine Mass (kg)	HLFC System Mass (kg)	Max. Take-Off Mass (kg)	Design Mission		Alternative Mission	
								Cruise CL	Cruise CD	Profile Drag	Cruise CL	Cruise CD	Thrust- Sea Level Static (N)						Mfuel (kg)	DOC/ ASK (p/ask)	XMFLU (kg)	DOC/ ASK (p/ask)
0	97.27	9.02	10.01	13.47	0.118	0.274	0.01523	0.41874	0.02298	0.02156	0.37987	0.02156	118637	25030	27142	4692	133	44749	9245	1.403	2695	2.205
2	97.16	9.02	10.15	13.56	0.118	0.282	0.01525	0.41924	0.02301	0.02159	0.38031	0.02159	118694	25036	27149	4694	133	44749	9247	1.407	2695	2.213
4																						
6																						
8	96.48	8.91	8.52	12.04	0.114	0.277	0.01528	0.4227	0.02324	0.02178	0.3834	0.02178	119287	25103	27172	4704	128	44800	9268	1.422	2698	2.242
10																						

HLFC System Production Costs

LF Cost/ system cost (per kg)	Wing Area m ²	Aspect Ratio	1/4c Sweep (deg)	L.E. Sweep (deg)	Thick./ Chord	Taper Ratio	Profile Drag	Design Mission			Average Mission			Thrust Cruise (N)	Thrust- Turbulent Cruise (N)	Engine Mass (kg)	HLFC System Mass (kg)	Max. Take-Off Mass (kg)	Design Mission		Alternative Mission	
								Cruise CL	Cruise CD	Profile Drag	Cruise CL	Cruise CD	Thrust- Sea Level Static (N)						Mfuel (kg)	DOC/ ASK (p/ask)	XMFLU (kg)	DOC/ ASK (p/ask)
0	97.16	9.02	9.93	13.37	0.117	0.277	0.01524	0.41927	0.02301	0.02159	0.38034	0.02159	118694	25037	27145	4693	132	44752	9247	1.401	2695	2.202
2	95.54	8.76	8.1	11.43	0.114	0.311	0.0154	0.42712	0.02365	0.02213	0.38715	0.02213	120250	25288	27340	4737	125	44828	9325	1.412	2709	2.218
4																						
6																						
8																						
10																						

Short Range Twin

	Wing Area m ²	Aspect Ratio	1/4c Sweep (deg)	L.E. Sweep (deg)	Thick/Chord	Taper Ratio	Profile Drag	Design Mission				Average Mission				Thrust Cruise (N)	Thrust-Turbulent Cruise (N)	Engine Mass (kg)	HLFC System Mass (kg)	Max. Take-Off Mass (kg)	Design Mission		Alternative Mission	
								CL	CD	Cruise CL	Cruise CD	Thrust-Sea Level Static (N)	Mfuel (kg)	DOC/ASK (p/ask)	XMFLU (kg)						DOC/ASK (p/ask)			
Turbulent Baseline	118.54	9.69	25.60	28.14	0.112	0.300	0.01805	0.58676	0.03266	0.49196	0.02801	228,716	42,404	0	0	7,809	0	74,300	18,348	1.254	3,407	2,350		
HLFC Wing	117.49	9.87	24.99	27.50	0.110	0.300	0.01580	0.58161	0.02994	0.49457	0.02573	221,579	38,764	41,407	41,407	7,586	256	72,901	17,007	1.227	3,199	2,330		
HLFC Fin	118.35	9.68	25.53	28.07	0.112	0.300	0.01744	0.58504	0.03197	0.49218	0.02742	226,963	41,497	42,217	42,217	7,713	127	73,937	18,021	1.248	3,356	2,345		
HLFC Tailplane	118.67	9.66	25.46	28.00	0.112	0.300	0.01751	0.58407	0.03202	0.49106	0.02747	226,916	41,671	42,272	42,272	7,722	117	74,024	18,089	1.250	3,367	2,347		
HLFC Nacelles	117.62	9.64	25.67	28.21	0.112	0.300	0.01743	0.58732	0.03212	0.49409	0.02752	227,480	41,430	42,210	42,210	7,721	74	73,762	17,983	1.244	3,346	2,338		
HLFC WFTN	116.67	9.85	24.40	26.94	0.108	0.300	0.01391	0.57856	0.02793	0.49732	0.02398	217,469	36,087	40,905	40,905	7,463	552	71,943	16,032	1.206	3,045	2,316		

Fuel Price - Laminar

Fuel Price (£/kg)	Wing Area m ²	Aspect Ratio	1/4c Sweep (deg)	L.E. Sweep (deg)	Thick./Chord	Taper Ratio	Profile Drag	Design Mission				Average Mission		Thrust Cruise (N)	Thrust-Turbulent Cruise (N)	Engine Mass (kg)	HLFC System Mass (kg)	Max. Take-Off Mass (kg)	Design Mission		Alternative Mission	
								Cruise CL	Cruise CD	Cruise CL	Cruise CD	Thrust-Sea Level Static (N)	Mfuel (kg)						DOC/ASK (p/ask)	XMFLU (kg)	DOC/ASK (p/ask)	
0.05	117.57	9.08	23.87	26.65	0.104	0.3	0.01575	0.58295	0.03098	0.49333	0.02635	227380	40031	42601	7792	246	73131	17453	0.982	3247	2.006	
0.1	117.22	9.43	24.53	27.18	0.107	0.3	0.01579	0.58355	0.03057	0.49494	0.02612	224047	39429	42026	7681	251	72990	17241	1.07	3224	2.123	
0.2	117.47	9.89	24.9	27.41	0.11	0.3	0.0158	0.58173	0.02993	0.49474	0.02572	221515	38738	41379	7583	254	72907	16997	1.244	3198	2.353	
0.3	117.86	10.25	24.94	27.37	0.111	0.3	0.01579	0.57977	0.02941	0.49405	0.02539	218703	38231	40905	7490	254	72888	16820	1.415	3181	2.582	
0.4	117.82	10.45	24.94	27.32	0.111	0.3	0.01581	0.58013	0.02922	0.49495	0.02527	218088	37998	40680	7462	252	72915	16736	1.586	3173	2.81	

Fuel Price - Turbulent

Fuel Price (£/kg)	Wing Area m ²	Aspect Ratio	1/4c Sweep (deg)	L.E. Sweep (deg)	Thick./Chord	Taper Ratio	Profile Drag	Design Mission				Average Mission				Thrust-Turbulent Cruise (N)	Engine Mass (kg)	HLFC System Mass (kg)	Max. Take-Off Mass (kg)	Design Mission		Alternative Mission	
								Cruise CL	Cruise CD	Cruise CL	Cruise CD	Thrust-Sea Level Static (N)	Cruise CL	Cruise CD	Mfuel (kg)					DOC/ASK (p/ask)	XMFLU (kg)	DOC/ASK (p/ask)	
0.05	118.27	9.08	25.8	28.49	0.112	0.3	0.01802	0.589	0.03356	0.49196	0.02855	233121	43401	0	7971	0	74422	18693	0.987	3442	2.006		
0.1	118.38	9.32	25.69	28.32	0.112	0.3	0.01803	0.58795	0.03318	0.49185	0.02832	231145	42980	0	7900	0	74354	18548	1.083	3427	2.129		
0.2	118.52	9.71	25.49	28.02	0.111	0.3	0.01805	0.58691	0.03263	0.49217	0.02799	228431	42362	0	7800	0	74303	18334	1.273	3406	2.374		
0.3	118.54	10	25.51	27.97	0.112	0.3	0.01808	0.58688	0.0323	0.49295	0.0278	227199	41973	0	7747	0	74304	18198	1.462	3393	2.618		
0.4	118.56	10.23	25.4	27.81	0.111	0.3	0.01809	0.58701	0.03206	0.49366	0.02766	226213	41695	0	7708	0	74334	18101	1.649	3384	2.861		

Short Range Twin (Continued)

Fuel Reserves

Frac. cruise without laminar flow	Wing Area m ²	Aspect Ratio	1/4c Sweep (deg)	L.E. Sweep (deg)	Thick./Chord	Taper Ratio	Profile Drag	Design Mission			Average Mission			Thrust Cruise (N)	Thrust Turbulent Cruise (N)	Engine Mass (kg)	HLFC System Mass (kg)	Max. Take-Off Mass (kg)	Design Mission		Alternative Mission	
								Cruise CL	Cruise CD		Cruise CL	Cruise CD							Mfuel (kg)	DOC/ASK (p/ask)	XMFLU (kg)	DOC/ASK (p/ask)
0	117.48	9.86	25.04	27.55	0.111	0.3	0.0158	0.58151	0.02994	0.49448	0.02573	0.02573	221013	38760	41404	7574	257	72891	17007	1.225	3199	2.326
0.3333	117.56	9.81	24.74	27.28	0.108	0.3	0.01656	0.58779	0.03101	0.49668	0.02661	0.02661	224390	40088	41838	7676	252	73631	17504	1.239	3278	2.343
0.6667	117.81	9.76	24.45	27.01	0.105	0.3	0.0173	0.59121	0.03201	0.4982	0.02743	0.02743	227560	41390	42259	7774	248	74368	17993	1.254	3357	2.361
1	117.85	9.65	24.46	27.05	0.103	0.3	0.01805	0.59665	0.03316	0.50036	0.02836	0.02836	231900	42811	42812	7906	249	75104	18521	1.269	3438	2.378

Maintenance Costs

LF Maint/airframe maint (per kg)	Wing Area m ²	Aspect Ratio	1/4c Sweep (deg)	L.E. Sweep (deg)	Thick./Chord	Taper Ratio	Profile Drag	Design Mission			Average Mission			Thrust Cruise (N)	Thrust Turbulent Cruise (N)	Engine Mass (kg)	HLFC System Mass (kg)	Max. Take-Off Mass (kg)	Design Mission		Alternative Mission	
								Cruise CL	Cruise CD		Cruise CL	Cruise CD							Mfuel (kg)	DOC/ASK (p/ask)	XMFLU (kg)	DOC/ASK (p/ask)
0	117.61	9.89	25.11	27.62	0.111	0.3	0.0158	0.58084	0.02987	0.494	0.02568	0.02568	220763	38711	41364	7565	258	72882	16990	1.223	3197	2.321
2	117.38	9.85	24.9	27.42	0.11	0.3	0.01581	0.58222	0.02999	0.49505	0.02577	0.02577	221795	38789	41426	7592	254	72911	17015	1.228	3200	2.334
4	117.27	9.8	24.31	26.87	0.107	0.3	0.01581	0.58319	0.0301	0.49576	0.02583	0.02583	222529	38883	41495	7613	245	72960	17044	1.233	3203	2.348
6	118.15	9.64	23.66	26.29	0.105	0.3	0.01573	0.5792	0.03002	0.49202	0.02575	0.02575	223127	39065	41683	7638	244	73009	17113	1.24	3212	2.363
8	119.44	9.54	21.9	24.63	0.099	0.3	0.0156	0.57377	0.02975	0.48742	0.02552	0.02552	221181	39130	41742	7600	228	73129	17145	1.245	3218	2.377
10	116.83	9.72	24.26	26.84	0.106	0.3	0.01584	0.58559	0.03034	0.49752	0.026	0.026	223462	39033	41625	7642	243	72986	17094	1.25	3208	2.392

HLFC System Production Costs

LF Cost/ system cost (per kg)	Wing Area m ²	Aspect Ratio	1/4c Sweep (deg)	L.E. Sweep (deg)	Thick./Chord	Taper Ratio	Profile Drag	Design Mission			Average Mission			Thrust Cruise (N)	Thrust Turbulent Cruise (N)	Engine Mass (kg)	HLFC System Mass (kg)	Max. Take-Off Mass (kg)	Design Mission		Alternative Mission	
								Cruise CL	Cruise CD		Cruise CL	Cruise CD							Mfuel (kg)	DOC/ASK (p/ask)	XMFLU (kg)	DOC/ASK (p/ask)
0	118.42	9.88	25.05	27.56	0.112	0.3	0.01573	0.57596	0.02959	0.4899	0.02547	0.02547	219120	38617	41298	7525	260	72776	16962	1.218	3194	2.314
2	117.54	9.83	24.03	26.59	0.106	0.3	0.01577	0.58094	0.02992	0.49402	0.0257	0.0257	219757	38748	41365	7544	246	72863	16998	1.229	3198	2.335
4	117.38	9.71	23.25	25.88	0.102	0.3	0.01576	0.58233	0.03011	0.49494	0.02582	0.02582	220215	38926	41511	7564	237	72948	17040	1.241	3201	2.357
6	117.09	9.72	21.36	24.06	0.094	0.3	0.01576	0.58571	0.03024	0.49795	0.02592	0.02592	221314	39011	41540	7589	212	73177	17083	1.25	3211	2.375
8	117.1	9.66	21.37	24.09	0.094	0.3	0.01575	0.58594	0.03032	0.498	0.02597	0.02597	220682	39109	41634	7582	213	73382	17068	1.261	3210	2.398
10	115.83	9.94	21.63	24.26	0.093	0.3	0.01589	0.59338	0.03046	0.50493	0.02613	0.02613	224380	38888	41389	7647	210	73314	17029	1.27	3205	2.416

Medium Range Twin

	Wing Area m ²	Aspect Ratio	1/4c Sweep (deg)	L.E. Sweep (deg)	Thick/Chord	Taper Ratio	Profile Drag	Design Mission			Average Mission			Thrust Cruise (N)	Thrust Sea Level Static (N)	Thrust Cruise (N)	Thrust-Turbulent Cruise (N)	Engine Mass (kg)	HLFC System Mass (kg)	Max. Take-Off Mass (kg)	Design Mission		Alternative Mission	
								Cruise CL	Cruise CD	Cruise CL	Cruise CL	Cruise CD	Cruise CD								Mfuel (kg)	DOC/ASK (p/ask)	XMFLU (kg)	DOC/ASK (p/ask)
Turbulent Baseline	372.17	9.82	29.74	32.44	0.12	0.225	0.01451	0.54412	0.0278	0.46592	0.02378	0.02378	0.02378	109020	514736		0	19295	0	208709	60168	1.122	24928	1.313
HLFC Wing	365.72	10.03	29.48	32.1	0.121	0.234	0.01223	0.53813	0.02504	0.46738	0.02144	0.02144	0.02144	97213	491945		105378	18560	1260	202474	54314	1.09	22572	1.286
HLFC Fin	371.82	9.87	29.79	32.49	0.121	0.224	0.01415	0.54246	0.02732	0.46554	0.02338	0.02338	0.02338	107157	510988		108428	19175	260	207821	59262	1.118	24569	1.31
HLFC Tailplane	372.16	9.86	29.9	32.61	0.122	0.221	0.01388	0.54001	0.02691	0.4642	0.02306	0.02306	0.02306	105731	508274		107907	19078	403	207028	58578	1.114	24302	1.307
HLFC Nacelles	370.17	9.84	29.84	32.53	0.121	0.227	0.01412	0.54334	0.02736	0.46632	0.02341	0.02341	0.02341	106857	510460		108301	19153	155	207224	59073	1.115	24482	1.306
HLFC WFTN	363.21	10.06	29.26	31.92	0.121	0.227	0.01087	0.5323	0.0234	0.46606	0.02004	0.02004	0.02004	90646	478788		103463	18157	2022	198710	51034	1.071	21243	1.27

Fuel Price - Laminar

	Wing Area m ²	Aspect Ratio	1/4c Sweep (deg)	L.E. Sweep (deg)	Thick/Chord	Taper Ratio	Profile Drag	Design Mission			Average Mission			Thrust Cruise (N)	Thrust Sea Level Static (N)	Thrust Cruise (N)	Thrust-Turbulent Cruise (N)	Engine Mass (kg)	HLFC System Mass (kg)	Max. Take-Off Mass (kg)	Design Mission		Alternative Mission	
Fuel Price (£/kg)								Cruise CL	Cruise CD	Cruise CL	Cruise CL	Cruise CD	Cruise CD								Mfuel (kg)	DOC/ASK (p/ask)	XMFLU (kg)	DOC/ASK (p/ask)
0.05	363.28	9.16	29.18	32.04	0.116	0.236	0.01227	0.54237	0.02623	0.46862	0.02223	0.02223	0.02223	100838	508616		108635	19157	1227	202740	55840	0.841	23044	1.03
0.1	363.75	9.6	29.55	32.25	0.12	0.238	0.01226	0.54039	0.02562	0.46816	0.02183	0.02183	0.02183	98781	499180		106786	18818	1252	202422	54962	0.931	22764	1.122
0.2	365.74	10.04	29.43	32.09	0.12	0.225	0.01222	0.53731	0.02499	0.46669	0.02141	0.02141	0.02141	97043	490606		105180	18518	1256	202184	54230	1.107	22541	1.303
0.3	364.06	10.05	29.38	32.01	0.119	0.231	0.01225	0.5399	0.02512	0.46894	0.02151	0.02151	0.02151	97089	491445		105193	18533	1244	202218	54229	1.285	22534	1.484
0.4	364.8	10.1	29.07	31.78	0.117	0.217	0.01223	0.53916	0.025	0.46851	0.02142	0.02142	0.02142	96850	490313		104895	18485	1226	202348	54130	1.461	22508	1.664

Fuel Price - Turbulent

	Wing Area m ²	Aspect Ratio	1/4c Sweep (deg)	L.E. Sweep (deg)	Thick/Chord	Taper Ratio	Profile Drag	Design Mission			Average Mission			Thrust Cruise (N)	Thrust Sea Level Static (N)	Thrust Cruise (N)	Thrust-Turbulent Cruise (N)	Engine Mass (kg)	HLFC System Mass (kg)	Max. Take-Off Mass (kg)	Design Mission		Alternative Mission	
Fuel Price (£/kg)								Cruise CL	Cruise CD	Cruise CL	Cruise CL	Cruise CD	Cruise CD								Mfuel (kg)	DOC/ASK (p/ask)	XMFLU (kg)	DOC/ASK (p/ask)
0.05	371.6	9	29.91	32.74	0.12	0.242	0.01448	0.54599	0.02881	0.46531	0.0244	0.0244	0.0244	112533	531557		0	19921	0	209116	61631	0.844	25372	1.032
0.1	371.51	9.41	29.99	32.77	0.121	0.229	0.0145	0.54479	0.02827	0.46542	0.02408	0.02408	0.02408	110549	522220		0	19570	0	208600	60794	0.944	25112	1.133
0.2	371.7	9.9	29.97	32.62	0.122	0.228	0.01453	0.54445	0.02775	0.46635	0.02376	0.02376	0.02376	108720	513651		0	19248	0	208567	60039	1.142	24887	1.333
0.3	370.37	9.99	29.78	32.45	0.12	0.223	0.01453	0.54651	0.02775	0.4684	0.02376	0.02376	0.02376	108346	512929		0	19199	0	208596	59857	1.339	24824	1.532
0.4	371.33	10.01	29.62	32.34	0.117	0.214	0.01449	0.54547	0.02752	0.46794	0.02362	0.02362	0.02362	107788	512128		0	19131	0	208716	59641	1.534	24768	1.731

PERFORMANCE AND ECONOMY

Fuel Reserves

	Wing Area m ²	Aspect Ratio	1/4c Sweep (deg)	L.E. Sweep (deg)	Thick./ Chord	Taper Ratio	Profile Drag	Design Mission			Average Mission			Thrust- Sea Level Static (N)	Thrust Cruise (N)	Thrust- Turbulent Cruise (N)	Engine Mass (kg)	HLFC System Mass (kg)	Max. Take-Off Mass (kg)	Design Mission		Alternative Mission	
								Cruise CL	Cruise CD	Cruise CL	Cruise CD	Cruise CL	Cruise CD							Mfuel (kg)	DOC/ ASK (p/ask)	XMFLU (kg)	DOC/ ASK (p/ask)
Frac. cruise without laminar flow	0	365.84	10.03	29.47	32.13	0.121	0.225	0.01222	0.5371	0.02499	0.02141	0.46649	0.02141	490641	97054	105196	18520	1259	202161	54237	1.089	22543	1.285
	2	363.33	10.04	29.39	32.08	0.118	0.223	0.01299	0.54266	0.02604	0.02228	0.46912	0.02228	502392	101512	106927	18884	1256	205635	56512	1.111	23464	1.307
	4	364.72	10.06	29.29	31.95	0.119	0.226	0.01224	0.53899	0.02506	0.02146	0.46832	0.02146	490836	97023	105121	18516	1242	202250	54206	1.1	22530	1.302
	6	362.43	10.03	29.45	31.95	0.119	0.256	0.01227	0.54335	0.02532	0.02165	0.47187	0.02165	494064	97398	105534	18609	1242	202593	54358	1.108	22575	1.314
	8	359.02	9.94	28.83	31.41	0.113	0.252	0.01231	0.54896	0.0257	0.02192	0.47649	0.02192	496845	97885	105816	18683	1189	202753	54511	1.116	22610	1.325
	10	359.82	9.8	29.39	31.75	0.118	0.295	0.01231	0.54897	0.02584	0.02201	0.47612	0.02201	501234	98616	106719	18845	1229	203206	54871	1.125	22735	1.338

Maintenance Costs

	Wing Area m ²	Aspect Ratio	1/4c Sweep (deg)	L.E. Sweep (deg)	Thick./ Chord	Taper Ratio	Profile Drag	Design Mission			Average Mission			Thrust- Sea Level Static (N)	Thrust Cruise (N)	Thrust- Turbulent Cruise (N)	Engine Mass (kg)	HLFC System Mass (kg)	Max. Take-Off Mass (kg)	Design Mission		Alternative Mission	
								Cruise CL	Cruise CD	Cruise CL	Cruise CD	Cruise CL	Cruise CD							Mfuel (kg)	DOC/ ASK (p/ask)	XMFLU (kg)	DOC/ ASK (p/ask)
LF Maint/ airframe maint (per kg)	0	366.39	10.03	29.5	32.15	0.121	0.227	0.01222	0.53636	0.02495	0.02138	0.46585	0.02138	490472	97060	105225	18521	1264	202185	54248	1.087	22549	1.281
	2	365.4	10.04	29.41	32.07	0.12	0.226	0.01223	0.53788	0.02502	0.02143	0.46719	0.02143	490829	97056	105183	18522	1253	202210	54231	1.093	22540	1.291
	4	364.72	10.06	29.29	31.95	0.119	0.226	0.01224	0.53899	0.02506	0.02146	0.46832	0.02146	490836	97023	105121	18516	1242	202250	54206	1.1	22530	1.302
	6	362.43	10.03	29.45	31.95	0.119	0.256	0.01227	0.54335	0.02532	0.02165	0.47187	0.02165	494064	97398	105534	18609	1242	202593	54358	1.108	22575	1.314
	8	359.02	9.94	28.83	31.41	0.113	0.252	0.01231	0.54896	0.0257	0.02192	0.47649	0.02192	496845	97885	105816	18683	1189	202753	54511	1.116	22610	1.325
	10	359.82	9.8	29.39	31.75	0.118	0.295	0.01231	0.54897	0.02584	0.02201	0.47612	0.02201	501234	98616	106719	18845	1229	203206	54871	1.125	22735	1.338

HLFC System Production Costs

	Wing Area m ²	Aspect Ratio	1/4c Sweep (deg)	L.E. Sweep (deg)	Thick./ Chord	Taper Ratio	Profile Drag	Design Mission			Average Mission			Thrust- Sea Level Static (N)	Thrust Cruise (N)	Thrust- Turbulent Cruise (N)	Engine Mass (kg)	HLFC System Mass (kg)	Max. Take-Off Mass (kg)	Design Mission		Alternative Mission	
								Cruise CL	Cruise CD	Cruise CL	Cruise CD	Cruise CL	Cruise CD							Mfuel (kg)	DOC/ ASK (p/ask)	XMFLU (kg)	DOC/ ASK (p/ask)
LF Cost/ system cost (per kg)	0	366.47	9.98	29.81	32.41	0.123	0.237	0.01222	0.53642	0.02501	0.02142	0.46576	0.02142	492019	97280	105505	18574	1284	202250	54358	1.081	22586	1.275
	2	363.58	10.04	29.21	31.84	0.118	0.234	0.01225	0.54189	0.02522	0.02158	0.47066	0.02158	493435	97348	105420	18588	1232	202689	54343	1.101	22576	1.299
	4	360.71	10.04	28.54	31.35	0.111	0.209	0.01228	0.54727	0.02549	0.02177	0.47532	0.02177	496055	97617	105442	18632	1175	203074	54410	1.124	22591	1.326
	6	357.26	9.9	27.95	30.7	0.106	0.231	0.01232	0.55402	0.02598	0.02212	0.48081	0.02212	500718	98468	106165	18781	1129	203610	54738	1.146	22688	1.351
	8	357.37	9.79	27.95	30.75	0.106	0.227	0.01232	0.55352	0.02608	0.02218	0.48006	0.02218	502108	98833	106490	18836	1129	203495	54893	1.167	22735	1.375
	10	357.49	9.82	27.51	30.34	0.103	0.224	0.01231	0.55435	0.02607	0.02217	0.48091	0.02217	502139	98860	106471	18835	1108	203866	54908	1.187	22746	1.399

Long Range Quad

	Wing Area m ²	Aspect Ratio	1/4c Sweep (deg)	L.E. Sweep (deg)	Thick/Chord	Taper Ratio	Profile Drag	Design Mission Cruise CL	Design Mission Cruise CD	Thrust-Sea Level Static (N)	Thrust Cruise (N)	Thrust-Turbulent Cruise (N)	Engine Mass (kg)	HLFC System Mass (kg)	Max. Take-Off Mass (kg)	Design Mission Mfuel (kg)	DOC/ASK (p/ask)	Alternative Mission XMFLU (kg)	DOC/ASK (p/ask)
Turbulent Baseline	350.57	8.85	27.61	30.57	0.103	0.250	0.01430	0.48818	0.02545	0.36776	0.02037	531,461	115,595	0	233,739	99,212	1.354	36,109	1.507
HLFC Wing	342.16	9.42	27.25	30.06	0.107	0.250	0.01237	0.46690	0.02209	0.36108	0.01795	473,095	97,937	1,043	217,949	86,171	1.274	31,629	1.433
HLFC Fin	349.24	8.84	27.27	30.26	0.102	0.250	0.01387	0.48322	0.02480	0.36567	0.01988	518,602	112,248	295	230,464	96,675	1.339	35,210	1.491
HLFC Tailplane	345.55	8.76	27.20	30.22	0.102	0.250	0.01362	0.48350	0.02465	0.36674	0.01972	513,938	110,372	449	228,122	95,045	1.327	34,576	1.480
HLFC Nacelles	344.25	8.83	27.50	30.48	0.102	0.250	0.01386	0.48753	0.02499	0.36920	0.01999	519,977	111,483	174	229,140	95,868	1.330	34,875	1.482
HLFC WFTN	330.99	9.29	26.11	29.02	0.102	0.250	0.01090	0.45845	0.02040	0.36046	0.01655	440,255	87,481	1,776	206,839	77,737	1.218	28,518	1.377

Fuel Price - Laminar

	Wing Area m ²	Aspect Ratio	1/4c Sweep (deg)	L.E. Sweep (deg)	Thick/Chord	Taper Ratio	Profile Drag	Design Mission Cruise CL	Design Mission Cruise CD	Thrust-Sea Level Static (N)	Thrust Cruise (N)	Thrust-Turbulent Cruise (N)	Engine Mass (kg)	HLFC System Mass (kg)	Max. Take-Off Mass (kg)	Design Mission Mfuel (kg)	DOC/ASK (p/ask)	Alternative Mission XMFLU (kg)	DOC/ASK (p/ask)
Fuel Price (£/kg)	0.05	343.09	8.79	27.21	30.22	0.106	0.01239	0.46662	0.02267	0.3586	0.01824	480,381	100,791	1,044	218,480	87,894	0.959	32,074	1.131
	0.1	348.08	9.39	28.04	30.82	0.113	0.01231	0.45907	0.02175	0.35474	0.01773	472,143	98,086	1,077	218,026	86,492	1.073	31,787	1.241
	0.2	342.12	9.53	27.63	30.39	0.109	0.01238	0.46664	0.022	0.36116	0.01791	472,837	97,516	1,060	217,782	85,931	1.296	31,571	1.454
	0.3	341.07	9.82	27.69	30.36	0.109	0.01238	0.46833	0.02183	0.36343	0.01784	471,907	96,489	1,055	217,857	85,297	1.518	31,405	1.667
	0.4	341.57	10.16	28.35	30.9	0.114	0.01238	0.46763	0.02156	0.36377	0.0177	470,991	95,410	1,088	217,806	84,702	1.737	31,272	1.879

Fuel Price - Turbulent

	Wing Area m ²	Aspect Ratio	1/4c Sweep (deg)	L.E. Sweep (deg)	Thick/Chord	Taper Ratio	Profile Drag	Design Mission Cruise CL	Design Mission Cruise CD	Thrust-Sea Level Static (N)	Thrust Cruise (N)	Thrust-Turbulent Cruise (N)	Engine Mass (kg)	HLFC System Mass (kg)	Max. Take-Off Mass (kg)	Design Mission Mfuel (kg)	DOC/ASK (p/ask)	Alternative Mission XMFLU (kg)	DOC/ASK (p/ask)
Fuel Price (£/kg)	0.05	351.9	8.38	27.82	30.94	0.103	0.01427	0.48749	0.0259	0.36544	0.02056	539,421	118,115	0	234,336	100,655	0.99	36,459	1.163
	0.1	352.38	8.53	27.26	30.35	0.101	0.01424	0.48609	0.02564	0.3651	0.02042	539,13	117,053	0	233,992	100,051	1.121	36,311	1.286
	0.2	352.26	8.88	27.83	30.78	0.105	0.01429	0.48549	0.02529	0.36573	0.02028	529,784	115,416	0	233,581	99,182	1.38	36,129	1.531
	0.3	349.67	9.13	28.05	30.9	0.105	0.01435	0.48938	0.02526	0.36955	0.02032	530,012	114,452	0	233,667	98,993	1.638	35,976	1.775
	0.4	347.15	9.29	28.1	30.9	0.105	0.0144	0.49353	0.02533	0.37327	0.02039	532,579	113,945	0	233,895	98,240	1.895	35,870	2.018

Long Range Quad (Continued)

Fuel Reserves

Frac. cruise without laminar flow	Wing Area m ²	Aspect Ratio	1/4c Sweep (deg)	L.E. Sweep (deg)	Thick./Chord	Taper Ratio	Profile Drag	Design Mission Cruise CL	Average Mission Cruise CL	Thrust-Sea Level Static (N)	Thrust Cruise (N)	Thrust-Turbulent Cruise (N)	Engine Mass (kg)	HLFC System Mass (kg)	Max. Take-Off Mass (kg)	Design Mission Mfuel (kg)	DOC/ASK (p/ask)	Alternative Mission XMFLU (kg)	DOC/ASK (p/ask)
0	342.16	9.42	27.25	30.06	0.107	0.25	0.01237	0.4669	0.02209	0.36108	0.01795	97937	106467	1043	217949	86171	1.274	31629	1.433
0.3333	347.44	9.19	27.43	30.3	0.105	0.25	0.01301	0.47435	0.02233	0.3634	0.01877	104588	110255	15767	224933	91311	1.314	33422	1.471
0.6667	354.04	8.96	27.6	30.53	0.105	0.25	0.01362	0.48013	0.02243	0.36445	0.01953	114465	114294	16464	232098	96615	1.354	35270	1.511
1	362.81	8.68	27.33	30.37	0.102	0.25	0.01414	0.48352	0.02526	0.36367	0.02018	118729	118745	17193	239636	102177	1.396	37196	1.553

Maintenance Costs

LF Maint./airframe maint (per kg)	Wing Area m ²	Aspect Ratio	1/4c Sweep (deg)	L.E. Sweep (deg)	Thick./Chord	Taper Ratio	Profile Drag	Design Mission Cruise CL	Average Mission Cruise CL	Thrust-Sea Level Static (N)	Thrust Cruise (N)	Thrust-Turbulent Cruise (N)	Engine Mass (kg)	HLFC System Mass (kg)	Max. Take-Off Mass (kg)	Design Mission Mfuel (kg)	DOC/ASK (p/ask)	Alternative Mission XMFLU (kg)	DOC/ASK (p/ask)
0	342.46	9.41	27.23	30.05	0.106	0.25	0.01237	0.46649	0.02208	0.36072	0.01795	97975	106306	15072	217955	86205	1.272	31640	1.429
2	340.58	9.51	27.85	30.6	0.11	0.25	0.01241	0.46871	0.02212	0.36267	0.01799	97628	106222	15116	21742	85953	1.277	31562	1.438
4	341.35	9.4	27.25	30.06	0.106	0.25	0.01238	0.46809	0.02217	0.36193	0.018	98062	106560	15110	217982	86219	1.284	31632	1.448
6	340.75	9.38	27.24	30.06	0.106	0.25	0.01239	0.46897	0.02223	0.36256	0.01804	98147	106622	15124	218008	86252	1.29	31634	1.458
8	338.97	9.42	27.47	30.27	0.107	0.25	0.01243	0.4714	0.02233	0.36452	0.01811	98070	106539	15166	217962	86155	1.296	31593	1.467
10	342.58	9.32	27.11	29.96	0.106	0.25	0.01236	0.46647	0.02216	0.36042	0.01798	98349	106829	15107	218031	86425	1.303	31696	1.478

HLFC System Production Costs

LF Cost / system cost (per kg)	Wing Area m ²	Aspect Ratio	1/4c Sweep (deg)	L.E. Sweep (deg)	Thick./Chord	Taper Ratio	Profile Drag	Design Mission Cruise CL	Average Mission Cruise CL	Thrust-Sea Level Static (N)	Thrust Cruise (N)	Thrust-Turbulent Cruise (N)	Engine Mass (kg)	HLFC System Mass (kg)	Max. Take-Off Mass (kg)	Design Mission Mfuel (kg)	DOC/ASK (p/ask)	Alternative Mission XMFLU (kg)	DOC/ASK (p/ask)
0	343.42	9.44	27.25	30.05	0.107	0.25	0.01235	0.46511	0.02198	0.35977	0.01788	97802	106374	15052	217921	86129	1.266	31631	1.423
2	336.59	9.43	27.55	30.34	0.106	0.25	0.01247	0.475	0.0225	0.3673	0.01823	98130	106551	15214	218049	86125	1.28551	34564	1.4498
4	340.74	9.35	26.55	29.42	0.102	0.25	0.01238	0.4699	0.02227	0.3633	0.01806	98345	106735	15113	218444	86368	1.30809	31664	1.47057
6	337.8	9.22	26.17	29.09	0.099	0.25	0.01243	0.47511	0.02264	0.36701	0.01828	99113	107333	15238	218953	86737	1.33	31730	1.494
8	338.76	9.15	25.75	28.71	0.097	0.25	0.01241	0.47445	0.02266	0.36634	0.01828	99460	107631	15249	219290	86975	1.351	31801	1.518
10	338.5	9.15	25.74	28.71	0.097	0.25	0.01241	0.4749	0.02268	0.36668	0.01829	99494	107658	15270	219324	86986	1.372	31802	1.542

Maximum Transition Reynolds Number

Max. Transition Reynolds No (million)	Wing Area m ²	Aspect Ratio	1/4c Sweep (deg)	L.E. Sweep (deg)	Thick./Chord	Taper Ratio	Profile Drag	Design Mission Cruise CL	Average Mission Cruise CL	Thrust-Sea Level Static (N)	Thrust Cruise (N)	Thrust-Turbulent Cruise (N)	Engine Mass (kg)	HLFC System Mass (kg)	Max. Take-Off Mass (kg)	Design Mission Mfuel (kg)	DOC/ASK (p/ask)	Alternative Mission XMFLU (kg)	DOC/ASK (p/ask)
20	344.06	9.43	27.52	30.31	0.107	0.25	0.01268	0.47091	0.02256	0.36292	0.01831	100554	107810	15370	221063	88268	1.292	32385	1.45
25	342.16	9.42	27.25	30.06	0.107	0.25	0.01237	0.4669	0.02209	0.36108	0.01795	97937	106467	15081	217949	86171	1.274	31629	1.433
30	340.65	9.24	26.37	29.28	0.102	0.25	0.01215	0.46539	0.02196	0.36034	0.01781	96937	106186	14951	216292	85193	1.264	31223	1.422
35	339.99	9.27	26.99	29.85	0.106	0.25	0.01205	0.46296	0.02174	0.35889	0.01765	95766	105886	14846	214723	84302	1.257	30915	1.415
40	339.26	9.16	26.96	29.86	0.105	0.25	0.01203	0.46353	0.02184	0.35907	0.0177	96015	105883	14876	214532	84387	1.257	30911	1.413
45	339.73	9.15	26.87	29.78	0.105	0.25	0.01202	0.46291	0.02182	0.35857	0.01768	96040	105913	14870	214548	84411	1.257	30920	1.413

Super Jumbo

	Wing Area m ²	Aspect Ratio	1/4c Sweep (deg)	L.E. Sweep (deg)	Thick/Chord	Taper Ratio	Profile Drag	Design Mission			Average Mission			Thrust-Cruise Sea Level Static (N)	Thrust-Cruise (N)	Thrust-Turbulent Cruise (N)	Engine Mass (kg)	HLFC System Mass (kg)	Max. Take-Off Mass (kg)	Design Mission		Alternative Mission	
								Cruise CL	Cruise CD		Cruise CL	Cruise CD								Mfuel (kg)	DOC/ASK (p/ask)	XMFLU (kg)	DOC/ASK (p/ask)
Turbulent Baseline	733.16	8.36	34.04	36.77	0.109	0.249	0.01251	0.52325	0.02656	0.39722	0.02006	0.02006		1,345,929	278,350	0	33,299	0	533,911	215,809	1.234	72,209	1.373
HLFC Wing	724.57	8.78	34.16	36.71	0.115	0.259	0.01127	0.50975	0.02412	0.39411	0.01843	0.01843		1,257,120	251,160	263,720	31,221	3,143	513,705	197,582	1.199	66,668	1.346
HLFC Fin	726.04	8.41	33.85	36.57	0.109	0.251	0.01213	0.52131	0.02602	0.39770	0.01967	0.01967		1,317,104	270,371	274,225	32,643	712	526,684	210,038	1.220	70,333	1.360
HLFC Tailplane	723.74	8.31	33.61	36.44	0.106	0.239	0.01201	0.52090	0.02601	0.39746	0.01961	0.01961		1,314,086	269,368	274,214	32,588	789	524,586	208,996	1.215	69,890	1.355
HLFC Nacelles	723.36	8.36	33.88	36.62	0.109	0.249	0.01209	0.52050	0.02600	0.39704	0.01964	0.01964		1,308,965	269,148	273,459	32,471	• 383	523,945	209,000	1.213	69,951	1.352
HLFC WFTN	701.24	8.80	33.10	35.79	0.109	0.243	0.00995	0.50232	0.02242	0.39448	0.01714	0.01714		1,172,136	227,037	251,464	29,305	4,657	489,612	179,496	1.148	60,634	1.297

Fuel Price - Laminar

	Wing Area m ²	Aspect Ratio	1/4c Sweep (deg)	L.E. Sweep (deg)	Thick/Chord	Taper Ratio	Profile Drag	Design Mission			Average Mission			Thrust-Cruise Sea Level Static (N)	Thrust-Cruise (N)	Thrust-Turbulent Cruise (N)	Engine Mass (kg)	HLFC System Mass (kg)	Max. Take-Off Mass (kg)	Design Mission		Alternative Mission	
								Cruise CL	Cruise CD		Cruise CL	Cruise CD								Mfuel (kg)	DOC/ASK (p/ask)	XMFLU (kg)	DOC/ASK (p/ask)
0.05	719.32	8.2	33.82	36.58	0.11	0.254	0.01129	0.51529	0.02513	0.39561	0.01892	0.01892		1281808	259203	271072	31907	3018	515670	201940	0.903	67547	1.071
0.1																							
0.2	723.31	8.83	33.93	36.5	0.113	0.255	0.01126	0.51082	0.0241	0.39526	0.01843	0.01843		1255063	250545	263070	31162	3100	513877	197157	1.219	66554	1.365
0.3	735.42	9.04	34.53	37.08	0.121	0.241	0.01122	0.5021	0.02342	0.38936	0.01807	0.01807		1250981	247784	260719	31013	3288	513475	196058	1.429	66493	1.562
0.4	738.16	9.31	34.63	37.08	0.123	0.244	0.01121	0.5005	0.02307	0.38918	0.01789	0.01789		1243568	245210	258460	30806	3341	513692	194704	1.634	66246	1.756

Fuel Price - Turbulent

	Wing Area m ²	Aspect Ratio	1/4c Sweep (deg)	L.E. Sweep (deg)	Thick/Chord	Taper Ratio	Profile Drag	Design Mission			Average Mission			Thrust-Cruise Sea Level Static (N)	Thrust-Cruise (N)	Thrust-Turbulent Cruise (N)	Engine Mass (kg)	HLFC System Mass (kg)	Max. Take-Off Mass (kg)	Design Mission		Alternative Mission	
								Cruise CL	Cruise CD		Cruise CL	Cruise CD								Mfuel (kg)	DOC/ASK (p/ask)	XMFLU (kg)	DOC/ASK (p/ask)
0.05	741.85	7.94	33.94	36.87	0.102	0.241	0.01234	0.52069	0.02649	0.39505	0.02004	0.02004		1397242	280850	0	34336	0	537290	217582	0.916	72843	1.084
0.1	733.23	8.2	34.44	37.11	0.113	0.266	0.01254	0.52333	0.0268	0.39634	0.02017	0.02017		1351070	280768	0	33468	0	534109	217232	1.027	72531	1.183
0.2	733.12	8.37	33.92	36.68	0.108	0.245	0.01251	0.52338	0.02655	0.39741	0.02005	0.02005		1342251	278219	0	33227	0	534042	215736	1.257	72190	1.394
0.3	733.17	8.53	33.81	36.52	0.108	0.247	0.01251	0.5236	0.02635	0.39838	0.01997	0.01997		1340635	276321	0	33140	0	534236	214699	1.486	71991	1.605
0.4	737.81	8.74	33.99	36.67	0.11	0.238	0.01252	0.51987	0.02591	0.39644	0.01976	0.01976		1327991	273602	0	32824	0	533778	213422	1.711	71815	1.814

Super Jumbo (Continued)

Fuel Reserves

	Wing Area m ²	Aspect Ratio	1/4c Sweep (deg)	L.E. Sweep (deg)	Thick./ Chord	Taper Ratio	Profile Drag	Design Mission Cruise CL	Average Mission Cruise CL	Thrust Cruise Sea Level Static (N)	Thrust Cruise (N)	Thrust- Turbulent Cruise (N)	Engine Mass (kg)	HLFC System Mass (kg)	Max. Take-Off Mass (kg)	Design Mission Mfuel (kg)	DOC/ ASK (p/ask)	Alternative Mission XMFLU (kg)	DOC/ ASK (p/ask)
Frac. cruise without laminar flow	0	724.57	8.78	36.71	0.115	0.259	0.01127	0.50975	0.02412	0.39411	0.01843	251160	31221	3143	513705	197582	1.199	66668	1.346
	0.3333	741.55	8.67	34.53	0.118	0.246	0.01165	0.50915	0.02459	0.39131	0.01878	261664	32186	3276	525221	205990	1.22632	69338	1.37375
	0.6667	739.93	8.37	34.08	0.11	0.269	0.01206	0.52241	0.02605	0.3983	0.01964	275875	33578	3150	537839	214827	1.253	71965	1.398
	1																		

Maintenance Costs

	Wing Area m ²	Aspect Ratio	1/4c Sweep (deg)	L.E. Sweep (deg)	Thick./ Chord	Taper Ratio	Profile Drag	Design Mission Cruise CL	Average Mission Cruise CL	Thrust Cruise Sea Level Static (N)	Thrust Cruise (N)	Thrust- Turbulent Cruise (N)	Engine Mass (kg)	HLFC System Mass (kg)	Max. Take-Off Mass (kg)	Design Mission Mfuel (kg)	DOC/ ASK (p/ask)	Alternative Mission XMFLU (kg)	DOC/ ASK (p/ask)
LF Maint/ airframe maint (per kg)	0	720.95	8.72	33.71	0.111	0.255	0.01127	0.5129	0.02412	0.3964	0.01855	252189	31225	3046	514392	198016	1.19639	66709	1.34119
	2	721.15	8.69	33.59	0.109	0.247	0.01126	0.5129	0.02437	0.3963	0.01856	252459	31286	3026	514478	198137	1.20215	66730	1.35019
	4	720.04	8.67	33.82	0.111	0.264	0.01128	0.5136	0.02445	0.3966	0.0186	252839	31347	3057	514398	198357	1.20811	66774	1.36048
	6	719.23	8.64	33.64	0.11	0.259	0.01128	0.5145	0.02452	0.3972	0.01864	253302	31370	3022	514691	198574	1.21539	66807	1.37061
	8	721.34	8.69	33.7	0.11	0.251	0.01127	0.5126	0.02437	0.396	0.01856	252513	31257	3044	514368	198203	1.22135	66752	1.38099
	10	718.11	8.57	33.37	0.107	0.254	0.01128	0.5159	0.02468	0.3979	0.01872	254508	31391	2969	515339	199224	1.22881	66936	1.39091

HLFC System Production Costs

	Wing Area m ²	Aspect Ratio	1/4c Sweep (deg)	L.E. Sweep (deg)	Thick./ Chord	Taper Ratio	Profile Drag	Design Mission Cruise CL	Average Mission Cruise CL	Thrust Cruise Sea Level Static (N)	Thrust Cruise (N)	Thrust- Turbulent Cruise (N)	Engine Mass (kg)	HLFC System Mass (kg)	Max. Take-Off Mass (kg)	Design Mission Mfuel (kg)	DOC/ ASK (p/ask)	Alternative Mission XMFLU (kg)	DOC/ ASK (p/ask)
LF Cost/ system cost (per kg)	0	736.45	8.96	34.63	0.122	0.241	0.01122	0.5015	0.02348	0.38852	0.01809	248723	31079	3309	513606	196660	1.188	66644	1.336
	2	717.49	8.63	33.67	0.11	0.275	0.01129	0.5161	0.02464	0.3984	0.01871	260969	31371	3019	515130	198884	1.21389	66869	1.36113
	4	716.97	8.51	33.14	0.105	0.252	0.01127	0.5174	0.02483	0.3989	0.01879	255529	31494	2925	516023	199745	1.24149	67035	1.39152
	6	716.77	8.52	32.8	0.102	0.244	0.01126	0.5184	0.02498	0.3993	0.01886	256985	31582	2870	516972	200553	1.26857	67211	1.42152
	8	716.48	8.34	32.57	0.1	0.242	0.01126	0.5195	0.02513	0.3998	0.01892	258291	31682	2834	517826	201284	1.29514	67372	1.45105
	10	717.55	8.22	32.08	0.096	0.231	0.01124	0.5204	0.02531	0.4	0.019	271884	31866	2768	519543	202532	1.32145	67667	1.47988

Maximum Transition Reynolds Number

	Wing Area m ²	Aspect Ratio	1/4c Sweep (deg)	L.E. Sweep (deg)	Thick./ Chord	Taper Ratio	Profile Drag	Design Mission Cruise CL	Average Mission Cruise CL	Thrust Cruise Sea Level Static (N)	Thrust Cruise (N)	Thrust- Turbulent Cruise (N)	Engine Mass (kg)	HLFC System Mass (kg)	Max. Take-Off Mass (kg)	Design Mission Mfuel (kg)	DOC/ ASK (p/ask)	Alternative Mission XMFLU (kg)	DOC/ ASK (p/ask)
Max. Transition Reynolds No (million)	20	726.49	8.58	33.41	0.107	0.243	0.01149	0.51618	0.02489	0.39724	0.01889	259504	31906	3008	521688	203103	1.215	68272	1.361
	25	726.74	8.82	34.08	0.115	0.244	0.01125	0.50814	0.02397	0.39314	0.01835	250410	31196	3140	513590	197189	1.198	66603	1.346
	30	729.62	9.02	34.52	0.121	0.243	0.01101	0.50021	0.02315	0.38878	0.01785	243118	30593	3264	507472	192452	1.186	65262	1.335
	35	725.72	9.13	34.23	0.118	0.24	0.0108	0.49849	0.02267	0.38916	0.01756	237169	30091	3192	502926	188283	1.172	64011	1.322
	40	705.51	8.73	33.26	0.108	0.248	0.01073	0.50992	0.02364	0.39668	0.01802	244412	30253	2916	500239	188717	1.166	63591	1.312
	45	702.56	8.76	33.58	0.111	0.263	0.01063	0.50846	0.02344	0.39612	0.01789	237127	29948	2958	496711	186625	1.159	62920	1.304