DESIGN OF A HIGH SPEED BUSINESS TRANSPORT P. 4

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The design of a High Speed Business Transport, the HSBT, was considered by the Aeronautical Design Class during the academic year 1989-90. The project was chosen to offer an opportunity to develop user friendliness for some computer codes such as WAVE DRAG, supplied by NASA/Langley, and to experiment with several design lessons developed by Dr. John McMasters and his colleagues at Boeing. Central to these design lessons, used at the beginning of each semester, was an appeal to marketing and feasibility considerations from the very beginning and the emphasis upon simplified analytical techniques to study trades and to stimulate creative thinking before committing to extensive analytical activity.

All design teams considered the same general category of aircraft, one that was to fly supersonically to foreign business regions. Neither the Mach number nor the range were specified by the instructor. The choice of number of passengers was also undefined initially. As a result, no design group developed exactly the same RFP. Although a number of excellent designs were developed, two designs stood out above all the rest because of the depth of thought and consideration of alternatives. These two designs used quite different methods to meet approximately the same RFP.

One design, the Aurora, used a fixed wing design to satisfy the design mission, while the other design, the Viero, used a swing wing configuration to overcome problems related to overland supersonic flight. The Aurora design was composed of seven students led by Mr. Lyle Dailey, while the Viero group consisted of five students led by Mr. Dan Cler. What follows is a summary of each of those designs.

AURORA DESIGN SUMMARY

A Request For Proposal (RFP) was developed for a Mach 2.2, 8-passenger business transport with a range of 4980 n.m. capable of serving transpacific business routes. The Aurora will have an approach speed of 160 kts. The target date for delivery of the Aurora is the year 2005. The Aurora can deliver passengers from Los Angeles to Tokyo in 4.43 hours, approximately one-third the travel time of current subsonic aircraft. Figure 1 provides a three-view of the Aurora together with several cabin arrangements.

The Aurora has an overall length of 110 ft and wing span of 47.2 ft. The external hull diameter is 6.5 ft at its maximum dimension. The cabin section has a length of 24 ft 8 in (including flight deck) and an internal diameter of 5 ft 8 in, allowing an aisle height of 5 ft 6 in. The cabin has first class seating with an 18-in aisle width and 44-in seat pitch.

A three engine configuration is used to satisfy FAR 25 one-engine-inoperative safety requirements for transoceanic flight.

One podded engine is located under each wing, with the third engine placed on top of the aft fuselage extending through the vertical tail.

Wing Span	47.2 ft
Wing Area	1210 ft²
Aspect Ratio	1.84
Sweep Angle	
inboard	71.0 deg
outboard	61.5 deg
Tip Over Angle	16.0 deg
Fuselage Length	110.0 ft
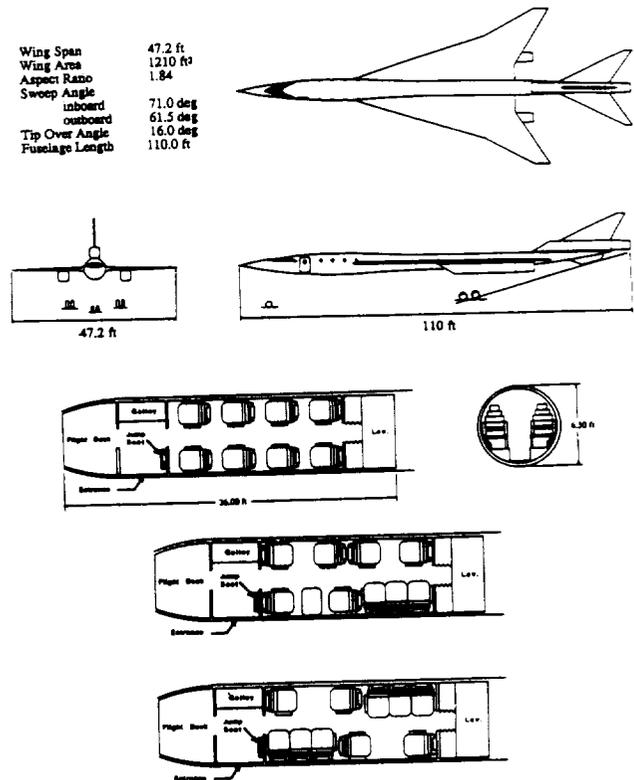
Fig. 1. Aurora Three View and Cabin Layout

Aurora Design Features

A long-range supersonic transport such as the Aurora requires high aerodynamic efficiency, measured by the lift-to-drag ratio (L/D) during supersonic cruise, to minimize fuel requirements and to maximize range. However, supersonic transports must also operate effectively at subsonic speeds, especially for takeoff and landing.

Because of these requirements, a highly swept, low aspect ratio, modified arrow wing was selected because of its low supersonic cruise drag. Wing geometry information is contained in Table 1. The Aurora has a trimmed supersonic L/D of 7.07 at cruise.

Table 1. Aurora Planform Geometry Parameters

Wing Area:	1210 ft²	Aspect Ratio:	1.84
Wing Loading:	90 lb/ft²	Wing Span:	47.2 ft
Root Chord:	48.3 ft	Tip Chord:	4.21 ft
Mean Aerodynamic		Tip-Root	
Chord:	34.5 ft	Chord Ratio:	0.076
Wing Length:	65.2 ft	Box Ratio:	0.362
Thickness-Chord Ratio:	0.06		

The inadequate subsonic performance of an arrow wing requires that leading edge vortex flaps and trailing edge flaps be incorporated into the Aurora design to provide high lift during takeoff and landing. For trimmed takeoff, with leading edge flaps deployed, the Aurora needs a lift coefficient of 0.7, requiring a wing angle of attack of 10°, and a trailing edge flap deflection of 5°. During subsonic cruise at Mach 0.85, the Aurora has an L/D of 9.5.

The total net thrust required at takeoff is 40,900 lb. This thrust is produced by three non-afterburning turbojet engines that satisfy one-engine-inoperative criteria. With one engine out, the Aurora can still take off at a throttle setting of 97%. For supersonic cruise at Mach 2.2 ft, the thrust specific fuel consumption is 1.192 lb/lb/hr. At this condition, each engine produces 10,700 lb of thrust. During subsonic operation at Mach 0.85 and 30,000 ft, each engine produces 8308 lb of thrust.

The aircraft has a TOGW of 104,500 lb, determined using the Flight Optimization System (FLOPS). The Aurora has eight fuel tanks; three are located in each wing and two are located in the aft fuselage. This configuration allows a fuel burning sequence that keeps the static margin between 5 and 24%.

The Aurora employs a tricycle landing gear configuration. The nose gear has a length of 10.0 ft and uses a dual wheel arrangement, while the main gear has a length of 11.5 ft and uses a twin tandem wheel configuration. A tipback angle of 16° allows safe rotation for takeoff and landing and a turnover angle of 57° provides sufficient ground maneuverability.

Aluminum was selected as the primary material for the Aurora because of its low cost. At the cruise Mach number and altitude, stagnation temperatures will reach 310°F. Aluminum will lose 15% of its yield strength at this temperature; as a result, titanium is used in the higher temperature regions such as leading edges, engine nacelles, and the nose cone. Titanium was not used as the primary material, even though it has better temperature strength, temperature, and fatigue characteristics, because the cost per aircraft would increase by 60%.

Providing the stability and control necessary for the mission involves meeting three requirements. These requirements are that the aircraft is stable, can be controlled, and can be trimmed. Achieving these requirements involves empennage design, static stability analysis, and trim analysis.

Empennage design efforts resulted in a conventional tail arrangement employing "all-moving" horizontal and vertical tail surfaces. The horizontal tail was sized to meet the requirements of rotation on takeoff. The result was a 140-ft² horizontal tail which must be deflected 18° leading edge down for

takeoff. The vertical tail was sized to meet the one-engine-inoperative condition. This requirement produced a 69.2-ft² vertical tail which needs to be deflected 10° to maintain a zero sideslip angle with one engine inoperative.

An attempt was made to keep the static margin between 5 and 10%. The subsonic static margin was between 5% and 16%, while the supersonic static margin is between 18 and 24%.

The aircraft trim was determined for several different flight conditions. As expected, the low-speed trim angles α and δ_e are rather large (5 to 10°), while the high-speed angles are very small (less than 3°). These small trim angles at supersonic speeds cause very little trim drag, and thus improve performance.

Cruise range, operation altitude, and trip time are measures of the overall aircraft performance. Other areas of interest include the ability of the aircraft to take off and land under off-design conditions. The Aurora was designed to meet the goals set by the RFP and an analysis of the final design showed that, with the exception of the takeoff field length, all those goals were met. A field length of 8800 ft, 300 ft greater than the target stated in the RFP, is needed for takeoff. All of the major and international airports that were targeted for the normal flight operation of the Aurora have runways that exceed 10,000 ft. As a result, the takeoff field length of 8800 ft will not restrict the normal operation of the Aurora.

The total cost of an aircraft from its design to its retirement is defined as the Life Cycle Cost (LCC). Included in the LCC are research, development, test, and evaluation (DT&E), acquisition, and operations. The research phase includes the research, exploratory and advanced development efforts needed to initiate the design process. Research cost is not included in the cost analysis due to the difficulty in its determination. The DT&E phase determines the cost to design and develop a working aircraft to satisfy the needs of the customer and the industry.

The development cost for the Aurora HSBT is $1.93 billion. The production cost is the cost to produce the aircraft and results in a price per copy. The total production cost for the Aurora HSBT is $6.4 billion, and the total price per aircraft, based on 150 aircraft, is $47.3 million.

Direct operating costs involve fuel and oil consumption, maintenance, and the number of crew needed to operate the aircraft. Other factors included are depreciation and insurance. The direct operating cost per flight for the Aurora, based on 110 flights per year, is approximately $47,000 for a 4980 n.m. trip.

The Aurora HSBT bears a striking resemblance to the Gulf-stream/Sukhoi HSBT design. The development cost for the Gulfstream HSBT is over $1 billion compared to $1.93 billion for the Aurora. The price per aircraft for the Gulfstream is $50 million compared to $47.3 million for the Aurora.

THE VIERO VARIABLE - SWEEP TRANSPORT

The Viero design team chose a cruise Mach number of 2.5, a cruise range of 4750 n.m., and a payload of nine first-class, business passengers with a crew of two. The Viero, with its

variable-sweep wing shown in Fig. 2, was designed to meet the needs of fast and long-range business travel. It also must have a substantially better subsonic cruise efficiency than a typical supersonic transport to be competitive with current business aircraft. Table 2 presents performance parameters of the Viero.

Fig. 3. Viero Payload-Range Curve
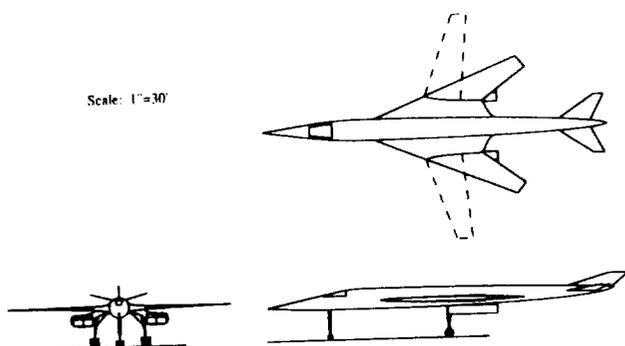
Fig. 2. Three-View of the Viero Executive Jet

Table 2. Viero Performance Parameters

Cruise Mach Number	2.5
Cruise Altitude	73,000 ft (supersonic)
	35,000 ft (subsonic)
Takeoff Gross Weight	128,348 lbs
Payload	1,881 lbs
Operating Empty Weight	54,264 lbs
Fuel Burned	73,724 lbs (JP8)
Range	5,262 n.m. (including reserves)
Block Time	4 hrs 34 min (including reserves)
Block Fuel	72,206 lbs
Takeoff Distance	3,357 ft
Takeoff g's	0.12 g's
Landing Distance	4,610 ft
Rate of Climb	3,000 ft/s (cruise)
	9,300 ft/s (sea level)
Thrust	17,000 lbs per engine
Cruise Specific Fuel Consumption	1.192 lbs/lbs/hr(supersonic)
	0.8 lbs/lbs/hr (subsonic)
Wing Reference Area	1,032 ft²
Wing Spans	89 ft (unswept), 55 ft (swept)
Aspect Ratio	7.624 (unswept), 2.931 (swept)
Wing loading	120.9 lbs/ft² (max)
Cruise Lift-To-Drag Ratio	6.3 (supersonic), 14.7 (subsonic)

The Viero payload-range curve (Fig. 3) indicates that the Viero payload has little effect on range because the maximum payload is less than 1.5% of the takeoff gross weight. For most commercial transports the payload can comprise almost 50% of the takeoff gross weight.
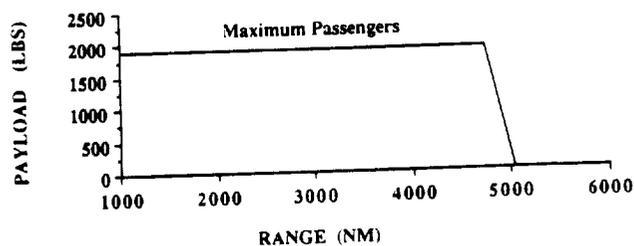
The Viero's takeoff and landing field lengths allow the use of smaller airports. The FAR 25 balanced takeoff distance is 3300 ft. The balanced landing distance is 4700 ft.

Figure 4 shows the fuel burned during a Viero mission per trip cost is more than $17,700, since 73,700 lb of JP8 fuel are used based on $1.50 per gallon (typical private aircraft fuel costs).

The Viero is compared to the Concorde in Fig. 5. The structure of the Viero is designed to keep the empty weight to a minimum. By using integrally stiffened skin panels and lightweight composite materials for the structural cover, the weight is reduced by about 10% when compared to a similar aircraft constructed of aluminum.

The cabin layout shown in Fig. 6 will seat nine first-class, business passengers. Several aspects of the Viero make it stand out from other HSBTs. The high cruise wing loading creates a smooth and comfortable ride by not being so sensitive to atmospheric disturbances. The swing wing utilized on the Viero not only allows for supersonic flight but enables efficient subsonic cruise over land where supersonic flight is not allowed. The variable-sweep wing allows takeoffs and landings from smaller, less congested airports.

Based on an operating empty weight of 52,000 lb, a design speed of Mach 2.5, and an estimated production quantity of 200 between the years 2002 and 2016, the Viero cost is
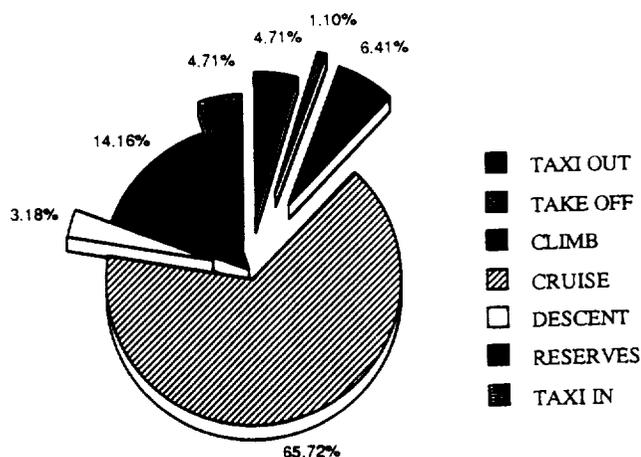
Fig. 4. Viero Fuel Burned as Percentage of Total Used
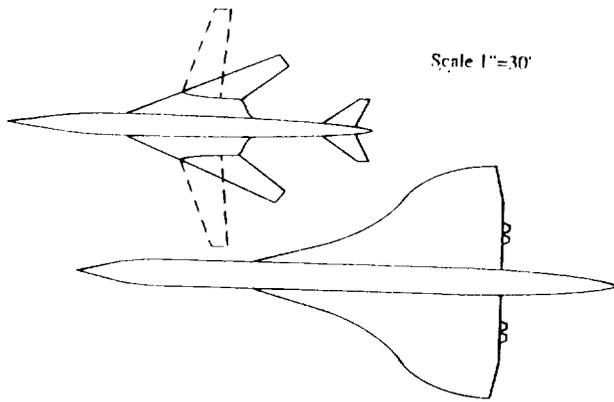
Fig. 5. Planform Comparison: Viero and Aerospatiale/BAC Concorde

CABIN CUTAWAY VIEW

Fig. 6. Cabin Layout of the Viero

estimated to be $47.5 million. With engine costs of around $1 million each, this brings the Viero's selling price up to $51.5 million. Initial estimates of quantity to produce and orders to be taken indicate a project net present value (year 2002) of over $60 million. Direct operating costs based on $1.50 per gallon of fuel are shown in Table 3.

Table 3. Direct Operating Costs (1989 dollars)

Fuel	$16,870
Crew	$1,045
Maintenance	$1,329
Depreciation	$8,141
Insurance	$577
Total	$27,963
Cost Per Passenger	$3,107
Seat-Miles Flown	$2,750
DOC/Mile ($/Mile)	$5.89
DOC/Seat-Mile ($/ASLM)	$0.65

These costs combined with comparable indirect operating costs (overhead, ground facilities depreciation, customer service, etc.) lead to a round trip ticket price per passenger of around $6,000, competitive with that of the Concorde.

SUMMARY

Two designs for a High Speed Business Transport were developed in response to a similar RFP. These design efforts showed the enormity of the cost of such a project. The integrated use of empirical estimation techniques, together with sophisticated analytical prediction enhanced the design effort. Inclusion of cost estimation at the earliest possible time emphasized the design trade-offs.