

# DEVELOPMENT OF ENVIRONMENTALLY-FRIENDLY TECHNOLOGIES AND CONFIGURATIONS FOR SUBSONIC JET TRANSPORTS

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## Abstract

*This paper will initially describe two very large conventional-configuration aircraft group design projects designed by Cranfield University. It will show their strengths and weaknesses for conventional technology and versions incorporating laminar-flow and other advanced technologies.*

*Discussion will follow concerning environmental issues posed by such very large aircraft together with results of studies on specific fuel and mass-saving technologies and their impact on the environment.*

*A description will then be given of progress on the comprehensive blended-wing-body airliner programme being performed by Cranfield University, with support from BAE SYSTEMS and Rolls-Royce plc.*

*Examples will be given of Cranfield's pattern of proving concepts by means of flying demonstrator aircraft and how this will be applied to the BWB programme. This design programme has already isolated many of the aircraft design and operational challenges posed by such a configuration, some of which have already been met. More solutions will follow as a result of the effort and initiative being produced by the four year 80,000 engineer – hour programme.*

*Initial numerical results will be shown for the environmental impact of the above range of technologies and configurations.*

## 1 Introduction

The world has accepted that flying is an extremely efficient means of quickly transporting people, cargo or equipment, and performing a wide range of other activities. All

operators need to increase safety, efficiency, costs, effectiveness and environmental compatibility. It has been realized that the latter point is becoming increasingly important and this was recognized by the important IPCC report [1]. This report states:-

“Aircraft emit gases and particles directly into the upper atmosphere and lower stratosphere where they have an impact on atmospheric composition. These gases and particles alter the concentration of atmospheric greenhouse gases, trigger formation of condensation trails (contrails) and may increase cirrus cloudiness – all of which contribute to climate change.”

There is some uncertainty about the cumulative effect of aircraft pollution, but it seems that it currently contributes more than 2% of global carbon dioxide and 3.5% of all human-produced global warming effects. This is continuing to grow, at a smaller rate than the growth in air transport, but it conflicts with pressure to reduce aircraft-based pollution.

The pressure must be balanced with those of aircraft safety and economics, to produce an optimum aircraft. This paper will describe some of the efforts being made by Cranfield University, in terms of developing advanced technologies and configurations, supported by a technology demonstrator programme.

## 2 Fuel and Operating Cost Studies of Laminar Flow and Variable-Camber Flaps on Conventional Aircraft

Wilson and Jones [2] performed a number of studies to examine the effects of hybrid laminar flow control (HLFC) devices fitted to various

sizes and ranges of transport aircraft. The work predicted potential aerodynamic benefits from retro-fitted or re-sized aircraft. Allowance was made for increases in mass and power off-take penalties and associated maintenance costs.

Fielding and Vaziry-Zanjany [3] performed parallel studies to predict the effects of the use of variable-camber wing flaps (fig. 1).

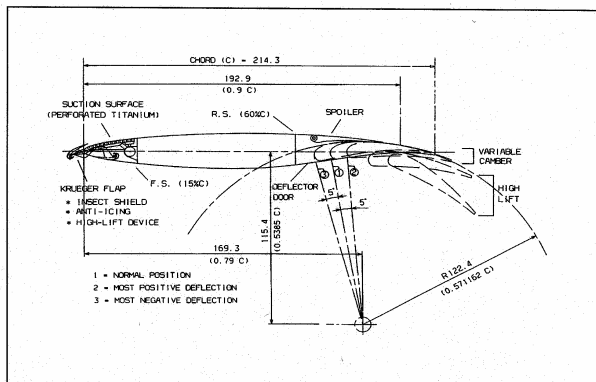


Fig. 1

The fuel-burn and D.O.C. effects of both technologies are summarized in table 1. The HLFC technology assumed wing and tail upper surface trailing edges and engine intakes, with fuel and mass effects leading to re-sized aircraft by use of multi-variable optimization techniques.

It can be seen that both technologies give modest fuel burn improvements at short and medium ranges (2 to 10%), but only modest DOC improvements (or penalties!). Long-range aircraft give more significant fuel and cost advantages, but the former is still well below the IPCC objectives. The results are approximate and could be affected by significant changes to fuel and maintenance costs from current values. Green et al [4] discusses such effects, and makes a strong case for the development of large short range aircraft. Such aircraft burn significantly less fuel per passenger mile over short routes, as they do not have to carry the extra weight of fuel for later sections of long flights. Such aircraft can thus have smaller wings with commensurate weight, cost and pollution savings. Such aircraft however pose other problems, in terms of airport congestion, passenger acceptance and local airport noise

pollution. Such an aircraft is shown in the next section of this paper, alongside a more conventional longer range derivative.

### 3 Group Design Project Studies of Large Conventional Configuration Transports

#### 3.1 Design Project Methodology

Many Universities use group projects as powerful means of pulling together aeronautical teaching programmes in realistic applications of design integration. Cranfield's design course is unique in the magnitude of the student, staff and equipment resources used in the projects.

Some 25-30 graduate students per year are allocated responsibility for preliminary/detail designs of major parts of the aircraft such as the forward fuselage, a flying control surface or a mechanical system such as fuel, environmental control, propulsion, landing gear or the control system. This allows much more realistic estimates to be made of mass and performance and show if the construction methods are feasible.

#### 3.2 The A-90 Short-Range 500 Seat Airliner

The A-90 project was performed to investigate one of the possible means of alleviating the chronic and worsening congestion at many of the world's airports, by producing a larger aircraft. The aim would be carry many more passengers on high density routes in Europe, North America and the Pacific Rim.

A full report of the project is contained in [4], the main features of which are reported here.

##### 3.2.1 Aircraft Requirements

It was decided to take the radical approach of aiming for a 500 seat aircraft. This could replace DC10-10 and A300 aircraft over most of their operations and meet growth generated by such aircraft as the 757, 767 and A321.

The strong predicted growth in cargo led to the requirement for carriage of standard containers above and below the main deck in cargo or COMBI versions of the aircraft and be compatible with military cargo operations, providing that this would not detract from civil operations.

The major features of the specification were:

- (a) Passenger and bag range of 2000 N.miles with FAR reserves with max. cruise speed greater than 340 knots. Range of 3,500 n.m with reduced payload
- (b) All-up mass take off in 8300ft, landing 5660 ft, ISA, sea level.
- (c) Runway loading less than that of the A330.

### 3.2.2 A-90 Configuration

The cross-sections of current aircraft were examined and it was decided to use a double-bubble fuselage, with a lower-lobe of similar width to the Boeing 747, with an upper lobe of similar width to the Airbus A320. Figure 2 shows a side-view of the final fuselage configuration. All-economy seating has a capacity of 620 passengers. The main deck can accommodate two rows of 8ft x 8ft x 20ft containers in a cargo version.

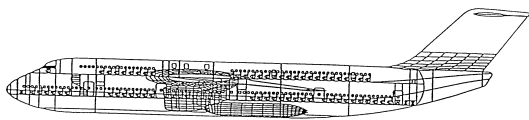


Fig.2

The controversial shoulder-wing arrangement has many advantages, not least being good ground clearance for the large Trent wing-mounted engines. This layout led to some difficulties in the rare event of aircraft landing in water.

### 3.2.3 Predicted Performance

The detail designs produced by the students allowed a more accurate prediction of aircraft mass than given by the original empirical methods. These showed that the Manufacturer's empty mass would be some 5 tones lighter than the target of 114T, but so many novel features could easily erode this margin.

Other performance calculations showed that the aircraft should meet or exceed its performance and operating - cost objectives, with the exception of minor field-length non-compliance, that could be achieved with small modifications.

## 3.3 The A-94 Long Range 600 Seat Airliner

### 3.3.1 Description

In common with industrial practice, it was decided to extend the A-90 family using as much as possible of the earlier design. The fuselage was stretched to accommodate 754 passengers in a high density layout and range extended to compete with that of the Boeing 747-400. Mixed-class capacity was 600 passengers. This is some 50 passengers more than the initial model of the Airbus A-380.

The wing position reverted to the more conventional low-wing configuration, from the shoulder-wing-A-90 and the aircraft became the A-94. Further details are shown in Ref. 6.

### 3.3.2 Performance, Cost And Lessons Learnt

Most performance targets were met or exceeded, except for rather disappointing cost predications. Acquisition costs were typically \$200m per aircraft (1995 values), depending on build numbers and technology risk factors. Direct operating costs per seat mile were at best, some 12% lower than the Boeing 747-400.

Emergency evacuation of passengers from such a high-capacity aircraft posed considerable problems, (Fig.3). An interesting lesson learnt was the cargo volume limitations posed by this type of aircraft. A consequence of double-deck aircraft is the reduction in the cargo baggage container capacity relative to the number of passengers carried.



Fig.3

This is because although the fuselage lengths are little longer than the 747, there is only the space below the main deck for baggage storage for 50% extra passengers. This is compounded by the fact that the new aircraft have bigger wings and landing gear, which further erode under-main-deck space.

Table 2 shows the number of under-deck LD3 containers that may be carried by some wide-body aircraft.

It can thus be seen that most of the container space is likely to be used for passenger baggage, thus reducing the amount of space available for cargo.

#### 4 Large Aircraft Environmental Issues

Such very large aircraft may be more environmentally damaging than current large airliners, but strenuous efforts are being made to mitigate such effects

##### 4.1 Noise

Industry claims that through advanced technology particularly on engines their target is that the A94/A380 class of aircraft will be quieter than the 747-400, even with 30-50% more passengers.

#### 4.2 Emissions

The A380 should have emissions at the bottom end of the 747 spectrum for emissions of nitrous oxides during the Landing-Take-off cycle. gaseous emissions are not currently regulated in the higher atmosphere but the A94/A380 Class of aircraft will minimise the fuel burn per passenger by some 20%, with consequent reduction in emissions. There is still however, a significant potential problem in that the projected increase in air travel will deposit considerable amounts of nitrous oxides and other pollutants in the region of the tropopause. This is the case even with the improved fuel consumption efficiencies already mentioned. Another significant atmospheric phenomenon is the creation of water vapour in the troposphere caused by the engine combustion process, amplified by atmospheric conditions. Aircraft trail artificial clouds behind them thus artificially increasing cloud cover and probably increasing the “greenhouse effect”.

The previously mentioned “Greener by Design” report [4] discusses a comparative study of a wide range of technologies, designed to reduce greenhouse effects. The majority of the work concerned kerosene-fuelled aircraft, but also made initial comparisons with those using liquid hydrogen fuel. The various categories were:-

- i) Swept Wing, Long Range (SWLR). This covered conventional configuration long-range aircraft such as the Boeing 777, Airbus A340 and A380 and the Cranfield A-94.
- ii) Swept Wing, Medium Range (SWMR). This covers project aircraft such as the Cranfield A-90. There are no current aircraft in this category, but the short-range version of the Boeing 747, comes closest to this.
- iii) Blended Wing Body (BWB). There have been a number of project studies, such as that described later in this paper.
- iv) Laminar Flying Wing (LFW). This is perhaps, the ultimate lowest-fuel aircraft under current consideration. It has no



fuselage and uses extensive hybrid laminar flow control. Fig. 4 shows an early Handley-Page design.

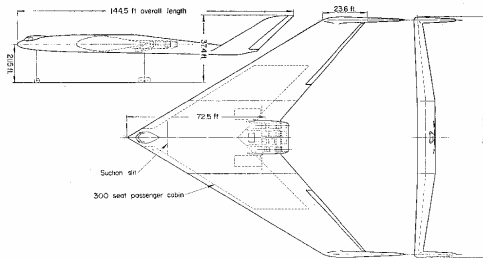


Fig. 4

- v) Laminar Flying Wing with Unducted Fans (LFW/UDF). This is as iv), above, but using fuel-efficient unducted fans, rather than conventional turbo fans.

Fig. 5 show a comparison of the relative Greenhouse-effect predictions for the above aircraft categories, plus their liquid-hydrogen-fuelled alternatives SWLR(h) etc.

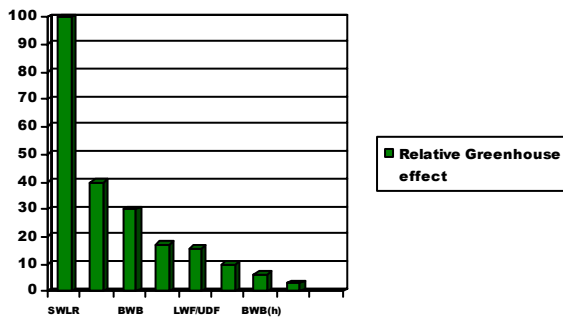


Fig. 5

It can be seen that the more radical configurations may offer very significant reductions in Greenhouse effect, but will be at considerable technical risk. The blended-wing body is mid-way in the risk spectrum, and will be discussed further.

### 4.3 Wake Vortex

All aircraft produce turbulent vortices, primarily from their wing tips. This phenomenon increases with aircraft mass and reaches such

proportions as to be a flight hazard to smaller aircraft, particularly close to the ground. Airport separation distances are increased to overcome this effect, but this reduces runway utilisation, with consequent negative economic effects. Current research is being performed to produce wing-tip devices which may reduce vortex strengths and aircraft drag.

### 4.4 Airport Issues

Conventional wisdom limits the ground “box” size of aircraft to 80m span x 80m, length. This will minimise changes to airport ground handling in terms of runway, taxi ways and gates. However the large increase in passengers will have significant effects on passenger terminals, customs, immigration and, more significantly local airport surface transport infrastructure.

## 5 The Blended-Wing-Body Concept

### 5.1 Potential Advantages of BWB

#### Aerodynamics

- Low wetted area to volume ratio
- form conducive to low interference drag

#### Structures

- Efficient deep sections
- Favourable span loading

#### Human Factors

- Huge volumetric capacity
- Flexible cabin layout potential

#### Systems

- Potential for highly integrated airframe/engine
- Ideal configuration for application of laminar flow technology
- Significant advantages from control configuring the vehicle

#### Economics

- Particularly suitable for high capacity applications
- Significant D.O.C. reduction should be achievable

## 5.2 Blended Wing Body Challenges

The novel nature of the BWB concept inevitably leads to technical challenges, of which the following items are the most important:

### Systems

- design of fully integrated and novel propulsion systems
- Design and integration of possible laminar - flow systems
- Control allocation

### Operations

- Span/wheel track limits
- airport passenger handling

### Manufacture

- Manufacture and assembly of very large components, probably of composite materials

### Aerodynamics

- drag of thick aerofoils and the achievement of laminar flow

### Structures

- Unconventional layout
- non-circular cabin
- aeroelasticity
- major cut-outs for exits

### Human Factors

- Embarkation time
- passenger comfort/appeal
- no windows
- emergency evacuation
- pilot workload

### Airworthiness Requirements

- Safety
- Evacuation
- Stability augmentation

### Conceptual Design

- Tools
- Methods

## 5.3 Cranfield College Of Aeronautics BWB Programme [7]

For those involved in the aircraft design business the design of an aircraft is usually a relatively straightforward process. The tools and procedures are readily available and proficient engineers are always at hand to offer the benefit

of their years of experience. However, where a novel configuration or concept is being considered none of these advantages can be taken for granted. In the case of the BWB concept, whilst a few historical precedents have existed, it is necessary to start from first principles. Thus prior to the initiation of the design process, the infrastructure of tools and procedures must be set in place.

A programme of activities (Fig. 6) is now in place to meet this requirement. The primary objective of this programme is to develop the tools, knowledge and understanding required to fully evaluate the BWB configuration and, in particular, its application to high capacity civil transports. The programme has had some technical input from BAE SYSTEMS and Rolls-Royce, and involved the expenditure of more than 80,000 engineer-hours.

### Schedule

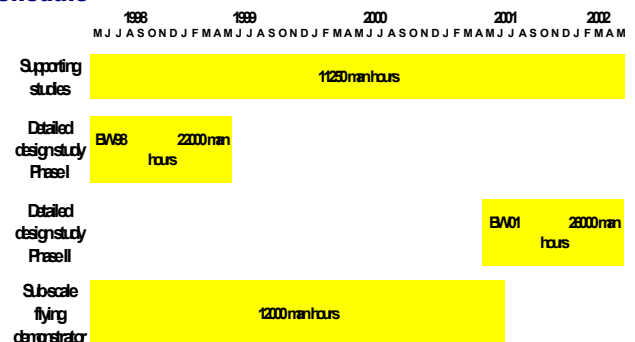


Fig.6

This gives rise to the following programme objectives:-

“To complete a detailed design study of a fully optimised BWB configuration with integrated propulsion system, incorporating all appropriate technologies (e.g. laminar flow) within a rigorous framework of constraints to ensure that it can be successfully and profitably manufactured and operated and to the benefit of passenger appeal and safety. This will provide a considerable degree of confidence that all major design problems have been identified and addressed.”

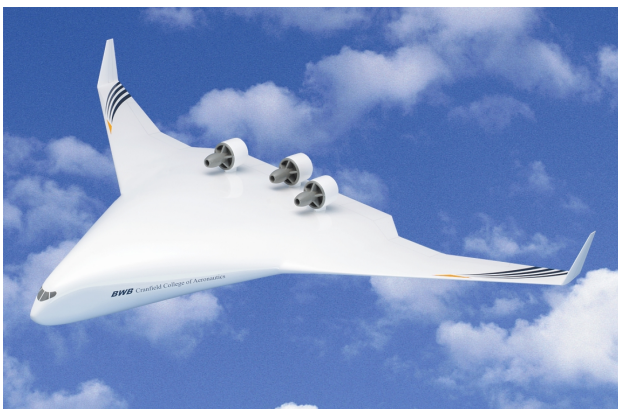
To achieve this an incremental approach is being utilised including:

- The creation and continued development of design tools
- Development of appropriate design methodologies
- An incremental programme of detailed design studies
- The design and manufacture of a sub-scale flying demonstrator
- Detailed studies within a number of identified Key Technology Areas feeding back into the tools and methodologies above

*5.3.1 Detailed Design Study – Phase 1 – The BW-98*

This design study was based on the specification of what was then known as the AIRBUS A-3XX-200 high capacity civil airliner (later becoming the A380). The design addressed airport operational constraints and assumed a technology level consistent with A-380. The study proceeded to a level of detail sufficient to resolve potential structural and system problems and explore their solution. This level of detail was required, since many of the challenges, both engineering and human factors, are not apparent at the conceptual design stage.

The BWB configuration poses many challenges not least being the passenger accommodation. Fig. 7 shows the overall configuration of the aircraft.



The passengers sit in a non-circular pressure cabin, without windows.

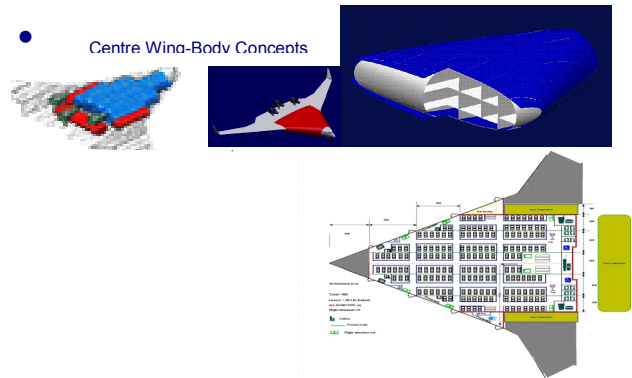


Fig. 8

Fig. 8 shows schemes for the plan view of alternative passenger decks. It also shows a scheme for a double-skinned pressure vessel, and an alternative sandwich construction. The latter gives considerable freedom of movement for passengers, and layout flexibility. The flight-control system has to provide power and control to the large number of trailing-edge devices. The area aft of the pressure cabin is used to attach the main landing gear, some baggage and powerplants. The wings are more conventional in construction. Fig. 9 shows an early finite-element structural model.

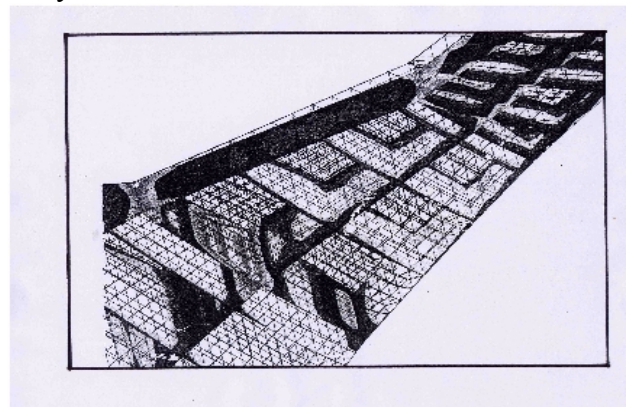


Fig.9

The 80 metre span limitation meant that such a large aircraft had to accept a sub-optimum wing aspect ratio, but the resulting aircraft was still able to offer a D.O.C. per seat mile saving of some 19% relative to the Boeing 747 and a fuel-burn per passenger mile of some 18% relative to the A-380 class of aircraft.

The study showed considerable potential, and formed the basis for a number of subsequent European and National projects. It showed that a smaller, single-deck aircraft of some 250 seats would be extremely attractive.



This concept is currently being studied at Cranfield, as the BW-01 project.

### 5.3.2 BWB Supporting Studies

Concurrent with the full sub-scale design work, a variety of studies are exploring some of the most challenging issues facing the design of BWB aircraft. Many of these have already been identified, such as the design of a non-circular pressure cabin and emergency evacuation, many more will only come to light as the preliminary design studies proceed. The full capability of the College of Aeronautics is being drawn up, including human factors, flow control, flight simulation, structures and materials as well as its expertise in the operational aspects of air transport. The college is also investigating alternative propulsion systems. The result of these studies are being fed into the advanced technology preliminary design study (BW-01, below). Some of these activities focus upon detailed aspects of the design and others are concerned with wider issues such as the application of the BWB concept to roles other than the civil transport. The intrinsically stealthy nature of the configuration lends itself to military roles such as the military transport or an air-refuelling tanker, which could achieve significantly increased range or payload performance. Combat aircraft, both manned and uninhabited, stand to benefit from the configuration's layout, structural and aerodynamic advantages.

### 5.3.3 Sub -Scale Flying Demonstration

There is a high degree of uncertainty associated with many aspects of the vehicle's aerodynamics, stability and control. As a highly cost-effective method of risk reduction in these areas the programme incorporates the design and manufacture of a flying test-bed to evaluate and explore the aerodynamic characteristics of the configuration. The vehicle will be capable of flying a programme of specified maneuvers whilst simultaneously transmitting telemetry data to the ground for analysis. On the basis of these results, configurational modifications can be re-evaluated on subsequent test flights. The College of Aeronautics has considerable

expertise in the area of unmanned aerial vehicle (UAV) and is certainly the UK's foremost centre of excellence. The latest vehicle is the Cranfield A-3 (Figure 10), which is produced for the British Government. It is a small man-portable research vehicle with a broad delta planform with wing tip fins and rudders. It successfully completed its first flight on Thursday the 11<sup>th</sup> March 1999.



Fig. 10

The College's design and production facilities are not limited to U.A.V's This capability has been utilized by BAE SYSTEMS to help train their engineers to be able to execute an aircraft design projects starting from a clean sheet of paper through to the vehicles flight-testing. Engineers participating in the Aircraft Engineering Masters course are given the opportunity to contribute to a design-build-fly project. Previous projects have included substantial modifications to the College's A-1 aerobatic aircraft the production of an advanced planform UAV, the Eclipse (Figure 11). All of these capabilities are vital to the success of the BWB sub-scale flying test-bed and are being utilized to the fullest extent.



Fig. 11



The demonstrator has been named the Kestral and has been subjected to half-scale wind-tunnel tests. The flying vehicle is almost physically complete and has a wing span of some 4 metres, a mass of 90 kg, and is powered by a pair of AMT Olympus jet engines. First flight is expected within the next few months..

#### 5.3.4 Detailed Design Study – Phase 11 – The BW-01(Fig. 12)

The advanced technology concept preliminary design study is building on the baseline study by incorporating a number of synergistic technologies that enable the full potential of the BWB concept to be realized. Technologies likely being incorporated include Hybrid Laminar Flow Control (HLFC), a Stability Augmentation System (SAS) and an advanced propulsion system.

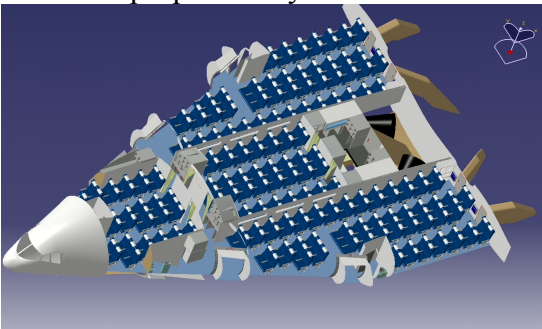


Fig.12

Lessons learnt from the BW-98 suggested that a 250-jet aircraft would be particularly beneficial. The external configuration is a scaled-down version of the earlier aircraft, but the cruise range has been extended to some 8 - 9,000M, miles, to make a comparison with the performance of the Boeing Sonic Cruiser. The BW01 retains a cruise Mach number of 0.85. The effects of increased aspect ratio will be examined on future projects.

## 6. Conclusions

- The history of aviation has demonstrated a constant search for increased efficiency in terms of cost, safety and comfort. Subsonic aircraft have reached a cruise-speed plateau and so improvements have been achieved by increased size, and more efficient propulsion, aerodynamics, structures and systems.
- Air Transport requires the acquisition of significantly increasing amounts of passenger capacity. This will aggravate already crowded airport and air-lane capacity. Such increases in activity will add to concerns about noise and atmospheric pollution.
- Increased aircraft size is attractive in terms of reducing flight movements for a given number of passengers. Increases in size and technology as in the Cranfield A90 & A94 projects can also offer improvements in passenger economics and lead to reduced fuel burn per passenger-mile, and consequent reduction in pollution. Incremental improvements in airframe and engine efficiencies will add to these benefits. It is, however, debatable if these improvements will compensate for the projected increase in air traffic.
- Hybrid laminar flow control and variable camber wings appear to offer useful reductions in fuel burn and operating costs for long-range flights, but offer little benefit, and can cause cost penalties on short or medium-range flights.
- More significant reductions in operating cost and pollution require a step-change in aeronautical technology, such as that offered by the blended-wing-body concept. Significant work has been performed by the US Government-funded NASA/Boeing/Stanford University work.
- Cranfield University together with BAE SYSTEMS and Rolls-Royce has made significant progress in the exciting UK National BWB project, without benefit of direct Government funding.
- The current work has, as planned, isolated many of the challenges of such concepts, as well as offering some

olutions. This progress will continue in the remainder of the current 4 year programme and will utilize Cranfield University’s whole-aircraft design, manufacture and operational capability.

- The sub-scale BWB flying demonstrator will build on the expertise already demonstrated on the A1 Eagle, the A3 and Eclipse unmanned vehicles and will provide valuable data for future aircraft.
- It is hoped, that such work will lead to significant improvements in the reduction of the greenhouse effect, consistent with cost effectiveness.
- The BWB and other radical technologies and configurations are inherently risky and considerable future research is required.
- Cranfield University will, by means of recent challenging design projects, continue to provide experienced, innovative graduates. They will rise to the highest level of the Aeronautical Business, as has happened since 1946.

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TABLE 1 – Fuel and D.O.C.

Predicted changes due to hybrid laminar flow and variable-camber technologies

AIRCRAFT RANGE	HLFC FUEL CHANGE %	VCW FUEL CHANGE %	HLFC D.O.C. CHANGE %	VCW D.O.C. CHANGE %
Short	-8	-2	-2.5	+1
Medium	-10	-4	-3.5	0
Long	-15	-7	-8.2	-2

Where:- HLFC = Hybrid Laminar Flow Control  
 VCW = Variable Camber Wing  
 D.O.C. = Direct Operating Cost

TABLE 2: Comparison of underfloor storage of standard LD3 containers

AIRCRAFT TYPE	NO OF LD3s	NO OF PASSENGERS/CONTAINER (MIXED CLASS)
Airbus A340-300	32	9.2
Boeing 747-400	30	14
Cranfield A-94	26	23