CONVENTIONAL AND UNCONVENTIONAL CONFIGURATIONS FOR ULTRA-HIGH CAPACITY AIRCRAFT

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Summary

Three conceptual designs are discussed for an Ultra-High Capacity Aircraft capable of carrying 1000 passengers and of ranges up to 10000km. One design is a conventional configuration, one is a long-coupled canard and one is a three-surface arrangement. Factors which are considered, besides wing layout, are fuselage geometry, undercarriage arrangement, propulsion, weights and performance. These are compared for the three designs. A comparative assessment is made of direct operating costs relative to the Boeing 747-400. Some areas of concern for all UHCAs are briefly discussed.

Notation

A	Aspect ratio
b	Wing span
c	Local chord
$\bar{c}$	Mean chord
C_D	Drag coefficient
C_i,C_5, C_6	Constants in relative DOC calculation (see Equation 3)
C_L	Lift coefficient
DOC	Direct operating cost
FAR	Federal Aviation Regulations
h	Height
ICAO	International Civil Aviation Organisation
JAR	Joint Airworthiness Requirements
K	Range parameter
l	Length
L/D	Lift to drag ratio
M	Mach number
MLW	Maximum landing weight
MPL	Maximum payload
MTOW	Max. take-off weight
NPax	Number of passengers
OEW	Operating empty weight
R	Range
S	Gross wing area
T	Thrust
W	Weight
y	Spanwise co-ordinate

Subscripts

cr	Cruise
f	Fuselage
ref	Reference
to	Take-off
747	Data for Boeing 747-400

Introduction

Ultra-high capacity aircraft (UHCA) are currently receiving wide-spread industrial interest[1] due to the increasing problems of air traffic control overloading and forecasts of traffic growth. For instance, Bayer[2] suggests a 5-6% annual increase in revenue passenger miles continuing into the next century. This would give a 250% increase in air traffic by the year 2010. The major international airports cannot handle what might amount to 1000 more aircraft movements per day. At the same time larger aircraft are seen to be more productive even on short-haul routes, as Japanese operators have found from their use of wide-body aircraft between Tokyo and Sapporo - the busiest city pair in the world for air traffic[3]. British Airways are actively looking at UHCA because of the traffic growth and capacity limitations mentioned above and because of competitive pressures[4].

Against this background teams of aircraft designers at RMCS Shrivenham and ETSIA Madrid agreed to collaborate on conceptual design studies of possible UHCA. At Shrivenham two teams of third-year undergraduate engineering students each worked on a different design, whilst at ETSIA one fifth-year student produced a design to a similar outline specification. Thus, three conceptual designs have been produced: a conventional layout; a long-coupled canard configuration; a three-lifting-surface layout with an horizontal-oval fuselage. Subsequent studies have involved detailed investigations of certain key areas of these designs.

"Pegasus" - conventional configuration

Design considerations

The "Pegasus" design is a conventional low-wing monoplane configuration with a circular-section fuselage, four engines mounted under the wings and an aft tail (see Fig 1). The initial outline specification called for a 10000km (5400nm) range with 1000 single-class seats or 600-700 seats in a three-class arrangement. Discussions with British Airways led to the requirement for improved passenger comfort and service, a point echoed by Acton[4]. The aircraft was required to operate from existing major-hub airport runways and had to offer significant reductions in operating costs.

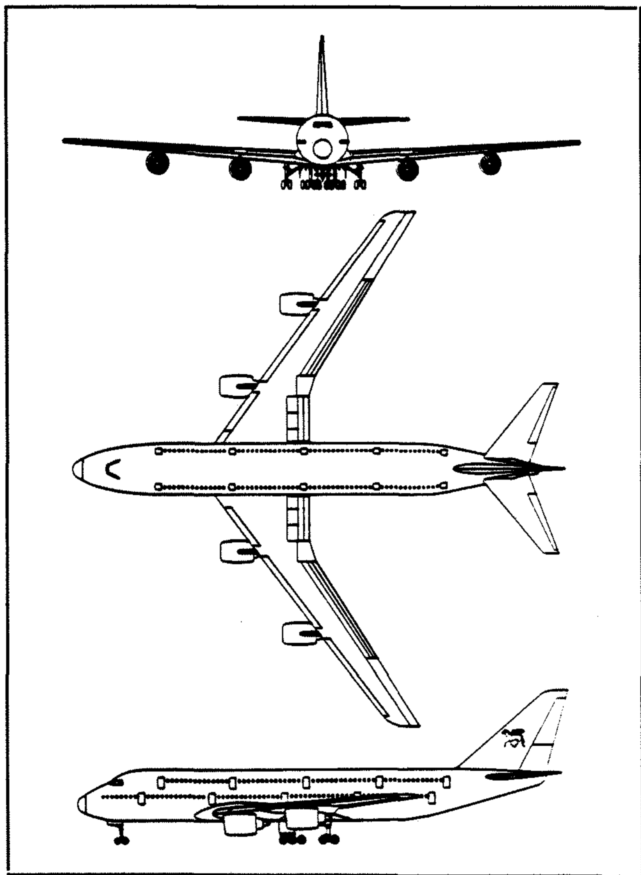

Figure 1 General arrangement of Pegasus

One of the limitations which had to be relaxed in the final design was that on wing span. To retain an efficiently high aspect ratio a wing span of 85m (279ft) was adopted. This exceeds the current span limit of 65m (ICAO Code E) but, as argued by Whitford[5], it was felt that this limit would be relaxed to accommodate such UHCA - as happened when the Boeing 747 first entered service. Indeed, European airports are apparently[6] currently considering extending this limit to 90m. Other data for "Pegasus" are given in Table 1; many of the design considerations have been discussed previously by Whitford[5,7].

The wing chosen for this design uses NASA Series 3 aerofoil sections, with 14.5 percent thickness at the root, tapering linearly to 12 percent at the inboard engine position and thence to 10 percent at the tip. As shown in Table 1, a relatively high aspect ratio (9.4) was chosen, in an attempt to minimise drag.

Fuselage and undercarriage

The evolution of the fuselage design and details of the cabin layout have been discussed by Whitford[5]. A circular cross-section was chosen (see Fig 2) to simplify design, manufacturing and future "stretching" and to reduce structural weight. Other cross-sections were considered, including double bubbles, but an acceptable volume utilisation was achieved with a two-deck layout within the circular section by lowering the upper deck slightly[5]. Oelkers[6] has discussed UHCA design trade-offs at DASA which produced a moderate triple-bubble design for the 700-800 passenger category. In outline this cross-section is very close to our circular section but achieves a minimum wetted area per passenger.

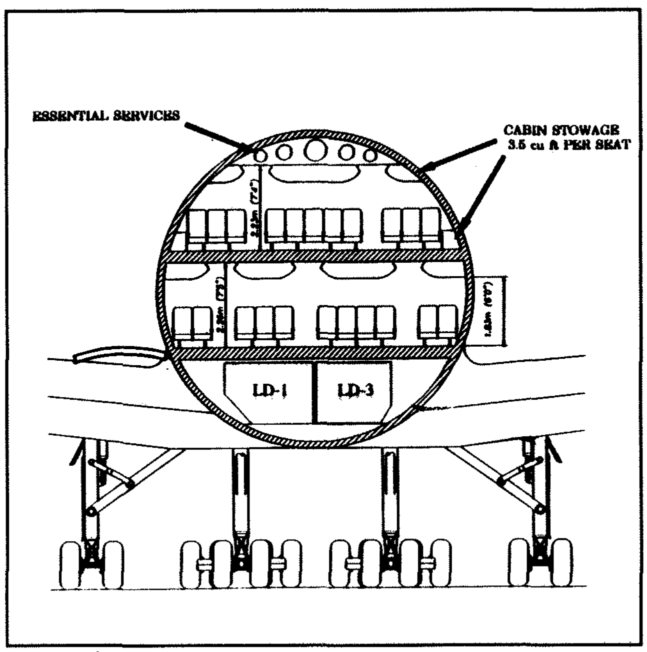

Figure 2 Fuselage cross-section - Pegasus

Fig 2 shows the seating arrangement for the 1000 seat version of "Pegasus". With the more usual three-class cabin seating capacity is 660 (22 at 60in, 92 at 40in and 545 at 34in pitch). As mentioned above, cabin comfort was a primary consideration in designing the layout. This seems to have imposed penalties, as discussed by Whitford[7] who compared this design with a similar NASA study. The 3-class layout has a 19-abreast seating arrangement in the economy cabin (9+10). According to Jagger[8] this could give A320 comfort levels in a fuselage which is only 70m long - 1m more than a 747-400. This again emphasises the penalty paid in this design for cabin comfort.

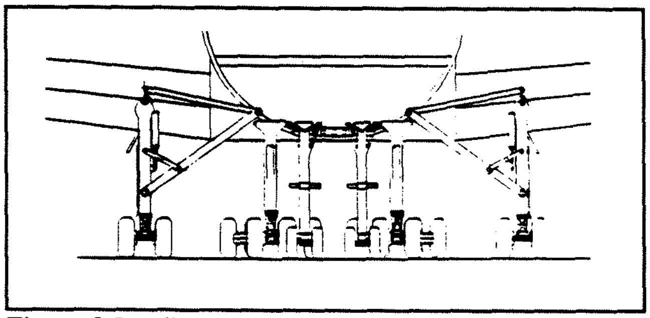

Figure 3 Landing gear arrangement - Pegasus

The landing gear arrangement chosen for "Pegasus" is shown in Fig 3. There are 32 wheels in total: two wing-mounted and two body-mounted 6-wheel bogeys and two four-wheel nose legs. Limited steering capability was included in the main gear to minimise tyre scrubbing. Particularly long undercarriage struts were required because of the large-diameter engines and this in turn lead to the need to shorten the oleo struts on retraction to minimise stowage volume.

Engines

A development of the Rolls-Royce Trent was adopted for this design. Rolls-Royce performed design calculations for an engine to meet our requirements of 388kN (87200lb) SLS take-off thrust. The resulting design has a fan diameter of 2.72m. Engine installation considerations have been discussed by Whitford[7]. Other possible engines were the General Electric GE90 and the Pratt and Whitney PW4078.

Weights and performance

As shown in Table 1, "Pegasus" has a maximum take-off weight of 544 tonnes (1.2 x 10^6lb). By comparison, the Boeing 747-400 has a MTOW of 395T and the Antonov An-225, six-engined heavy transport, has a MTOW of 600T.

Drag estimations using various techniques led to a cruise drag equation of:

$$C_{D_{cr}} = 0.0172 + 0.0398 C_L^2 \qquad (1)$$

Comparison with Eqn 3 reveals the benefit of the high aspect ratio wing used here and the lower wetted area of the traditional design over the three-surface, lifting body. The estimated cruise L/D is 19.2 for the "Pegasus" design.

The payload/range performance of this design is compared with that of the long-coupled canard and the three-surface design in Fig 7. The Boeing 747-400 is also included as a reference point. It can be seen that "Pegasus" not only offers more than twice the payload capacity of the 747-400 but can also match its long-range performance.

"Millennium" - long-coupled canard

Design considerations

The original outline specification for this aircraft was the same as for the "Pegasus" design discussed above. Similar fuselage and engine arrangements were adopted and the main difference with "Millennium" is the long-coupled canard layout (Fig 4). As with "Pegasus", cabin comfort was a primary consideration and both designs include business centres in the three-class configuration. In the case of "Millennium", this arrangement gave 39 first class seats at 62in pitch, 116 business class at 40in pitch and 500 economy seats at 34in pitch.

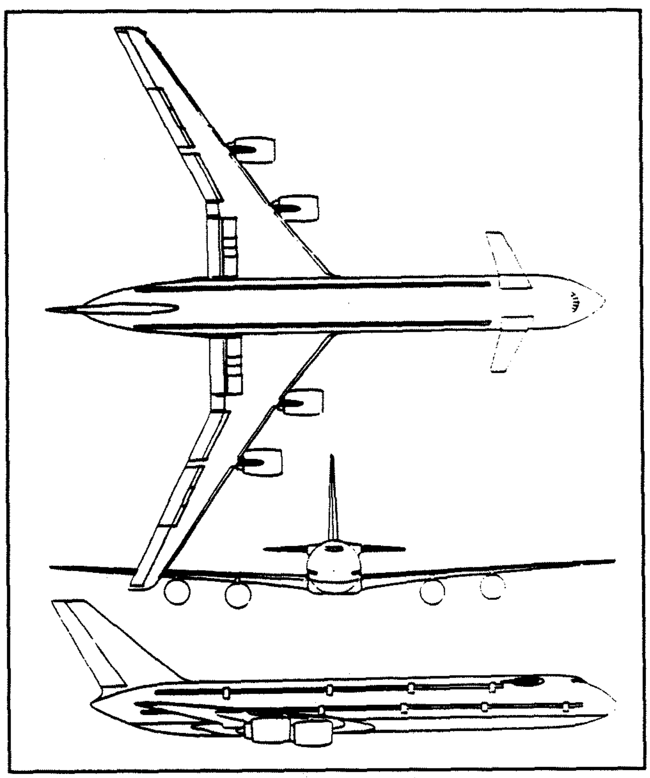

Figure 4 General arrangement of Millennium

Emergency evacuation was an important consideration in all three designs and is discussed later under "Urano", where it is perhaps most critical. The main problem with the double deck designs was the height of the upper deck above the ground. Covered escape chutes were felt to provide a psychologically-acceptable solution.

Weights and performance

As Fig 7 reveals, the "Millennium" design offers the best payload/range performance of the three configurations presented here. It is, however, the heaviest of the three designs, as seen in Table 1. The benefit of the configuration seems to come in allowing a slightly smaller overall wing span together with a higher mainplane aspect ratio.

"Urano" - three-lifting-surface configuration

Design considerations

The main design criteria for the Spanish team were: to accommodate 1000 passengers in an all tourist (not high density) configuration; ability to use existing airport runways and terminals with the corresponding limitations; and a trans-atlantic range. Thus, the initial specifications for the aeroplane under study included a range of 5500km (3000nm) at maximum payload corresponding to 1000 passengers plus baggage and freight, take-off field length around 3500m and airworthiness requirements at FAR-JAR 25 level[9]. The task was initiated without discarding any layout either from those published in the literature[10,11] or from others conceived by the team members. However, for various reasons the most unconventional ones such as multibodies, diamond wings, etc had eventually to be put aside. Considering all appropriate factors, and resolving most compromises, the selected layout was the three-lifting-surface arrangement (Fig 5). These compromises are discussed further below.

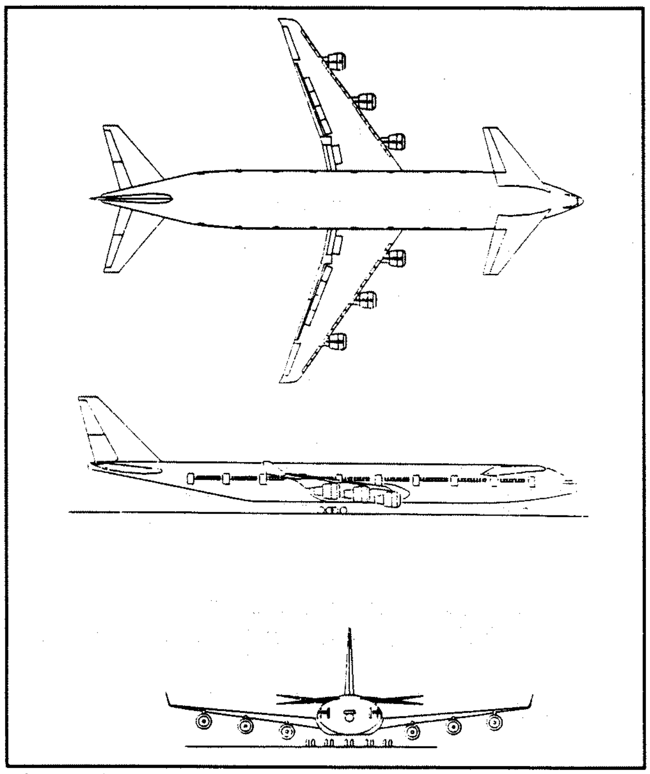

Figure 5 General arrangement of Urano

Quite different problems arise from the fuselage on one side and the wing, weights and performance on the other side. The design task was, therefore, split into two main areas: fuselage and related items (cabin arrangement, loading and unloading, evacuation, landing gear, etc); and layout and performance (main aeroplane weights, structural weights, aeroplane layout, drag, payload-range diagram, etc). Accordingly development in these two areas was carried out simultaneously with suitable information exchange.

The design incorporates six engines in an attempt to avoid using very large, partly unknown turbofans, and to reduce the difficulties associated with retracting and locating the main landing gear, as was the case with "Pegasus" and "Millennium".

Fuselage and undercarriage

Two distinct cross-sections were evaluated: a double-deck and an horizontal-oval, single deck. A circular single deck solution was discarded for unacceptable volume utilization. In spite of other considerations that will be mentioned later, but bearing in mind the problems found with the lift force, the horizontal-oval was selected as the most suitable solution. In fact this type of fuselage positively contributes to carry over some lift and to trim the aircraft[12]

The handicaps associated with the structural weight and with emergency evacuation requirements of this layout are also counterbalanced by a very large freighthold volume, as shown in Fig. 6, and a very efficient occupancy of the main cabin.

Once the horizontal-oval cross-section was selected the next step was to establish the seating arrangement. The layout that satisfied most requirements and minimized the structural difficulties was 18 abreast; that also gave the minimum length with three aisles and lead to an acceptable slenderness of the fuselage. Table 1 shows, however, that this is the longest of the three designs. Extrapolation of data given by Jagger[8] (on number of passengers against fuselage length) suggests that 912 passengers could be accommodated in this fuselage, in a three-class layout, at

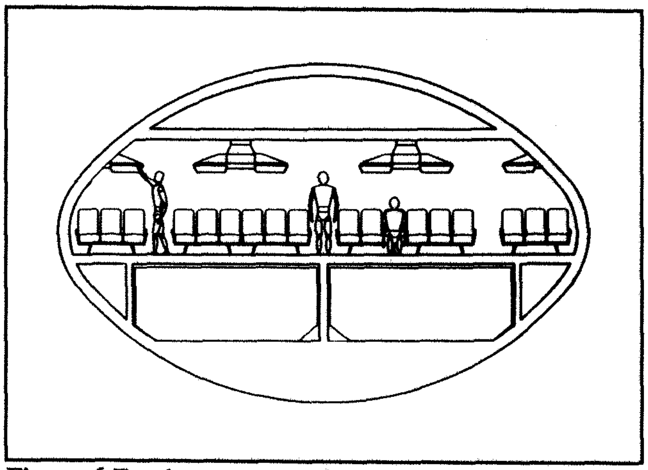

Figure 6 Fuselage cross-section - Urano

A320 comfort levels. The primary reason for this long fuselage is probably the initial requirement to carry 1000 passengers with a 34in seat pitch, rather than the 31in pitch used for "Pegasus" and "Millennium" in their high capacity (i.e. 1000 seat) configurations.

The weight of the fuselage structure, following Torenbeek's method[16], is 58369kg, i.e. 10.9% of MTOW (cf 7.7% for "Pegasus"). It was suggested that this figure should be increased up to 62400kg, following reference to DATCOM. On the other hand, the structural slenderness used in Torenbeek's method was based on h_f/l_f, while a more realistic criterion should have included the beneficial influence of the fuselage width.

Regarding the fuselage production cost, essentially a function of weight, size and complexity, it seems that the horizontal-oval configuration does not imply a specific burden. As formerly indicated, the weight is roughly equal to that of other layouts; no individual structural component has a size that could represent a severe distortion in a manufacturing or assembly line; moreover, the number of parts is roughly proportional to the weight. Finally, since all frames are joined circular segments, the level of complexity is similar to that of current layouts.

Airport terminal compatibility is guaranteed and optimized through the location and sill height of doors and the possibility of boarding the aircraft from both sides through the terminal's telescopic boarding bridges (a point made by Whitford[5] and Bayer[2], amongst others). This is achieved by keeping the wing span within the current 65m limit and locating the canard at an appropriate position, allowing either the ordinary skewed attitude or a position perpendicular to the building. Round terminal halls would certainly improve this feature.

Emergency evacuation is a real matter of concern in very large aircraft. The all-tourist arrangement considered has a seating capacity of 960 passengers (at 0.86m - 34in - seat pitch), to which some 30 crew members are added. The aeroplane has ten A type doors on each side of the fuselage. Following Lockheed's rule[13] every A type door contributes to evacuating 2 persons at 1.34 second intervals, after an initial delay of 20 seconds needed by crew staff to reach the door, open it, and deploy the slides. Thus, the evacuation can be completed in around 86 seconds; less than the 90 seconds limit imposed by airworthiness standards. It is difficult to foresee higher passenger densities for these long range giants, but in a such a case the aeroplane would need an additional door on each side to fulfil the requirement.

Since the aforementioned rule is too simple to be reliable and in some cases it has been shown not to be suitable[14] the study of evacuation carried out during the project included histograms of distances from seat to door[9] as an alternative way of assessing this feature. The horizontal-oval cabin compares satisfactorily with the lower deck of Boeing 747.

In "Urano" the main landing gear was analyzed in some depth, due to the anticipated problems of determining the number of legs, number of tyres per leg, volume needed, etc. The horizontal-oval cross-section proved to be a benefit here, as it provided room for ventral legs without affecting the structural integrity of the wing-body-keel junction too much. After trying diverse solutions, a nose leg with two tyres and five main legs with four tyres each was chosen; giving a static load evenly distributed in all tyres. This disposition is fairly different from those suggested by other authors[15]. Two main legs were conventionally located near the wing root rear spar, but with two others under the fuselage side (retracting to its centre) and a central leg (retracting rearwards).

Weights and performance

Within the accuracy of the conceptual design , the maximum take-off weight is essentially dependent on payload and range[16,17]. Moreover, in a multi-engined transport aeroplane the design point (W_{to}/S, T_{to}/W_{to}) is almost uniquely determined by take-off and cruise considerations. The corresponding figures in this design are: MTOW=533100kg; OEW=261400kg; W_{to}/S=7500Pa; T_{to}/W_{to}=0.253.

From the outset it was clear that the overall layout had to produce a compromise solution due to the competing limitations of: 65m wing span imposed (hitherto) by airport authorities; wing loading for structural considerations (W_{to}/S around 7500Pa or 156 lb/ft^2); and a high aspect ratio for low drag. For a range parameter of 25000km, A=7.5. In closed form this implies

$$MTOW \leq (W_{to}/S)_{max}\frac{b^2_{max}}{A_{min}} \tag{2}$$

The solution to these limitations was to design the aeroplane with a three surface arrangement, with the wing providing about 85 percent of the total lift, and other two surfaces sharing (with positive lift during cruise) the remaining force.

Aeroplane performance is based on the drag polar. For the three-lifting surface configuration this can be expressed as

$$C_{D_{cr}} = 0.0190 + 0.0405C_L^2 \tag{3}$$

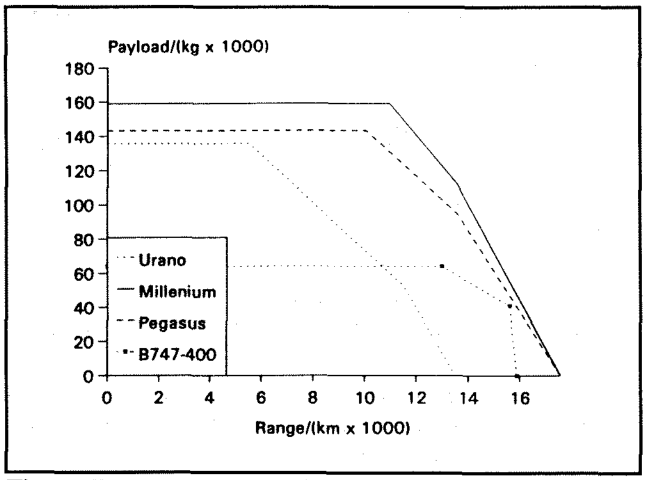

Figure 7 Payload:range diagrams for the three designs compared with the Boeing 747-400

The constant term is larger than that of current long range aircraft. This is due to the higher wing loading (and the corresponding relatively large wetted area of the fuselage). The lift-to-drag ratio in cruise reaches 17.5, leading to a range parameter of 25500km. With some optimization these values could be slightly improved, taking advantage of the variable lift distribution and trim of the aircraft[18]. The corresponding payload-range diagram is shown in Fig. 7.

It is important to note that, as in all canard layouts, the wing is subject to the distorting and perturbing trailing vortex shed from the foreplane (see Fig. 8). Hence, the wing spanwise lift distribution becomes less uniform and, in the outer edge of such a trailing vortex, the aerofoils must withstand very high lift coefficients, close to the local

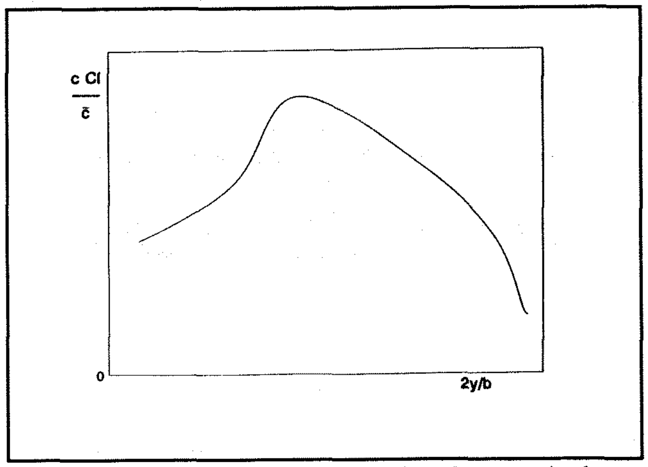

Figure 8 Spanwise lift distribution for Urano mainplane

maxima. This effect must be studied in detail to avoid buffeting and other undesirable phenomena.

In the three-lifting surface arrangement both stable and marginally unstable solutions are compatible with low values of induced drag[18], consequently controlling the aeroplane should not be an important issue. On the other hand, due to its specific layout the moments of inertia are increased with respect to aeroplanes of the same span or length, thus slowing the dynamic response and the dynamic stability modes.

Discussion

DOC comparison

One key to the successful introduction of any UHCA is the level of improvement in operating costs. To compute the absolute value of DOC of the aeroplane is difficult without access to current commercial costings. In the present case, and having in mind that only very global variables are known, the Spanish team has used a simplified method that provides the DOC relative to that of the Boeing 747-400. This comparison[18] requires the following variables: number of passengers, maximum take-off weight, stage length, range parameter, wing loading and thrust loading.

The corresponding mathematical expression for cost per passenger-mile is:

$$DOC_{rel} = \frac{NPax_{747}}{NPax}[\sum C_i(\frac{MTOW}{MTOW_{747}})^{n_i} + C_5\frac{MTOW(1.03-e^{-R/K})}{MTOW_{747}(1.03-e^{-R/K_{ref}})} + C_6\frac{T_{to}}{T_{to_{747}}}] \tag{4}$$

There are four terms in the summation (C_i with i = 1 to 4); these correspond to crew, depreciation, airframe maintenance, and landing and navigation taxes. The fifth term (C_5) accounts for the cost of fuel while the sixth (C_6) represents engine maintenance. Both maintenance terms may include complexity factors to reflect appropriately the extra cost due to unconventional layouts, number of engines, etc.

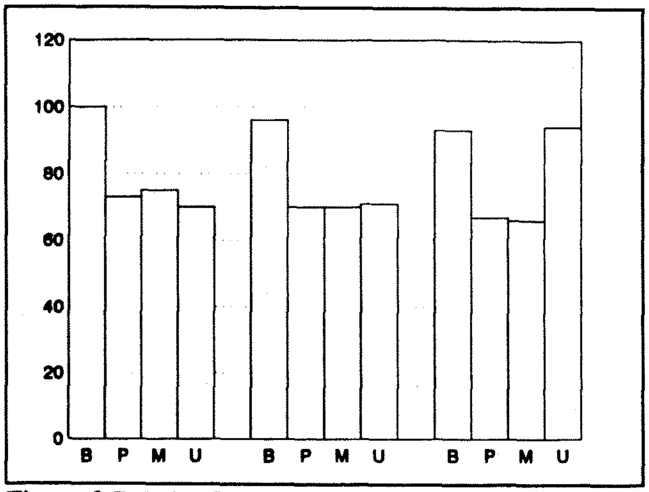

Figure 9 Relative DOC, for three stage lengths. (B=Boeing 747-400, P=Pegasus, M=Millennium, U=Urano)

Figure 9 depicts the results obtained for the three designs over three different stage lengths. For consistency in the calculation, the number of passengers is determined for the all tourist arrangement (seat pitch of 0.86m or 34in). At trans-atlantic ranges, say around 5500km (3000nm), the three-lifting surface layout exhibits some superiority, but from some 6500km "Pegasus" (with its conventional design) offers an advantage. This is the case up to about 8500km when "Millennium" (the long-coupled canard layout) shows a slight improvement over "Pegasus" and "Urano" offers no DOC saving over the 747-400. These trends can be explained as follows. "Urano" has been designed and optimised for medium-long ranges, i.e. pure trans-atlantic capability, and within a very limited design space. In consequence, its payload-range diagram sinks quicker (Fig 7). The complexity and extra weight associated with this uncommon layout, is also penalised (for example the ratio OEW/MTOW is fairly high). "Pegasus" has lower performance but is cheaper than "Millennium", for MTOW and complexity considerations, which provides a certain advantage at appropriate ranges. For very long stages this last offers cost benefits, thanks to its best range parameter.

General considerations for UHCA design

There are many challenges which have to be met in designing a successful UHCA and introducing it into service. Some of these have been discussed above, such as the problems of emergency evacuation, standard disembarkation, aircraft size limits and passenger appeal. There are a number of other important factors which have not been addressed explicitly so far. These will be discussed below as will some areas where advanced technologies may offer benefits.

Environmental impact. Noise certification of future UHCA could present a problem. The current limits under ICAO Annex 16 Chapter 3 or FAR Part 36 Stage 3 vary with aircraft weight (and number of engines), up to a certain MTOW. Above this there is a flat noise limit. This flat limit starts at 617300lb (280T) for approach for a four engined aircraft. (Noise certification also involves sideline and flyover measurements where the flat limit starts at 882000lb and 850000lb respectively.) The three UHCA proposed here are firmly in this flat-limit region. Studies by Rolls-Royce[19] suggest that aircraft of the size under discussion here could just achieve certification under current legislation using current technology engines. Approach certification would be marginal but current rules allow some "trade-off" between the noise in the three flight phases (i.e. an excess of noise in approach can be counterbalanced by reduced levels in the sideline or on flyover). More stringent noise limits are currently being debated, in particular a 3dB reduction in current limits. According to Ref 19, even a UHCA powered by "year 2000" technology engines would have difficulty being noise certificated under these regulations.

Wake vortex separation. Currently the spacing between aircraft on approach to an airport is limited by the need to avoid disturbance to a following aircraft from the trailing vortices of a leading aircraft. The separation depends on the respective weights of the leading and following aircraft but, in the UK, it is between 3 and 8 nautical miles[20]. In the USA closer spacings are often allowed (when conditions permit Visual Flight Rules) and there have been cases of upsets caused by wake vortices, under still air conditions. If the introduction of UHCA necessitates even wider approach separations then there will be no airport productivity gain. Research in this area[20,21] seems to be proceeding along three avenues: determining atmospheric conditions under which wake vortex decay is slow; developing airport instrumentation to detect wake vortices; examining the wing design factors which minimise the trailing vortex effects. In this last respect the canard and three-surface designs may offer some benefits. Other benefits can come from tip devices[22].

Benefits of advanced technology. There are a number of technologies which may benefit UHCA design. Extensive use of structural composites can help to stave off the "square-cube law". Whitford[7] noted the benefits in a NASA design which he compared with "Pegasus". Extensive laminar flow will have obvious benefits; it is unlikely to be a sufficiently mature technology to be designed in to a UHCA. Passive turbulent drag reduction is, perhaps, more likely to see early service[23]. Improvements in engine technology may be essential to meet new noise regulations as noted above.

Conclusion

Three different designs of UHCA have been described: a conventional configuration, a long-coupled canard and a three-surface layout with an horizontal-oval fuselage. All these designs are capable of carrying 1000 passengers over trans-Atlantic ranges. All offer significant improvements in direct operating costs over the Boeing 747-400, for ranges below 8500km; above this the three-surface design shows no advantage because of its optimisation for shorter ranges. New noise certification limits and vortex wake separation criteria could be problems for these aircraft. There are substantial benefits to be gained from drag reduction and structural weight reduction.

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Table 1 Comparison of the three UHCA designs

	Pegasus (Conventional)	**Millennium** (Canard)	**Urano** (Three-surface)
MTOW/kg	544000	563100	533100
MLW/kg	516000	435000	443900
OEW/kg	225000	265800	261400
MPL/kg	143200	159000	135700
Overall length/m	77.00	78.00	91.00
Wing span/m	85.00	83.20	65.00
Height to fin tip/m	25.10	23.30	21.40
Fuselage max. width/m	8.40	8.00	11.00
Fuse. max. height/m	8.40	8.00	8.13
Quarter chord sweep	35.0°	32.3°	30.0°
AR of real wing	9.4	9.5	7.5
Area of real wing/m^2	768.6	727.5	584.0
Area of virtual wing/m^2			682.0
Cruise L/D	19.2	20.0	17.5
Cruise M	0.84	0.85	0.83
Range at MPL/km	10056	10860	5500
Range at MTOW/km	13600	13600	11500
Cabin length/m	59	60	65.00
Seating capacity	1000 at 31in pitch	1000 at 31in pitch	960 at 34in pitch