Cranfield UNIVERSITY

Descriptions of Cranfield Aircraft Group Design Projects (1979-96)

Prof.J.P.Fielding

COA report No.9602
January 1996

Department of Aerospace Technology
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ISBN 1 871 564 80 8

£8

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COLLEGE OF AERONAUTICS

DEPARTMENT OF AEROSPACE TECHNOLOGY

Descriptions of Cranfield Aircraft Group Design Projects (1979-1996)

Introduction

This report is a compilation of reprints of papers and articles describing the aircraft design group projects for the period between 1979 to 1996.

In Cranfield projects, each student takes responsibility for part of the design of a project aircraft, which is used as a design case study for the whole group of students of the course. This teamwork exercise, with specified individual tasks, is organised on the lines of a project as carried out in industry. It is undertaken over eight months, in parallel with the lectures and individual research studies. It is assisted by displays of aircraft components and manufacturing processes, and field visits are made to aircraft manufacturers and operators.

The nature of the course and the future occupations of the students, give guidance to the choice of subject aircraft. The aim is to ensure industrial relevance, but also to include a significant research element in each project. The size of the course usually precludes the design of light aircraft. It is usual to alternate between civil and military aircraft, and each project has a unique configuration.

The project specifications are available in the College of Aeronautics and individual project theses are held in the Institute Library, but be WARNED! - each project is reported in approximately 4000 pages of text and 200 drawing!

Most of the articles are re-printed from the College of Aeronautics AEROGRAM magazine, but other sources are listed below:-

A large executive jet design project

DR. J. P. FIELDING
Lecturer in Aircraft Design, College of Aeronautics, Cranfield Institute of Technology

INTRODUCTION

The College of Aeronautics performs an annual group project as a major part of its Aircraft Design MSc programme. Projects are chosen to be representative of current areas of interest and the programme carried out in a manner which is as close as possible to that of aircraft manufacturers.

The chosen projects alternate annually between civil and military types to give breadth to the course. It was decided that an executive jet would be a suitable subject for examination and a market study was performed. The small capacity end of the market was served by such aircraft as Learjets and medium capacity by BAe 125s and Citations. The top end of the market was of more interest because suitable aircraft could also perform other roles. The main reason for this was that market pressure for unrestricted headroom pointed towards larger diameter fuselages which could also be used for commuter aircraft.

There is also a requirement for transcontinental or transoceanic range. The two main contenders in this market are, the Canadair Challenger and the Dassault Falcon 50B, which are designed to cruise at Mach numbers in the range 0·8-0·88. The former aircraft also has a commuter aircraft role with seating for 30 passengers. Examination of these aircraft suggested a slightly larger aircraft and a number of alternative roles emerged and the following specification was written.

Design specification

The specification was written after a study of the current market and discussion with air transport specialists.

(i) The executive role

(a) Cabin height 6 ft 1 in to allow 97% of male passengers to stand upright. The cabin to be spacious, quiet and be capable of other roles.
(b) Cruise Mach number of 0·75 with a range of 3500 n miles with reserves. Maximum cruise altitude of 40-45 000 ft.
(c) Good field length of the order of 4000 ft.
(d) To have good fuel economy and to meet projected noise requirements.
(e) To have a first cost of $7m at 1979 values and have good maintainability.

(ii) The commuter role

(a) 35 to 40 seats at 30-35 in seat pitch. Four-abreast seating.
(b) Engines to be new generation fans with low fuel consumption, noise and pollution.
(c) Range of about 500 nm with full payload.
(d) Field lengths of about 1000 m.
(e) Operating costs should be as close as possible to depreciated 40/50 seat turboprop aircraft.

(iii) The freight role

This is an extension of the commuter role. The main differences are a large door suitable for the loading of standard LD1 and LD3 containers and a floor strengthened to take three such containers.

(iv) The maritime reconnaissance role

(a) Long range and endurance.
(b) Spacious fuselage for rest station, avionic consoles dinghies etc.
(c) Good low speed performance and pilot vision.
(d) Space and power provision for a search radar.
(e) Door for in-flight dropping of dinghies, supplies and flares.
(f) Strong points for the carriage of underwing stores.

INITIAL DESIGN

The author performed this part of the study to determine the basic shape of the aircraft. More weight was given to the executive role in the wing design, for which a parametric study was performed. This suggested the use of an advanced aerofoil section allied with an aspect ratio of 8 and quarter-chord sweep of 25°.

Fuselage layouts were drawn for three and four abreast commuter seating. The former would carry fewer passengers but result in a smaller aircraft powered by a pair of 5000 lb turbofans. The latter would be capable of carrying more passengers or containers in its larger diameter, but heavier fuselage. This design dictated the use of the three engines, but it was chosen because this arrangement was more suitable for transoceanic and reconnaissance flights.

High and low wings were examined but the latter was preferred as it gave an uninterrupted cabin, simpler undercarriage and good ditching characteristics. Underwing podded turbofans are unsuitable in this size of aircraft so a rear engined configuration was used.

The variety of roles gave a large cg range which led to the use of relatively large T-tail. The final shape is shown in Fig. 1.

Having determined the aircraft shape, calculations yielded aerodynamic, weight and loading information which was given to the students in the form of Ref. 1.

THE DESIGN PROGRAMME

Each student was given responsibilty for the detail design of a major part of the aircraft at the start of the academic year. This was either a structural component or a system, such as an undercarriage. fuel system or environmental control system.

Paper No. 893.

The project was managed to a tight eight-month programme by means of weekly project meetings where design compromises were hammered out and progress monitored.

The programme ended in May 1980 with the submission of voluminous project theses containing detailed drawings and calculations. It has been estimated that at least 12 000 manhours were spent on the programme, which produced some excellent design work and gave the 13 students considerable design experience.

The programme was aided by a visit to British Aerospace, Chester, where the BAe 125 production line was examined minutely and the aircraft's designers and producers questioned. This had a valuable input into the design process.

The programme produced such interesting results that it was selected as a display at the Design Council's headquarters in London.

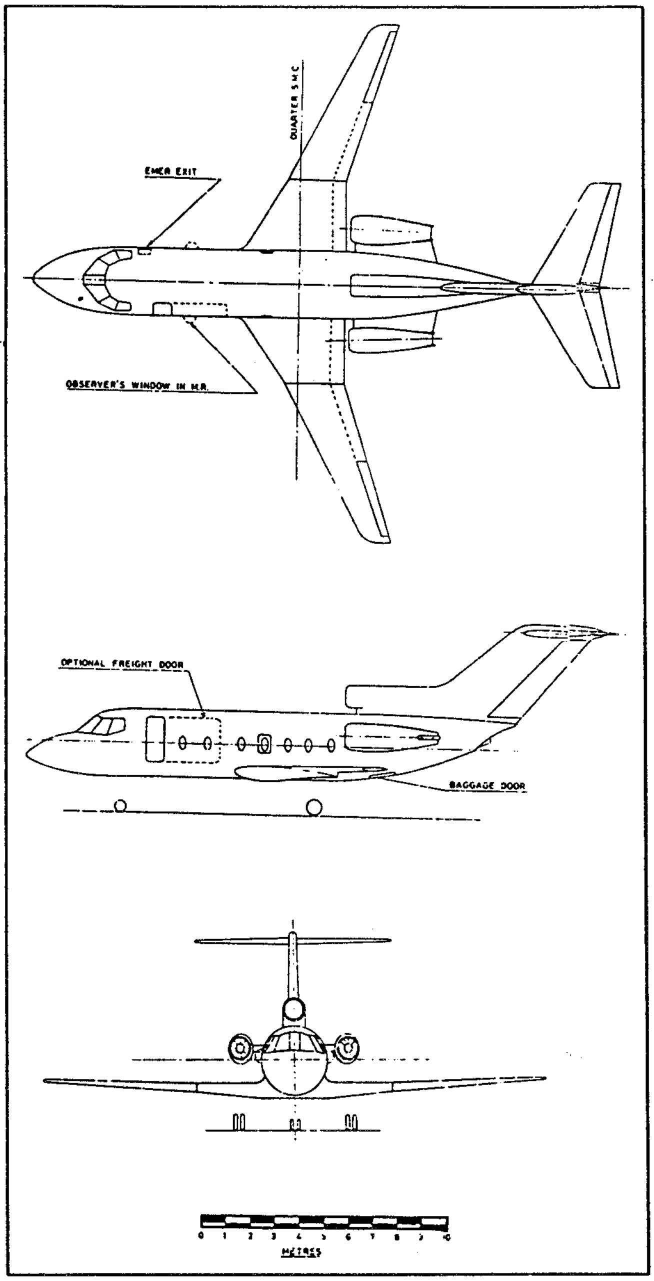

Figure 1.

DESIGN DESCRIPTION

Figure 2 shows an artist's impression of the project aircraft, designated E79. More details are contained in the individual student's project theses(2).

(i) Wing

A moderate sweepback combined with a relatively thick advanced wing section enables cruise Mach numbers in the region of 0·8 to be achieved. The aspect ratio is 8 and there is sufficient fuel tankage in the wing for a range of 3500 n miles with reserves. Single-slotted flaps and moderate wing loading combined with high thrust give good field performance and manoeuvrability. One 'hard' point is provided on each wing capable of sustaining 500 kg stores in the maritime role.

The wing structure is of conventional aluminium alloy built-up construction using extruded 'Z' section stringers riveted to NC machined skins. The upper panel was designed by constrained optimisation of a panel in compression, while the lower panel dimensions were determined by a preliminary fatigue analysis. The two main wing spars are constructed from webs using stiffeners, supported by heavy spar caps for fail-safety. A rear false spar is used to support part of the undercarriage pintle and the inner flap attachments. The wing, a one-piece unit from tip to tip, is attached to the fuselage at the root rib, using four attachment points per semi-span. The root rib is a NC machined I-beam transferring the attachment loads and the wing sweepback kink loading. The attached pick-up points are of failsafe design or have secondary load paths. A simple hinged single slotted flap system employs two flaps per wing semi-span. Each segment is operated by a single ballscrew actuator, driven by conventional torque shafts, from a single, centrally mounted power and control unit. Hydraulic power is used. Conventional aluminium alloy pressed rib construction is used, with a honeycomb sandwich trailing edge portion.

(ii) Fuselage

A relatively large fuselage diameter gives an aisle headroom height of 6 ft 1 in. This gives plenty of scope for a luxurious executive cabin layout without giving a cramped effect.

In the commuter role there is space for 38 passengers, a stewardess, toilet and baggage space. Additional baggage space is available under the floor. The port passenger door forms an integral stair.

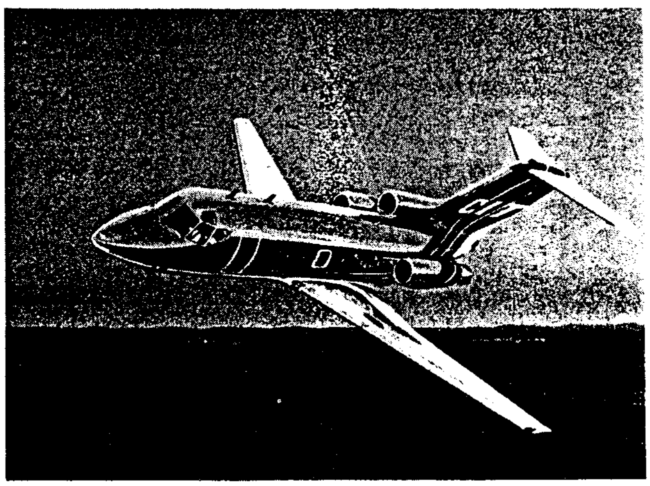

Figure 2.

The large optional freight door permits the loading of three LD1 or LD3 containers in the freight role.

The nose of the aircraft has been designed to accommodate the antenna of a MAREC search radar. Other features which enhance the reconnaissance role are good visibility from the cockpit, large fuselage for consoles and rest stations, underwing hard points for stores and a door for in-flight dinghy dropping.

Semi-monocoque aluminium alloy built-up construction was used throughout the fuselage. Calculations were performed to optimise frame, skin and stringer pitches, but these were overridden locally because of cutouts.

The main problem in the forward fuselage was the very large freight door and two longerons above and below the door were designed to carry longitudinal end loads normally carried by the stringers interrupted by the cutout. The longerons redistribute the end load back into the reinforced shell. The top longeron is in line with the cockpit window top edge member. The door is hinged on the top edge longeron by a robinot 'piano-type' hinge with machined knuckles and a pivot pin and it is operated by a simple single extension telescopic jack.

The circumferential loads due to cabin pressure are taken by the door with five hook-type latches.

The wing torsion box passes uninterrupted below the centre fuselage structure ahead of the main undercarriage bay. Heavy frames pick up the wing front and rear spars and a keel member carries bending loads through the undercarriage bay. The rear fuselage structure was, to a large degree, dictated by the positions of the powerplants, the fin pick-up points and the other equipment stored in the rear fuselage. Most of the alternatives considered were in the design of more detailed items such as joints and engine pick-ups. A major consideration was the need to provide good access to systems, APU and, particularly, the centre engine.

(iii) Tail unit

The fin is a single cell structural box consisting of aluminium alloy front and rear spars and covering skin/stringer panels. The interconnecting ribs are perpendicular to the rear spar, with the exception of the root rib, which is horizontal and the tip rib, which makes an angle of 41° with the rear spar.

The all moving tailplane is mounted on top of the fin. It is attached to the rear spar/tip rib by a pivot fitting (Fig. 3) and to the tip rib by an actuator fitting. The rudder is attached to the fin by three hinges.

The tailplane has been designed using conventional materials and manufacturing techniques. It is a one piece structure with two spars continuous across the centre section. The root ribs are positioned just outside the fin contour line and support the pivot hinge attachment. The centre structure between the root ribs acts as a torsion box to carry torque under asymmetric loading. Because of the high rolling moment under asymmetric loading inherent in T-tail designs, the centre structure is relatively heavy compared to the structure outboard. The leading edge is detachable and incorporates a hot air anti-icing system. Access panels are provided in the front and rear spar web adjacent to each rib for access at manufacture, and for later inspection and maintenance.

The tailplane trim actuator provides longitudinal pitch trim by setting the variable incidence tailplane between 0 and −6°. It is an electrically powered screw jack and, in the event of power failure, has manual reversion. The gear reduction system has been primarily designed for beam strength, with suitable wear strength provided for.

The elevator is supported by three hinges per side, and is of conventional built up construction, using aluminium alloy materials. All main load paths in the hinge regions have been duplicated to ensure integrity. Due to the high hinge loads the elevator is fully powered and is actuated at the inboard hinge. Aerodynamic, or mass balancing, has not been employed.

(iv) Engines

The aircraft uses three Rolls-Royce 401-07 engines. These engines have good performance, excellent fuel consumption and have good size, noise and weight characteristics. Three engines were chosen so that the aircraft would be safe to operate over long transoceanic flights. In the reconnaissance role it will be possible to shut down one engine to conserve fuel.

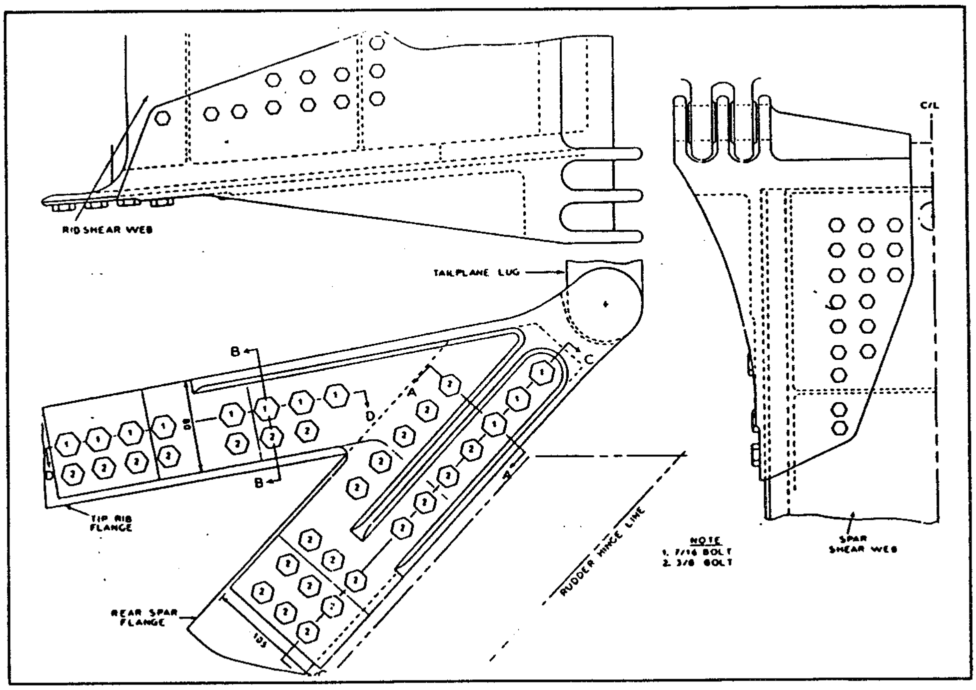

Figure 3.

(v) Undercarriage

The nosewheel is a twin-wheel forward retracting oleo pneumatic strut unit with a multiplying lever steering linkage. The steering is electrically controlled and hydraulically powered, and retraction is effected with hydraulic power.

The proposed wing and centre fuselage layout gave rise to a fairly severe space constraint for the main undercarriage unit which meant that the lever arm type design was not a viable proposition. Thus it appeared that the sliding type design would be the best course to follow. The main unit has wide track and tyres capable of operation at an LCN of 15.

(vi) The environmental control system

The main elements of the system are two ECS packs which condition the air supply by use of engine bleed air and ram air. Locating the packs inside the tail cone gives very good accessibility as well as reducing the noise that reaches the cabin. The latter improvement is largely due to the fact that the luggage compartment is between the tail cone and cabin.

The best arrangement of the location of packs inside the tail cone was felt to be an across arrangement whereby each pack has its own coolant intake at port and starboard sides. This arrangement not only has the advantage of providing side intakes, which would reduce the entry of the undesirable objects, it would also reduce the duct and pipe running to and from the pack. Conventional ducting was used for air distributions and the high cabin differential pressure of 0·7 bar maintained by two valves located at the rear pressure bulkhead. The high differential gives an extremely comfortable environment for the executive role with little weight penalty.

A number of anti-icing systems were investigated, but a hot-air type was chosen.

(vii) The fuel system

The system comprises of four main integral wing fuel tanks together with an auxiliary centre section tank which is only used in the long-range executive role. Design maximum fuel load is 6729 kg which is sufficient to give the aircraft transoceanic range with normal reserves.

Reliability calculations led to the choice of eight identical AC fuel boost pumps, two in each inboard fuel tank, two in the auxiliary tank and one in each outboard tank. They are mounted in isolation chambers to allow their removal without draining the fuel tank. In the main wing tanks the boost pumps are surrounded by collection tanks which are maintained full by both gravity flow and jet pumps. Each boost pump is capable of supplying fuel to one engine at all power settings. Further, the engines will operate on suction feed alone up to specified altitudes. A three-way crossfeed cock allows fuel to be fed from all tanks to all engines.

Refuelling is via a standard aircraft adaptor mounted in the starboard wing leading edge; normal refuelling time in the commuter role is 15 minutes. Both automatic and manual control of refuelling are possible through the refuel control panel sited adjacent to the aircraft adaptor. Standby overwing refuelling points are provided. Defuelling is accomplished through the aircraft adaptor using bowser suction.

The open vent system is sized to prevent structural damage in the event of either refuelling shut-off failure or refuel/defuel gallery failure. Under normal conditions the system prevents a tank differential pressure of more than 14 KN/m^2. The vent outlets are provided by NACA non-icing intakes mounted away from the lighting strike high risk zone.

(viii) The flying control system

The pitch and yaw control forces dictated power assistance but it was possible to design a manual roll control system. In the case of the power assisted controls the pilot's feel is supplied artificially and the feel units are installed in convenient locations. Autopilot is provided for all three control systems and autopilot servo outputs (correction signals) directly operate the same power units (hydraulic actuators) in the pitch and yaw circuits which are used in pilot controlled flights. Safety and reliability are attained through good basic design and through redundancy with multiple hydraulic pressure sources. In the unlikely event of complete loss of hydraulic power systems, the elevator and rudder controls will revert to manual controls. Independent trim circuits are provided for the rudder, aileron tabs and tailplane actuation unit (motion of tailplane being used for pitch trims). This provides duplication in the mechanical systems in all the three channels, and removes any danger from a single system failure being catastrophic.

(ix) The flight deck layout

The criteria employed in the design of civil transport flight decks were examined and applied to the aircraft and ergonomic factors and their effect on the overall local geometry of the nose section were specified. An avionics fit using off-the-shelf equipment was defined within the limitations of manufacturers' information available and radar installations were outlined. The crew management tasks and the nature of their piloting duties were analysed and optimum control equipment layouts arrived at. Forthcoming developments in flight displays were considered.

AIRCRAFT DATA

PERFORMANCE	
Maximum cruise speed	195 m/s EAS or M = 0·8
Range	3300 n miles with reserves
Maximum cabin pressure differential	0·7 BAR
Take off distance to 50 ft	3810 ft (1160 m)
Landing distance from 50 ft	4050 ft (1230 m)
WEIGHTS	
Maximum take-off weight	17 621 kg
Maximum landing weight	16 250 kg
Minimum flying weight	9961 kg
Maximum payload-freighter role	3854 kg
DIMENSIONS	
Wing span	20·4 m
Wing aspect ratio	8·0
Gross wing area	52·035 m²
Quarter chord sweep	25°
Aerofoil section, Root — 15%	Advanced section based on
Tip — 12%	RAE 9550
Fuselage length	20·0 m
Maximum diameter	1·33 m
POWERPLANTS	
3 x Rolls-Royce RB 401-07 with SL static thrust of 24.64 kN each	
GENERAL	
Airframe life of 40 000 hours in the commuter role with average flights of 45 minutes. Commuter dispatch reliability target of 99% based on 15 minute delays.	

PERFORMANCE

The table summarises estimates of the major performance characteristics. The specification is quite closely matched, but the cruise speed is higher and the range a little lower in the executive role. In the other roles all the requirements are met or exceeded with the exception of the commuter field lengths. This is one of the consequences of designing for more than one role. Another is that the aircraft has excessive commuter range capability, but this could be advantageous.

Simple calculations suggested that the first cost target was feasible if the aircraft was produced in sufficient numbers. Calculations using the Cranfield direct maintenance cost formula indicated that the E79 hourly costs would be 88% of an existing 50 seat turboprop. Reference 3 was used to compare the E79's direct operating costs with the same turbo-prop, assuming that the latter was depreciated. This showed that the E79's costs were 104% those of the turbo-prop, but many assumptions were made which would have to be justified if the design proceeded.

CONCLUSIONS

The programme investigated many of the design problem areas of the aircraft and good detail designs were produced.

The resulting aircraft appeared to be feasible and warrants further investigations.

The exercise gave the students considerable design experience on a relevant aircraft design.

The design aroused interest in the aircraft industry and was used as a display at the Design Council's Headquarters in London.

REFERENCES

1. Fielding, Dr. J. P. College of Aeronautics Publication DES 7900 — Executive/Commuter Aircraft — E79, September 1979.
2. Cranfield Institute of Technology Project Design MSc Theses 1979/80:

G. W. Cunningham	—	Fuel system
P. L. Dippenaar	—	Wing mainplane
R. S. Fitzpatrick	—	Flight deck
M. P. Foster	—	Nose undercarriage
N. J. Honey	—	Main undercarriage
S. P. Hull	—	Rear fuselage
D. L. Lucas	—	Elevator and tailplane actuation
J. H. Mangan	—	Trailing edge flaps
E. L. Mertsoy	—	Environmental control system
A. P. Pimblott	—	Centre fuselage
N. G. Schmidt	—	Tailplane
J. Singh	—	Control system and ailerons
S. Tsaklas	—	Front fuselage
J. R. Wojcik	—	Fin and rudder

3. Boeing 1978 Operating cost Methods. Document 6-1445-5-310. Boeing Commercial Airplane Co.

A supersonic V/STOL fighter design project

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INTRODUCTION

The College of Aeronautics performs an annual group design project as a major part of its Aircraft Design MSc programme. Projects are chosen to be representative of current areas of interest and the programme is carried out in a manner which is as close as possible to that of aircraft manufacturers.

Vice Admiral Forrest S. Peterson, Commander Naval Air Systems Command, said at the AIAA/NASA-Ames V/STOL Conference in 1977 that:

'V/STOL appeared to be the most effective, most economical means of addressing many of our major military needs: dispersal of air assets over a broad geographic range, reducing the present reliance on relatively few ships and large permanent bases and reducing the cost of maintaining an adequate, efficient air arm.'

There have been many attempts to develop V/STOL, but most of them have come to nothing. The outstanding exception has been the Kestrel/Harrier/Sea Harrier family of aircraft. The great success of these aircraft has prompted many studies for follow-on aircraft for both land and ship-based operations. The most publicised specifications were those proposed by the US Navy in 1977. The most important one being for the type B supersonic aircraft, as follows:

Naval operations
High performance V/STOL fighter/attack aircraft
Supersonic dash capability with sustained Mach number capability of at least 1·6
Operational from land and from ships smaller than CV's without catapults and arresting gear — good short take-off capability
Sustained load factor of 6·2 at Mach 0·6, 10 000 ft altitude at 88% VTOL gross weight
Specific excess power at 1 g (Ps 1 g) of 274 m/s (900 ft/s) at Mach 0·9, 10 000 ft altitude at 88% VTOL gross weights
VTOL gross weights = 9072 to 15 876 kg (20 000 to 35 000 lb)
STO sea-based gross weight = VTOL gross weight plus 4536 kg (10 000 lb).

This was initially investigated as an individual student research study in 1979. This showed such potential that it was chosen as the basis of the 1980 group project.

The initial project design was performed by a member of staff. This process determined the basic shape of the aircraft together with aerodynamic, weight and loading information, this being equivalent to the work done in an Initial Projects Office in industry. Reference 1 summarised this phase of the study, and provided the starting point for the students' work.

Paper No 995.

THE DESIGN PROGRAMME

At the start of the Academic Year, 21 Aircraft Design students were each given responsibility for the detail design of a major part of the aircraft. This was either a structural component or system, such as an undercarriage, fuel system or environmental control system.

The project was managed to a tight eight-month programme by means of weekly project meetings where design compromises were hammered out and progress monitored.

The programme ended in May 1981 with the submission of voluminous project theses containing detailed drawings and calculations. It has been estimated that at least 30 000 manhours were spent on the programme, which produced some excellent design work and gave the students considerable design experience.

The aircraft utilised many advanced electronic systems which were examined by nine students of the School of Electronic Systems Design. Subsequently, two Aircraft Design students simulated the aircraft's longitudinal response on a analogue computer. Thus the project provided extremely relevant work for a large number of students.

DESIGN DESCRIPTION

Figures 1 and 2 show general arrangements of the aircraft.

The overall dimensions were chosen so that the aircraft could use the 55 ft × 32 ft flight deck lifts of the Invincible-class ship without folding wings.

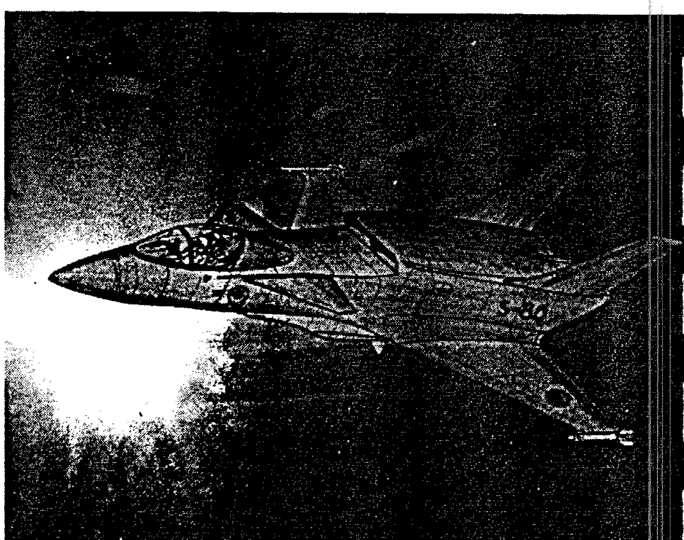

Figure 1. Artists' impression of the aircraft.

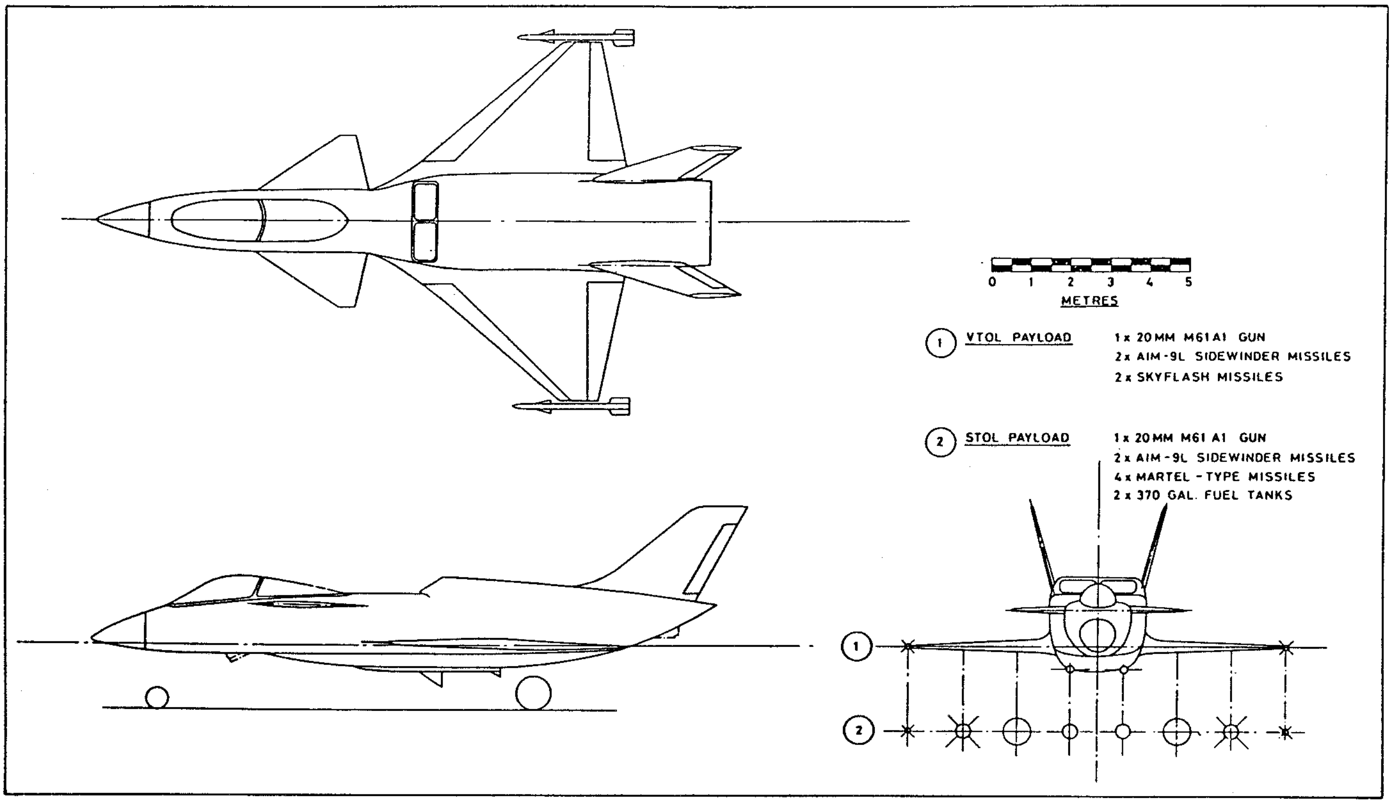

Figure 2. General arrangement of the aircraft.

The College of Aeronautics has been engaged in research into the construction of carbon and glass-fibre composite structures for the past 12 years. This included such areas as:

(i) Joints
(ii) Material properties
(iii) Buckling and post-buckled behaviour
(iv) Impact and battle damage repair
(v) Fatigue
(vi) Design, construction and flight test of remotely-piloted vehicles with composite primary structures.

This experience prompted the decision to design the fighter to utilise carbon fibre reinforced plastic construction wherever possible.

Conservative estimates of weight savings were:

Wing type components	=	15%
Fuselage	=	16%
Undercarriage	=	10%

Table 1 shows the estimated weight break-down for the aircraft.

Detailed descriptions of the aircraft and components are contained in individual students' project theses(2), but brief descriptions follow:

(i) Layout

A close-coupled canard arrangement was chosen because it gave improved lift characteristics for short take-off and combat. The foreplane enables the achievement of high angles of attack and improved area-ruling for reduced supersonic drag as well as providing active control to overcome the relaxed longitudinal stability of the aircraft.

The engine intakes are on the top of the rear fuselage. This reduces the radar cross-section, gives a better area distribution and reduces the inlet duct volume. This releases additional critical fuselage volume for fuel tanks and the remote augmentor duct.

Some doubts have been expressed about the efficiency of such intakes, but wind-tunnel tests of a generally similar configuration showed promising results. The under-fuselage pod is used to house the gun, the submerged part of the Skyflash missiles and the main undercarriage. The semi-submerged missiles reduce drag relative to using pylons and the pod improves the area distribution.

Twin fins are a feature of some recent military aircraft and their feasibility for this study was investigated. On a conventional single fin design, directional stability reduces at high incidence because vortices, originating from separation on the forebody, both increase the destabilising effect of the body and

Table 1

Mass Breakdown

Component	Mass kg	% AUM VTO
Wing	1003	7·15
Fuselage and paint	1303	9·29
Fins	100	0·71
Foreplane	100	0·71
Main undercarriage	473	3·37
Nose undercarriage	157	1·12
Total Structure	3136	22·35
Engines (incl Aden nozzles)	2568	18·30
Rals duct	93	0·66
Rals nozzle and control	89	0·63
Total powerplant	2750	19·59
Fuel system	430	3·06
Unused fuel	80	0·57
Hydraulics	157	1·12
Flying controls	417	2·97
Electrical system	165	1·18
Instruments	54	0·40
Avionics	534	3·81
Air conditioning	120	0·86
Seat/furnishings	110	0·78
Intake de-ice	12	0·01
Armour and protection	100	0·71
M61 gun + conveyor + mount + bin	158	1·13
Total systems	2337	16·69
Basic equipped mass	8223	58·61
Crew	100	0·71
Operating zero fuel mass	8323	59·32
VTO fuel	4740	33·78
Payload (2 × Sidewinder, 2 × Skyflash + ammo.)	967	6·89
All up mass (VTO)	14030	100·00
Extra fuel and payload (STOL)	4324	—
All up mass STOL	18354	—

destabilise the lower part of the fin. Twin fins can be located to either avoid these adverse interferences effects or obtain favourable interference. The twin fin arrangement also reduces the height of the aircraft which is particularly advantageous for naval aircraft.

(ii) Wing (Figure 3)

The wing is a highly swept clipped delta with an aspect ratio of 2·2 and thickness/chord of 5%.

A small percentage of fuel is carried in the wing, which is also used to mount the main undercarriage, the reaction control system for roll control in the hover, and Sidewinder missiles.

The inner wing structure is a multi-spar construction. It contains eight spars, all being unswept along the span. The number of spars decreases only outboard of main undercarriage rib. The top and bottom skins are of sandwich construction with carbon-Kevlar composite faces and high strength polymide honeycomb core. Spar booms are accommodated inside the skins by adding longitudinal carbon fibres and discontinuing the honeycomb core locally. The four main spars which pick up the wing fuselage attachment loads are of sandwich construction. The remaining four are made of sinusoidal corrugated webs. All the spar webs are made of ±45 angle ply laminates.

This extensive use of composite materials necessitated the performance of a considerable amount of background research. The final sizing of the structural elements was aided by the use of finite element analysis which took account of the material's othotropic properties.

Four of the seven centre-section cells contain fuel and the two rearmost cells accommodate roll control ducts, hydraulic pipe lines and electrical connections for the 'fly by wire' system.

Two students designed an alternative, variable camber wing This utilises flexible skins on both leading and trailing-edge regions to give smooth variations in camber. The design was feasible but requires the use of a very large number of links to achieve the required shape.

(iii) Fuselage

The forward fuselage contains a partially reclined ejector seat surmounted by a large canopy with good pilot visibility.

A simple cockpit mock-up was constructed to check pilot reaction to the design (Fig. 4).

The forward fuselage bending loads are taken by four longerons which are positioned such that the top two longerons form the cockpit coaming, while the bottom longerons are a continuation of the two longerons of the centre fuselage at floor level.

Square section CFRP longerons have been used because they are readily manufactured by the filament winding process.

The carbon-fibre skin was designed to be effective in shear and torsion only, as the presence of large cut out areas had dictated the use of longerons to take the compressive/tensile loads.

The centre fuselage construction was constrained by the centre of the wing-box, air intakes and the gun installation. The top longerons continue the canopy-sill/longerons of the forward fuselage from the foreplane mounting frame. From there they run aft and outboard onto the top corners of the fuselage, at the start of the air intakes the longerons roll off the corner radius and pass along the skin, angled upwards to meet the top longerons of the rear fuselage.

The lower longerons were positioned, at the forward end, by the need to provide rapid access to the gun and its ammunition drum. By running the longerons above the level of the ammunition drum and keeping all the primary structure away from this region, it has been possible to have the gun mounting effectively hung from the bottom of the fuselage and covered only by a quickly detachable fairing. This has resulted in a loss of efficiency of the primary structure, as the depth of the 'bending' material has been reduced but this is acceptable when one considers the improvement in maintainability made possible by this arrangement. At the rear end of the centre fuselage the bottom longeron passes over the wing centre-box, thus permitting the wing to be removed downwards.

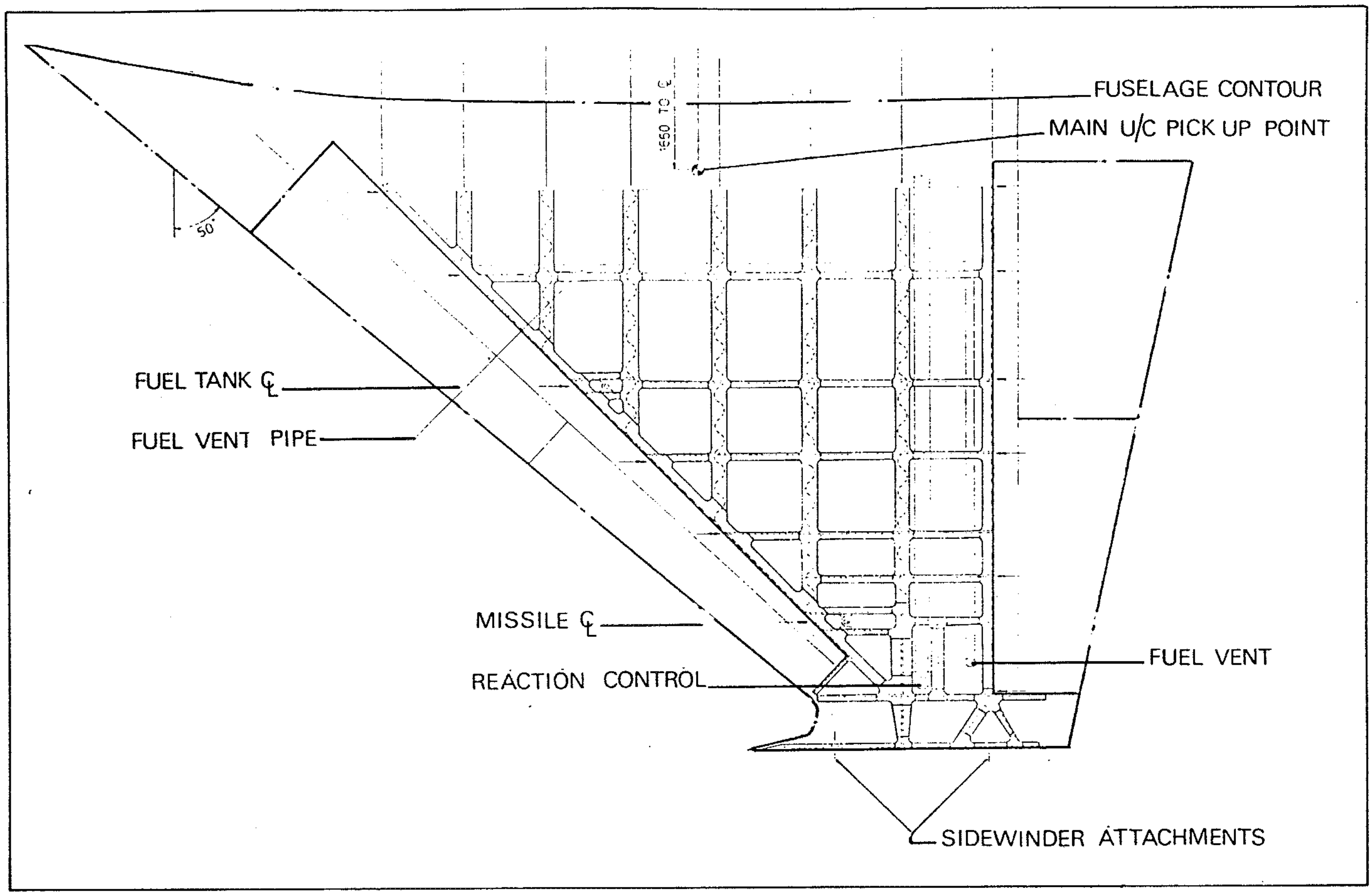

Figure 3. Scheme of the outer wing construction.

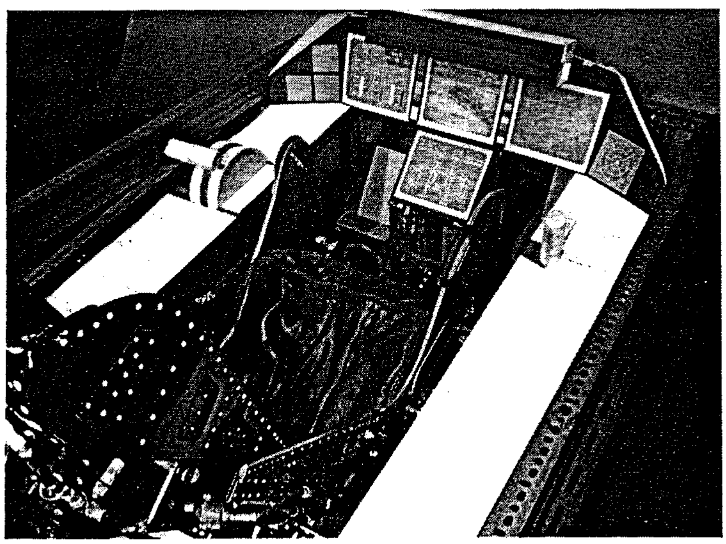

Figure 4. Cockpit mock-up.

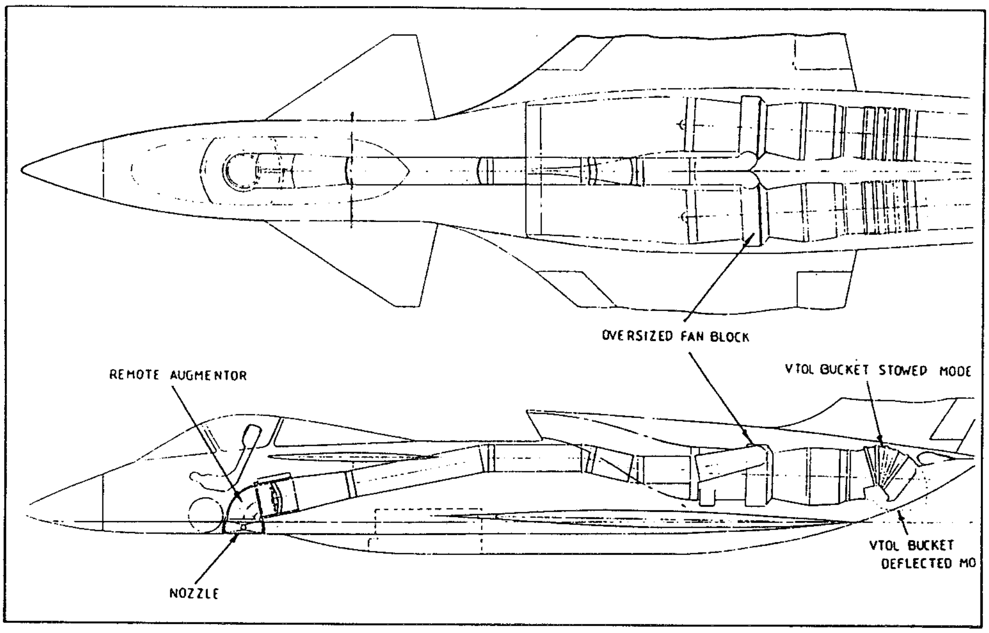

Figure 5. Powerplants and remote augmented lift system.

The skin around the under-floor armaments bay is simply a fairing designed to resist air loads and provide a degree of protection for the gun ammunition. In addition to these, the design considers aspects of fatigue, corrosion, economic manufacture, economic repair, inspection (at manufacture and in service) and maintainability.

Several skin configurations were investigated for the centre fuselage before it was decided to use carbon-fibre faced honeycomb sandwich panels.

The four-longeron construction was continued into the rear fuselage where they are used to mount the speed brake. Frames are used to mount the engines and fins. Removal of the engines is accomplished by pulling them aft along rails.

The intakes employ a two-dimensional single-shock supersonic compression, followed by subsonic diffusion to a low Mach number at the engine face. The inlet geometry is designed for maximum efficiency at cruise Mach number of 1·6. Auxiliary intakes are provided in the duct for improved engine performance at low speeds. These intakes are closed at an altitude of 91·44 m (300 ft) and flight Mach 0·65. The auxiliary intake doors are spring loaded and closed by pressure differential.

Fuselage boundary layer is separated before entry into the intakes.

(iv) Powerplant and Vertical Take-Off System

The aircraft uses the remote augmented lift system (RALS) being developed by the General Electric Company. Two propulsion units are used, mounted side by side in the rear fuselage, having variable cycle capability and a double bypass split fan to provide airflow to the single remote augmentor nozzle during vertical take-off and landing. Primary exhaust is through ADEN nozzles (Augmentor Deflector Exhaust Nozzle).

For vertical take-off the aircraft rises on three columns of high-energy air, one from the RALS nozzle and the other two from the deflected ADEN nozzles. For forward flight the RALS is shut off and the ADEN nozzles point aft. The RALS nozzle is gimballed to provide tilting to produce pitch and yaw control in the hover.

The RALS consists of two main sections which are characterised by their vastly different maximum operating temperatures. The first main section is the duct leading from the fan block outlet ports on each engine to the beginning of the diffuser leading to the forward augmentor; the maximum operating temperature of this section being 240°C.

The duct wall is a composite sandwich consisting of a 9·5 mm thick core polymide foam sandwiched between two 0·25 mm thick symmetric lay-ups of unidirectional high tensile strength graphite fibres in a matrix of polyimide resin.

The second main section begins with the diffuser, and following that is the forward augmentor and the last bend before the variable area vectorable nozzle; the maximum operating temperature of this section being 1760°C. This section begins at the end of the composite duct, where there is firstly a titanium alloy expansion joint followed by a 4° conical diffuser. The diffuser is fabricated by welding Nimonic Alloy PK 33. Following the diffuser there is a division of the flow, with 15% of the flow passing into the annulus formed by the flame tube and the outer wall for cooling, and the remaining 85% continuing through to the augmentor.

The flame tube is manufactured from Carborundum Sintered Alpha Silicon Carbide (SASC), to resist the very high temperatures.

Roll control in the hover is achieved by the use of a reaction control system which bleeds high pressure compressor air and ducts it to wing tip mounted convergent-divergent nozzles. These ducts and nozzles have maximum operating temperatures of 480°C and are manufactured from nickel alloys.

These components posed great installation problems because of limited space in the very thin wing section. This section also initially produced aeroelastic problems from the wing-tip missile installation. These problems are resolved by a local increase in chord and careful siting of the nozzles.

(v) The Flying Control System

The flying control system uses three channel electrical signalling to hydraulic actuators at the control surfaces. The aircraft is deliberately unstable in the pitch sense, control being achieved by the actively controlled all-moving canard foreplane. The two halves of the foreplane are rigidly connected by a titanium torque tube. The foreplanes use a large centre spar allied to high modulus carbon fibre reinforced plastic skins supported by full-depth honeycomb core. Lateral stability is aided by twin fins. These have five carbon fibre spars each and use high-modulus carbon-fibre skins protected with an outer layer of Kevlar. The twin rudders are constructed from glass-fibre reinforced plastic supported by honeycomb core. The design allows the wing trailing edge control to work as normal sealed high-speed ailerons in cruise flight, as drooped ailerons in high-speed combat and as slotted flaps with differential aileron motion for conventional and vertical take-off and landing. Two control surfaces are included on each semi-span. The surfaces can be operated independently, or together, and allow the wing lift distribution to be modified if required for bending moment relief in high *g* manoeuvres.

These surfaces are constructed of carbon-epoxy laminates with a full depth honeycomb core. Actuation of the aileron motion is by a large hydraulic actuator on each control surface. Actuation of the flap is by three ball-screw linear actuators per control, powered by electrical motors in the fuselage.

(vi) Hydraulic System

The hydraulic power source comprises two completely independent systems, each with its own reservoir, pump, accumulators and piping with a stand-by system.

The two main hydraulic system pumps are driven from airframe mounted gearboxes. The stand-by system pump is electrically driven by an AC motor.

Both main systems share the operation of the flying control actuators. Each system supplies the actuator with 50% of the power required. In case of one system failure, the remaining system will supply the actuator (through a change-over valve) with the power required.

The stand-by system supplies most of the surfaces in case of both systems failure. It is switched on automatically by a duplex system pressure drop.

The system pressure is 4000 psi (27·58 MN/m²).

All pressure pipes are of DTD 5016 stainless steel and the return pipes are of titanium alloy DTD 5073, the latter being used to save weight.

(vii) Fuel System

The total internal fuel capacity of aircraft is 4700 kg, the tanks being located in the fuselage and innerwing. Two 100 gallon drop tanks are carried in the STOL mission under the outer wings.

The fuel system uses both integral and self sealing type tank construction. Each engine is fed separately by a collector with a provision for cross-feed in case of emergencies. The transfer of fuel from the main tanks to the collectors is by tank mounted booster pumps. Transfer from the drop tanks is by means of compressor bleed air.

The centre of gravity limitations of the aircraft are met by suitable selection of tank locations and transfer sequence and no recourse is made to an automatic centre of gravity control system.

As far as possible measures have been taken to use standard fuel components. Vulnerability to enemy action, reliability and accessibility have been given due consideration in the design.

(viii) Undercarriage

It was decided to make the undercarriage suitable for use from semi-prepared airstrips. This made the wheels rather large, but it was felt that it was necessary to give the aircraft the ability to operate from beach heads in the STOL mode.

The undercarriage configuration is of standard tricycle form using an aft-retracting nosewheel with twin wheels. The main legs retract inboard into the fuselage fairing and mount single wheels.

(ix) Armament

(a) VTOL Mode

1 Vulcan 20 mm rotary cannon — M61 Al
2 Short-range Sidewinder missiles on wing tips
2 Medium-range Skyflash missiles under fuselage.

(b) STOL Mode

In this role the Skyflash missiles are replaced by four Martel or Sea Eagle anti-ship missiles and range is augmented by external fuel tanks.

(x) Survivability Considerations

The aircraft was designed to have reduced vulnerability. The overall shape and positioning of intakes considerably reduced the radar cross-section. Extensive penetration calculations were performed to predict the shot lines of high-explosive and armour-piercing shells. This lead to careful positioning of components and armour. Fuel positioning and protective measures were also optimised and infra-red calculations performed. Systems were duplicated and separated to further reduce vulnerability.

PREDICTED PERFORMANCE

Table 2 summarises estimates of the major performance characteristics, weights and dimensions. The specification is closely matched, but stores drag in the STOL role led to reduced range.

Table 2

Aircraft Data

Performance	
Maximum cruise speed	650 kt EAS or M = 1·6
Intercept flight profile:	
1. Vertical take-off — 5 minutes at max. continuous power	
2. Climb — max. continuous power	
3. Cruise at M 1·6, 40 000 ft at 150 N miles radius	
4. Descent to 10 000 ft	
5. Combat — 2 minutes at max. A/B at M 1·0	
6. Climb — max. continuous power	
7. Cruise return at M 1·6, 40 000 ft	
8. Descent	
9. Loiter — 20 minutes at sea level — M = 0·35	
10. Vertical landing — 5% total fuel reserve.	
Specific excess power — As requirement using 31% reheat	
Weights	
All up mass (VTOL Mode)	14030 kg
All up mass (STOL Mode)	18354 kg
Basic equipped mass	8223 kg
Dimensions	
Wing span	9·14 m
Wing aspect ratio	2·2
Quarter chord sweep	40°
Aerofoil section	NACA 65A005
Fuselage length	20·0 m
Fuselage max. width	2·72 m
Powerplants	
2 variable cycle turbofans based on G.E.16/VVCE-6	
Sea level static thrust of 93·42 kN each	

CONCLUSIONS

The programme investigated many of the design problem areas and good detail designs were produced.

The resulting aircraft appeared to be feasible and warrants further investigations in following area:

(i) Further development of the powerplant and RALS system
(ii) Wind tunnel tests to prove the air intake configurations and performance estimates
(iii) Analogue simulation of longitudinal aircraft motion showed promise and should be continued
(iv) Further investigation of high-temperature materials and insulation for the RALS nozzle.

REFERENCES

1. Fielding, Dr. J. P. DES 8000. Naval V/STOL Fighter S-80. College of Aeronautics, Cranfield Institute of Technology, January 1981.
2. Cranfield Institute of Technology Project Design MSc Theses 1980/81:

ALI	Hydraulic system
ASHOORI	Leading edge flaps
BALDWIN	Main undercarriage
BURLEIGH	Centre fuselage
CHAKRABARTI	Inner wing
FROSST	Trailing edge auxiliary surface (fixed geometry wing)
HOOD	Nose undercarriage and front bulkhead
HUGHES	Survivability
LIM	Control systems, outside cockpit
LUBBE	Outer wing
MATTHEWS	Rear fuselage
MORGAN	Fins
NADGIR	Rudders
NAWI	Air intakes and engine mounting
RAJAN	Fuel system
ROBINS	Cockpit layout, controls, seat, environmental control
SCOTT	Nozzles and powerplant offtakes
STOCKING	Foreplane
TOWELL	Variable camber wing, main structure
VERGHESE	Variable camber wing, moving surfaces
YAQUB	Nose fuselage

Big isn't always beautiful
A very large Freight Aircraft Design Project

by Dr. John Fielding, Lecturer in Aircraft Design

Dr. John Fielding

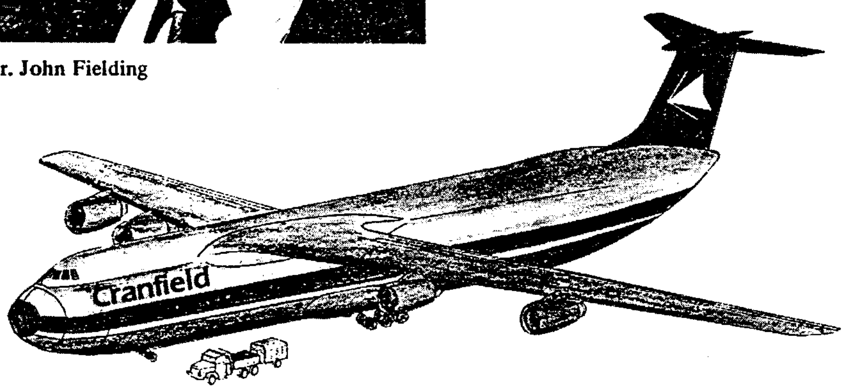

Fig. 1 F.81 Advanced Freight Aircraft

The Overall Programme

For many years, it has been the College of Aeronautics' philosophy that the best way to teach aircraft design is actually to do it. To this end, the Aircraft Design MSc students perform an annual group design project based on types of aircraft that are of current interest.

Commercial air freight operations have grown in importance in recent years due mainly to cost reductions caused by increasing aircraft and freight terminal efficiencies. The bulk of the cargo is carried in the underfloor holds of wide-body passenger aircraft, but there is a significant sector of the market served by 'dedicated' freighters such as the 747F and DC8-63F. These aircraft are often equipped with standard containers and pallets which are loaded at factories or freight depots. The largest and most efficient container is the 8 ft x 8 ft x 20 ft size.

NASA felt the need to study the air freight market and commissioned the extensive C.L.A.S.S. study (Ref. 1). This report suggested that significant operating cost savings would be required, together with improved ground interfaces, to make more inroads into the surface transport market.

It studied the economics of aircraft derived from current types, together with new designs. The former was more immediately attractive but a market existed for new aircraft from the mid 1990's.

The most attractive new type would be a long range aircraft with payload in the 75 to 165 ton range. The lower size aircraft was slightly more economic, but would pose grave airport frequency saturation problems and therefore a larger aircraft was preferable. Aircraft much above the 165 ton class however, would lead to development costs higher than the market could stand.

An aircraft of about 165 tons payload seemed to be a good solution which could be made more attractive if it were designed to satisfy both civil and military requirements, thus spreading development costs. This philosophy was aimed at during the design of the Lockheed C-141 but too much emphasis was placed on military properties and no civil versions were sold. This should be avoided on a new design which ought to be capable of augmenting and partially replacing current fleets of 747F, DC10 CF and Lockheed C-5A aircraft.

It was decided to study such an aircraft with the main emphasis being on civil operations with modifications such as a kneeling undercarriage as military options.

A conceptual design study was performed by the author, based on the specification shown below. This process determined the basic aircraft shape and weight, aerodynamics and loading information. This work is summarised in reference 3, which was given to each student at the start of the academic year. Nineteen students were then each given responsibility for the detail design of a major part of the aircraft. This was either a structural component or a system such as an undercarriage, fuel system or environmental control system. Each student had responsibility as designer, stressman and draughtsman for his component.

The project was managed to a demanding eight-month programme by means of weekly project meetings where design compromises were resolved and progress monitored.

The programme ended in May 1982 with the submission of voluminous project theses containing detailed drawings and calculations. It has been estimated that at least 20,000 manhours were spent on the programme, which produced some excellent design work and gave the students considerable design experience.

The knowledge gained during lectures,

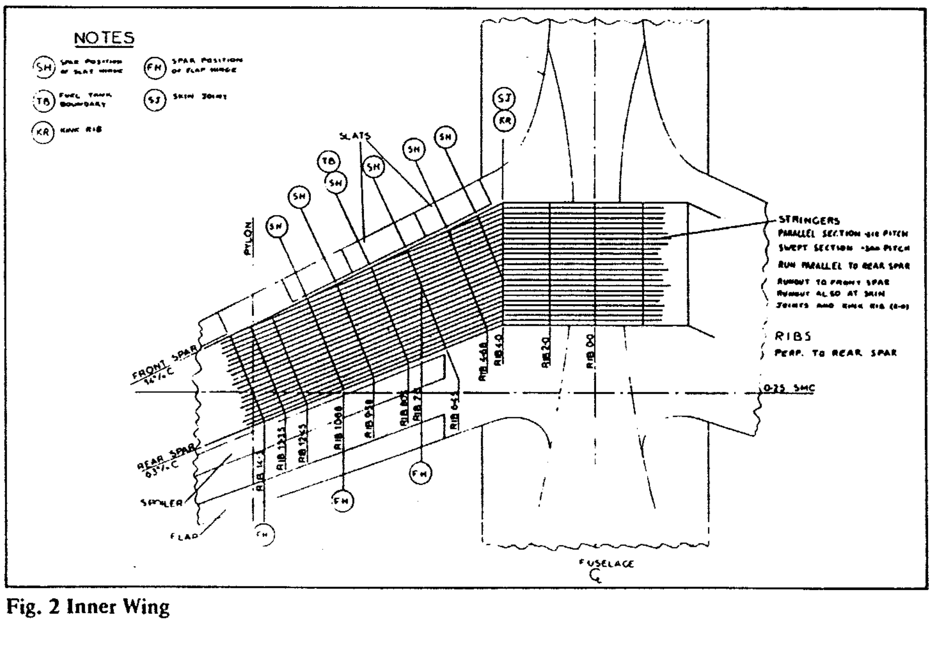

Fig. 2 Inner Wing

2

project meetings and discussions with members of staff, was augmented by several valuable visits. Students visited two operators of Boeing 747 freight aircraft and close examination of these huge aircraft and loading facilities was most instructive. Visits were also made to see a C-5A Galaxy aircraft and to British Aerospace – Hatfield. The latter enabled close examination of the British Aerospace 146 airliner. Although much smaller than the F-81, the 146 had a similar general configuration and provided good examples of modern construction techniques.

The Design Specification

A specification was derived from refs. 1 and 2 together with information about current freighter aircraft.

a) The *Range* with maximum payload should be 4,000 n. miles with reserves.

b) The *Payload* should be in the range 330-390,000 lb (150-175,000 kgs). Civil operators would use 8 x 8 x 20 ft containers with provision for a height extension to 10 ft.

Military payloads would include most of the major equipment. Typical extremes in size and weight are:

1) Weight Chieftain Main battle tank (52.3 tonnes)
2) Length 175 mm self propelled gun (11.3 m)
3) Height Puma helicopter rotor to retracted undercarriage (13.2 ft [4 metres])

c) *Field Performance* in the civil version should be similar to that of the 747F:

Take off to 35 ft = 11,000 ft (3350 m)
Landing = 7,000 ft (2130 m)

The runway load classification number should be 87 on a 20 inch pavement. There should be sufficient power to meet commercial engine-out climb gradient requirements.

d) *Speed*
Cruise Mach numbers in the 0.75-0.8 range.

e) *Technology*
Technology that is likely to be available by the mid 1990's is to be used which should include:

i) Advanced wing sections
ii) 'Active' controls.
iii) Some composite materials.
iv) More fuel efficient engines.
v) Lighter weight systems.

f) *Noise*
To achieve current noise requirements.

g) *Costs*
The aircraft first costs should be S132 x 10^6 (US) in 1994 with direct operating costs 30% below those of 747 Fs.

Design Description

A general arrangement drawing is shown in Fig. 1, some points of which are discussed below:

Wing

A moderate sweepback, combined with a relatively thick supercritical wing section enable cruise Mach number in the region of 0.75 to be achieved. The aspect

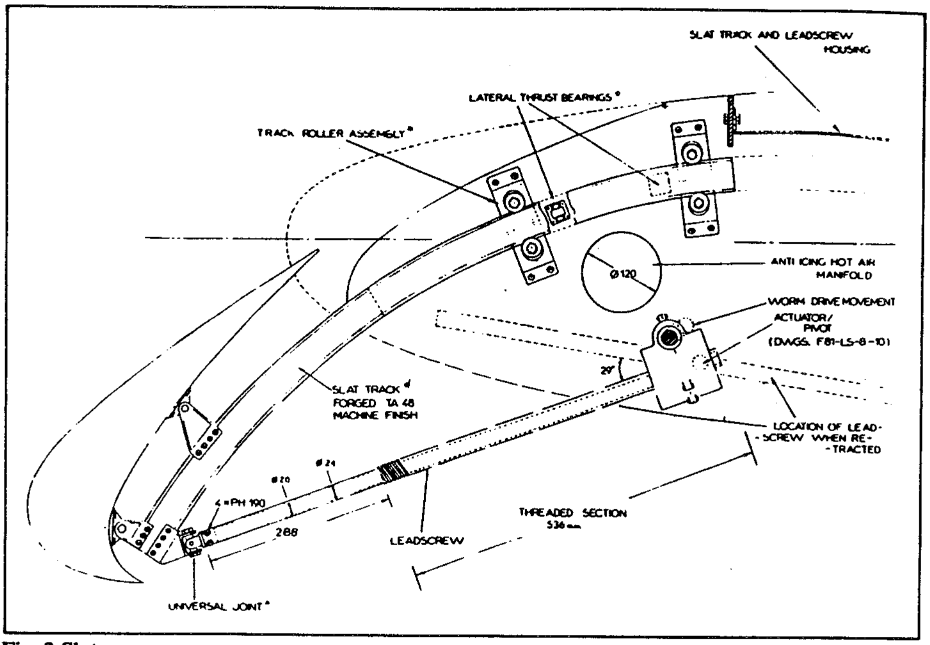

Fig. 3 Slat

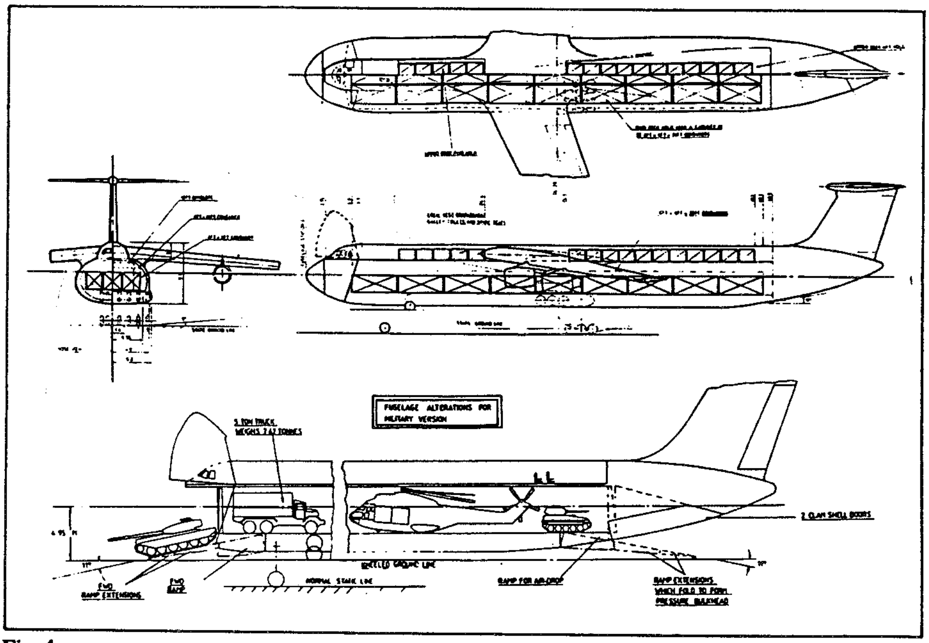

Fig. 4

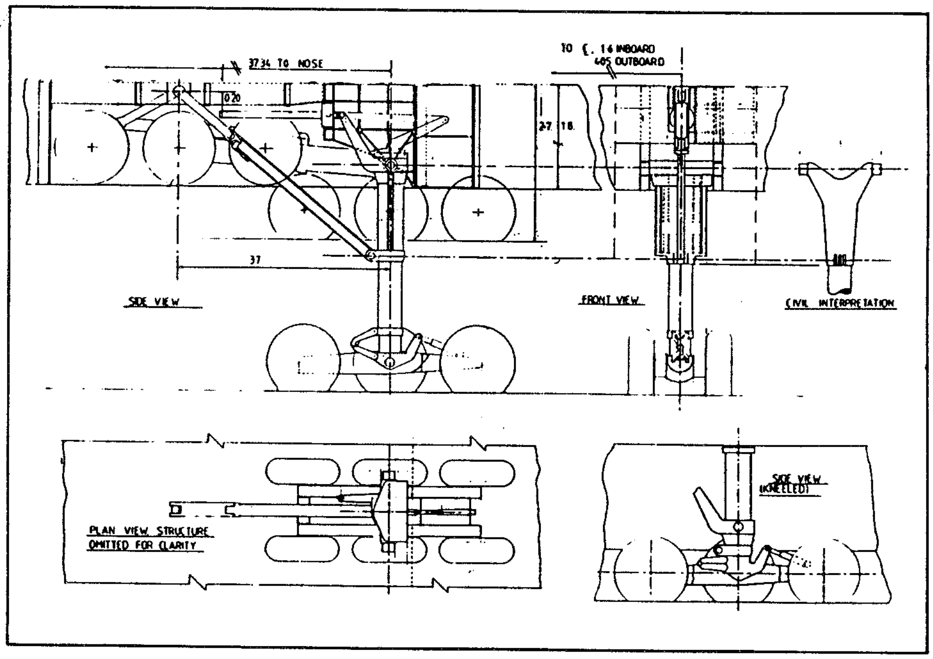

Fig. 5 Main Undercarriage

ratio is 11 and there is sufficient fuel tankage in the wing for a range of 4000 n. miles with reserves. The very high aspect ratio improves fuel burn and airfield performance. The large bending moments produced by such a wing are alleviated by "active" ailerons which modify the air-load distribution. Single-slotted Fowler flaps, moderate wing loading, spoilers and the high aspect ratio give adequate field performance which may be augmented by leading edge slats for military operations.

Fig. 2 shows the final configuration of the wing centre-section structure and Fig. 3 shows the optional wing slats.

Fuselage

The aircraft uses an extremely large fuselage. The main freight hold has a parallel section wide enough to accomodate three 8' x 8' x 20' containers side by side together with two walk ways. The elliptical section gives a maximum height of 10 ft at the corners of the compartments which can be used for LD-7 "igloo" containers or passengers. The normal freight loading is by means of the large nose 'visor' door. In military versions, this may be augmented by nose ramps which, when combined with a kneeling undercarriage, give an 11° drive on ramp. Provision is also made for a rear ramp door for the air-dropping of military supplies.

If the aircraft were used in an all passenger role, the high density capacity would be 1000 passengers on three floors.

Fig. 4 shows the fuselage configuration for both civil and military roles. The novel "ellipse plus semi-circle" cross-section produced the expected frame analysis and excess weight difficulties but provided an uncluttered freight hold to maximise volume and ease freight loading.

Engines

The aircraft uses four wing pod mounted RB211–524D engines which have good fuel comsumption, performance and noise characteristics. It is envisaged that by the mid 1990's, these engines or their derivatives should have had their fuel consumption improved by 13%.

Tail Unit

The aircraft utilises a moveable high TEE tailplane for trimming and an active elevator for control. The large size of the aircraft makes it possible for maintainers to climb an internal fin ladder to gain access to the tailplane.

Undercarriage

The maximum take-off mass of some 436 tonnes produced formidable runway flotation problems. The solution was to utilise 28 identical wheels and tyres distributed on one nose-leg and four main leg units. The nose unit utilises four wheels in line-abreast on a single axle. The main legs are also in line abreast and each utilises a six-wheel bogie. The military freighter requirements led to kneeling nose and mainwheel units to lower the fuselage to enable vehicles to drive on and off the freight hold. The civil version would use simpler and lighter units. Fig. 5 shows a military main wheel assembly.

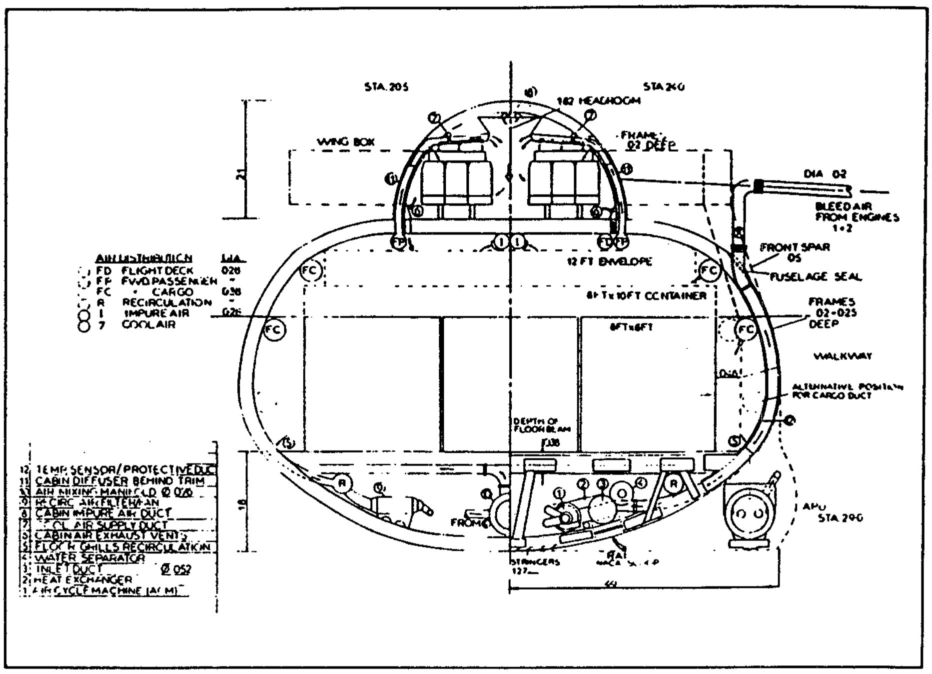

Fig. 6 E.C.S. Components

Mechanical Systems

Designs were carried out for fuel, flying controls and environmental control systems. They utilised conventional, very large aircraft philosophies typified by the Boeing 747. Fig. 6 shows part of the ECS system.

Predicted Performance

The table summarises the main feature of aircraft dimensions, weights and performance.

References

1 NASA CR 158950 Cargo logistics airlift system study Vol IV.

2 Article – Heavy lift aircraft studied by Air Force – *Aviation Week and Space Technology*. February 23rd 1981.

3 DES 8100 – A large advanced freight aircraft – F.81. Dr J.P. Fielding – College of Aeronatics, Cranfield Institute of Technology, November 1981.

AIRCRAFT DATA	
PERFORMANCE	
Maximum cruise speed – 173 m/sec EAS or M = 0.75	
Range with M = 0.75, 35,000 ft cruise and 15% reserves:	
Max. Civil payload (156 tonnes) =	6400 km
98 tonnes payload and extended max. fuel =	9700 km
MASSES	
Structure	102259 kg
As prepared for service (APS)	139005 kg
Max. landing mass	414048 kg
Max. take-off mass	435840 kg
DIMENSIONS	
Wing span	87.2 m
Gross wing area	688.9 m
Aspect ratio	11.04 m
Sweep of 0.25c line	25°
Fuselage overall length	78.6 m
Internal width of main hold floor	8.6 m
Max. height of main hold	3.94 m
Max. length of main hold	57.2 m
POWER PLANTS	
4 Rolls Royce RB211-524D turbofan engines with sea level static rating of 235.75 kN.	

A-82

An Advanced Short Range Airliner Design Project

by Dr John Fielding, Lecturer in Aircraft Design College of Aeronautics, Cranfield Institute of Technology

John P. Fielding, MSc, PhD, CEng, MRAeS, MSaRS, has been a lecturer in Aircraft Design at Cranfield Institute of Technology since 1978 and he is responsible for the annual MSc aircraft design group project and course tutor for the MSc design course. Specialist in research and teaching in aircraft initial project design, reliability and maintainability, and computer-aided design.

Born in 1945, worked for A. V. Roe (later Hawker Siddeley Aviation) between 1962 and 1975. During this time served an engineering apprenticeship, worked as a stressman and then became a design engineer on the HS748 and BAe 146 airliner projects. Was the first ARB Research Fellow at Cranfield between 1975 and 1977, studying the feedback of reliability information between operational aircraft and designers.

He published five technical papers at conferences, five papers in technical journals and gave the 21st Newton Lecture at King's School, Grantham.

The reference number of this paper is 1245.

The Overall Project Programme

The College of Aeronautics adopts a pragmatic approach to the teaching of aircraft design. Students will only be awarded an MSc degree if they have proved that they have the ability to produce workable, realistic designs in which all of the major problems have been addressed. This ability is assessed by means of annual group projects in which relevant aircraft types are studied, in this case an advanced short-range airliner.

It was felt that the current market presented an attractive climate for the launch of such an aircraft. The three major factors leading to this opportunity were considered to be:

(i) Noise legislation will make most current noisy aircraft unusable after 1985 without considerable modification.

(ii) Rapid fuel price increases in recent years have given a marked stimulus to requirements for more fuel-efficient aircraft.

(iii) There have been many improvements in aircraft equipment which can considerably reduce operating costs.

Figure 1 shows the types of aircraft that must be replaced and some of the options that are available.

A conceptual design study was performed by the author, based on the specification shown in this article. This process determined the basic shape of the aircraft together with weight, aerodynamic and loading information. This work was summarised in Ref 1, which was presented to each student at the start of the academic year. Twenty-one students were then allocated the responsibility for the detail design of a major part of the aircraft. These responsibilities took the form of a major structural component, such as the forward fuselage, a flying control surface or a mechanical system such as fuel, environmental control or the active control system. Each student was expected to act as designer, stressman and draughtsman for his component.

The project was managed to an exacting eight month programme by means of the weekly project meetings where students reported on progress, received advice and instructions for subseqent work. The most important role of the meetings however, was that of a forum where design compromises were resolved and students gained an appreciation of the problems being encountered on other parts of the aircraft.

The programme ended in May 1983, with the submission of voluminous project theses containing detailed drawings and calculations. It has been estimated that at least 20,000 manhours were spent on the programme, which produced some excellent design work and gave the students considerable design experience.

The knowledge gained during lectures, project meetings and discussions with members of staff, was augmented by several valuable visits. Westland Aircraft Ltd provided a good example of the production of large scale carbon fibre components as well as background knowledge of helicopter production.

A visit to British Aerospace Chester provided valuable insights into the production of what are, arguably, the most advanced airliner wings in service. The BAe 125 production line also showed examples of bonded aircraft structures. No design programme would be complete without a visit to a company operating the type of aircraft being designed. Two visits were therefore made to Britannia Airways' maintenance hangar where minute examinations were made of Boeing 737 aircraft which were undergoing maintenance.

The Design Specification

The most important aircraft to be replaced is the Boeing 727, which formed the basis

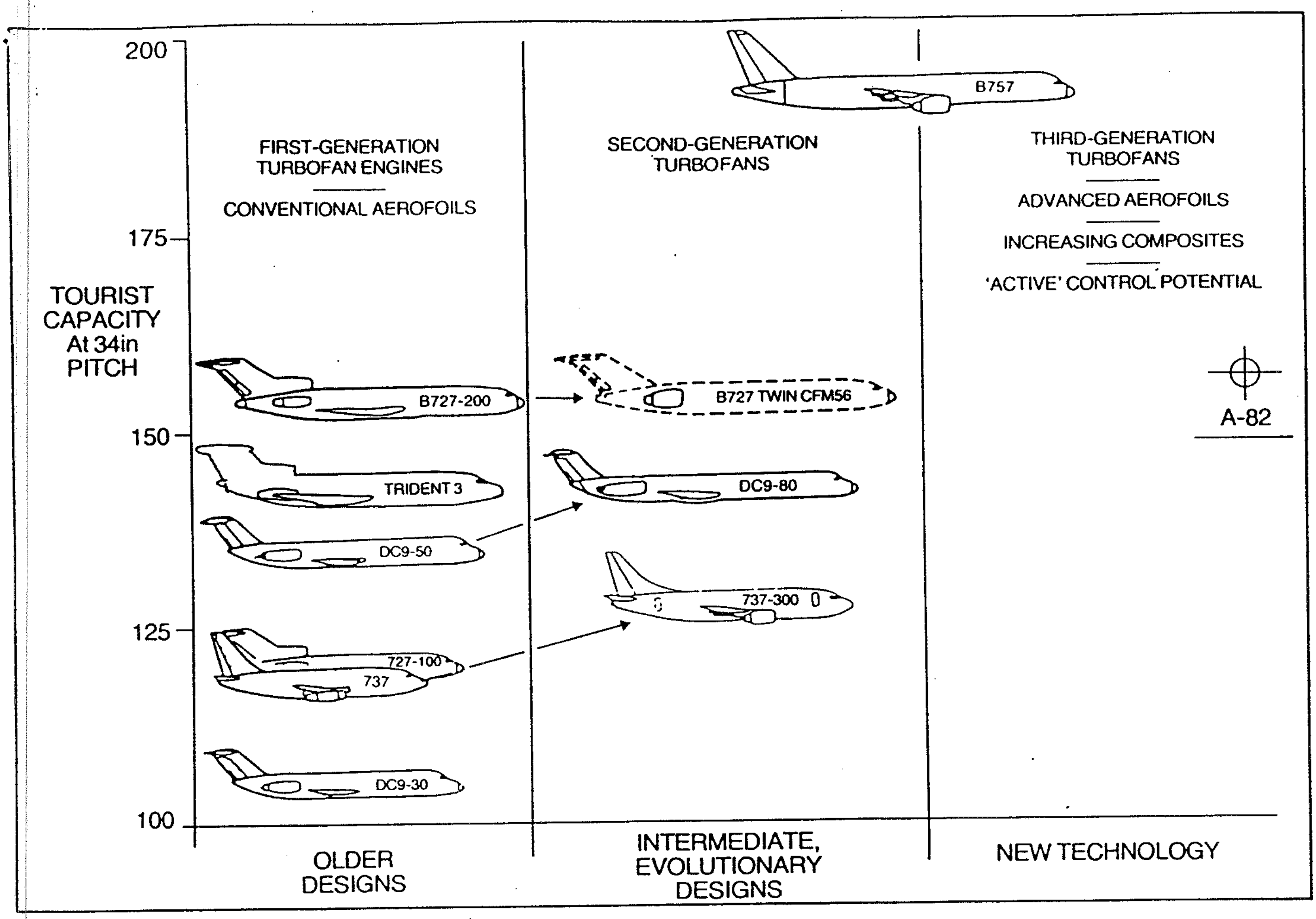

Fig 1. Types of aircraft to be replaced and some options.

of two recent Airline Specifications. The first was that of the very successful American airline — Delta (Ref 2). Several major European airlines also produced a composite specification which had many similarities (Ref 3). These documents were amalgamated to produce a specification, the major points of which are shown below:

Interior layout

Capacity
One-hundred and fifty mixed-class passengers with 138 tourists at 32in pitch and 12 first-class at 36in pitch. Comfort standards shall be at least as good as those of the Boeing 727.

Five attendants seats with sufficient galley space for 150 hot meals, three or four toilets and specified stowage space.

The flight deck shall be designed for a two-man crew with an option for a third.

Cargo
Baggage space should be determined by assuming 4cu ft per seat minimum. Cargo space should be an additional 4cu ft per seat. Cargo doors should be the same height as the bin interior height and be located so that loading can be accomplished without a mechanical loading system.

Performance
The operating fleet average trip length is 370 statute miles.

The minimum trip length with a full space limit payload shall be 1,000 statute miles. Passenger and bag payload range shall be approximately 1400 statute miles with FAR reserves.

The maximum design cruise speed will be approximately Mach 0.83 with minimum cost cruise at Mach 0.76-0.78. Maximum approach speed will be 130 knots.

Maximum cruise altitude should be around 39,000ft with initial cruise altitude of 31,000ft.

Fuel efficiency targets are:

Trip length (SM)	Available Seat Miles/US gall
400	77.6
600	85.0
1000	92.0

at full passenger and baggage payload.

Maximum certificated runway for 370 statute mile trip with space limit payload is 6,000ft for takeoff on a 90° day at sea level.

The dry FAR landing distance with maximum payload and standard reserves should not exceed 4,600ft at 2,000ft altitude with a 35kt crosswind.

Runway loading should not exceed that of a 727-200 at 195,000lb taxi weight.

Exterior noise levels should be lower than FAR 36 stage 3.

General
The major design objectives are to include minimum seat-mile costs with maximum passenger comfort. It is expected that the aircraft will use the latest aerodynamic systems and material technology consistent with maximum service life reliability and maintainability.

Description of the final design

The main difference between the A-82 and comparable aircraft is that the structure is to be constructed of advanced composite materials, wherever possible. This should produce considerable weight savings and produce a smaller and lighter aircraft to meet the specification, with obvious fuel saving benefits. Research into the production and testing of carbon fibre components has been performed for many years at Cranfield. Comprehensive lecture courses were attended by the students who wrote computer programs which enabled optimum use to be made of the directional properties of the material. A representative of the Civil Aviation

Authority came to give advice on Certification of composite material design, together with suggested safety factors to allow for such problems as environmental deterioration, impact damage and lighting protection.

The four students working on the fuselage used the above information as inputs into a comprehensive Finite Element structural simulation of the fuselage, which gave valuable results.

Figure 2 shows a model of the final aircraft configuration, whilst Fig 3 shows the General Arrangement of the drawing of the aircraft. The major design features are discussed below and shown in much more details in Ref 4.

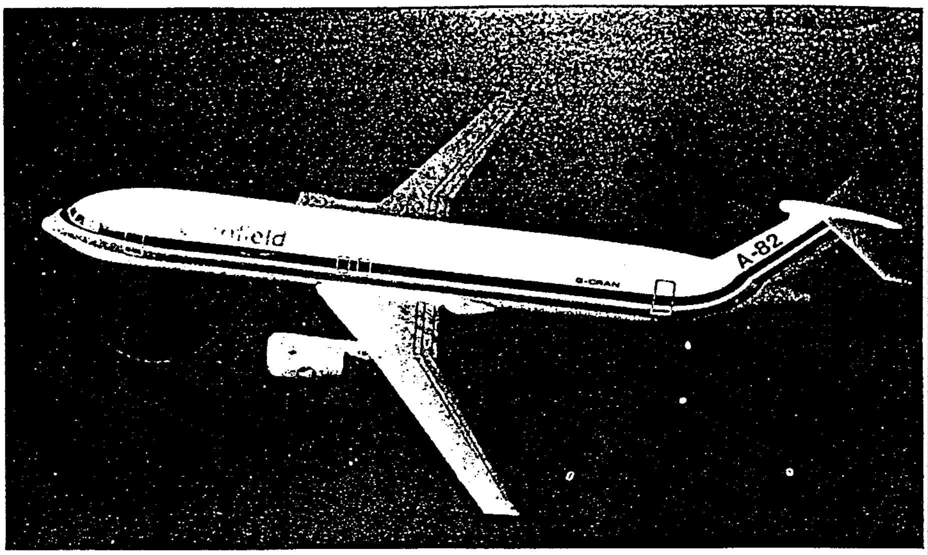

Fig 2. Model of the final aircraft configuration.

Wing

A moderate sweepback combined with a relatively thick supercritical wing section to enable cruise Mach numbers in the region of 0.83 to be achieved. The aspect ratio is 9.86 and there is sufficient full tankage at spec payload for a range of 1727 miles with FAR reserves. The high aspect ratio improves fuel burn and airfield performance. The large bending moments produced by such a wing were alleviated by "active" ailerons which modify the airload distribution. The ailerons are augmented by small inboard "active" flaps. The active system was designed to reduce the maximum wing bending moment by 33% so that in the event of a system failure the aircraft could be flown home with reduced manoeuvring capability. The very slender wing posed aeroelastic problems that were solved by the use of high modulus carbon fibre construction protected by an outer layer of impact-resistant KEVLAR composite material. Slotted Fowler flaps, slats, moderate wing loading, spoilers and the high aspect ratio give adequate field performance.

Doubt was expressed as to the bird-impact resistance of composite slats. Use was made of fluid de-icing because of potential thermal problems associated with the use of hot-air in composite slats.

Fuselage (Fig 4)

The circular-section fuselage permits single-aisle, six-abreast seating in greater comfort than in the 727. The under-floor holds permit the carriage of

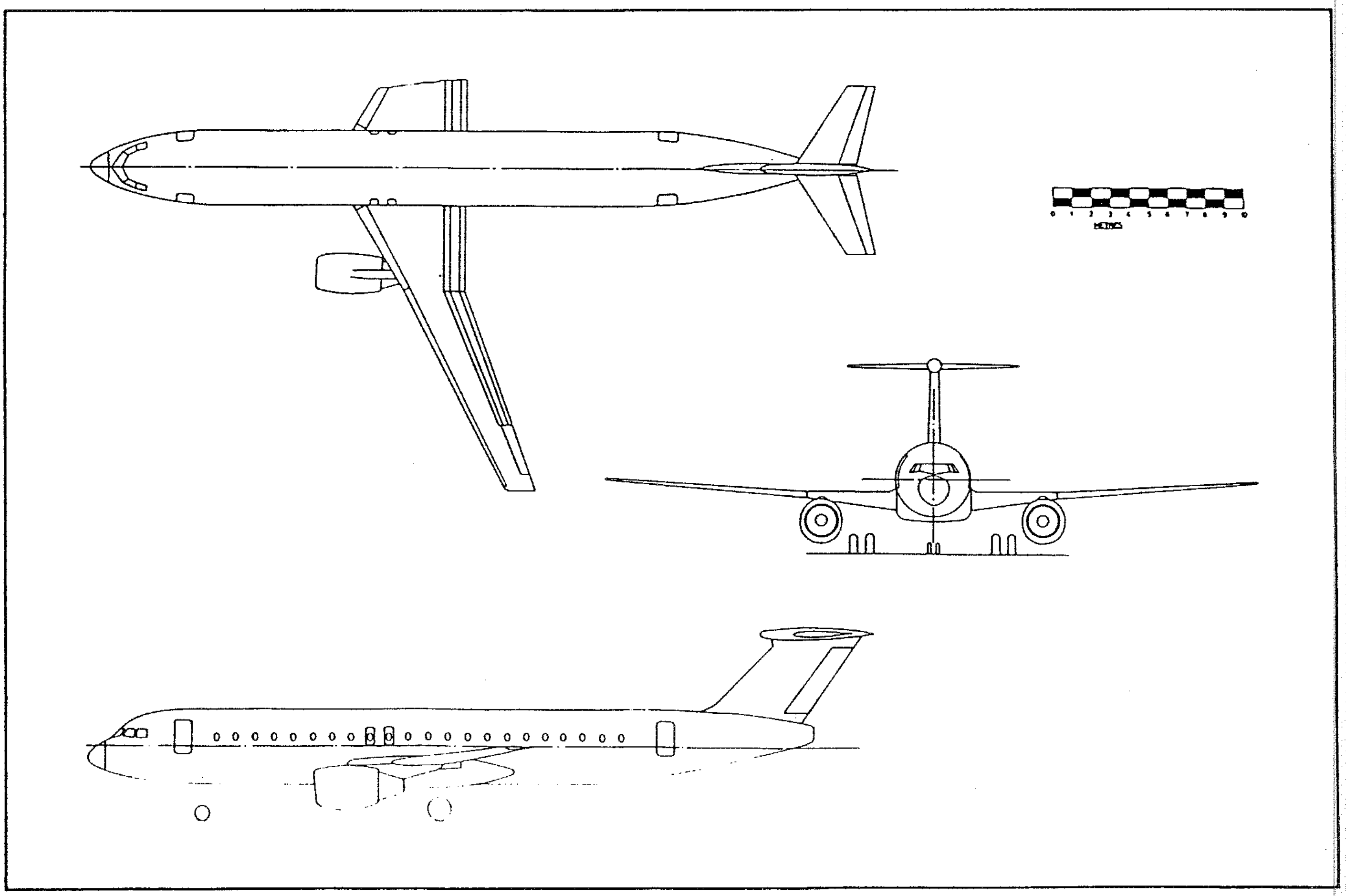

Fig 3. General Arrangement drawing of the aircraft.

727/707 type containers. The seating arrangements are as in the specification but an alternative layout accommodates 162 passengers at 32in seat pitch.

Mention has already been made of the use of the finite element model of the fuselage. This was extensively used in the design process and several novel features were used to make the best use of composite materials. Figure 5 shows how the skins were designed for the honey comb sandwich construction of the rear fuselage. Extensive design work was performed to investigate the fire-proofing of the auxiliary power unit in the tail of the aircraft.

A conventional all-moving tailplane is used, but studies were performed to investigate an "active" tailplane. The "bullet" fairing at the top of the fin allowed the use of a wide base for the tailplane pick-up with consequent weight savings.

Powerplant (Fig 6)
The aircraft uses two wing pod mounted RJ500 engines. This was a Rolls-Royce project engine for which that company supplied extensive information. The engine promised good fuel consumption, performance and noise characteristics but it has since been superseded by another project engine. The critical engine case was that of rapid engine deceleration due to such things as foreign object damage. This imposed a severe torque on the engine mounts, pylon and local wing structure. A computer program was written to optimise the aerodynamic shape of the nacelle.

Mechanical Systems
The aircraft utilises a conventional tricycle undercarriage with twin wheels on each leg. The main wheels retract sideways into an under fuselage fairing whilst the nose leg retracts fowards. The fuel is contained within conventional wing tanks and provision is made for extended-range versions of the aircraft by space provision in the wing centre-section. State of the art environmental control systems were designed with provision for cruise at an altitude of 40,000ft. Flying controls are actuated by means of hydraulic actuators which are signalled electrically for the active control system but have manual reversion.

Predicted Performance
Table 1 highlights the main dimensions and performance predictions for the aircraft. Comparison with the specification shows that the aircraft meets or exceeds most of the performance requirements.

The only shortfall is in the fuel efficiency performance. The aircraft almost meets the targets at longer ranges but is more deficient on short flights. The calculations made the rather pessimistic assumption that the average cruise altitude would be 31,000ft.

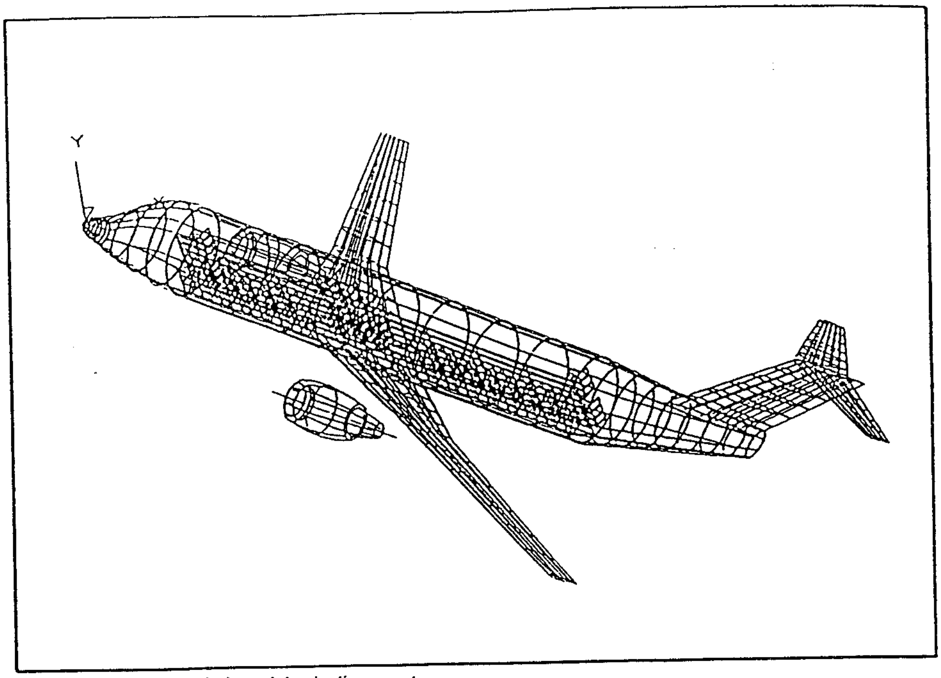

Fig 4. C.A.D. plot of aircraft including seats.

Table 2 summarises the predicted aircraft component masses.

The predicted performance is based on relatively simple drag and weight predictions but the work carried out by the students went some way towards confirming the latter although much more work would be required for absolute confidence. Comparison with other projects designed to meet the same specification shows that the extensive use of composite materials gives significant performance advantages. Initial work suggests that the inherent problems associated with the use of composites can be overcome but more research is required to verify this.

One interesting result of this exercise can be seen by examination of the aircraft general arrangement. The wing is considerably smaller than that of a conventional metal aircraft because it has to support less aircraft mass, but the fuselage remains the same size because passengers do not get any smaller!

A simple cost prediction program was written, based on the Boeing cost method. This was used to assess the predicted first and operating costs of the A-82 aircraft. This program used empirical data based on the weight of conventional construction methods and was considered to be slightly optimistic in terms of aircraft structure costs. A comparison was made between the A-82 and an aircraft designed to meet the same specification, which used mainly aluminium construction methods. The aerodynamics and powerplants were similar but the airframe was some 20% heavier. The predicted cost savings of the A-82 relative to this aircraft, based on 162 passengers at a 3,000km range were:

Direct Operating Cost per aircraft km	= 11.2%
Total Operating Cost per aircraft km	= 8.9%
Aircraft first cost	= 19%

The assumptions made in the calculation of DOC were reasonable but the latter two figures are slightly optimistic because of higher airframe production costs in composites. The cost program should be modified as information becomes available.

Conclusions

The design programme fulfilled its main aim of providing a powerful means of training designers. The use of a challenging and interesting project was a means of investigating many of the problem areas of such an aircraft, and produced some good detail design work.

The aircraft that was designed showed considerable promise but required further work to confirm the performance predictions. The information that was available to determine the predicted Direct Operating Costs of the aircraft showed that that weight savings due to the use of composites should produce operating cost savings.

References

1. DES 8200. Fielding, Dr J. P., College of Aeronautics, Cranfield Institute of Technology, Cranfield, Bedford. February 1983.
2. Short Range Airplane Requirements. Delta Air Lines, Atlanta, Georgia, USA March 1981.
3. Requirements for Short/Medium Range Aircraft for the 1980s. Association of European Airlines. January 1978.
4. Cranfield Institute of Technology Project Design MSc Theses 1983/4:

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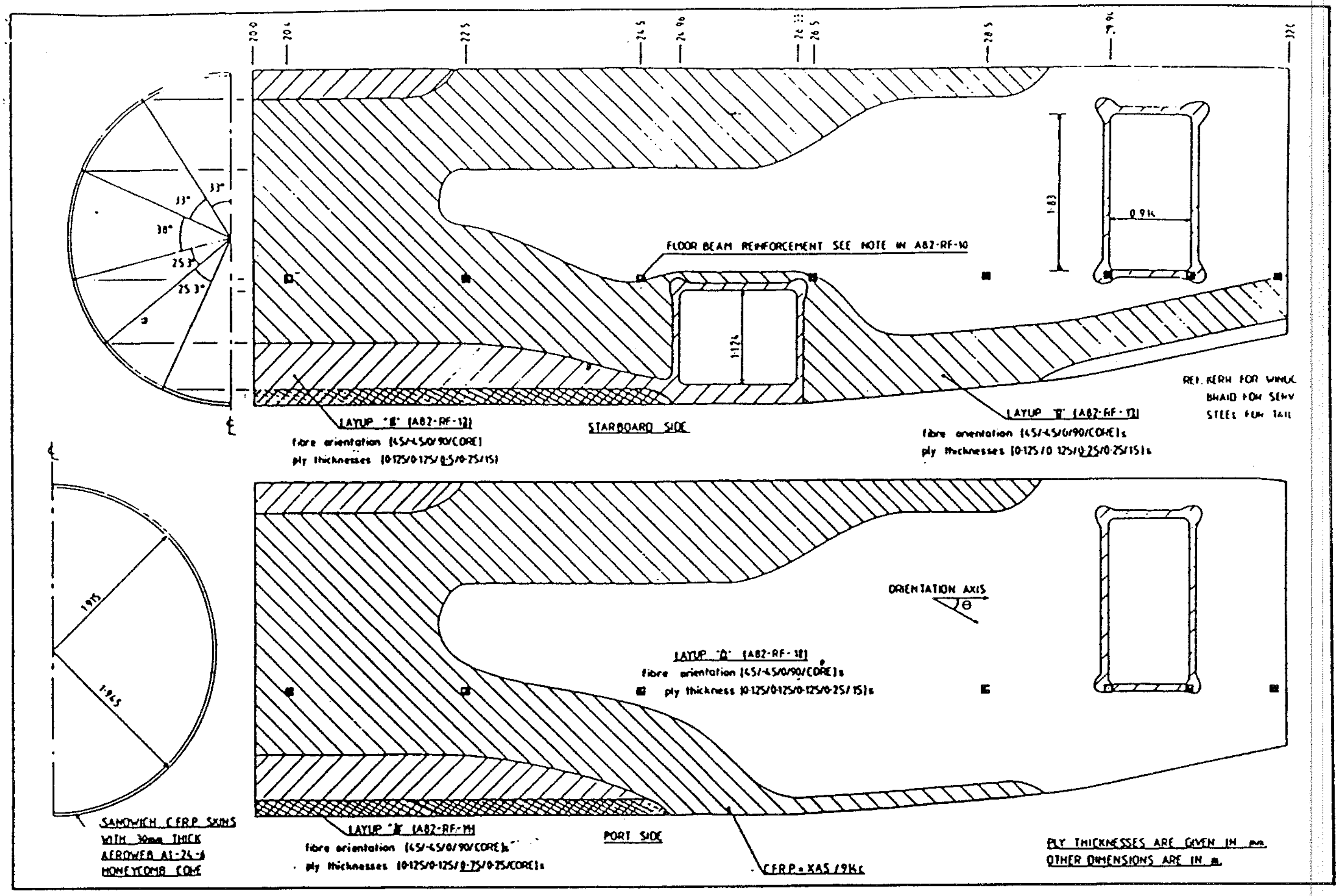


Fig 5. Rear fuselage composite lay up pattern.

TABLE 1
ESTIMATED PERFORMANCE AND DIMENSIONS

PERFORMANCE	A-82	SPECIFICATION
Maximum Cruise Mach No	0.83	0.83
Range with volume limited payload, ISA, Mach 0.77, 33,000ft. FAR reserves	1,772km (1,100 st miles)	1,000 st miles
Range with 162 passengers + baggage at the same conditions as above	2,780km (1,727 st miles)	1,400 st miles
Take off to spec conditions	5,100ft (1,555m)	6,000ft
FAR landing to spec conditions	4,580ft (1,400m)	4,600
ASM/US gallon: 400 SM	70.2	77.6
600 SM	82.7	85.0
1000 SM	91.5	92.0
At full passenger and bag payload ISA, FAR reserves, fuel density 787kg/cu m		
MASSES		
Structure	14,630kg	
Operating Empty Mass	33,516kg	
Max Landing Mass	53,653kg	
Max All Up Mass	58,959kg	
Minimum Payload	18,110kg	
DIMENSIONS		
Wing section based on RAE9550 Root t/c	15%	
Kink t/c	11%	
Tip t/c	10%	
Wing span	33.7m	
Gross wing area	115.24sq m	
Sweep of 0.25c line	25°	
Fuselage length	38.1m	
Maximum fuselage diameter	3.89m	
POWERPLANTS		
2 Rolls Royce RJ500 turbofan engines, Sea level Static Thrust	97.86kN	

TABLE 2 MASS BREAKDOWN

COMPONENT	MASS KG	% AUM
Wings (inc auxiliary surfaces struct)	4,543	7.70
Fuselage	6,342	10.76
Fin (inc rudder)	637	1.08
Tailplane (inc elevator)	789	1.34
Main undercarriage	1,956	3.32
Nose undercarriage	363	0.61
STRUCTURE	14,630	24.81
Engines (dressed)	3,738	6.33
Powerplant struct (pylons, cowlings)	1,645	2.80
POWERPLANT	5,383	9.13
Fuel System	448	0.76
Flying controls system	621	1.05
Hydraulics	785	1.33
Electrical system	1,453	2.46
Aux power unit	363	0.61
Instruments and avionics	1.071	1.82
Wing de-ice	345	0.59
Paint	53	0.09
Fire protection	177	0.30
Furnishings (inc seats, galleys etc)	5,682	9.46
Environmental control	689	1.17
BASIC EMPTY MASS	31,700	53.76
Crew and provisions	527	0.89
Operating weight empty allowance	1,289	2.19
OPERATING EMPTY MASS	33,516	56.84
Max passenger and baggage (162 seats)	14,710	24.95
Fuel at above payload	10,733	18.21
MAX ALL UP MASS	58,959	100.00

Continued from page 14

Alderman — Flying Control System (mechanical)
Braid — Nose fuselage (inc nose u/c installation)
Chodera — Tailplane
Edge — Fin
El-Hag — Main landing gear
Hensor — Outer wing
Hinshelwood — Fuel System
Holden — Trailing edge flaps
Jackson — Ailerons
Kerr — Centre fuselage
Kobayashi — Elevators
Martyn — Engine pylon
Medeiros — Environmental control system
Murphy — Rear fuselage
Nicholas — Inner wing
Power — Active control system
Smith — Leading edge devices
Steele — Tail fuselage
Theophilou — Engine installation
Viruchkul — Spoilers
Wells — Rudder

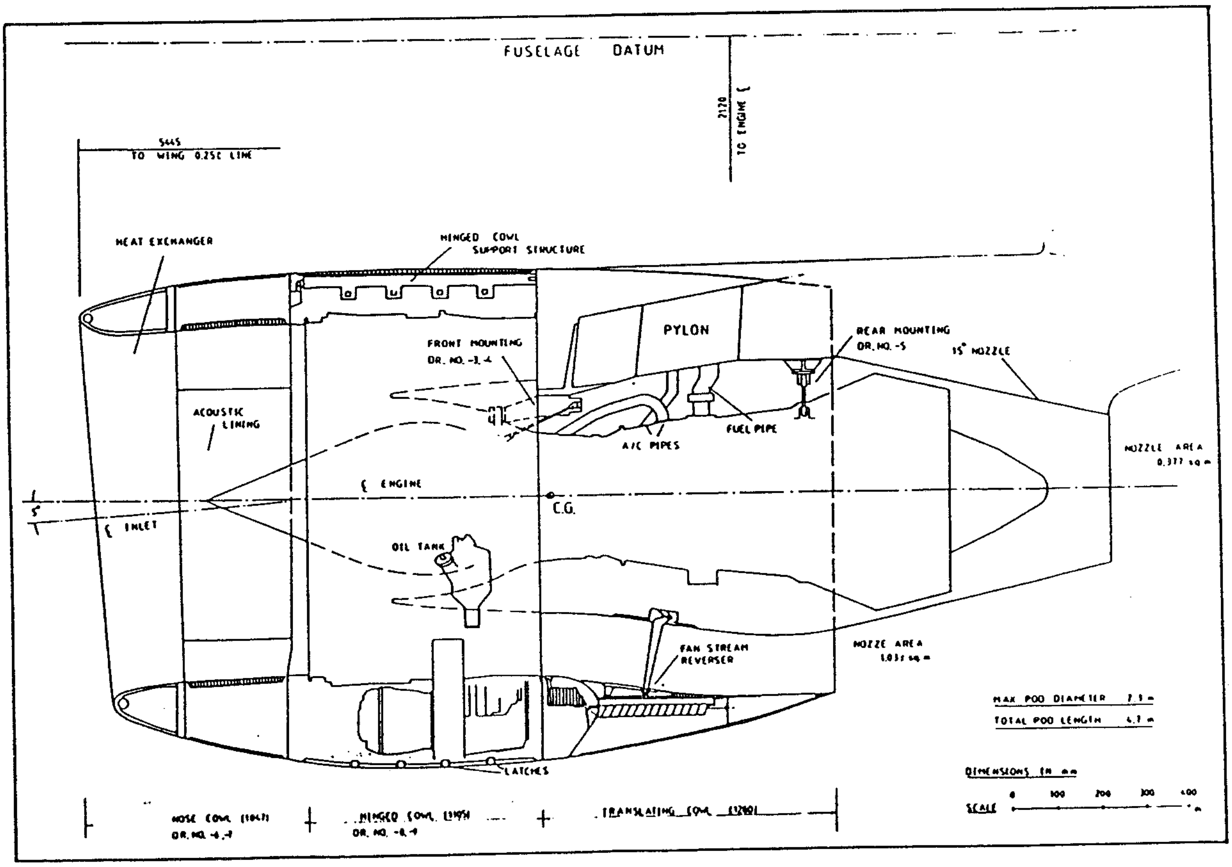
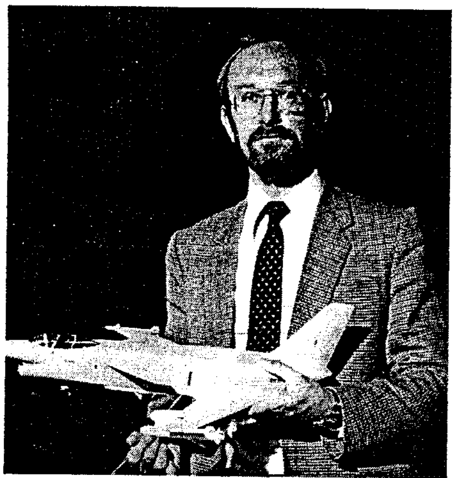


Fig 6. Powerplant arrangement.

The S-83 Design Project, a Supersonic V/STOL Fighter with Forward Swept Wings

by Dr John Fielding, Lecturer in Aircraft Design



Dr John Fielding

1. The Overall Project Programme

The College of Aeronautics teaches aircraft design by using a combination of theoretical and practical instruction. Students will only be awarded an MSc degree if they have proved that they can produce an acceptable piece of individual research, together with proof of design competence. The latter ability is assessed by means of individual contributions made towards the group design project. Project subjects are chosen which are representative of current areas of interest in aircraft design. The 1983/84 choice was a supersonic V/STOL fighter.

There have been many attempts to develop V/STOL, but most of them have been abortive. The outstanding exception has been the Kestrel/Harrier/Sea Harrier family of aircraft. The great success of these aircraft has prompted many studies for follow-on aircraft for both land and ship-based operations. The most publicised specification was that proposed by the US Navy in 1977. The main points of this specification were:

- Naval operations,
- High performance V/STOL fighter/attack aircraft,
- Supersonic dash capability with sustained Mach number capability of at least 1.6,
- Operational from land and from ships smaller than CV's without catapults and arresting gear — good short take-off capability,
- Sustained load factor of 6.2 at Mach 0.6, 10,000 ft altitude at 88% VTOL gross weight,
- Specific excess power at 1g (ps 1g) of 274 m/s (90 ft/s) at Mach 0.9, 10,000 ft altitude at 88% VTOL gross weight.

This specification was used as the basis of the S-80 design project (refs. 1 and 2). This aircraft was a close-coupled canard which used an aft-swept cropped delta wing.

Recent research work with composite materials, and forward swept wings suggested that the S-80 might benefit from the use of forward sweep. Ref. 3 investigated this possibility and formed the starting point for the current study.

The next part of the programme was the conceptual design of the S-83 by the author. This process determined the basic shape of the aircraft together with weight, aerodynamic and loading information. This work was summarised in ref. 4, which was presented to the fourteen students working on the project at the start of the academic year. Each student was given responsibility for the design, stressing and fatigue analysis of a major structural part of the aircraft such as forward fuselage, inner wing, foreplane, etc. Some of the students designed systems such as fuel, flying controls, weapons installations and undercarriage.

Figure 1. One of the S-83 Project meetings

The project was managed to an exacting eight month programme by means of weekly project meetings where students reported on progress, received advice and instructions for subsequent work. Fig. 1 shows an S-83 project meeting in progress. The most important role of the meetings was that of a forum where design conflicts were resolved and students gained an appreciation of problems being encountered on other parts of the aircraft.

Sub-groups were formed to work on common loading problems and local interfaces were sorted out.

The knowledge gained during lectures, project meetings and discussions with members of staff was augmented by several valuable visits. The USAF station at Upper Heyford afforded an invaluable opportunity to study the layout and construction of supersonic F-111 fighters. Other supersonic aircraft were also seen at the Imperial War Museum at Duxford and modern composite material production techniques were examined at the British Aerospace factory at Stevenage.

Special lectures gave insight into Sea Harrier operations in the Falklands, cost engineering techniques and the avionics and weapon installations of the S-83.

The programme ended in May 1984 after the project design theses had been submitted. A model of the final aircraft configuration was made, a photograph of which is shown as Fig. 2.

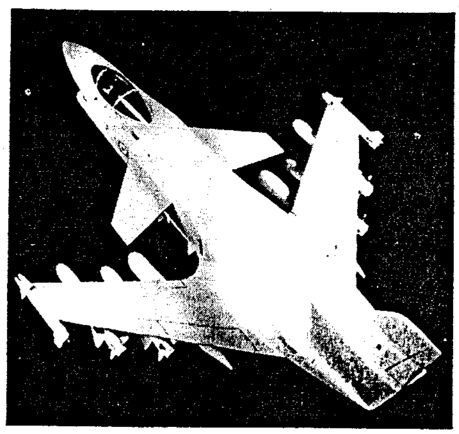


Figure 2. Model of the S-83

2. Description of the Final Design

It was decided to retain a considerable amount of the earlier S-80 design but, in practice, only the powerplant arrangement was retained. An early decision that was made was that the airframe would be constructed primarily of carbon fibre composites as these would be required to prevent divergence of the forward-swept wings (FSW).

Conventional alloy weight estimates were therefore reduced by the following factors:

Wing	=	20%
Fin and Canard	=	25%
Fuselage	=	20%
Undercarriage	=	10%

The aircraft was designed to have reduced vulnerability. The bulk of the fuel is in the fuselage, which reduces the exposed surface area relative to wing tanks. Allowance was made for some armour protection.

2.1 Wing and Canard Foreplane

A close-coupled canard arrangement was chosen because it gave improved lift characteristics for short take-off and combat. The foreplane enables the achievement of high angles of attack and improved area-ruling for reduced supersonic drag. Negative subsonic longitudinal stability combined with active controls gave improved aerodynamic performance.

The forward-swept wing has an aspect ratio of 4 and utilises a 5.9% thick supercritical aerofoil section. Claimed advantages of such a configuration summarised from Ref. 5 are:

(a) Configuration flexibility
(b) Significant higher manoeuvre lift/drag ratio
(c) Lower trim drag
(d) Lower stall speeds and slower landings
(e) Virtually spin proof
(f) Better low-speed handling
(g) Volume benefits and hence lower wave drag.

An obvious source of data on forward-swept wing aircraft was the X-29 aircraft programme. This aircraft, which first flew during the winter 1984/85, utilises a 29° swept wing. The S-83 uses a similar section wing but has a sweep angle of 35° as the cruise Mach No. of 1.6 is higher than that of the X-29.

A small percentage of fuel is carried in the S-83 wing, which is also used to mount the main undercarriage, the reaction control system for roll control in the hover, Sidewinder and Martel missiles and external fuel tanks in the sea patrol mission.

The wing has a very severe structural environment and extensive use was made of finite element modelling. This was particularly important at the vital undercarriage/inner wing interface (Fig. 3).

2.2 Fuselage (Fig. 4)

The forward fuselage contains a partially reclined ejector seat surmounted by a large canopy with good pilot visibility.

The aircraft utilises chin-mounted pitot intakes which ensure good engine airflow at high angles of attack and yaw, whilst minimising hot air re-ingestion from the forward nozzle. The intakes are kinked round the forward nozzle and occupy a considerable amount of fuselage volume, but area ruling was used to reduce wave drag and wing interference effects and this increased volume. The fuselage is also used to house the gun, the submerged part of the Skyflash missiles and the undercarriage.

The positions of fuselage-mounted weapons were slightly altered to better accommodate launchers and to ease reloading the gun.

Extensive use was made of the McAuto Computer-aided design system. It was used to define geometry and interfaces and enabled an accurate engine-removal check to be made. Figure 5 shows the forward fuselage scheme, which was based on the CAD system output. The bulk of the fuel was contained within integral tanks in the centre fuselage.

2.3 Powerplant

The aircraft uses the remote augmented lift system (RALS) developed by the General Electric Company. Two propulsion units are used, mounted side by side in the rear fuselage having variable cycle capability and a double bypass split fan to provide airflow to the single remote augmentor nozzle during vertical take-off and landing. Primary exhaust is through ADEN nozzles (Augmentor Deflector Exhaust Nozzle).

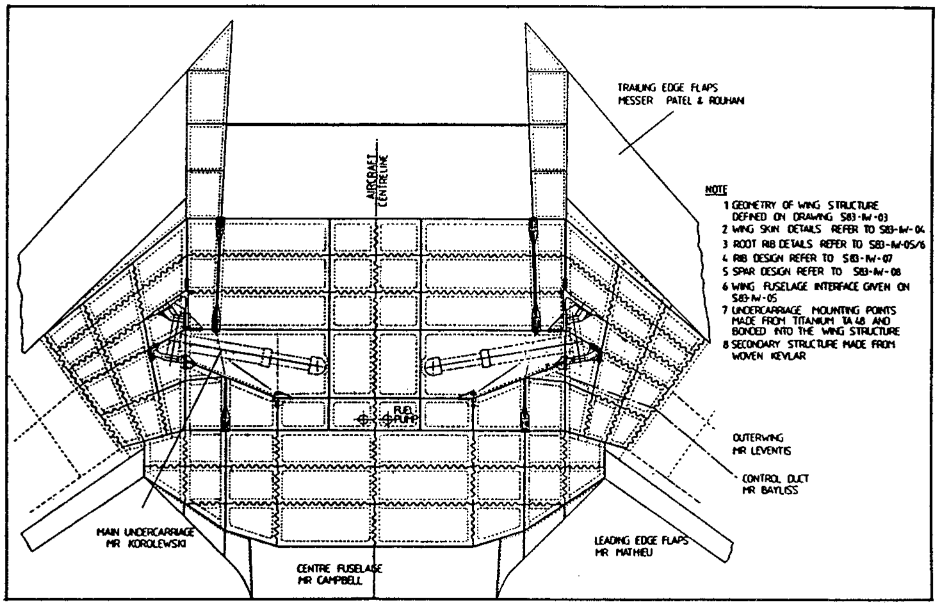


Figure 3. Plan view of inner wing structure

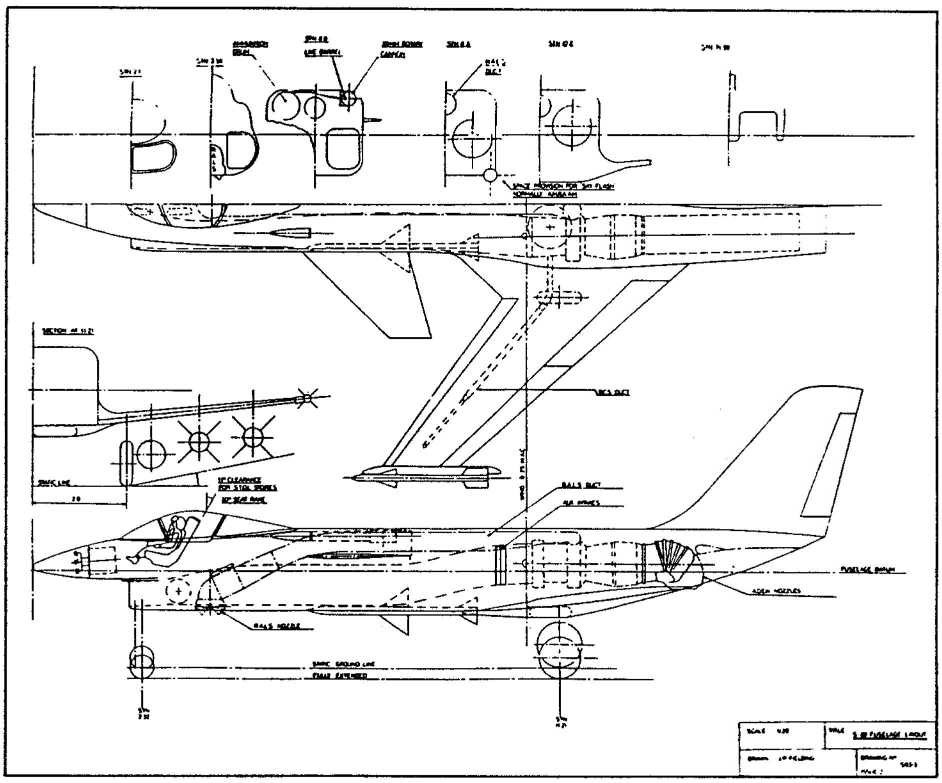


Figure 4. S-83 fuselage layout

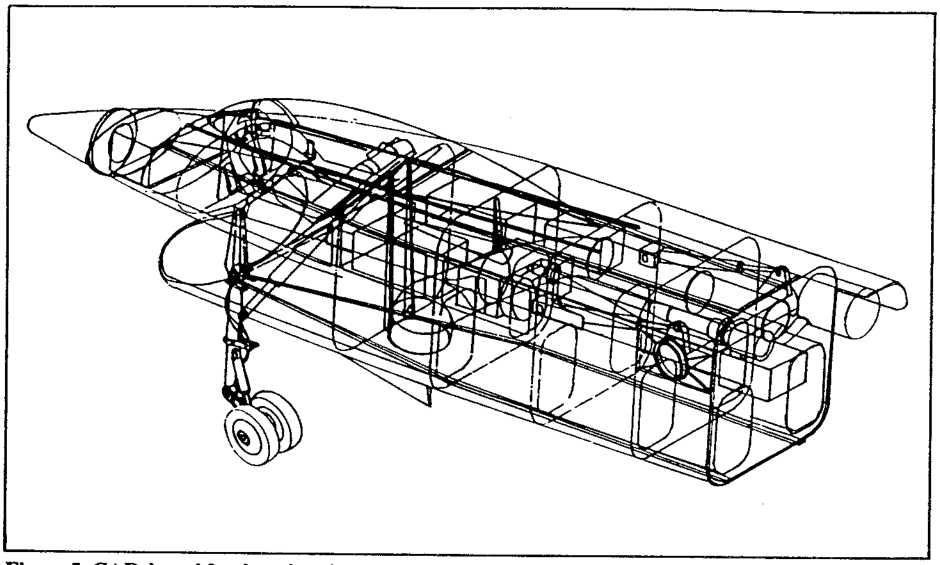


Figure 5. CAD-based fuselage drawing

2.4 Fin

The fin is sufficiently large to offset the instability effect of the forward-swept wing. It is sufficiently tall to be effective, even at high angles of attack. The structure was analysed using finite element techniques and uses a multi-spar carbon-fibre composite construction.

2.5 Undercarriage

It was decided to make the undercarriage suitable for use from semi-prepared air-strips. This made the wheels rather large, but it was felt that it was necessary to give the aircraft the ability to operate from beach heads in the STOL mode.

The main undercarriage legs mounted one wheel each. The initial scheme used a skew hinge attached to the wing front spar. The leg retracted forward into the wing root fillet. This configuration required a large wheel off-set which produced unacceptably high-loads. The final arrangement used a simpler retraction arrangement whereby the leg retracted into a cut-out in the inner wing and the wheel into an under-fuselage fairing.

Restrictions in fuselage volume required the use of pre-compression of the nose leg for stowage.

2.6 Weapons Installations

The payload for intercept is as follows:

2 short range missiles — AIM-9 Sidewinder or ASRAAM — Wing Tips,
2 medium range missiles — Skyflash or AMRAAM — Semi-recessed fuselage,
1 gun and ammunition — M61A1 20 mm six-barrel — fuselage — buried.

The payload for sea patrol is as follows:

2 short range missiles — Sidewinder or ASRAAM — Wing Tips
1 gun and ammunition — M61A1 — Fuselage — buried
4 air to surface missiles — Martel or Sea Eagle — Wing pylons
2 fuel tanks — 230 Imp. Gall. — Wing pylons..

The semi-active Skyflash and AMRAAM missiles are guided by a nose-mounted radar system.

3. Predicted Performance

The table shows the predicted performance and mass characteristics of the aircraft. Comparisons are made with the aft-swept S-80 project but differences in some masses and intake configurations make direct comparison difficult. The higher aspect-ratio FSW configuration reduced induced drag, but increased profile drag. It can be seen that this resulted in superior sustained turn rate performance for the FSW configuration. The increased profile drag of FSW at Mach 1.6 resulted in slightly reduced range relative to the S-80 but both aircraft had adequate performance. The use of relatively high aspect ratio gave a structural weight penalty, but this was largely off-set by a reduction in fuselage weight. This latter effect was not a direct result of FSW, indeed the fuselage had to be longer to provide a sufficiently long fin arm. The use of active controls in the pitch plane required extensive reliability calculations and equipment changes to meet the specified targets. Ref. 6 (Meng) describes this process for the generally similar flying control system of the S-80.

4. Conclusions

The group project exercise fulfilled its primary aim of being an important design teaching tool. There is no substitute for involvement in a realistic design environment. The use of such a challenging subject was daunting at times and many assumptions had to be made because of the programme timescale. Nevertheless, the study was a means of investigating many of the problem areas of an advanced aircraft with many novel features.

The resulting aircraft met most of the performance requirements but no clear case was made for the relative advantages of FSW for this aircraft. The FSW showed advantages in terms of supersonic manoeuvring but this was at the expense of a marginal degradation of supersonic cruise performance.

Much of the work depends on the use of relatively simple performance computer programs and estimates of stability and control characteristics. Work is currently being performed to investigate the latter within the College of Aeronautics.

5. References

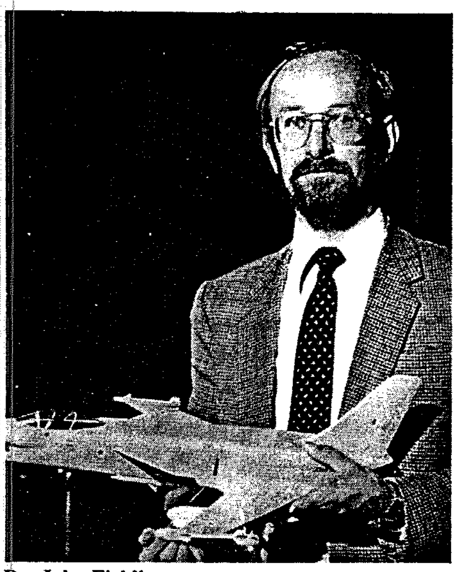
1. Naval V/STOL Fighter. Dr J. P. Fielding, College of Aeronautics, DES 8000.
2. A supersonic V/STOL fighter design project. Paper in the Journal of the Royal Aeronautical Society, August/September 1982, by Dr J. P. Fielding.
3. Assessment of certain merits of FSW and effect of the sign of the sweep angle on the stressing of a wing structure. A. Souahi, paper in the Aeronautical Journal of the Royal Aeronautical Society.
4. Supersonic naval V/STOL fighter with Forward Swept Wing — S83. Dr J. P. Fielding, College of Aeronautics, DES 8300.
5. Flight demonstration and the Forward Swept Wing. Paper by N. J. Krone, Bristol University, 1982.
6. Some aspects of the design of a 'Fly-by-Wire' flying control system for a supersonic V/STOL fighter aircraft. College of Aeronautics Report No. 8413. March 1983 by J. P. Fielding and X. Z. Meng.

S-83 FIGHTER WITH FORWARD-SWEPT WING LEADING PARTICULARS

		S83	S80	Specification
MAXIMUM CRUISE SPEED 650 KT EAS OR M (STRUCTURE LIMIT)	=	1.6	1.6	1.6
INTERCEPTION RADIUS — SUPERSONIC FLIGHT PROFILE (INC. COMBAT FUEL ALLOWANCE)	=	175 N. MILES	180 N. MILES	150-200
SUSTAINED TURN RATE, COMBAT WT, MACH 0.6 10,000 FT ALTITUDE, DRY	=	6 'G'	5.7 'G'	
WITH AFTER BURNER 30% AUGMENTATION	=	7 'G'	6.6 'G'	6.2 'G'
VTOL TAKE-OFF MASS	=	14030 KG	14030 KG	
OPERATING ZERO FUEL MASS	=	8997 KG	8860 KG	
WING SPAN	=	11.31 M	9.914 M	
WING AREA	=	32.0 M^2	38.2 M^2	
ASPECT RATIO	=	4.0	2.2	
WING SWEEP FORWARD/AFT	=	-35°	50°	
FUSELAGE LENGTH	=	16.98 M	15.6M	

The T-84 Group Design Project – an Aircraft Designed to Replace the Jet Provost

By Dr. John Fielding — Senior Lecturer in Aircraft Designs



Dr. John Fielding

The Requirement

The Jet Provost twin seat aircraft has been used as the basic jet trainer by the Royal Air Force since the mid fifties. During this time, it has been progressively developed from the original Piston Provost conversion to include ejection seats, engines of greater thrust and cabin pressurisation. The latest mark in service is the T Mk 5A.

The T Mk 3 variant of the design has now been in service for over 22 years and the more modern T Mk 5 for 15 years. The RAF now requires a new aircraft to replace the Jet Provost before the need to embark upon an expensive fatigue modification programme arises. Furthermore, the Jet Provost design incorporates the Viper engine which is both noisy and has a very high fuel consumption.

The RAF recognised the need for a replacement for the Jet Provost by the issue of Air Staff Target No. 412. This set out design features which have been summarised below:

(a) *Costs*

Preliminary studies indicate that a new turbo-propeller or turbo-fan aircraft would provide performance and handling qualities appropriate to the basic training task adequate for leading onto the Hawk for advanced training. Substantially lower operating costs and significantly better reliability and maintainability than offered by the Jet Provost are required.

(b) *Operating Speeds*

High operating speed is desirable because it makes possible the most efficient and flexible use of flight training time: the following speeds are the target minima.

Vno	270KCAS
Level speed, sea level, maximum continuous power	210-240 KCAS
Range speed, 20,000 feet	170 KTAS

(c) *Manoeuvrability*

Generally the aircraft manoeuvrability should conform to the appropriate design requirement of DEF STAN 00-970. Sustained turn rates of 2'g' at 20,000 ft are desirable.

(d) *Rate of Climb and Ceiling*

The aircraft should be capable of climbing to 15,000 feet within 7 minutes from brake release following take-off at maximum mass. The service ceiling should be at least 25,000 feet achievable direct from a take-off at maximum mass.

(e) *Airfield Performance*

Take-off and landing distances should not exceed 2000 feet on hard dry surfaces. The aircraft should be capable of routine operation in 25 kt crosswind components: the ability to operate in 30 kt crosswind components is desirable.

(f) *Crew*

The aircraft is to be capable of being flown with one or two crew throughout the flight envelope. Tandem seating for student and instructor is required. The cockpit should resemble that of the Hawk Trainer to the greatest possible extent.

The Overall Project Programme

The above requirement was of great interest to the aircraft industry during 1984 as it was the subject of a competition to replace the Royal Air Forces' Jet Provost aircraft. A large number of contenders had been whittled down to four when it was decided that the topic would be a suitable subject for a Cranfield design project. This type of project forms a major part of the MSc course in Aerospace Vehicle Design. Experience has shown that this sort of project is the best way to teach aircraft design in that it focuses the skills learnt in lectures, tutorials and other activities.

The whole design process started with the conceptual design of the aircraft, by the author, in the summer of 1984. This work was summarised in ref. 1, which was given to the 23 students in October of that year. Each student was given responsibility for the detail design, stressing and fatigue analysis of components such as forward fuselage, outer wing, boom etc. Some students designed mechanical systems such as fuel, flying controls, engine installations etc. One student undertook the vital work of designing to meet reliability and maintainability targets (refs. 2 & 3). The relatively large number of students enabled the achievement of parallel design of most of the structure in both metal and composite materials.

The project was managed to a demanding 8 month programme by means of weekly project meetings, where students reported progress, received advice and instructions for subsequent work. The most important function of these meetings was that of a forum where design conflicts were resolved. Sub-groups were formed to convert the author's aerodynamic, geometric and mass information into structure loads.

The knowledge gained during lectures, project meetings and discussions with members of staff was augmented by information from aircraft manufacturers and several visits. A particularly useful visit to RAF Cranwell gave a good insight into the operation and maintenance of Jet Provosts. Frank discussions with flying instructors were also valuable. A visit to examine the production line of the Optica aircraft was also of much interest. Visits of both the Firecracker and Tucano aircraft to Cranfield gave opportunities to examine these competing aircraft in considerable detail.

A considerable number of students used the McAUTO CAD system to help design their components and to define interfaces. A composite plot of the whole aircraft is shown at Fig. 1.

The programme ended in May 1985 with the submission of large design theses.

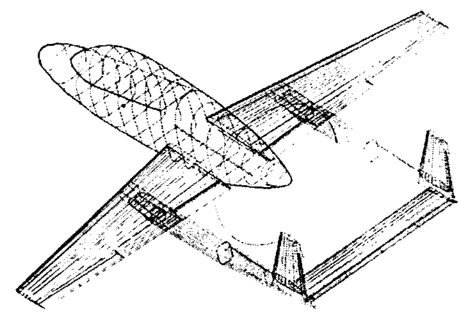


Figure 1. The T-84 aircraft

Description of the Final Design

Fuselage and Boom Arrangement

A primary requirement is that the aircraft should provide an environment within the cockpit which is as close as possible to that of the Hawk. The use of a twin-boom pusher arrangement removes the powerplant from the nose of the aircraft to enable the forward fuselage to have identical seat position and vision to that of the Hawk. This gives excellent vision for both the pupil and the instructor. The pusher arrangement gives clean fuselage lines, whilst the twin booms remove the tail-unit supporting structure away from the propeller disc. This is a simpler arrangement than mid-fuselage propellers and gives a more efficient structural solution. The booms also provide useful stowage for the undercarriage main units, which would otherwise interrupt the wing main structure. The fuselage provides adequate volume for the storage of crew, baggage, and space for the avionic and mechanical systems that are required. Fig. 2 shows a scheme of the structure of the metal forward fuselage. Mass comparison between it and its composite equivalent are shown in table 1 as are the values for all of the alternative construction components.

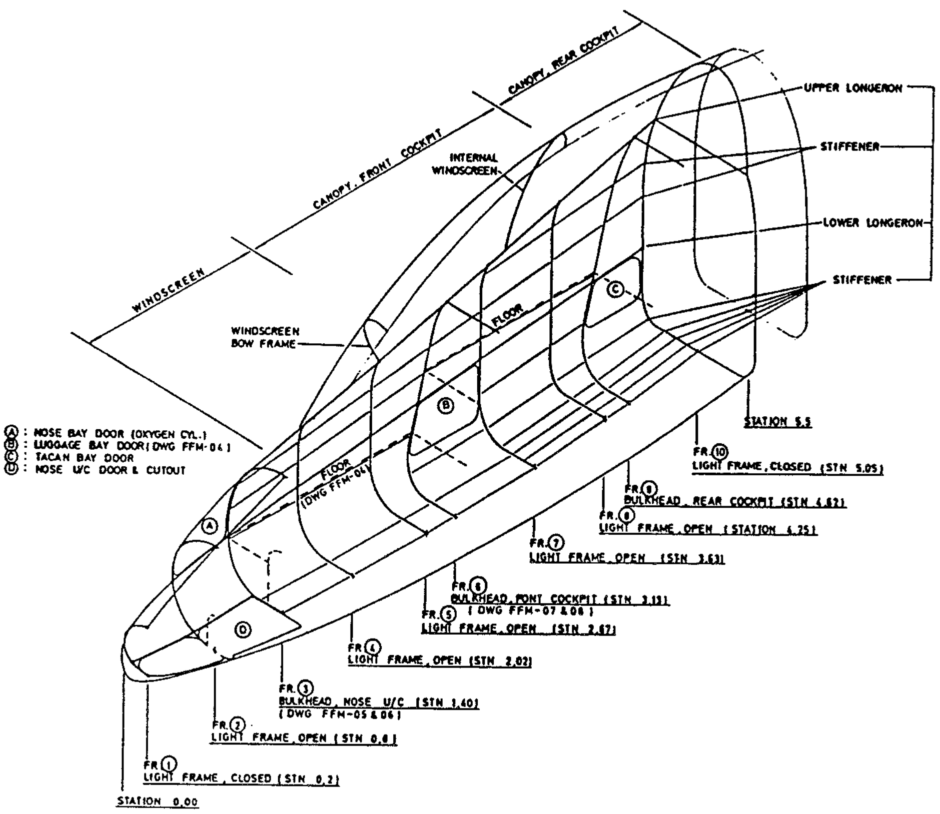


Figure 2. Forward fuselage

The lower part of the rear fuselage incorporates a hinged air brake to increase the aircraft's rate of descent. The aircraft is fitted with two Martin-Baker Mk12 ejector seats.

Wing

The wing uses conventional aerofoil sections and has an aspect ratio of 6.7 and modest wing loading. These factors give good high-altitude manoeuvrability and, when allied to the slotted flaps, give the required field performance. The wing uses a straight trailing edge to make it possible for both flap segments to be interchangeable. The ailerons are also interchangeable, port-to-starboard. The main structural complication was the attachment of the tail booms to the wing. This is shown in Fig. 3 for the composite design. This function was further complicated by the attachment of the main undercarriage leg, but all of the problems were successfully resolved.

Tail Unit

The tailplane connects the tail booms and is located towards the centre of the propeller disc. This is to ensure that at all pitch attitudes, the tailplane is subject to the slipstream for consistent control characteristics. The twin fins and rudders give satisfactory stability and control characteristics.

Powerplant

The aircraft uses the well proven Pratt and Whitney of Canada PT6A-25C turboprop engine, driving a three-bladed variable pitch propeller. The engine has a sea level static rating of 559 KW (750 shp) and has inverted flight capability. Fig. 4 shows the neat engine installation. Great care was taken to ensure that the engine could be easily maintained. The pusher arrangement gives improved visibility relative to the tractor arrangement in terms of lack of propeller blade blurring, exhaust gas vision distortion, and windscreen oil contamination.

Undercarriage

The aircraft uses a retractable tricycle landing gear with one wheel on each leg. The main legs retract aft into the tail booms, whilst the steerable nosewheel retracts into the forward fuselage.

Systems

The flight controls are actuated by a series of control rods and bellcranks, the movement of which is manually controlled from the front and rear cockpits by a simple column and pedal system. A hydraulically operated airbrake is also provided under the rear section of the centre fuselage.

The fuel is stored in two main, integral type wingtanks which contain a total of about 341 Kg and in a single collector tank which contains about 30 Kg. The system provides a 30 sec. inverted flight capability. Optional underwing tanks were also investigated.

An air conditioning system is provided for cockpit temperature control and canopy/windscreen defogging. The system is installed in the centre fuselage. A total of 2250 lts of gaseous oxygen is contained in three separate cylinders situated in a compartment above the nose undercarriage.

Provision was made for the carriage of underwing unguided rockets and two 0.50 calibre gun pods.

Hydraulic power for undercarriage retraction, nosewheel steering, flaps and air-

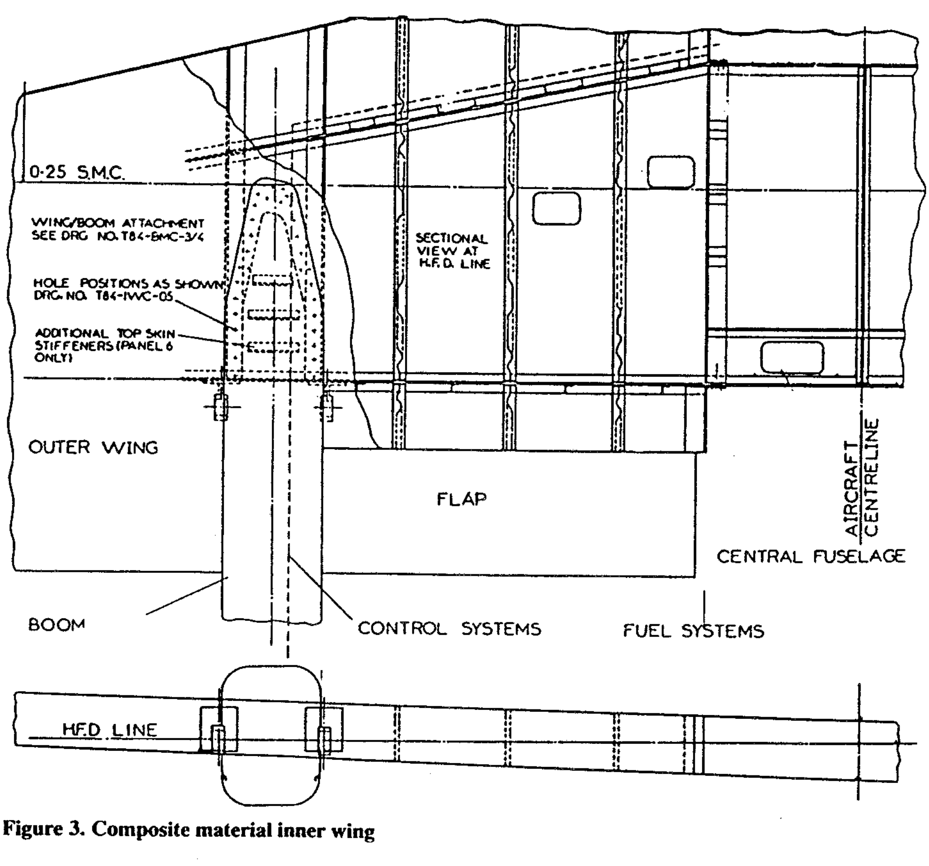


Figure 3. Composite material inner wing

brake operation, and ground braking is provided by a system installed in the centre fuselage. An emergency accumulator is also provided.

Electrical power is provided by an engine-driven DC generator and a battery. The electrics are installed in a bay on the top of the centre fuselage.

The aircraft is equipped with an avionics fit which consists of communications, radio navigation and data recording equipment.

Predicted Performance

Relatively simple performance estimates were made for the aircraft in four configurations. The first was the datum metal aircraft. The second estimate was based on the mass saving predicted by the design of some composite components (Table 1). In this case, the aircraft was considered to be the same size as the metal aircraft. The third option assumed the use of wing-tip sails as developed by Prof. Spillman. They were assumed to be fitted to the metal aircraft and to reduce the induced drag by 22%. The fourth option also used the sails, but the aircraft was re-sized to make the best use of them. This primarily affected the wing size, which was reduced, with consequent profile drag and mass savings.

The resulting performance estimates are shown in Table 2, together with the specification requirements.

It can be seen that the baseline aircraft met the specification and that the composite aircraft marginally exceeded them. The re-sized, wing sail-fitted aircraft had a considerably increased max. speed, but the landing target could not be met, although more powerful flaps would remedy this.

It was not possible to match the performance of the PC-9 or the re-engined Tucano, with the T84's 750hp. power unit, but it would be a relatively easy job similarly to re-engine the T-84.

Empirical relationships were used to predict the average unit price cost of the aircraft as £602,000 in 1984 values. This figure does not include development cost or profit, and is in line with comparable aircraft. Subsequent work by JAN G (Ref. 4) went a considerable way towards substantiating these figures. Fig. 5 shows a photograph of the T-84 model.

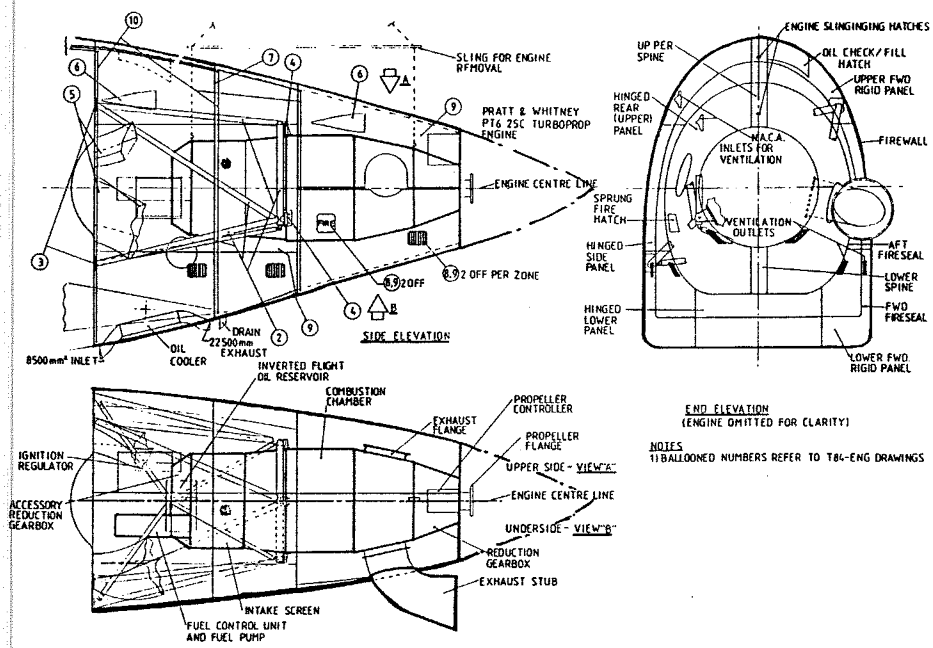


Figure 4. Power plant installation

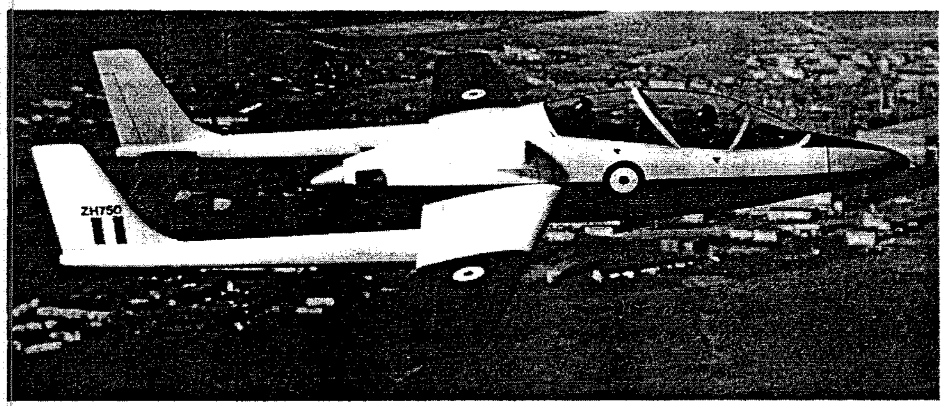


Figure 5. The T-84 model

Table 1. STRUCTURE COMPONENTS MASS ESTIMATES

COMPONENT	TARGET (KG)	METAL (KG)	COMPOSITE (KG)	DIFFERENCE (KG)
FWD FUSELAGE	210	197	178	19
WINGS + AIL & FLAPS	236	204	151	53
BOOMS	58	65	65	-
TAILPLANE & ELEV.	45	25	16	9
FINS	23	26	19	7
TOTALS	572	517	429	88

The above components were the only ones designed in *both* composite and metal materials.

TABLE 2. PERFORMANCE ESTIMATES OF FOUR ALTERNATIVE T-84 VARIANTS

PARAMETER	SPEC	METAL T-84	COMP T-84	METAL + SAILS	RE-SIZED METAL + SAILS
MAX. LEVEL SPEED (KCAS) (MAX CONT)	210-240	235	237	235	249
RANGE SPEED (20,000ft)	170	184	185	184	204
SUST. TURN RATE (20,000ft)	1.5-2g	1.97	2.03	2.19	1.97
TAKE OFF TO 50' (ft)	2000	1150	965	1150	1370
LANDING FROM 50' (ft)	2000	1815	1750	1815	2280

Conclusions

The choice of a relatively simple aircraft configuration, together with a large number of students led to a considerable amount of detailed design work. Many of the assumptions made in the conceptual design phase were substantiated. Interesting comparisons were made between metal and composite designs. It seems, however, for this class of aeroplane, that the performance gains of the latter would not justify its increased material and tooling costs.

The group project fulfilled its' primary aim of providing a realistic design environment for the training of aircraft designers.

The resulting aircraft seems to provide a realistic solution to the training aircraft requirement and has a number of advantages over its competitors.

References

1. Basic Training Aircraft T-84 Dr J.P. Fielding. College of Aeronautics DES 8400. Cranfield Institute of Technology.
2. A Reliability Modelling and Prediction Methodology for use in aircraft design. Paper by V.C. Serghides and J.P. Fielding. 5th EURE DATA Conference Heidelberg 1986.
3. A Maintainability Prediction Methodology for use in aircraft design. Paper by V.C. Serghides & J.P. Fielding. 9th Advances in Reliability Technology Symposium, Bradford 1986.
4. Manufacturing Costs and Factory Requirements for the Production of the T-84 Aircraft. MSc Research Thesis. S. S. Jang, Cranfield Institute of Technology 1985.

A-85

A Prop-fan Airliner Design Project

by Dr John Fielding, Senior Lecturer in Aircraft Design

Dr John Fielding

THE PROJECT PROGRAMME

The College of Aeronautics has a practical approach to the teaching of aircraft design. Students will only be awarded an MSc degree if they have proved that they have the ability to produce workable, realistic designs in which all of the major problems have been addressed. This ability is assessed by means of annual group projects in which relevant aircraft types are studied, in this case a prop-fan airliner. Our group project is unique by virtue of the amount of preparatory work done by staff before work is started by the students. All other known design projects start with the students being given the aircraft specification. They then have to perform a conceptual design, which leaves little time available for detailed design. With the Cranfield method, this work is done by the author, thus enabling the students to start much further down the design evolution process. They thus have an opportunity really to get to grips with the detail design problems, and become much more employable in the process.

The design of an advanced short-range airliner project was examined in 1982/83. This produced the A-82 design (Ref. 1) which used twin underwing turbo fan engines. Recent work has suggested that modern prop-fan engines could significantly reduce fuel and operating costs. It was decided to design an aircraft using those engines and compare its design with that of the A-82.

A conceptual design study was performed by the author, based on the specification shown in this article. This process determined the basic shape of the aircraft together with weight, aerodynamic and loading information. This work was summarised in (Ref. 2) which was presented to each student at the start of the academic year. Twenty students were then allocated the responsibility for the detailed design of a major part of the aircraft. These responsibilities took the form of a major structural component, such as the forward fuselage, a flying control surface or a mechanical system such as fuel, environmental control or the active control system. Each student was expected to act as designer, stressman and draughtsman for his component.

The project was managed to an exacting eight month programme by means of the weekly project meetings where students reported on progress, received advice and instructions for subsequent work. The most important role of the meetings, however, was that of a forum where design compromises were resolved and students gained an appreciation of the problems being encountered on other parts of the aircraft.

The programme ended in May 1986 with the submission of voluminous project theses containing detailed drawings and calculations. It has been estimated that at least 20,000 man-hours were spent on the programme, which produced some excellent design work and gave the students considerable design experience.

The knowledge gained during lectures, project meetings and discussions with members of staff, was augmented by several valuable visits. These were made to Dowty Rotol to examine advanced propellers and British Aerospace, Hatfield to look at BAe 146 production.

No design programme would be complete without a visit to a company operating the type of aircraft being designed. Two visits were therefore made to Britannia Airways' maintenance hangar where minute examinations were made of Boeing 737 aircraft which were undergoing maintenance. Individual students visited factories which were particularly relevant to their design specialisation, for example Triplex and Dunlop.

ABBREVIATED DESIGN SPECIFICATION

The specification was identical to that of the A-82 with the exception that the maximum cruise Mach No. was reduced from 0.83 because of the limitations of prop-fans.

Capacity

One hundred and fifty mixed-class passengers with 138 tourists at 32in pitch and 12 first-class at 36in pitch. Comfort standards shall be at least as good as those of the Boeing 727.

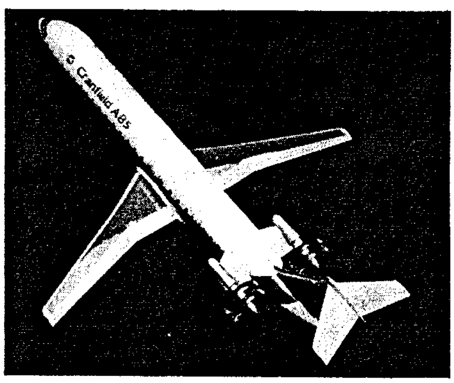


Figure 1. Model of A-85 Airliner

Five attendants seats with sufficient galley space for 150 hot meals, three or four toilets and specified stowage space.

The flight deck shall be designed for a two-man crew with an option for a third.

Performance

The operating fleet average trip length is 370 statute miles.

The minimum trip length with a full space limit payload shall be 1,000 statute miles. Passenger and bag payload range shall be approximately Mach 0.80 with minimum cost cruise at Mach 0.76-0.78. Maximum approach speed will be 130 knots.

Maximum cruise altitude should be around 39,000ft with initial cruise altitude of 31,000ft.

Fuel efficiency targets are:

Trip length (SM)	Available Seat Miles/US gall
400	77.6
600	85.0
1000	92.0

at full passenger and baggage payload.

Maximum certificated runway for 370 statute mile trip with space limit payload is 6,000ft for takeoff on a 90°F day at sea level.

The dry FAR landing distance with maximum payload and standard reserves should not exceed 4,600ft at 2,000ft altitude with a 35kt crosswind.

Runway loading should not exceed that of a 727-200 at 195,000lb taxi weight.

Exterior noise levels should be lower than FAR-36 stage 3.

General

The major design objectives are to include minimum seat-mile costs with maximum passenger comfort. It is expected that the aircraft will use the latest aerodynamic systems and material technology consistent with maximum service life reliability and maintainability.

DESCRIPTION OF THE FINAL DESIGN

The aircraft was designed using state-of-the-art materials, the majority of the structure being made from aluminium-lithium alloys, with some composite components. The current design differed in this respect from the earlier A-82 because that aircraft was almost entirely designed with composite materials. Figure 1 shows a photograph of a model of the A-85, the major design features of which are discussed below:

Wing

A modern sweepback combined with a relatively thick supercritical wing section enables Mach numbers in the region of 0.80 to be achieved. The aspect ratio is 9.502 and there is sufficient fuel tankage at max passenger payload for a range of 1540 n.miles with reserves. The high aspect ratio improves fuel burn and airfield performance. Figure 2 shows a CAD-produced drawing of the finally-chosen flap configuration.

Fuselage

The circular-section fuselage permits single-aisle, 6-abreast seating in greater comfort than in the 727. The under-floor holds permit the carriage of 727/707 type containers. The seating arrangements are as in the specification but an alternative layout accommodates 162 passengers at 32in seat pitch.

The rear-mounted prop-fans require strengthening and sound insulation in the rear fuselage.

The choice of rear-mounted engines had a detrimental effect on the cabin interior layout. The rear passenger doors had to be moved forwards and the area used for them used up more floor area than that of the A-82 where this space could double-up as galley access. CAA changes after the Manchester 737 accident led to more access space for over-wing exits. The use of the rear engines had already moved the cabin rear pressure bulkhead forward relative to the A-82. The same external fuselage geometry was used as the A-82, thus leading to cramped accommodation. This was alleviated by reducing the chord of the engine pylon box, and using a flat pressure bulkhead, but a better solution would have been a small extension of the fuselage length. Figure 3 shows the structure of the near fuselage.

Powerplant

The aircraft uses rear-mounted Rolls-Royce RB 509 contra-rotating pusher prop-fan engines. The engines are pod-mounted and attached to the rear fuselage via pylons — see Figure 4.

This arrangement was chosen because studies had shown that using mounted prop-fan engines produced too much noise and vibration in the cabin. The sound insulation mass required to overcome this would be prohibitive. Another problem would be the possibility of cabin depressurisation in the event of blade shedding. The choice of rear engines places the prop-fan blades aft of the cabin and reduces the insulation mass penalty to some ¼ of that of the wing-mounted value.

Tail Unit

The aircraft utilises an all-moving high-tee tail. Trim is obtained by tailplane movement whilst control is provided by the elevators. The tailplane is sufficiently far aft so that it is away from the plane of the aft row of prop-fan blades. This ensures that detachment of blades will not damage the tailplane. This is impossible for the fin and, therefore, a damage-tolerant structure is required.

Mechanical Systems

The aircraft utilises a conventional tricycle undercarriage with twin wheels on each leg. The main wheels retract sideways into an under fuselage fairing whilst the nose leg retracts forwards. The fuel is contained within conventional wing tanks and provision is made for extended-range versions of the aircraft by space provision in the wing centre section. State-of-the-art environmental control systems were designed with provision for cruise at an altitude of 40,000ft. Flying controls are actuated by

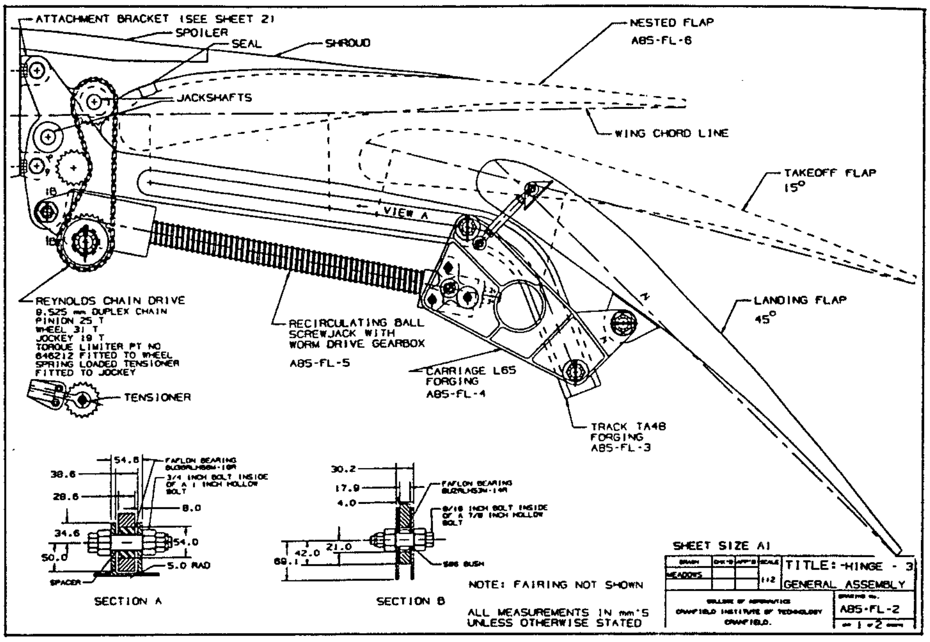


Figure 2. Flap Assembly

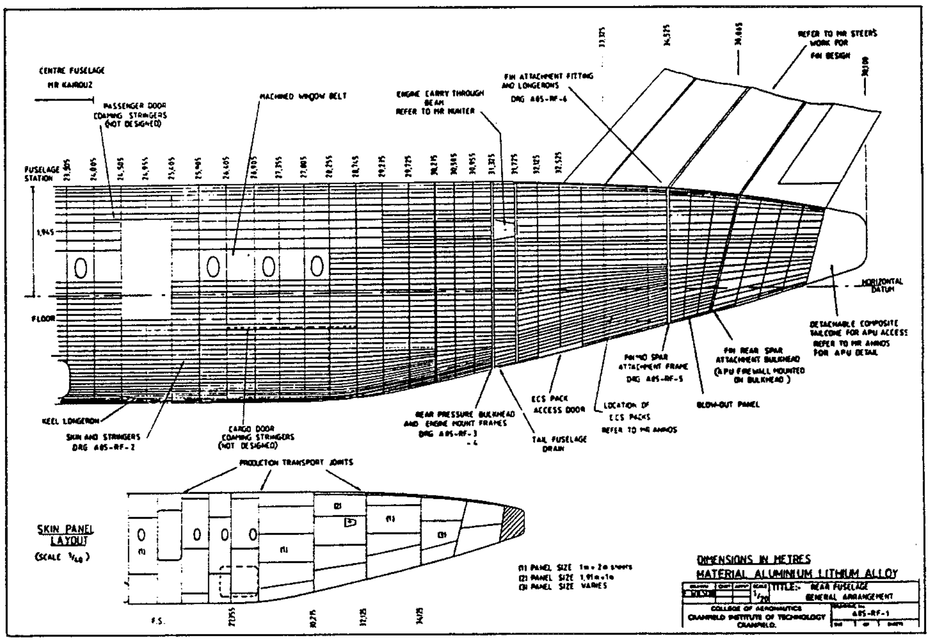


Figure 3. Rear Fuselage

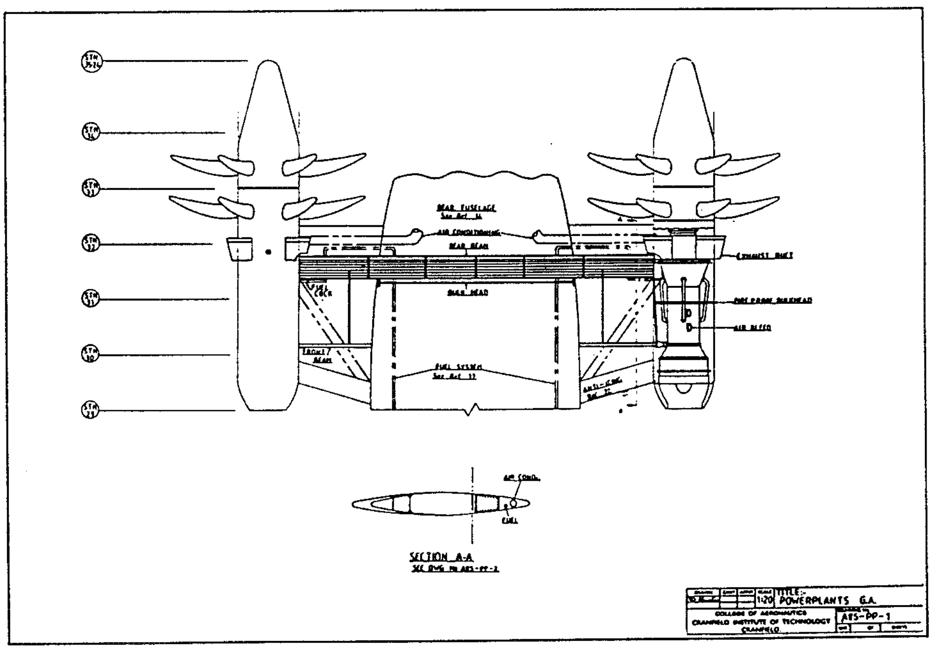


Figure 4. Powerplant Installation

COMPONENT	TARGET (KG)	PREDICTIONS (BASED ON DETAILED DESIGNS)
Wings (inc. auxiliary surfaces struct.) Fuselage Fin (inc. rudder) Tailplane (inc. elevator) Main undercarriage Nose undercarriage	5291 7638 657 868 1786 331	4920 6935 610 596 2030 363
STRUCTURE	16571	15454
Engines (dressed) Powerplant struct. (pylons, cowlings)	4995 294	4995 309
POWERPLANT	5289	5304
Fuel System Flying controls system Hydraulics Electrical system Aux. power unit Instruments and avionics Wing de-ice Paint Fire-protection Furnishings (inc. seats, galleys, etc.) Environmental control	446 619 734 1448 363 1071 134 53 176 5682 686	427
BASIC EMPTY MASS	33272	
Crew and provisions Operating weight empty allowance	527 1352	
OPERATING EMPTY MASS	35151	
Max. passenger and baggage (162 seats) Fuel at above payload	14710 9189	
MAX. ALL UP MASS	59050	

Table 1 — Mass Estimates

PERFORMANCE	SPECIFICATION	A-82	A-85
Maximum Cruise Mach. No.	0.83	0.83	0.80
Range with volume limited payload, ISA, Mach. 0.77, 33,000ft. FAR reserves	1,000 st miles	1,772km (1,100 st miles)	1,320km (820 st miles)
Range with 162 passengers + baggage at the same conditions as above	1,400 st miles	2,780km (1,727 st miles)	2,859km (1,780 st miles)
Take off to spec. conditions	6,000ft	5,100ft (1,555m)	
FAR landing to spec. conditions	4,600	4,580ft (1,400m)	
ASM/US gallon: 400 SM	77.6	70.2	121
600 SM	85.0	82.7	116
1000 SM	92.0	91.5	116
At full passenger and bag payload ISA, FAR reserves, fuel density 787kg/cu m			
MASSES			
Structure		14,630kg	16,571kg
Operating Empty Mass		33,516kg	35,151kg
Max. Landing Mass		53,653kg	53,911kg
Max. All Up Mass		58,959kg	59,050kg
Maximum Payload		18,110kg	18,110kg
DIMENSIONS			
Wing section based on RAE9550			
Root t/c		15%	14%
Kink t/c		11%	11.5%
Tip t/c		10%	10.5%
Wing span		33.7m	32.73m
Gross wing area		115.24 sqm	112.74 sq. m.
Sweep of 0.25c line		25°	22°
Fuselage length		38.1m	38.1m
Maximum fuselage diameter		3.89m	3.89m

Table 2 — Performance Estimators

means of hydraulic actuators which are signalled electrically for the active control system but have manual reversion. The relatively small core of the powerplant limited the amount of useable bleed air. This was used for the ECS system, and fluid de-icing was used.

PREDICTED PERFORMANCE

Table 1 shows the target masses for the major aircraft components. Shown alongside are predictions, based on the detailed designs produced at the end of the project. They cover only the structure powerplant and fuel systems, but do show reasonable results. They are rather lower than the targets because they cover structural components, but not miscellaneous items such as systems supports, brackets, etc. Table 2 shows performance estimates for both the A-82 and A-85 relative to the specification. It can be seen that the structure mass of the A-85 is some 11.5% greater than that of the A-82. The majority of this is because of the almost total composite construction of the latter. A rear-engined solution, however, is inherently heavier than wing engines. The final factor is the sound insulation required for the prop-fan.

The payload-range characteristics are illuminating in that the 1000st. mile volume-limited payload cannot be met by the A-85, whereas the A-82 exceeds it by 100 miles. This is because the higher empty mass of the prop-fan, combined with the same payload leaves only 5790KG available for fuel, which, even with the prop-fan's frugality only gives a range of 820 miles. Both aircraft have a very similar all-up mass. When one considers the passenger and baggage payload, the prop fan has the advantage of some 60 miles range. Both aircraft comfortably exceed the requirement in the specification. It is in the available seat miles per US gallon where the prop fan scores dramatically, with obvious cost advantages, particularly if fuel costs were to rise.

Conclusions

The design programme fulfilled its main aim of providing a powerful means of training designers. The use of a challenging and interesting project was a means of investigating many of the problem areas of such an aircraft and produced some good detailed design work.

The aircraft that was designed showed considerable promise but required further work to confirm the performance predictions.

The prop-fan aircraft seems an attractive alternative to a turbo fan provided that the fuel costs are such that fuel savings can exceed the probable extra structure costs and that the cost and reliability of prop-fan engines are comparable with turbo fans.

References

1. An Advanced Short Range Airliner Design Project, paper by Dr J. P. Fielding, Aerospace, April 1985. Royal Aeronautical Society.
2. DES8500 Fielding, Dr J. P., 150 Passenger Short-Range Airliner, with Prop-fan Engines. College of Aeronautics, Cranfield Institute of Technology, May 1986.

SL-86

Design Study of a 2-stage Horizontal Take-off Space Launcher

by Dr J. P. Fielding, Senior Lecturer in Aircraft Design

Dr. J. P. Fielding

The Overall Project Programme

The College of Aeronautics adopts a pragmatic approach to the teaching of aircraft design. Students will only be awarded an MSc degree if they have proved that they have the ability to produce workable, realistic designs in which all of the major problems have been addressed. This ability is assessed by means of annual group projects in which relevant aircraft types are studied, in this case a space launcher.

The past few years has seen renewed interest in orbital launch vehicles. The Space Shuttles, despite the tragic loss of the Challenger have given valuable service. Soviet and European launchers have lifted many satellites into orbit. All of the current launchers have been expendable with the exception of large parts of the Space Shuttle. Current launchers require extensive ground facilities and long periods of launch preparation. Heavy lift vehicles such as Shuttle will be required to build the proposed space station, but flexible smaller-lift vehicles will also be necessary. Extensive literature searches and discussion with various members of industry have led to the current Cranfield Project. It was decided to opt for a relatively modest 2-stage horizontal take-off configuration.

The advantages of this configuration over vertical launched vehicles are:

(i) The possibility of responsive flexible operations from existing airfields. Launch at short notice with quick turn-rounds.
(ii) Relatively low noise levels for take-off.
(iii) 100% re-usability.
(iv) The possibility of using the launcher to ferry the orbiter to other sites.
(v) Modest launch costs. A generally similar configuration has claimed launch costs of 1/5 those of Shuttle or Ariane.
(vi) Possibility of spin-off development of the launcher into a hypersonic airliner (Orient Express).

A conceptual design study was performed by the author, based on the specification shown in this paper. This process determined the basic shape of the aircraft together with weight, aerodynamic and loading information. This work was summarised in Ref. 1, which was presented to each student at the start of the academic year. Thirty-one students were then allocated the responsibility for the detailed design of a major part of the aircraft. These responsibilities took the form of a major structural component, such as the forward fuselage, a flying control surface or a mechanical system such as fuel, environmental control or the control system. Each student was expected to act as designer, stressman and draughtsman for his component.

The nature of the current project also involved these students following our aerospace engineering course option in such areas as thermal protection, trajectory, orbital manoeuvring, rocket propulsion, payload support and docking.

The project was managed to an exacting eight month programme by means of twice weekly project meetings where students reported on progress and received advice and instructions for subsequent work. The most important role of the meetings however, was that of a forum where design compromises were resolved and students gained an appreciation of the problems being encountered on other parts of the aircraft.

The programme ended in May 1987, with the submission of voluminous project theses containing detailed drawings and calculations. It has been estimated that at least 30,000 manhours were spent on the programme, which produced some excellent design work and gave the students considerable design experience.

The knowledge gained during lectures, project meetings and discussions with members of staff, was augmented by several valuable visits, including one to the Imperial War Museum, Duxford, where a pre-production Concorde was examined in detail. It's configuration is quite similar to that of our booster. Individual student visits were made to Rolls Royce, British Airways and Dowty Rotol. Several external lecturers visited Cranfield, including Ulf Merbold, an astronaut from ESA.

DESCRIPTION OF THE FINAL DESIGN

General

Figure 1 shows the booster-orbiter mated configuration.

The wing plan-form of the Booster is a scaled-up version of the B-75 bomber project. The aircraft utilises 4 underslung turbo-ramjet powerplants. The wing is set low to allow integration of the orbiter into its upper surface. Twin fins and rudders are used to give clearance to the orbiter's rocket motor. The rudders give yaw control to the whole aircraft configuration, whilst pitch and roll are provided by wing trailing-edge elevons. A conventional tricycle undercarriage is used. The fuselage contains cryogenic liquid hydrogen and oxygen, and is shaped to accommodate the orbiter. As the aircraft will fly for sustained periods up to Mach 4, the airframe structure will be largely fabricated from Titanium alloy.

The orbiter separates from the booster at Mach 4 at 80,000 ft. The large fuselage contains a 2-man flight deck, liquid oxygen and hydrogen tanks, a scaled space shuttle main engine and the payload bay. The cross section of the latter is similar to that of the space shuttle and can accommodate 8 passengers in a transport role. The structure will be "warm" with composite construction, capable of working at 180°C, with a thermal protection system to limit temperatures to this value. Aerodynamic yaw control is by twin fins and rudders whilst pitch and roll are

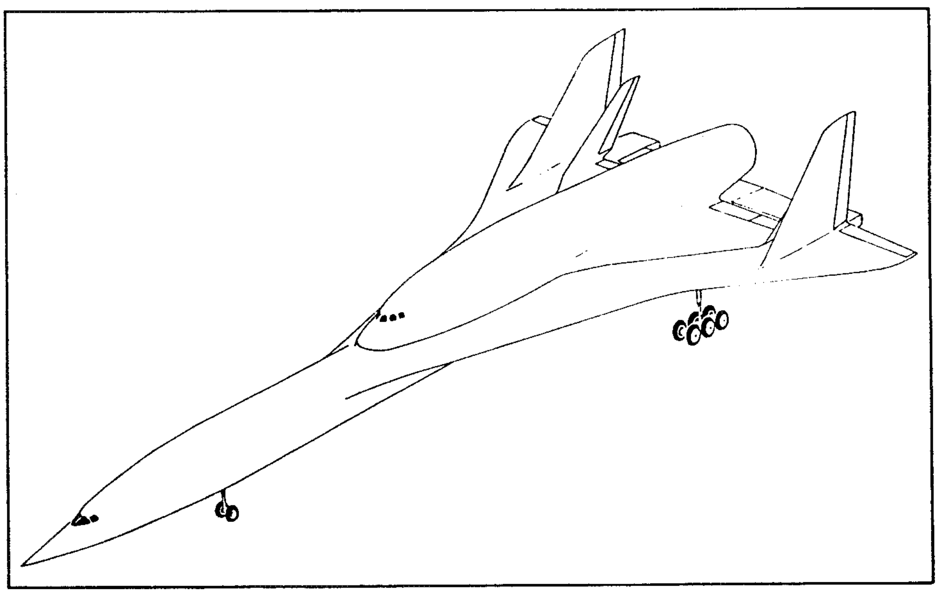


Figure 1. SL-86 Space Launcher

controlled by elevons. A reaction control system is used for control where aerodynamic surfaces are unsuitable. The aircraft uses a conventional tricycle landing gear. The orbital manoeuvring system (OMS) uses two small rocket motors.

Extensive use was made of computer techniques in terms of aerodynamic and structural analysis, together with CAD visualisation and detail design.

It was found that there were no suitable Airworthiness Requirements. It was therefore necessary to derive our own requirements, based on TSS and other space projects.

The rocket motor of the orbiter is used in the mated configuration to aid transonic acceleration and supersonic climb, prior to separation. It is important that the orbiter is fully-fuelled at separation, thus requiring extra tankage in the booster, and cross-fuelling between the vehicles.

Extensive stability, control and loading calculations highlighted areas where more research is required to provide simple methods for the analysis of such complex vehicles. The calculations showed that the wide C.G. ranges of both vehicles lead to conditions where control power was marginal. This is particularly the case for pitch control of the combination on take-off. Several remedies were proposed, but the most suitable would be a small canard control surface.

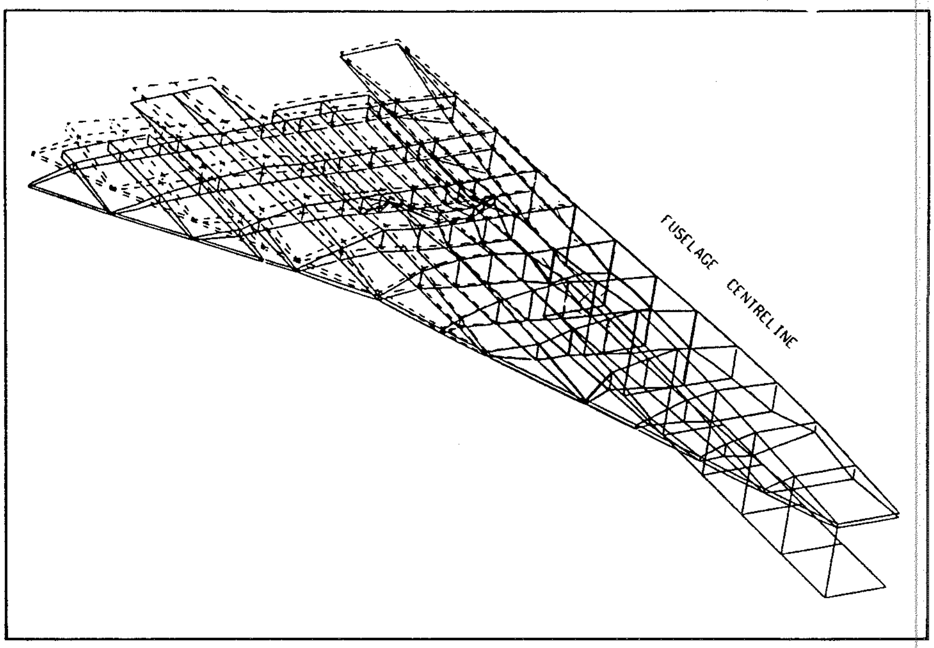


Figure 2. Finite Element Model of Booster Wing

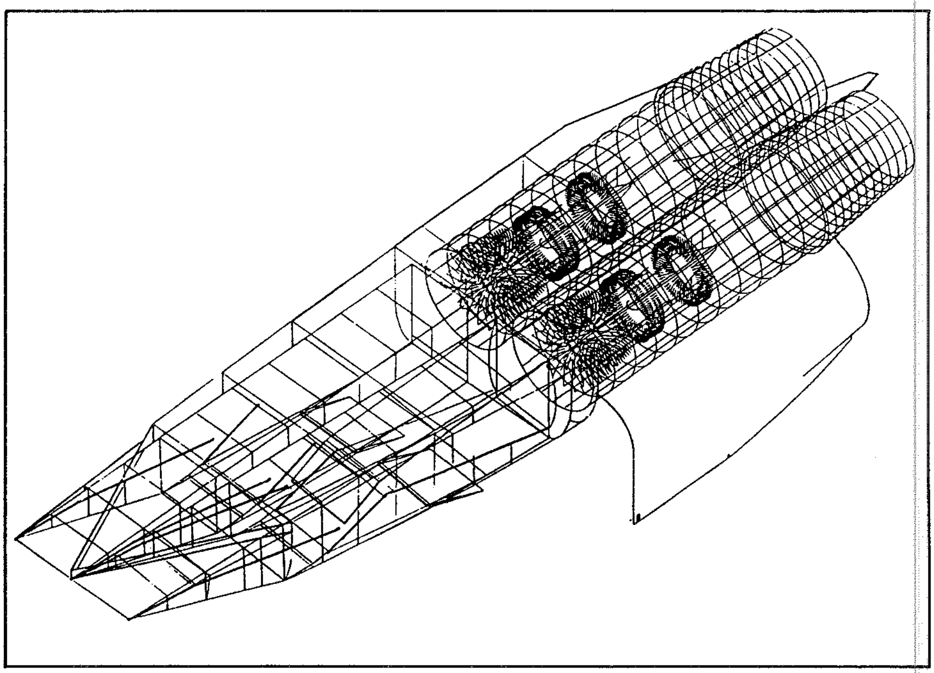


Figure 3. Booster Turbo-Ramjet Installation

Booster

The fuselage is constructed from titanium alloy, to resist kinetic heating. The forward fuselage contains a two-pilot flight deck, with a drooping section to improve landing vision. The whole of the nose section forms an escape capsule for emergency purposes. The integral cryogenic hydrogen fuel tank is immediately behind the flight deck. This tank feeds the four turbo-ramjet engines and cross-fuels the orbiter rocket motor prior to separation. The non-integral liquid oxygen tank is fitted aft of the hydrogen tank and is used solely for cross-fuelling the orbiter. The rear fuselage is a blended structure with the inner wing. It's design was complicated by the large recess required to accommodate the semi-recessed orbiter. Three hard points are provided with explosive release mechanisms. This is to aid the separation of the orbiter.

The wing recess for the orbiter led to complex geometrical interfaces, which were accurately defined by our CAD system. The reduction in wing depth in this region led to strength and stiffness problems. A multi-spar construction was used. The structure was manually stressed to give an input into the LUSAS finite element structural analysis, (see Fig. 2). Progressive runs were used to optimise the wing structure. This was the method used for the structure of both vehicles. Fin construction was of multi-spar titanium, attached to the outer wing at the same point as the outer powerplants.

Booster systems

Optimisation studies were performed to determine the best thermal insulation thickness to limit "boil-off" of the liquid fuels. The hydrogen volume available gave a cross-range of 230 miles prior to separation. Many abort and jettison options were examined. Fig. 3 shows the installation of the turbo-ramjet powerplants. These engines have no provision for secondary power off-takes so auxilliary power units were used for electrical and hydraulic power.

Orbiter structure

Fig. 4 shows the configuration of the orbiter.

It's thermal protection system is similar to that of the Space Shuttle, with insulation designed to protect the structure to a temperature of 180°C. The main structure is made of carbon fibre reinforced plastic. The forward fuselage contains the flight deck. Accommodation is provided for a crew of 4 and an airlock and docking port. The non-integral liquid hydrogen tank is mounted aft of the flight deck. Immediately behind this is the payload bay. This has large doors, which also act as radiators. The large structural cut-outs in this region necessitated the use of large CFRP longerons.

The non-integral liquid oxygen tank is mounted aft of the payload bay and above the main landing gear and wing carry-through structure. The rocket motor is mounted from a tubular space-frame structure. The wing structure is similar to that of the booster, except that it is constructed from CFRP. The fins and flying control surfaces presented considerable structural problems as the thermal protection system occupies up to 25% of the local depth. This considerably reduced the structural depth, with consequent mass increases. The alternative solution of use of carbon/carbon composites was rejected after advice from industry suggested that they would present unacceptable penalties in terms of strength and brittleness.

Orbiter systems

Our original design utilised the Space Shuttle main engine. It was found that this engine

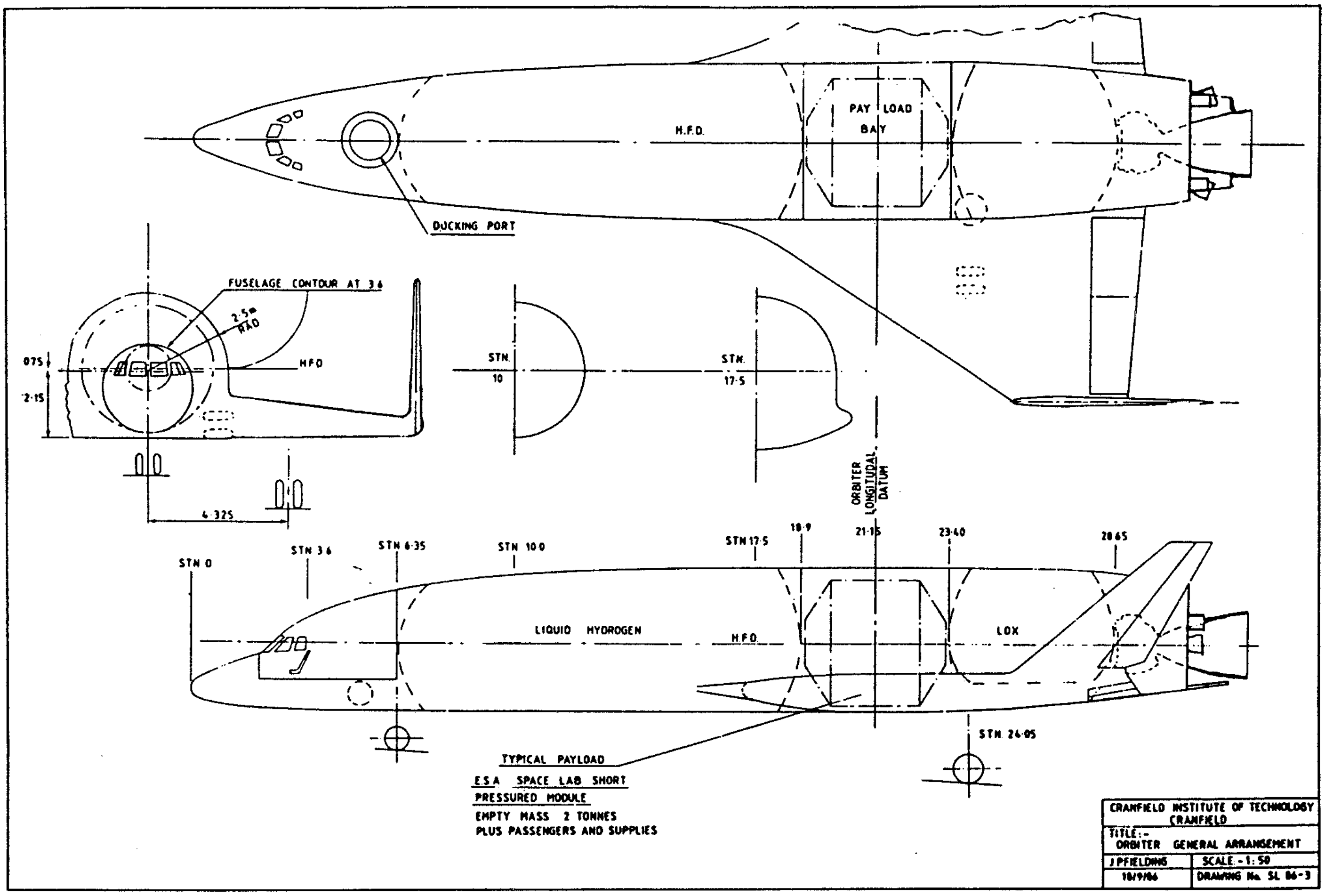


Figure 4. The Orbiter Configuration

gave an unacceptably high axial acceleration of 6 "g" at the end of engine burn. The engine was therefore scaled down to 60% of the maximum thrust. The engine takes the orbiter into an elliptical transfer orbit, which is then circularised by orbital manoeuvring system motors, mounted in the rear fuselage. This area also contains the aft reaction control system thrusters, whilst the forward RCS thrusters are in the vehicle's nose. The environmental control system is based on a crew of 4 on a three-day mission. On-board power is supplied by auxilliary power units and fuel cells, the latter supplying water as a by-product. The landing gear uses lightweight twin-wheel units. The payload bay will accommodate a standard ESA space lab short module or other payloads up to a maximum of 4.5 tonnes. A manipulator arm has been designed to fit in the payload bay, which also provides storage for two man manoeuvring units. Access to the payload bay is by means of a powered lanyard attached to a submerged rail between the airlock and payload bay.

Predicted Performance and Design Uncertainties

A major source of uncertainty is separation. Fig. 5 shows a plot of the CAD models of the two vehicles. The relatively large size of the orbiter, combined with unknown shockwave interactions at separation at Mach 4 means that wind tunnel testing or comprehensive computational fluid mechanics is required. The rocket motor, however, may be gimballed, thus aiding separation.

Reasonable drag estimates were made for both vehicles separately, but the drag of the mated configuration was difficult to determine. Conservative assumptions were made to allow for this. Performance calculations showed that the aircraft combination could achieve the conditions of separation at Mach 4 at 80,000 ft altitude. The author's initial calculations, however, were optimistic in terms of the fuel required for the acceleration and supersonic climb. With the available fuel volume in the fuselage, this limited the pre-separation cross-range to 230 miles rather than the 500 miles specified. The limiting factor was the volume of the hydrogen tank of the booster. A small increase in fuselage diameter would rectify this problem.

The above problems were aggravated by the manufacturer's reduction of turboramjet thrust by 13%. These factors led to an extra LOX requirement of some 17 tonnes for the booster. One solution would be to scale-up the booster to cater for this take-off mass increase.

The low thrust output from the turboramjets also leads to a very long take-off run, a slow climb and acceleration, and an

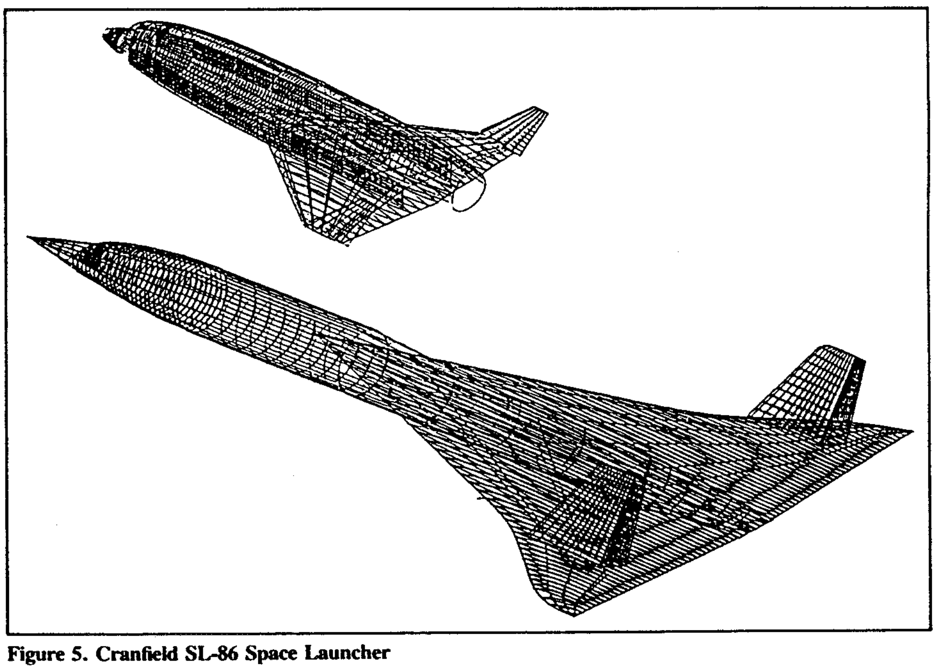


Figure 5. Cranfield SL-86 Space Launcher

inability to go quickly through the transonic region without using the rocket motor. It is suggested that a 50% increase in turbo-ramjet thrust is required. Although more LH_2 would be needed, the net reduction in the LOX requirement would outweight the mass of the larger engines. Extra thrust would shorten the take-off run so that existing runways could be used.

Post-separation calculations show that the initial orbiter allowance for LOX and liquid hydrogen had been too generous, but the OMS system required more fuel. Table 1 shows the estimates of orbiter mass after some detail design work had been completed. The system masses were in excess of the initial estimates.

The main mass growth was in the orbiter fuel system. The initial concept had been to use integral fuel tanks, but doubts about the effects of cryogenic fuels on carbon-fibre structure led us to non-integral tanks. This reduced the problem of the relative thermal compression of the fuselage tanks relative to the fuselage, because flexible mounts could be used. The differential expansion over the lengths of the hydrogen and oxygen tanks were 6 and 3 cm respectively. The non-integral tank was also a good solution for the LOX because it allowed adequate storage for the main landing gear and significant wing carry-through structure in the fuselage. This, however, reduced the LOX volume to barely adequate proportions.

We have a suspicion that a lighter overall orbiter solution might be to use a titanium structure working to, perhaps, 300°C rather than the 180°C of the composites. We would then be able to use an integral hydrogen tank with consequent weight savings. The higher structure temperature would reduce the thickness and weight of the thermal protection system. It is possible that these weight savings could be greater than the extra mass of a titanium, rather than a composite structure. Calculations should be performed to investigate this proposal.

Extensive safety and reliability calculations were performed to refine system design and examine abort options.

Table 2 summarises some of the main performance parameters and dimensions for both the booster and orbiter. The orbiter performance is based on the target masses.

The booster figures are those for the original turbo-ramjets and the target take-off mass for the combination of booster and orbiter.

These show that, if increase in booster power were achieved as suggested above and the booster mass was maintained at 250 tonnes, a payload of 4.5 tonnes could be inserted into LEO, giving a payload fraction of 1.8%.

Conclusions

The design programme fulfilled its main aim of providing a powerful means of training designers. The use of a challenging and interesting project was a means of investigating many of the problem areas of such an aircraft, and produced some good detail design work.

The students involved in the project experienced many of the problems of an industrial project and learnt how to tackle a difficult job. Their theoretical and practical

Table 1 — Orbiter Mass Breakdown

COMPONENT	INITIAL TARGET (KG)	PREDICTED MASS (KG)
Wing (incl. Controls)	3600	3536
Fuselage (inc. engine mounts)	5550	4012
Fins and Rudders	200	700
Main Undercarriage	430	394
Nose Undercarriage	150	138
Thermal Protection System	3400	3966
TOTAL STRUCTURE	13280	12806
Rocket Motor	3000	2500
OMS/RCS	200	550
TOTAL PROPULSION	3200	3050
APU's	—	500
Elect. Power and FCS (Fuel Cells)	300	192
Inst. & Avionics	300	500
ECS (incl. fluids)	150	600
Fuel system (incl. tanks)	—	1714
MMU Adaptor, payload access	—	70
TOTAL EQUIPMENT	750	3576
CREW (Incl. Provisions)	270	360
OPERATING EMPY MASS	17,500	19,792
Liquid Hydrogen Fuel	13,300	12,550
LOX	79,700	75,170
OMS/RCS Fuel	—	1830
Fuel for Fuel Cells	—	390
Contingency	—	768
Payload	4500	4500
ALL UP MASS (LAUNCH)	115,000	115,000

Table 2 — Performance and Dimensions

Target Masses

Maximum design (take off) mass	(both stages)	249,800 kg
Maximum landing mass (emergency)	(both stages)	167,000 kg
Maximum mass	(orbiter)	115,000 kg
Maximum design (take off) mass	(booster only)	135,000 kg
Maximum landing mass	(booster alone)	135,000 kg
Maximum landing mass	(orbiter)	22,000 kg

Performance

COMBINATION Take-off field length at max. AUM	3826 m (11662 ft)
BOOSTER NORMAL landing distance	3714 m (11320 ft)
ORBITER landing distance	3203 m (10510 ft)
COMBINATION ABORT LANDING DISTANCE*	3772 m (11496 ft)[2]
MACH. NO. AT SEPARATION	4
SEPARATION ALT.	25 KM
MAX. CROSS RANGE PRIOR TO SEPARATION	364 KM (230 Miles)
TIME PRIOR TO SEPARATION	21 Mins
ALT. OF ELLIPTICAL TRANSFER ORBIT	PERIGEE 100 KM
MACH. NO. IN TRANSFER ORBIT	26
TIME FROM SEPARATION TO TRANSFER ORBIT	6 Mins 10 Secs.
ALTITUDE OF LOW EARTH ORBIT	300 KM
PAYLOAD INTO LEO	4500 KG
PAYLOAD BAY SIZE	4.5 m dia. by 4.5 m long

Dimensions

BOOSTER WING AEROD. REF. AREA	548.6 m^2
WINGSPAN →	31.5 m
OVERALL LENGTH →	61.0 m
ORBITER WING AERO REF. AREA	164 m^2
WING SPAN	16.8 m
OVERAL LENGTH	32.74 m

*CONTROL PROBLEMS

training makes them well placed to make significant contributions to the Aerospace Industry.

Our investigations have shown that the basic concept of two-stage horizontal take-off is sound. There are many uncertainties remaining in our project, but relatively minor modifications should yield a very flexible, totally re-usable system. The major suggested changes are:

(i) Use of a canard foreplane for the booster.

(ii) Increased power turbo-ramjets for the booster.

(iii) Slightly increased booster fuselage diameter to aid hydrogen tankage.

(iv) Investigation of a metal-structure orbiter.

(v) More work is required into separation and launch trajectory optimisation.

It is hoped that the above recommendations will be investigated in a future group project.

Reference

1. DES 8600. Two Stage Horizontal Take-Off Space Launcher". Design Specification. Dr J. P. Fielding, College of Aeronautics, Cranfield Institute of Technology, Sept. 1986.

The S-87 Close Air Support Design Project

by Dr John Fielding — Senior Lecturer in Aircraft Design

Dr John Fielding

The Requirement

There have been many reports of the disparity in numbers of ground forces between the Warsaw Pact and NATO. One of the most potent means of countering this is the close air support aircraft. The most significant NATO Force is that of some 800 Fairchild A-10 aircraft, which the USAF is hoping to replace over the next few years. It was decided to design an aircraft for this role, using some of the requirements of the A/STOVL requirement. It was decided to avoid vertical landing and supersonic requirements in the interests of cost reduction in the hope that fleet size could be increased.

The requirement for the project was based on the fall-out mission of Reference 1, augmented by information from many prevous College of Aeronautics studies, including Reference 2. The main points were:

(i) **The role**
The need exists for a close air support aircraft capable of operating in support of ground troops in the vicinity of the Forward Edge of the Battle Area (FEBA).
The aircraft is required to operate some 100 km behind the FEBA. The targets will be first and second echelon troops — in particular, Main Battle Tank (MBT), Armoured Fighting Vehicle (AFV) and Armoured Personnel Carriers (APC) and their support vehicles, in daylight hours.

(ii) **Mission Radius**
The radius of action of the aircraft should be 500 km at 3.5 km, opt. speed with a 15 minute loiter/search time and a 10% fuel reserve. These figures are based upon the following mission at the spec payload:
(a) Cruise at optimum speed at low level 300 km to FEBA.
(b) Accelerate to 0.8 M at a height of 100 metres and carry out mission. (100 km penetration to target.)
(c) Optimum speed cruise at low level 300 km back to base.

(iii) **Take-off and landing performance.**
The aircraft should take-off from semi-prepared strips in a distance of 880 metres over a 15 metre obstacle. Landing ground distance should be 500 metres.

(iv) **Performance**
The following performance figures are required:
(a) Maximum speed:
0.8M at S.L. with SPEC PAYLOAD
0.9M at S.L. with ASRAAM'sALONE
(b) Maximum operational height: 3500 metres
(c) Maximum-Supstained G loading: 4g at SPEC payload at M=0.8 SL

(v) **Weapon Loads**
Possible weapon loads include:
(a) 6 × 277kg Cluster bombs + 2 ASRAAMS + GUN + AMMUNITION (SPEC PAYLOAD)
(b) 8 × 500kg low drag bombs + 2 ASRAAMS + GUN
(c) One JP233 Fuselage store of 2335kg + 2 ASRAAM + GUN
(d) 6 short range air-to-ground guided missiles + 2 ASRAAMS + GUN

(vi) **Avionics Fit**
Integrated communications, navigation and identification (ICNIA)
Inertial Navigational System
Controls and Display
Radar altimeter
Digital computers
Weapon Management
Tail warning (0.15m dia)
Radar warning receiver
2–18 G Hz jammer
CHAFF and flare dispensers
Ground attack, laser range finder
FLIR

The Project Programme

A study was conducted of current dedicated Close Air Support (CAS) aircraft such as the Jaguar, SUKHOI Frogfoot, AMX, HAWK 200, together with armed trainers. These studies led to the specification above.

The whole design process started with the conceptual design of the aircraft, by members of staff, in the summer of 1987. This work was summarised in Reference 3 which was given to the 28 students in October of that year. Each student was given responsibility for the detail design, stressing and fatigue analysis of components such as the forward fuselage, outer wing, tail etc. Some students designed mechanical systems such as fuel, flying controls, engine installations etc.

The large numbers of student meant that we were able to give students responsibility for the design of the weapon system, avionics installation, reliability, maintainability, survivability, aeroelectricity and performance. Parallel designs were also performed for fly-by-wire control systems and a composite fin and tailplane. The Cranfield group project is unique in the level of staff preparation, allowing more detailed work by students then in group projects elsewhere.

The project was managed to a demanding eight month programme by means of weekly project meetings, where students reported progress, received advice and instructions for subsequent work. The most important function of these meetings was that of a forum where design conflicts were resolved. Sub-groups were formed to convert the author's aerodynamic, geometric and mass information into structure loads.

The knowledge gained during lectures, project meetings and discussions with members of staff was augmented by information from aircraft manufacturers.

Vital information on the ADOUR 87 engine was given by Rolls-Royce and realistic information was received from avionic systems manufacturers. Extremely useful group insets were made to RAF Bentwaters and BAE Brough. In the former, we were allowed to crawl over USAF A-10's and query their ground crews and a pilot. The latter visit involved talks from high level designers, tours of the machine shop, HAWK and HARRIER production lines and fatigue and System test rigs. The visits were much appreciated and were useful practical inputs to our design. Individual student and staff visits were also made to:
(i) The Royal Ordnance Factory, Enfield
(ii) Headquarters — Strike Command
(iii) RAF Abingdon
(iv) Dowty Rotol

The nature of the project was such that significant configurational changes were not possible (as in the real thing!), but a number of detail changes were made, as explained later. A lecture given by an RAF pilot led us to introduce an extra weapon configuration which included 12 cluster bombs.

The programme ended in May, 1988 with the submission of large project theses which contained descriptions of the designed components, supporting analysis, drawings, CAD plots, and Finite Element results.

DESCRIPTION OF THE FINAL DESIGN

General Configuration

A general arrangement drawing is shown in Figures 1 & 2. In order to meet the specification, the aircraft is of simple layout with a moderate aspect ratio supercritical section wing. The modest wing loading, powerful flaps and high thrust to weight ratio give good manoeuvrability and STOL performance, together with adequate ride quality.

Early schemes include a low-winged variant, but problems were experienced with stores clearance and the wing box — engine interference. The side intakes and relatively forward semi-podded engines eased CG variation problems. The datum material was aluminium — lithium, with some composite materials.

Wings

The wings have an aspect ratio of five and have wing-tip mounted lanchers for

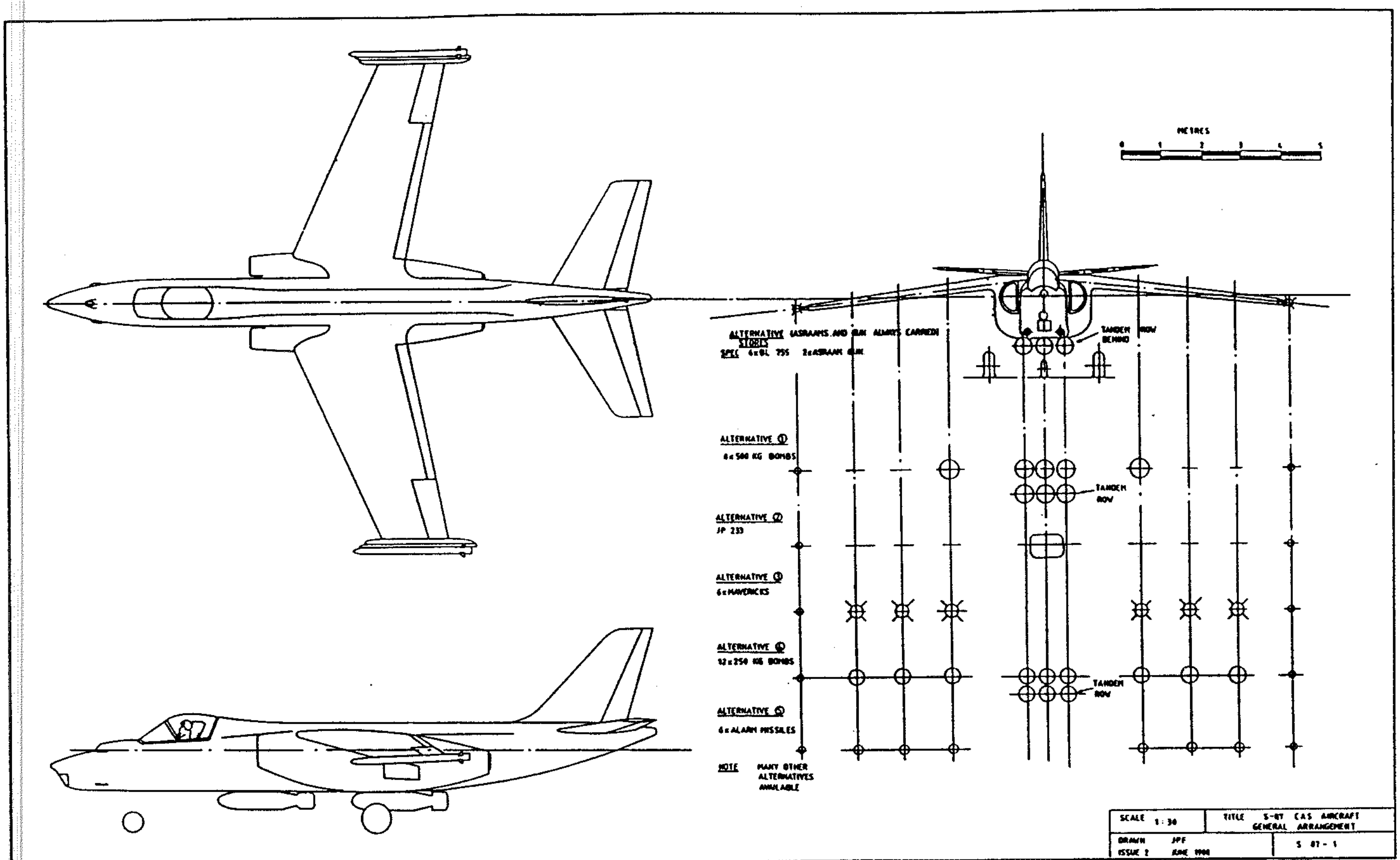


Figure 1

ASRAAM short-range missiles. Three pylons are fitted to each wing, for the carriage of bombs or air-to-ground missiles. Their positions were chosen so that they would act as fairings for the flap tracks. The wings utilise 3-spar construction, to help minimise the effect of battle-damage to the structure. Finite Element Analysis was performed to help in the wing design and to check the effect of the loss of a spar. Analysis showed that if a spar was lost, the wing structural manoeuvring ability would be considerably reduced from its 9g limit. Aeroelastic calculations showed that the wing had a considerable margin of stiffness in terms of divergence and aileron reversal and adequate performance in flutter.

Leading edge devices are not used, to simplify maintenance. The short-field requirement led to the use of very powerful 30% chord double-slotted. Fowler Flaps and drooped ailerons.

The choice of the RAE 9530 aerofoil section allowed the use of a relatively thick wing (10.5% t/c). The quarter-chord sweep of 22° meant that the flaps are more effective than for higher sweep angles. These advantages were bought at the cost of a heavily aft-loaded pressure distribution. This means that at M=0.9, there is a considerable load on the ailerons due to incidence. This is obviously increased when the ailerons are deflected, thus requiring large hydraulic flow rates to the actuators. It was suggested that local section changes are required to combat this.

Detailed calculations showed that low-speed roll control was marginal in some conditions. The solution adopted was to use segments of the wing trailing-edge shrouds as spoilers. A more radical solution would be to use all-moving tailerons.

The large flaps required complex track arrangements for optimum positioning. The geometry was simplified for a marginal reduction in flap effectiveness.

Fuselage (Figure 3)

The fuselage construction is semi-monocoque, utilising four longerons for much of its length. The initial configuration envisaged the use of common optics for both the FLIR and the laser range finder. Research suggested that this assumption was optimistic and therefore an extra optical sensor had to be provided. Information was not available for composite armour, so Titanium alloy was used for the pilot's "bathtub". The weight penalty was reduced by using it as a part of the fuselage structure. It was decided to use a pair of ADEN 25mm cannon instead of the one on the specifications to improve strafing ability. The space under the cockpit limited the ammunition to 120 rounds per gun. Spent links and cases are stored internally (Fig. 3). It is interesting to note that the recoil force of each of the

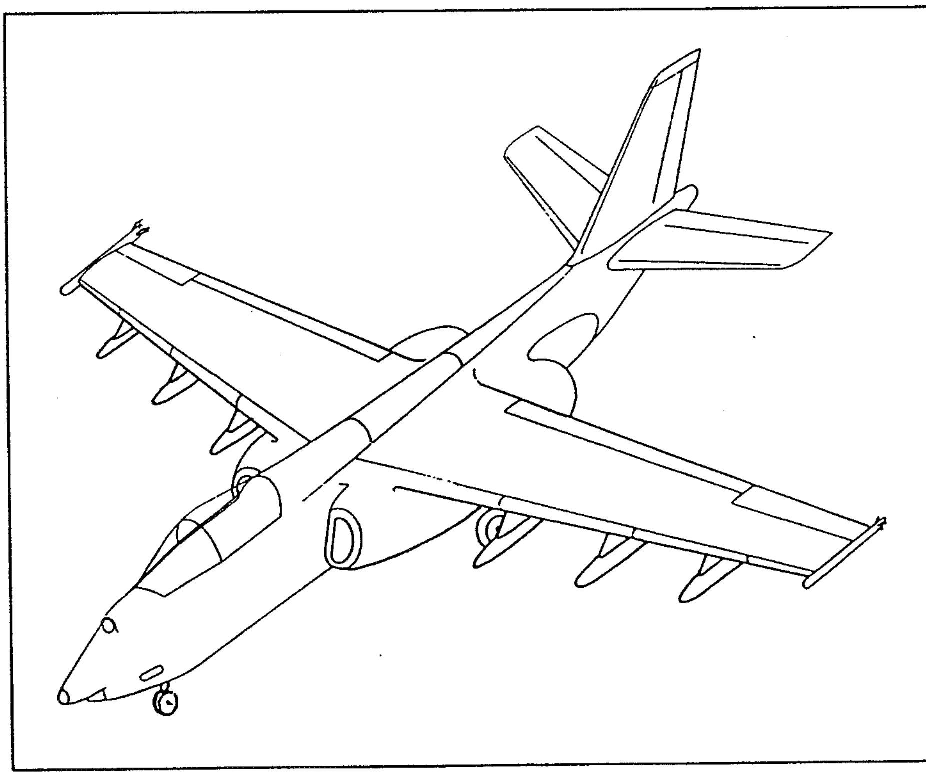


Figure 2

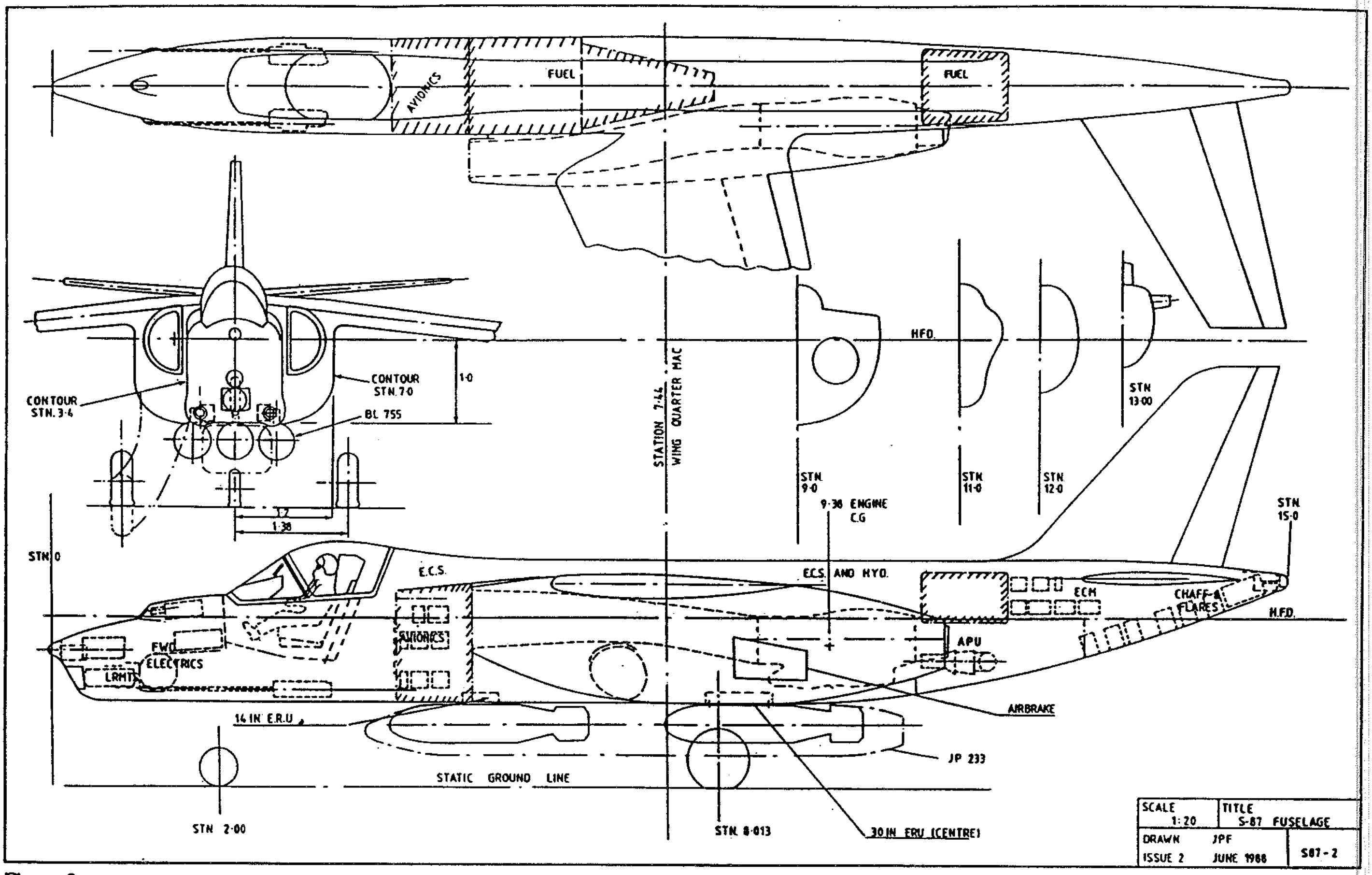


Figure 3

powerful guns was of the same order as the maximum vertical force on each of the nosewheel pintles.

The area immediately behind the cockpit is occupied by ECS and Avionic bays followed by highly-protected fuel tanks. The spine is used for the passage of ECS ducts and the cables for the signalling of the primary flight control system. Secondary runs are in the lower part of the fuselage. The lower part of the centre fuselage is used for the installation of six ejector release units for the fuselage stores. The centre fuselage caters for the attachment of the wing, engines and main undercarriage units. The latter presented particular problems due to the large wheel size and the complex geometric analysis required to derive the skrew hinge and retraction geometry. It became necessary slightly to re-position the underfuselage stores and engine intakes.

The rear fuselage continues the 4-boom arrangement and provides accommodation for an APU, electrics bay, ECM and rear fuselage fuel tank. Attachment is provided for airbrakes, fin and tailplane. Initial calculations showed that the latter had sufficient trim and control authority so that a fixed incidence unit could be used with consequent simplification. Chaff and flare dispensers and Radar Warning receivers are mounted in the tail fuselage, together with actuators for the rudder and elevators.

Figure 4 shows our CAD model of the aircraft which was used to define geometry and interfaces.

Engines

The twin ADOUR 872 bypass engines have the following advantages:

(a) Good fuel consumption
(b) Low noise
(c) Low smoke emission
(d) "Cool" infra-red signatures to make the aircraft less susceptible to heat-seeking missiles
(e) Modular construction for easier maintenance

The engines are the same as those used in the HAWK 200 aircraft. They retain a very high proportion of their static thrust during high subsonic flight. The installation in our aircraft includes firewalls, fire detections and suppression systems. Large hinged doors are used to facilitate vertical engine replacement.

Armament

The cluster bombs for the spec payload are carried tangentially on the lower surface of the fuselage in two rows of three. The ejector release units are arranged so that the centre two can be used to mount the JP233. Wing tip launchers are provided for the ASRAAM missiles while an additional 6 underwing pylons are provided for stores such as air-to-ground missiles. This gives 14 weapon stations and a maximum payload of some 4.2 tonnes. A typical wing pylon and the gun installation were designed in detail with information received from industry. The ECM is mounted internally and does not need to use a weapon station.

Fuel System

The majority of the fuel is carried within the fuselage but some occupies the wing structural box, and external tanks may be carried on the inboard wing pylongs, to give a ferry range of 4300 km.

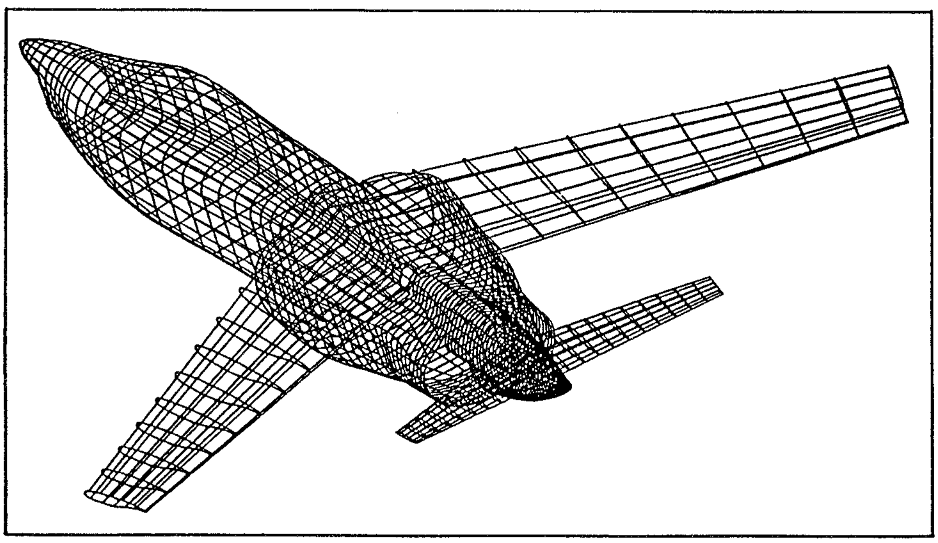


Figure 4

An additional fuel tank was incorporated into the rear fuselage to help keep the CG within limits and give greater weapon carriage flexibility. The five fuselage tanks are of the self-sealing bag type, using reticulated foam for fire and hydraulic ram suppression. There are three integral tanks in the centre and inner wing section. Fuel sequencing arranges that these are emptied first so they are empty before FEBA is reached, to reduce vulnerability.

Survivability

Analysis of Vietnam losses of single-engined aircraft yielded the following results:
62% — due to the fuel system being damaged, principally tanks.
18% — pilot incapacity
7% — loss of engine power
3% — structural and other damage.

Our aircraft was designed to increase its survivability. The fuel system measures are mentioned above, as is the pilot's bathtub. Most of the structure has redundancy in terms of extra spars and longerons. Great care was taken to separate duplicated systems and to protect the ammunition drum. The aircraft's agility and comprehensive ECM should reduce the probability of being hit. Vulnerability was analysed and information from this, together with reliability and maintainability predictions, was fed into a mission availability computer model.

Predicted Performance

The table shows the main points of the specifications together with S-87 predictions and published data for comparable aircraft.

It can be seen that preliminary calculations show that the aircraft met its requirements in all parts and exceeded them in terms of manoeuvrability. The aircraft does not match the A-10 in terms of payload or range but is comfortably superior in terms of speed, agility and field performance, thus giving more flexibility in terms of available airfields. The probability of being hit by opposing forces is considerably less than the A-10, but both aircraft have comparable levels of protections. Thus, the S-87 attrition rate should be less than that of the A-10. This, combined with increased speed and the possibility of operations from airfields closer to FEBA should mean that the S-87 would be able to deliver more payload on target for a given fleet size.

Operation Simulation data was available for the Fairchild A-10. Similar information about the S-87 CAS operations was obtained, so that the performance of the two aircraft could be compared by means of our operation simulation model.

For the purpose of this comparison, the operations of an initial fleet of 24 aircraft, of each kind, were observed over a conflict period of 10 days, to establish the total number of sorties generated by each fleet, and to find the respective numbers of aircraft available at the end.

Assuming a 12-hour flying day, a 24-hour maintenance day, and given average sortie times for the S-87, together with turn round times, a maximum of 12 sorties per day was calculated. The Fairchild A-10 being slower than the S-87, would only generate 9 sorties a day, for the same combat radius.

The model output can be provided in several forms but the most convenient was found to be a table giving the "end day" values of serviceability and cumulative sortie generation, with additional output of the number of aircraft that would be available to use on the day after the deployment is terminated or end of battle (Figure 5). Vulnerability calculations gave a 5% and 3% attrition for the A-10 and S-87, maximum respectively.

Given the respective A-10 and S-87 payloads of 7.26 T and 4.22 T, the number of sorties viz. 426 and 736, and assuming that maximum payload was dropped on each sortie, one can easily calculate the total payload delivered as 3093 and 3106 T, respectively.

More of the S-87 aircraft survive to the end of the 10 day period. Furthermore, although on day one there is not a very substantial difference between the two fleets, it grows progressively larger in favour of the S-87, because of its higher survival rate. Thus the longer the conflict, the more significantly this factor will come into play, and greater the payload delivery of the S-87 will be. The greater number of sorties also increases the possible number of targets that may be attacked.

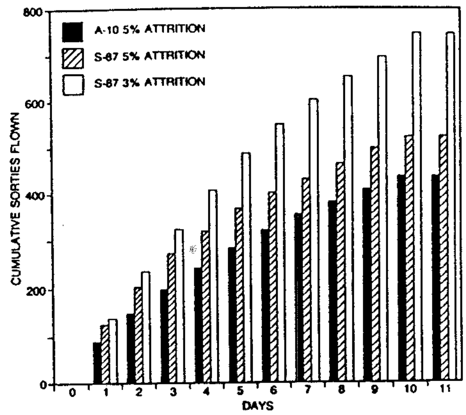


Figure 5. Results of operation simulation model runs (initial fleet of 24 aircraft)

Two other factors in favour of the S-87 are that its superior field performance allows closer basing to the battle area and improved avionics allow more operations at night, or in bad weather. These factors are not allowed for in the results shown.

It appears that the S-87 speed and agility are superior to the AMX and HAWK 200, and payload, range and field performance are superior.

Cost estimates have not been performed but the deliberate move towards simplicity should provide reduced first and operating costs. The use of simple structure together with the elimination of slats, moveable tailplane and brake parachute illustrate this approach.

The main cause for concern is that of the low-level ride quality. The good field performance was partially achieved by the use of a relatively low wing loading. Initial calculations showed barely adequate ride quality, but this should be checked.

Conclusions

The choice of a relatively simple aircraft configuration, together with a large number of students led to a considerable amount of detailed design work. Many of the assumptions made in the conceptual design phase were substantiated.

This project was the most comprehensive to date in terms of systems design and analysis of reliability, maintainability and survivability. This led to a much more integrated design of what could become a very potent close air support aircraft.

The group project fulfilled its primary aim of providing a realistic design environment for the training of aircraft designers.

TABLE PERFORMANCE ESTIMATES

Parameter	Specification	S-87 Prediction	A-10A	AMX	HAWK 200
Mission radius LO-LO-LO at Spec Payload	500km	500km	1000km	370km	482km
Ferry range	—	4300km (2 ext tanks)	3950km	2965km	3600km (2 ext tanks)
Max Mach No SL Spec Payload	0.8	0.8+	0.56	—	0.85 (CLEAN)
T.O to 15M	880	880	1220	1525	2134
Landing (Ground) Spec payload	500	500	610	—	854
Max STR (penetration speed, Spec payload)		4.8' g'	3.5' g'	—	—
MAX payload	4.22T	4.22T	7.26T	3.8T	3.08T
Max A.U.M.	—	12.6T	22.68T	12.2T	8.6T

References

1. Concept Evaluation Model, A. STOVL Airframe Studies. Ministry of Defence. June, 1986.
2. The Design of a Miniature Close Air Support Aircraft. Dr J. P. Fielding, College of Aeronautics Memo 8102, May 1981.
3. Close Air Support Strike Aircraft — S87. Dr J. P. Fielding and Dr R. I. Jones, DES 8700. Cranfield Institute of Technology, Oct. 1987.

The A-88 Regional STOL Airliner Project

by Dr J. P. Fielding, Senior Lecturer in Aircraft Design

Dr John Fielding

The Design Programme

The College of Aeronautics has a pragmatic approach to the teaching of aircraft design. Students are awarded an MSc degree if they have proved that they have the ability to produce workable, realistic designs in which all of the major problems have been addressed. This is assessed by means of annual group projects in which relevant aircraft types are studied. Our group project is unique by virtue of the amount of preparatory work done by staff before work is started by the students. All other known design projects start with the students being given the aircraft specification. They then have to perform a conceptual design, leaving little time available for detailed design. With the Cranfield method, this work is done by the author, thus enabling the students to start much further down the design process. They thus have an opportunity to get to grips with the detail design problems, and become much more employable in the process.

Those who wish to produce their own conceptual designs may do this as the research component of the MSc programme.

The opening of the London Docklands airport in the early 1980s made London-based short take-off and landing (STOL) operations a reality. Rapid and continuing growth of the air travel sector has stretched the capabilities of the current conventional airports to the point where maximum capacities are being reached. Subsequent flight delays and cancellations have manifested themselves in customer dissatisfaction. With airline travel predicted to continue growing at an unprecedented pace, the overall attraction of "hub and spoke" operations out of major airports is reduced. STOLport operations for short to medium length regional flights are predicted to become very attractive to both operators and customers.

Current STOLport operations are limited by the current generation of aircraft capable of operating profitably from STOL airfields. For reasons dictated by minimum available field length and maximum permissible noise levels, London's Docklands airport is limited by law to the exclusive use of DeHavilland (Canada) DHC-7 "Dash 7" turboprop aircraft. While the DHC-7 has impressive STOL capabilities, this design is approaching 20 years of age and is out of production.

The very design features of the DHC-7 which produce the excellent STOL performance also depress the profitability of the aircraft. The turboprop engines are speed-limited by propulsive efficiency. Furthermore, the engine/wing interface, which provides the excellent low speed lift also results in a high cruise drag. The overall effect is a relatively slow aircraft and subsequent high block time. This reduces the aircraft's profitability by reducing both the number of daily sorties and passenger appeal. This is particularly important for business passengers whose flights are often same day return excursions where the flight may consume a major portion of the working day.

Technological developments and refinements during the last 20 years present the opportunity for development of a STOL aircraft which overcomes the limitations experienced by current operational STOL aircraft. The A88 STOL regional airliner is a proposal to meet this opportunity.

A conceptual design study was performed by the author, based on the specification shown later. This process determined the basic shape of the aircraft together with weight, aerodynamic and loading information. This work was summarised in (Reference 1) which was presented to each student at the start of the academic year. Seventeen students were then allocated the responsibility for the detailed design of a major part of the aircraft. These responsibilities took the form of a major structural component, such as the forward fuselage, a flying control surface, a mechanical system, or the avionics installation.

Each student acted as design engineer, stressman or reliability engineer, and draughtsman. The advent of student's PC computers and word-processing packages has, in many cases, added the role of typists.

The project was managed to a demanding eight month programme by means of the weekly project meetings, where students reported on progress, received advice and instructions for subsequent work. The most important role of the meetings, however, was that of a forum where design compromises were resolved and students gained an appreciation of the problems being encountered on other parts of the aircraft.

The programme ended in May 1989 with the submission of voluminous project theses containing detailed drawings and calculations. It has been estimated that at least 15,000 man-hours were spent on the programme, which produced some excellent design work and gave the students considerable design experience.

The knowledge gained during lectures, project meetings and discussions with members of staff, was augmented by several valuable visits. One was to British Aerospace, Woodford to look at BAe 146 and ATP production.

No design programme would be complete without a visit to a company operating the type of aircraft being designed. A visit was therefore made to Britannia Airway's maintenance hangar where minute examinations were made of Boeing 737 aircraft which were undergoing maintenance.

Another visit was made to the London Docklands Airport. It was sobering to see aircraft landing on such a short strip, with large tracts of water on each side!

The Design Specification (From Reference 1)

A brief survey was carried out of current aircraft in this category, followed by discussions with Air Transport experts. The following specification was derived, with field performance based on that of the DASH-7.

Interior Layout

Capacity

70 + Economy class passengers at 32″ pitch with comfort standards at least as good as those of the Boeing 727.

Two attendants' seats with sufficient galley space for 70 snacks.

One or two toilets.

The flight deck shall be designed for a two-man crew with an option for a third.

Cargo

Baggage space should be determined by assuming 4 ft^3 per seat minimum. Cargo space should be an additional 4 ft^3 per seat. Cargo doors should be the same height as the bin interior height and be located so that loading can be accomplished without a mechanical loading system.

It should be possible to carry LD3 containers laterally on the main floor in an optional cargo version. There should be an optional door for this version.

Performance

(i) Passenger and bag payload range shall be approximately 1000 statute miles with FAR reserves.

(ii) The maximum design cruise speed will be approximately mach 0.75 with minimum cost cruise at Mach 0.70-0.72.

(iii) Maximum cruise altitude should be around 40,000 ft with short range cruise altitudes of 15 to 25,000 ft.

(iv) Maximum certificated runway for maximum all up mass take-off is 760 metres at ISA sea level conditions.

(v) The FAR landing distance at maximum landing mass should not exceed 660m at ISA sea level conditions.

(vi) Runway loading should not exceed that of a BAe 146-100 at ramp mass.

(vii) Exterior noise levels should not exceed:

Sideline	84	EPN d B
TO	81	,,
Approach	92	,,

Description of the Final Design

The aircraft was designed using state-of-the-art materials, the majority of the structure being made from aluminium-lithium alloys, with some composite components.

Figure (1) shows a shaded image of the Computer generated surface model of the project. The surface model was generated using McDonnell Douglas' Unigraphics software. Interactive programming techniques were used to ensure a logical build up of surfaces. In this manner, arrays of points were placed on the surface which represented the corner points of multiple flat panels. The coordinates of these points were then written to a file for direct input into an aerodynamic analysis package such as British Aerospaces "Hunt and Sample" panel method. Output from these analytical methods was part-processed to show a multi-coloured 3D image of the configuration showing lift and drag coefficients and their rate of variation. The model, which can be fully integrated, and manipulated, served as a useful visual represention of the configuration (Reference 2).

The major design features of the aircraft are discussed below:

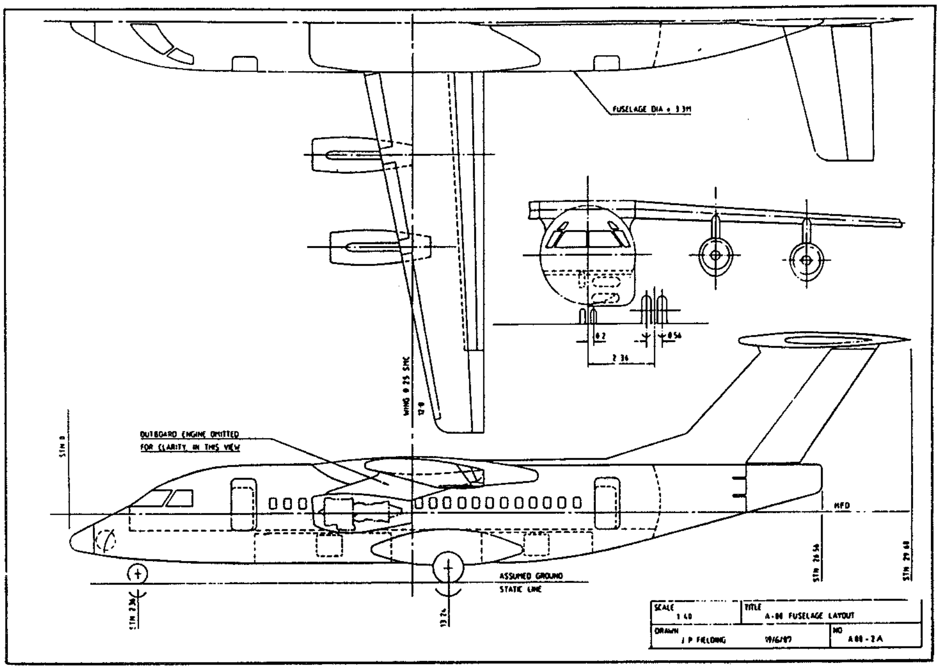


Figure 2. A-88 fuselage.

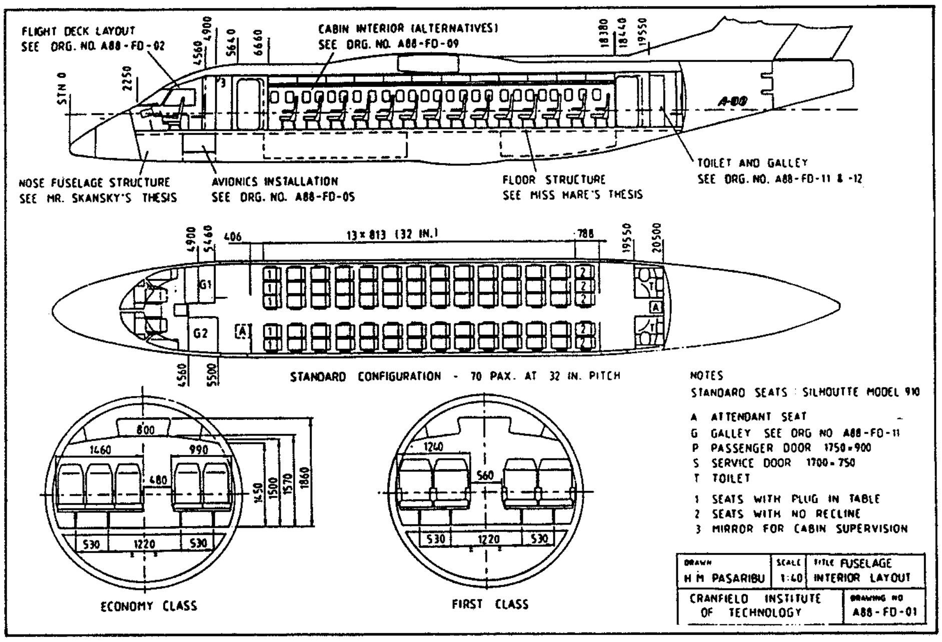


Figure 3. A-88 cabin interior.

Wing

A modest sweepback combined with a supercritical wing section enable Mach numbers in the region of 0.75 to be achieved. The aspect ratio is 9.12 and there is sufficient fuel tankage at spec. payload for a range of 1,100 STATUTE MILES. Tabbed Fowler flaps, slats, low wing loading, spoilers and the high aspect ratio give STOL field performance.

The sweepback and taper were chosen so that the wing trailing edge was perpendicular to the fuselage, thus maximising flap performance.

This effect, and the carry-over lift from the high wing contributed to the high estimated C_{LMAX} of 3.92. The wing torsion box gave more than adequate fuel volume and a simple tank arrangement was chosen. The extremely low wing-loading and high cruise speed, combined with good lifting properties, made the aircraft extremely gust-sensitive at low weights. This led to the adoption of gust load alleviation by means of actively controlled ailerons. The use of an electrically signalled flying control system was chosen to make this possible. This may seem excessive on this class of aircraft, but pioneering work on the Airbus A320 has shown its effectiveness and reliability. The ever increasing efficiency of computers and electronics suggest that this system should be cost-effective for regional airliners. An aerodynamic panel program was written to predict airflow over the slats and flaps.

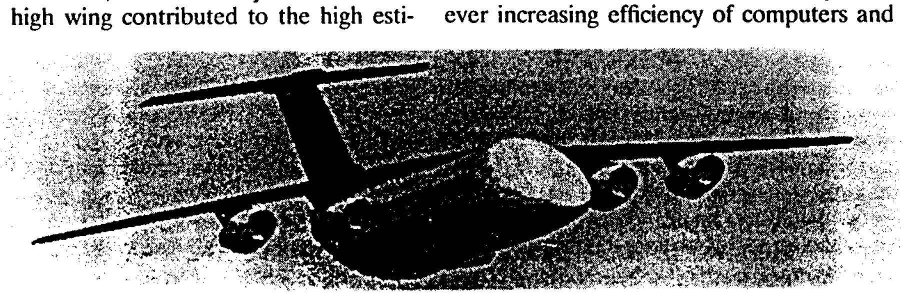


Figure 1. Computer generated model of the A-88 Airliner.

Fuselage — (Figure 2)

The circular-section fuselage permits single-aisle, 5-abreast seating and meets the LD-3 requirement in the cargo version. Passenger baggage is stored under the cabin floor. The seating arrangements are as in the specification but an alternative layout accommodates 75 passengers at 28" seat pitch. Figure 3 shows a typical cabin interior. A rear fuselage airbrake is used so that noisy and costly thrust reversing can be avoided.

Close investigation reduced the size of the flight-deck windows, relative to the author's initial scheme. Extensive structural analysis was carried out using conventional stressing, and finite-element modelling of detail components and large parts of the structure (figure 4). Particular attention was given to the design of bulkheads, windows, wing attachments and the floor. An auxiliary power unit was mounted in the tail fuselage.

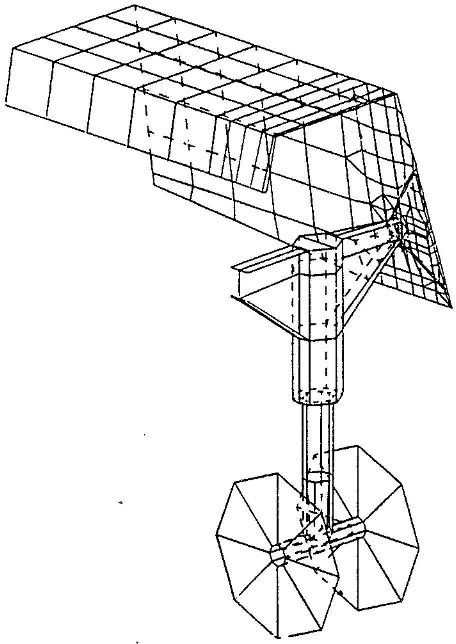


Figure 4. Finite element model of nose landing gear and part of fuselage.

Powerplant

The requirement for STOL performance led to the adoption of a high wing with 4 pod-mounted CFE 738 powerplants. The high wing improves lift and engine clearance while the 4 engines ease climb out requirements after a single engine failure.

The engines are very efficient and light and should enable the aircraft to achieve its performance and noise targets.

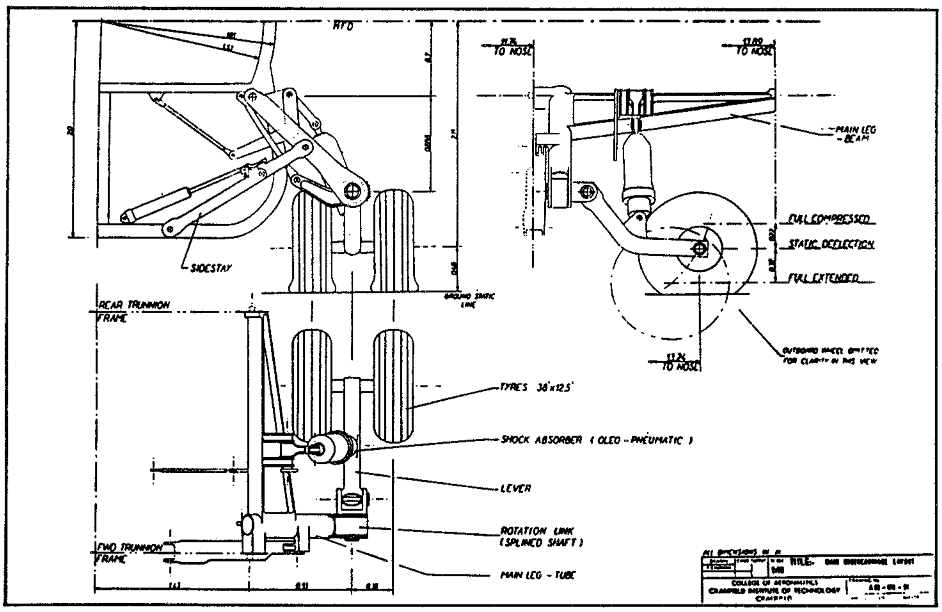


Figure 5. Main landing gear.

Tail Unit

The aircraft utilises an all-moving high-tee tail. Trim is obtained by tailplane movement while control is provided by the elevators. This powerful arrangement is necessary to trim out the large pitching moments produced by the wing high-lift devices. The use of a fin-top "bullet" fairing increased the base of the tailplane attachments and saved weight.

Landing Gear

Twin-wheel units are mounted on each leg. Main units retract into fuselage blisters, but the relatively wide track required considerable ingenuity to produce a satisfactory design (figure 5). The nose landing gear is a conventional twin-wheel unit which retracts forwards.

Predicted Performance

Table 1 shows the target masses for the major aircraft components. Shown alongside are the predictions that were made after the detailed designs had been completed. It can be seen that the author was somewhat optimistic in some of the component targets, particularly for the tail unit and the main landing gear. The latter result was due to the high rate-of-descent of STOL operations and the wide track specified. Another factor was that the short project time-scale meant that there was little opportunity of refining the first detail design that "worked". In a real project, this would have been done, yielding mass savings. It was only possible to perform one or two finite elements runs on most components. More detailed flight path analysis, however, showed that the initial assumptions had been rather cautious so that there was an average fuel surplus of some 1500 KG on most flights. These two factors thus virtually cancelled each other, giving some confidence that the payload range curve of figure 6 could be met. Similar curves are also shown for the BAe 146-100 and the DASH 7 by a considerable margin, as does its cruise speed. The aircraft should match the DASH 7's field performance and noise levels. The BAe 146 has superior payload performance up to 750 nautical miles, but is comparable above this. The A-88, however, has superior field performance and cruise speed.

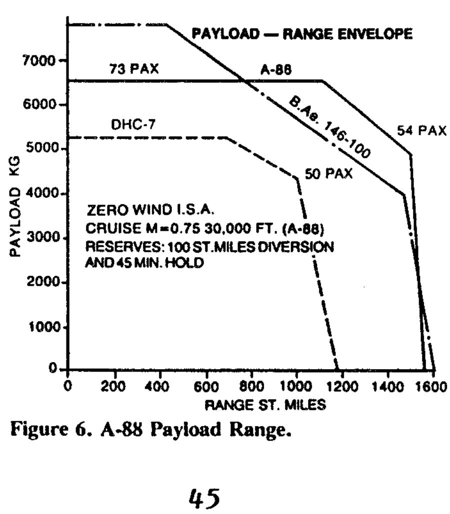


Figure 6. A-88 Payload Range.

Table — Mass Estimates

Component	Target (KG)	Prediction-based on detail design
Wing (inc. auxil. surface (structure)	2523	2942
Fuselage	2990	2810
Fin (inc. rudder)	220	387
Tailplane (inc. elevator)	110	301
Main undercarriage	770	1144
Nose undercarriage	350	316
Structure	6963	7900
Engines	2060	
Powerplant structure	840	
Powerplant	2900	
Fuel system	246	
Flying control system	350	
Hydraulics	350	
Electrical system	706	
APU	100	
Inst. and avionics	930	860
De-ice	280	
Fire protection	84	
Furnishings (inc. seats, galley, etc.)	1596	2160
Environmental control system	438	
Contingency	200	
Systems	5208	
Basic empty mass	15071	
Crew and provisions	624	
Operating empty mass	15695	
73 passengers and baggage	6570	
Fuel at above payload	5740	
Max all up mass	28005	

Conclusions

The design programme fulfilled its primary aim of providing a powerful means of training designers. The use of a challenging and interesting project was a means of investigating many of the problem areas of such an aircraft and produced some good detailed design work.

The aircraft that was designed showed considerable promise but required further work to confirm the performance predictions, and to evaluate its operating costs.

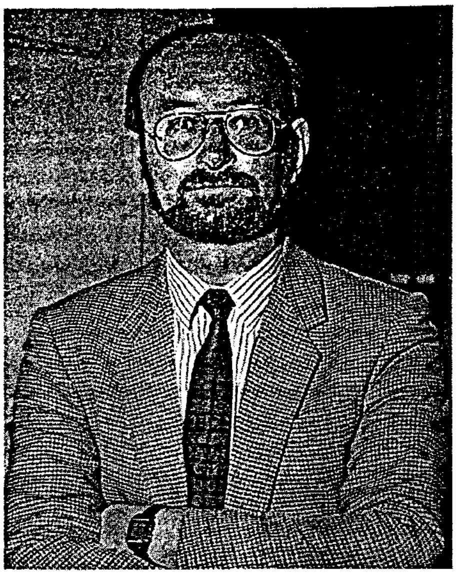
It is likely that a penalty would have to be paid for the STOL operations envisaged. The big wing led to off optimum cruise at low and medium altitudes, and the gust-alleviation system would need to be developed carefully. A regional aircraft, however, is a reasonable candidate for such a system.

References

1. 70 Passenger STOL Regional Airliner, A-88. Project specification. DES 8800. Dr J. P. Fielding, College of Aeronautics, Cranfield Institute of Technology, June 1989.
2. Aerodynamic CAD CAM. R. Jamieson. Aerospace. The Royal Aeronautical Society. May 1988.

Cranfield's New Fighter Project – The TF-89

By Dr John Fielding, Senior Lecturer in Aircraft Design



Dr John Fielding

THE NEED FOR NEW FIGHTERS

The need to replace ageing fighters has given rise to four current western fighter development projects, the European Fighter Aircraft (EFA), the Rafale, the Gripen and the Advanced Tactical Fighter (ATF). The first three are dog-fighting aircraft, designed to replace or compete with aircraft such as the F-16 or F-18. The ATF concept is an American requirement, essentially to replace the F-15 long-range interceptor. This role was chosen as a suitable topic for the current Cranfield design project. The ATF project, by its nature, is shrouded in mystery, but information has been gathered from the open literature and references 1 and 2 to derive the following specification.

THE PROJECT SPECIFICATION

Field Performance

The aircraft should take-off from concrete runways in a distance of 500m. Landing distance over a 15m obstacle should be 900m.

Sustained Cruise

The aircraft should be able to cruise at M 1.6 and 50,000ft on "dry" power over a range of 1000n. miles.

High Speed Dash

The aircraft should be able to fly at M 2.5 at 50,000ft.

Manoeuvrability

The following sustained "g" levels should be attained in turns:

M = 1.6,	36000ft altitude	= 5' g'
M = 0.9,	sea level	= 7.33' g'
M = 0.9,	20,000ft	= 7.33' g'

Weapon Load

The aircraft should carry four AMRAAM medium range missiles, four ASRAAM short range missiles and have an internally mounted cannon.

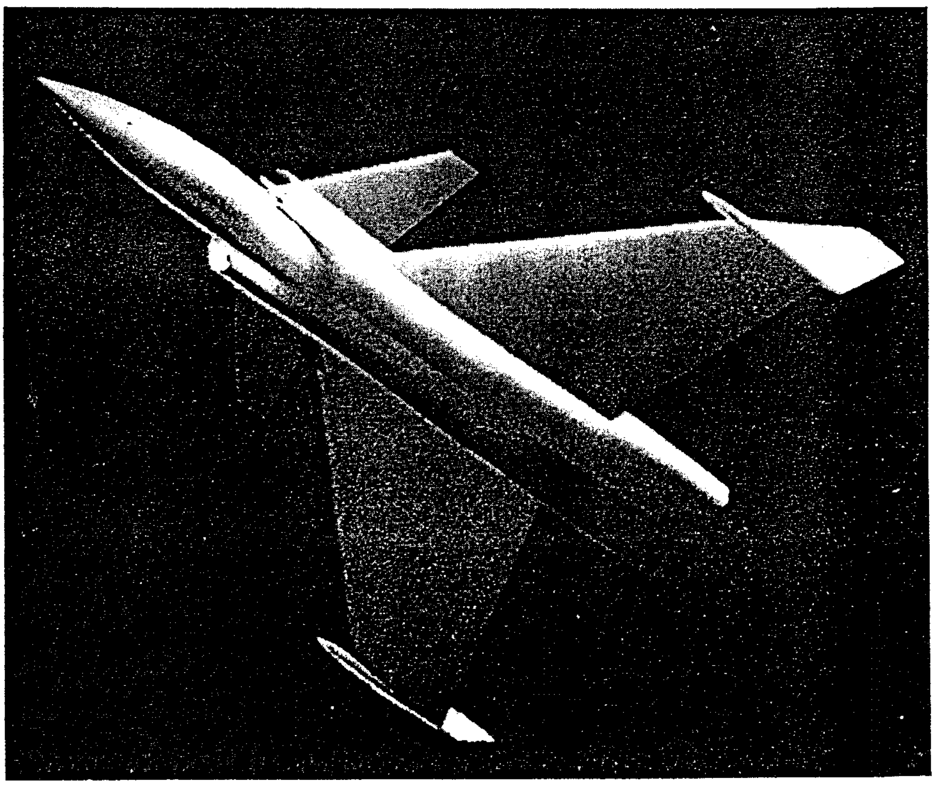


Figure 1. CAD surface model of TF-89.

Avionics Fit

Integrated communications, navigation and identification (ICNIA)
Inertia navigation system
Controls and display
Radio altimeter
Digital Computers
Airborne radar
Weapon Management System
Radar warning system
2-18 G.Hz jammer
Chaff and flare dispensers

General Requirements

The aircraft shall have a low radar cross-section to increase survivability. The aircraft is to have half the combat turn-round time of the F-15 and rather less than half the number of maintenance personnel per aircraft. The reliability is to be twice that of the F-15, while costs should be of the same order.

GROUP PROJECT ACTIVITIES

The design process started with the conceptual design of the aircraft, by members of staff, in the summer of 1989. This work was summarised in Reference 3 which was given to 18 students in October of that year. Each student was given responsibility for the detail design, stressing and fatigue analysis of components such as the forward fuselage, outer wing, tail, etc. Some students design mechanical systems such as fuel, flying controls, engine installations, etc.

The large numbers of students meant that we were able to give students responsibility for the design of the weapon system, avionics installation, reliability, maintainability and survivability.

The Cranfield group project is unique in the level of staff preparation, allowing more detailed work by students than in group projects elsewhere.

The project was managed to a demanding eight months programme by means of weekly project meetings, where students reported progress, received advice and instructions for subsequent work. The most important function of these meetings was that of a forum where design conflicts were resolved. Sub-groups were formed to convert the author's aerodynamic, geometric and mass information into structure loads, etc.

The knowledge gained during lectures, project meetings and discussions with members of staff was augmented by information from aircraft manufacturers.

Vital information on the project engine was given by Rolls-Royce and realistic information was received from avionic systems manufacturers. An extremely useful group visit was made to RAF Marham, where Tornado Aircraft were minutely examined.

Lucas Aerospace at Luton hosted another visit, which gave useful information on the manufacture of transparencies, anti-icing and composite components. British Aerospace, Brough, showed fighter aircraft manufacture and advanced systems research.

The programme ended in May, 1990 with the submission of large project theses which contained descriptions of the designed components, supporting analysis, drawings, CAD plots, and Finite Element results.

DESCRIPTION OF FINAL DESIGN

General

Figure 1 shows a CAD — generated surface model of the aircraft and Figure 2, the initial fuselage arrangement.

An unstable close-coupled canard arrangement was chosen to give improved lift characteristics in take-off, landing and manoeuvres. The relatively high wing aspect ratio and low wing loading and trailing edge flaps improve field performance and optimise lift/drag in flight. The foreplane trims out pitching moments from aerodynamic and vectoring thrust forces, as well as giving good manoeuvrabilty.

The aircraft uses two powerful Rolls-Royce Project augmented turbofan engines. They are fitted with two-dimensional nozzles to reduce infra-red signature and improve pitch manoeuvring. The intakes use translating half-cones fitted with radar absorbent material to improve "stealth".

The fins were placed on the wing tips to take them away from disturbed air from the foreplane and fuselage and from the engine flux. They also act as end plates to improve wing lift and are canted out to reduce radar signature. The "bullets" at the intersections improve the structural connections and provide housing for radar warning systems.

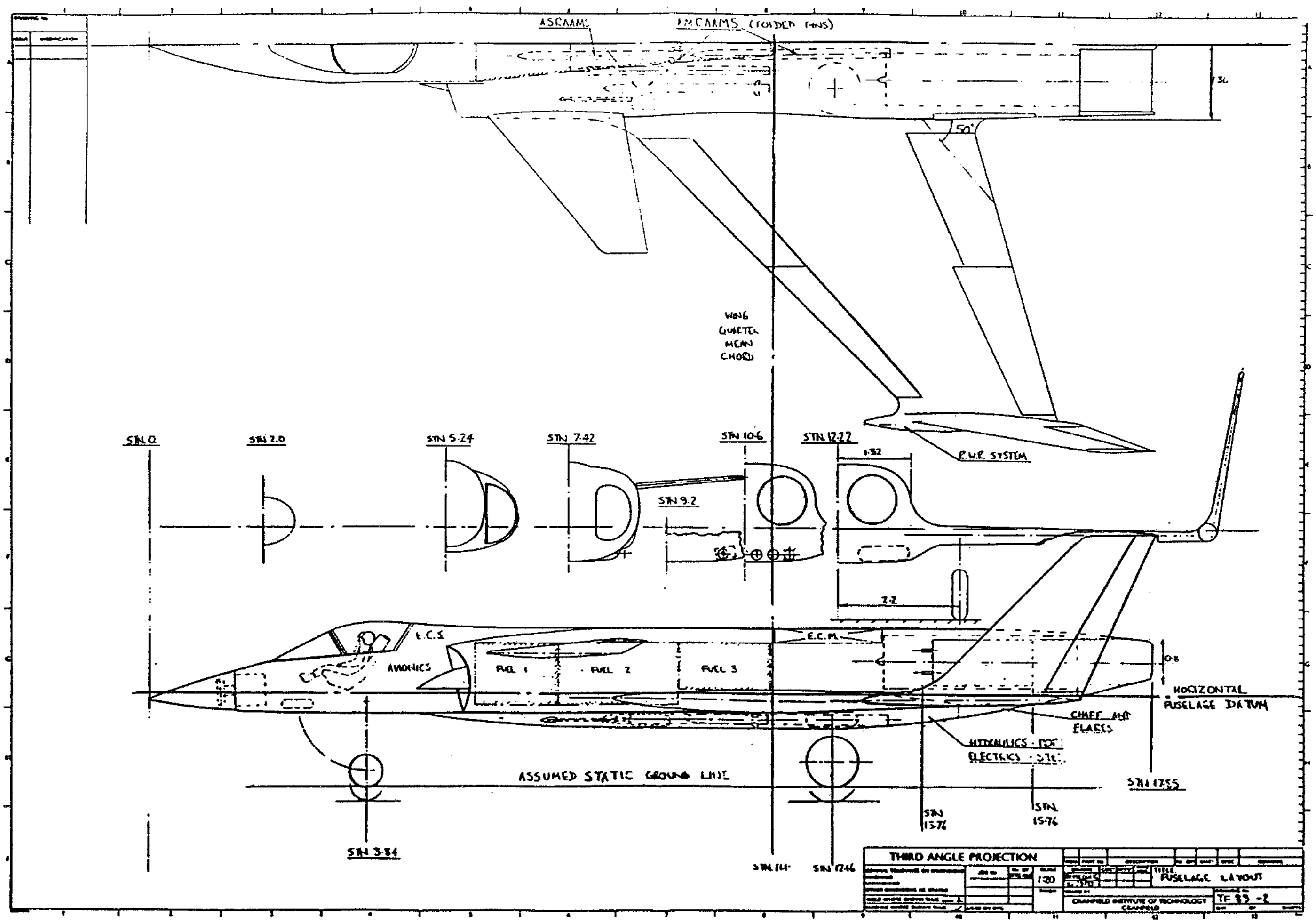


Figure 2. The Initial Fuselage Arrangement

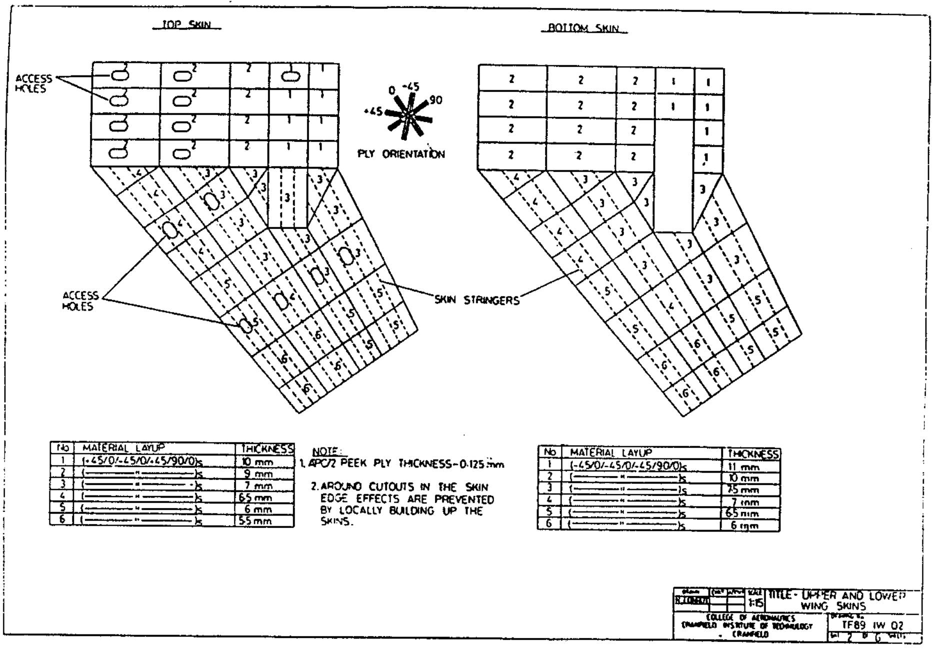


Figure 3. The skin arrangement for the inner wing

Wings

The wing has a relatively low wing loading and an aspect ratio of 2.82 with a 45° loading-edge sweep. It is fitted with plain leading and trailing edge flaps for good field performance and manoeuvring. All primary components were designed to use APC/2 PEEK carbon fibre composite material. The wing had five spars and an unbroken structural box across the fuselage. Figure 3 shows the skin arrangement for the inner wing.

Fins and Rudders

The attachment between the fins and wing gave predictably high attachment loads which were able to be carried by two 10mm diameter maraging steel bolts at each front and rear spar pick-up. The primary structural materials were also APC/2 PEEK, but extensive use was made of honeycomb sandwich in the fin leading and trailing edges, and in the rudder.

Fuselage

The fuselage is carefully blended with the wing to improve drag and "stealth" properties. The same reasons led to the complete submersion of missiles and gun into a ventral pannier. This may be completely removable to improve re-arming. The large engines dominate the rear fuselage, while avionics, pilot and fuel occupy the forward and centre fuselage. Fuel is also contained in the wings.

It was found that the author had made the forward fuselage too wide, so it was decided to re-design it, using the CAD system. Figure 4 shows a plot of the final shape. The primary structural material was Aluminium-Lithum alloy, for the fuselage. Conventional semi-monocoque construction was used, the most signficant members being strong longerons. A full-scale cockpit mock-up was constructed and checked by Cranfield test-pilots.

Foreplane

An APC/2-Peek all moving foreplane was attached to the fuselage by means of large spigots, attached to the air-intake frames. Space was "tight" for the spigot and foreplane actuator, but a successful design was produced.

Systems

Figure 5 shows a CAD generated model of the aircraft and shows both engines and the missiles. Those were folding fin versions of ASRAAMs and AMRAAMs. A 25mm ADEN cannon was fitted to the lower fuselage. The Avionics required in the Specification were accommodated in the fuselage nose and tail. All ECM equipment is internal. Detailed designs were performed for the secondary power, ECS, hydraulic and fuel systems. Figure 6 shows the installa-

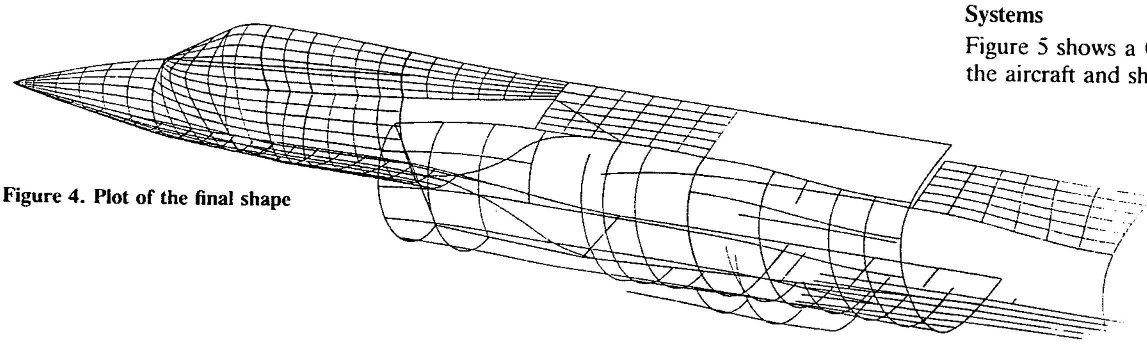


Figure 4. Plot of the final shape

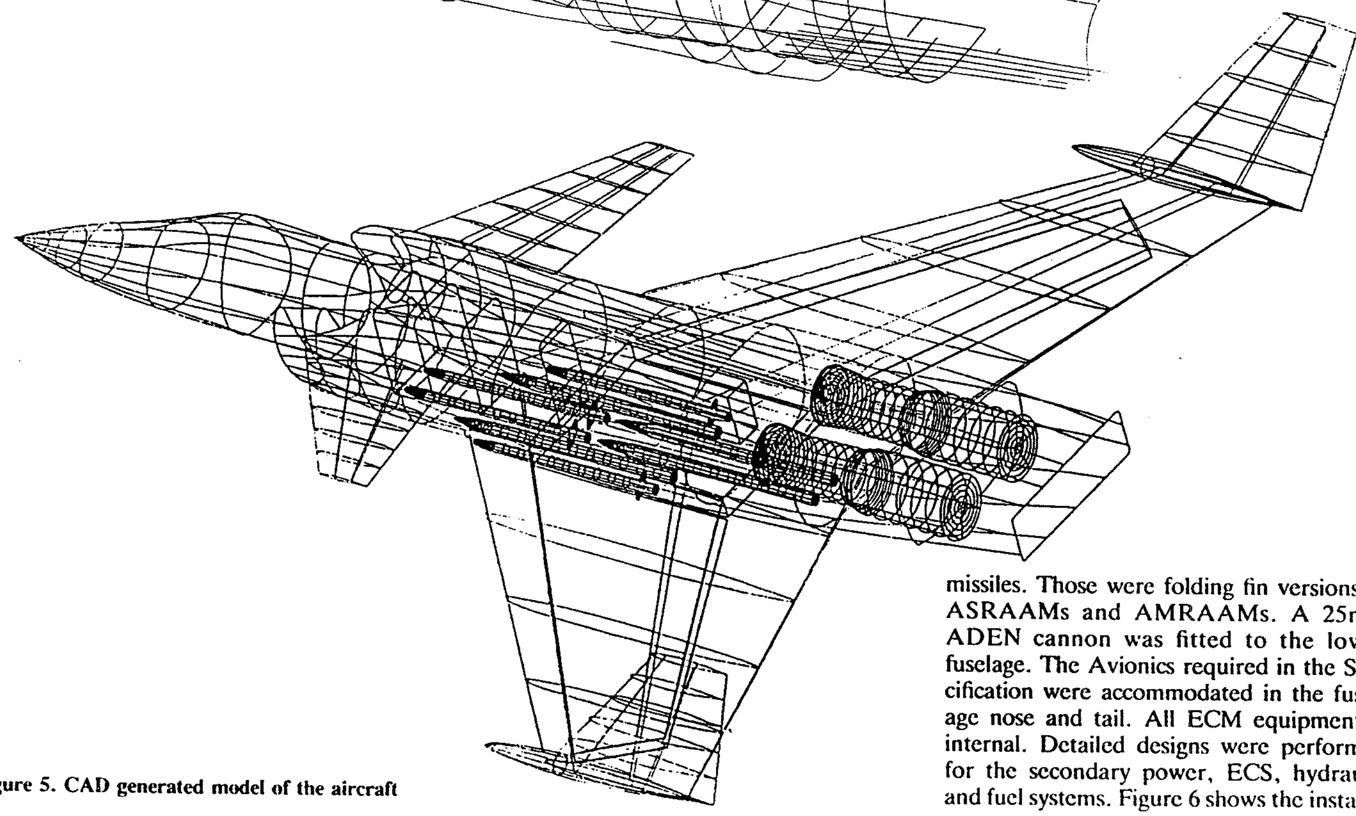


Figure 5. CAD generated model of the aircraft

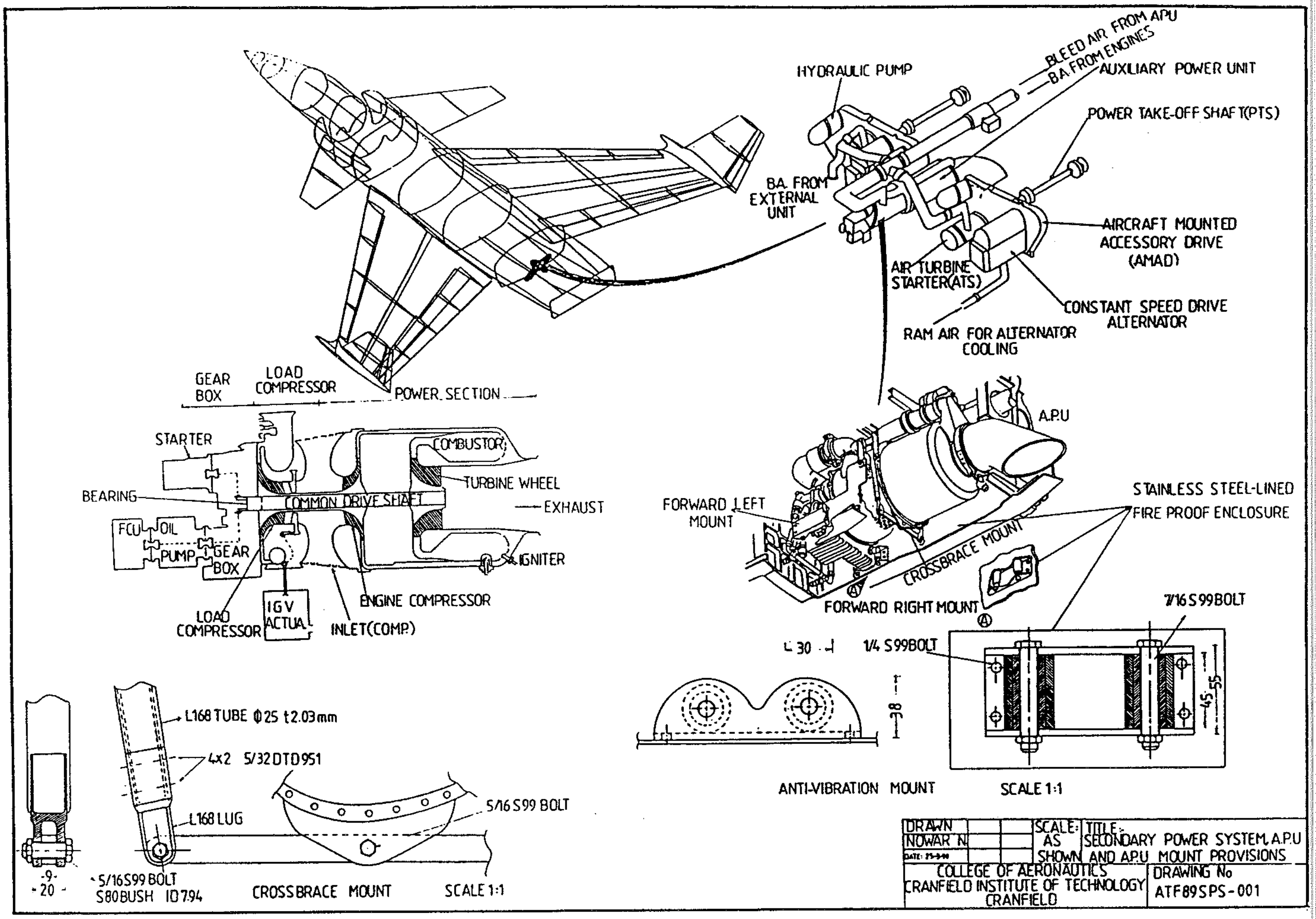


Figure 6. Installation of secondary power systems

tion of the former. Designs were also performed for the powerplant, airbrake, arrester hook and landing gear installations.

Extensive reliability and survivability analyses were performed and aircraft vulnerability protection designed.

PREDICTED PERFORMANCE

The work in the 18 project theses went a considerable way towards producing realistic component masses. Stressed items were based on adequate material volume and thus mass. Those showed that the airframe mass was approximately 150KG heavier than the target, but systems mass some 800KG lighter. It seems likely, therefore, that the overall mass targets should be met.

Predictions also showed that the speed range, payload and field performance could also be met. It was very difficult to estimate the cost of the aircraft, but its development, plus that of the Rolls-Royce project engine would put its initial cost at about twice that of the F-15 for small production numbers.

Table 1 shows the leading characteristics of the TF-89, compared with those for the F-15C, YF-22A and YF-23A obtained from reference 4.

These show that the TF-89 is lighter than the ATF designs, but has less fuel capacity. This implies that the range of the ATF aircraft is considerably greater than that specified for the TF-89. ATF range and performance figures have not yet been released.

The TF-89 has comparable wing loading and better thrust to weight ratios than ATF, implying better manoeuvrability, although it is likely to be less stealthy. The extra mass and thrust of the ATF contenders suggest that they will be even more expensive than the TF-89.

Table 1 — Comparative Characteristics

	TF89	F-15C	LOCKHEED YF-22A	NORTHROP YF-23A
ENGINES (2)	Rolls-Royce	P&W F100	YF119 or	YF-120
SLST IN AFTERBURNER	130KN	104KN	156KN	156KN
TAKE-OFF MASS	22160KG	27000KG	28150KG	29,000KG
OP. EMPTY MASS	13170KG	14530KG	15400KG	16,800KG
INT. FUEL CAPACITY	8040KG	6100KG	11350KG	10,900KG
STATIC T/W	1.19	0.76	1.03	1.0
LENGTH	17.8M	19.4M	19.57	20.54
WING AREA	$65M^2$	$56M^2$	$77M^2$	$88M^2$
ASPECT RATIO	2.82	3.01	2.23	2.0
LEADING EDGE SWEEP	45°	45°	48°	40°
WING LOADING KG/M^2	340	480	366	330
DRY CRUISE MACH No.	1.6	—	1.5	1.5

CONCLUSIONS

The TF-89 was one of the more challenging Cranfield projects. Excellent innovative design was performed, and many of the problems of such an advanced aircraft were explored.

This project made extensive use of computer aided design techniques, with impressive results. The aircraft was likely to meet the mass target, but doubts remain about the kinetic heating effects on APC-2 composite materials.

The group project fulfilled its primary aim of providing a realistic design environment for the training of aircraft designers.

References

1. Conceptual Design Study of an Advanced Tactical Fighter Aircraft MSc Research Thesis by T. Winstanley, College of Aeronautics, Cranfield Institute of Technology. Sept. 1987.
2. Concept Evaluation Model. A STOVL Airframe Studies. Ministry of Defence. June, 1986.
3. Tactical Fighter — TF-89 Project Specification DES8900. Aug. 1990 Dr J. P. Fielding, Dr R. I. Jones. Cranfield Institute of Technology.
4. Aviation Week and Space Technology. Sept. 17, 1990.

A-90

Cranfield's 500-seat Airliner Project

by Dr John P. Fielding, Senior Lecturer in Aircraft Design

Dr John Fielding

The Design Project

The A-90 project was initiated to satisfy the requirements of two organisations. Guinness Peat Aviation (GPA) wanted a realistic investigation of a large short-range airliner design. They felt that this was one possible means of alleviating the chronic and worsening congestion at many of the world's airports. Cranfield Institute of Technology performs annual group design projects as major constituents of its MSc course in Aerospace Vehicle Design. It is always monitoring the aerospace world so that it may choose relevant civil, military or spacecraft topics for its group projects, and the A-90 was chosen as a suitable project. The entire project programme is illustrated in Figure 1.

The conceptual design study was performed for the A-90 by the author, as described later in Reference 1. This process determined the basic shape of the aircraft together with weight, aerodynamic and loading information. The specification was presented to students at the start of the academic year. Twenty-three students were then allocated the responsibility for the detailed design of a major part of the aircraft. These responsibilities took the form of a major structural component, such as the forward fuselage, a flying control surface or a mechanical system such as fuel, environmental control, propulsion, landing gear or the active control system. Each student was expected to act as designer, stressman and draughtsman for his or her component.

The project was managed to an exacting eight month programme by means of the weekly project meetings where students reported on progress, received advice and instructions for subsequent work, from the staff project team. The most important role of the meetings, however, was that of a forum where design compromises were resolved and students gained an appreciation of the problems being encountered on other parts of the aircraft.

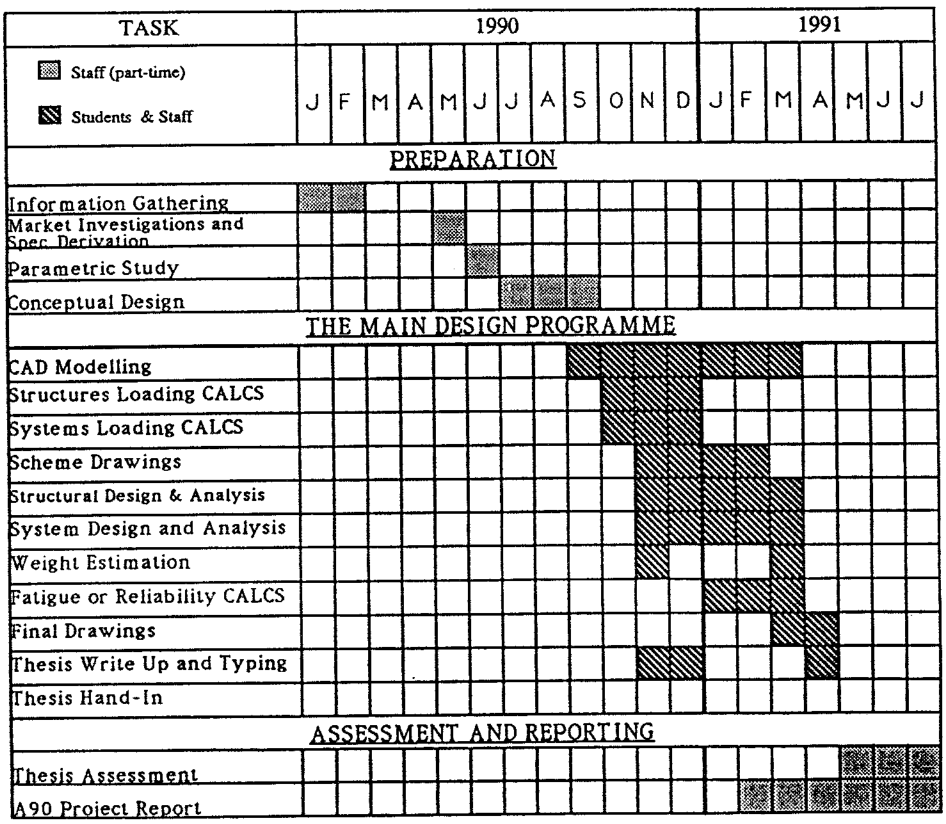


Figure 1. A-90 Programme Timescale

The programme ended in May 1991 with the submission of voluminous project theses containing detailed drawings and calculations. It has been estimated that at least 20,000 man hours were spent on the programme, which produced some excellent design work and gave the students considerable design experience.

The knowledge gained during lectures, project meetings and discussions with members of staff, was augmented by several valuable visits.

No design programme would be complete without a visit to a company operating the type of aircraft being designed. A visit was therefore made to Britannia Airways' maintenance hangar where minute examinations were made of Boeing 737 and 767 aircraft which were undergoing maintenance. Individual students visited factories which were particularly relevant to their design specialisations.

The A-90 project was also used as the basis of research projects by 15 students attending the Flight Mechanics MSc course.

Requirements for the Aircraft

The most important part of any design process is to get the requirements right! The first stage was to examine the main transport aircraft in use, or projected, together with suitable powerplants.

Several market surveys were examined and led to the conclusion that, despite short periods of recession, average growth rates for passengers will be 5.2% over the next 20 years. This growth is certain to strain aircraft capacity, which can only be alleviated by:

(i) Increasing aircraft load factors
(ii) Increasing aircraft utilisation
(iii) New airports and/or extra runways
(iv) Improved ATC
(v) Larger aircraft.

The design of the larger aircraft was the subject of the A-90 study. The market study showed the need for a 500 passenger, short-haul airliner to fit between the capacities of current aircraft, as shown in Figure 2. The major features of the specification were:

(a) 500 mixed class passengers
(b) Carriage of under floor LD3 containers and optional main deck cargo door
(c) Passenger and bag range of 2000 m.miles with FAR reserves with max cruise speed greater than 340 knots
(d) All-up mass takeoff in 8300 ft, landing 5650 ft, ISA, sea level
(e) Runway loading less than an LCN of 65.

Configuration Description

Wing

The modest quarter chord sweep of 30° combined with supercritical wing sections gave a max cruise Mach No of 0.86. The aspect ratio is just less than 9 and the outer wing and centre-wing torsion box gave sufficient volume for an optional range of 3,500 m.miles, when combined with the trimming fin fuel tank. Figure 3 shows the wing tank integral to the aluminium-lithium wing structure. Also shown is the optional wing-tip fold mechanism. The wing utilises variable camber leading and trailing-edge flaps to improve cruise efficiency, provide lift

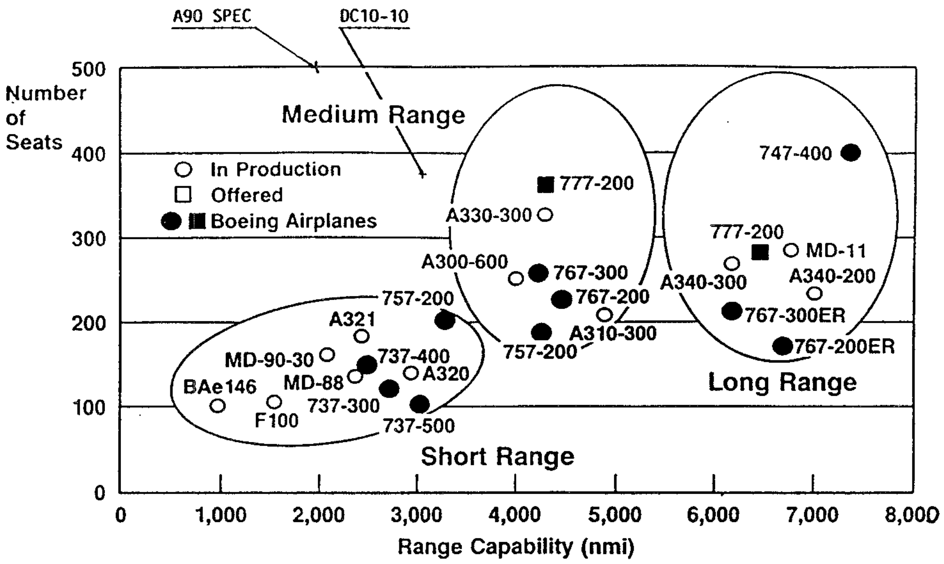


Figure 2. (Courtesy Boeing)

(i) Engine position was relatively close to the aircraft's fore-and-aft centre of gravity and gave payload and fuel loading flexibility.
(ii) Wing weight saving due to inertia bending relief from the engines.
(iii) Simple fuel feed from wing fuel tanks to the engines.
(iv) Relatively easy engine maintenance access.
(v) Avoidance of weight penalties and potential acoustic fatigue problems associated with fuselage-mounted engines.

It was felt that these advantages outweighed the disadvantages, compared to those of fuselage mounted engines, of inferior noise, interference with wing high-lift systems and yaw control following engine failure. The chosen engines were taken from the Rolls-Royce Trent family and shown attached to the pylon in Figure 5.

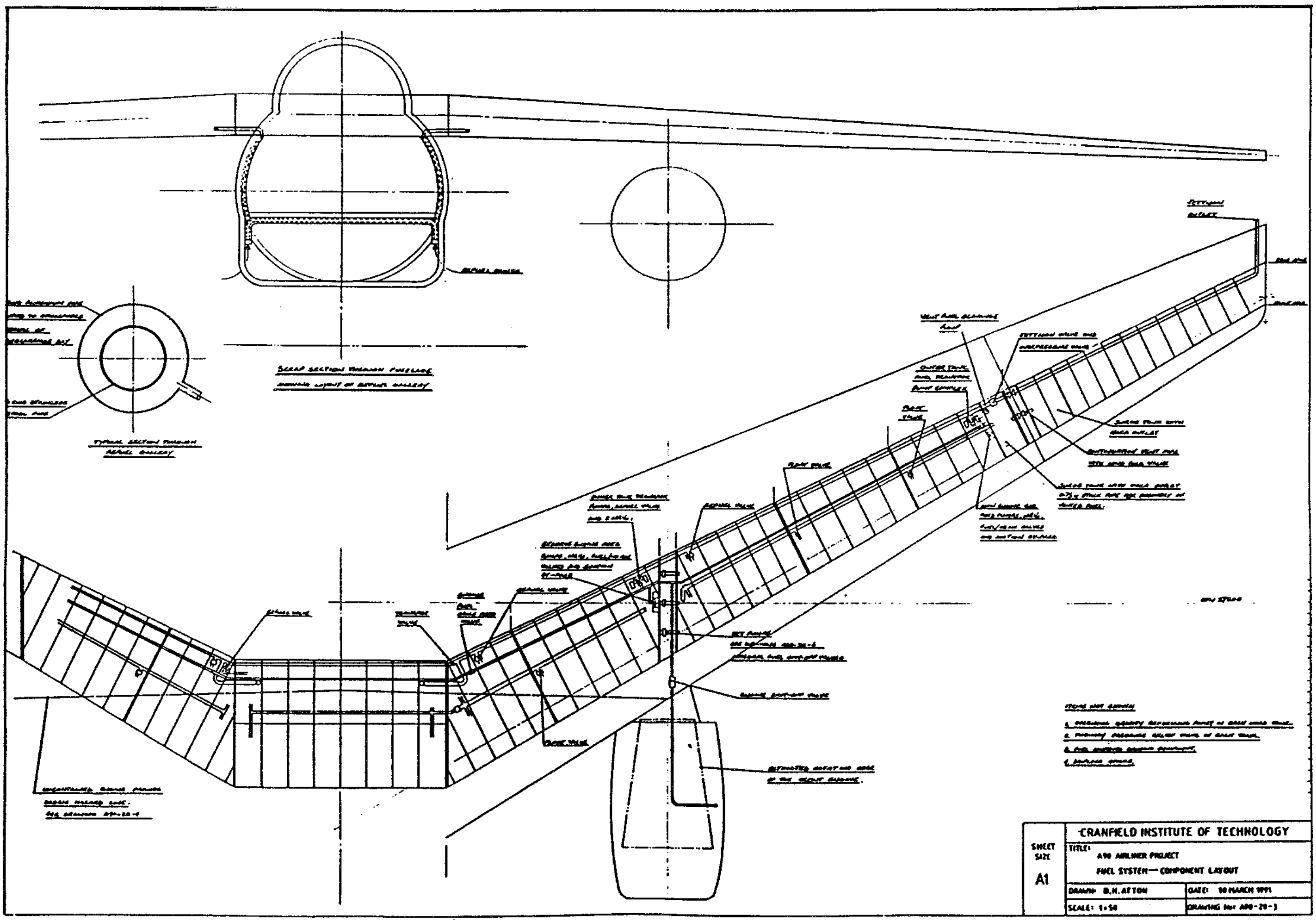


Figure 3.

growth potential and gust manoeuvre alleviation.

Fuselage
The cross-sections of current aircraft were examined and it was decided to use a double-bubble fuselage, with a lover-lobe of similar width to the Boeing 747, with an upper lobe of similar width to the Airbus A320. It was felt that this would give a reasonable fuselage length/diameter ratio (which was later confirmed as being correct).

Figure 4 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 8 ft × 8 ft × 20 ft containers in a cargo version.

Powerplant Layout Choice
The first configuration choices were made during the parametric study. They were that twin turbo-fan engines would be used. These were considered to be the most cost-effective solution for a high-subsonic speed airliner.

The choice of wing-mounted podded engines was made for the following main reasons:

Vertical Wing Position
The original choice was between high and low wing, because of the problem of providing wing bending carry-through structure in the fuselage. The first choice was a high-wing, but this was modified to a mid/high wing. Figure 6 shows a computer-aided design model of the aircraft. The wing structure passes through the fuselage at the intersection of the upper and lower fuselage lobes. There is a clearance of more than 8 ft between the wing lower surface and main-deck floor for uninterrupted loading of 8 ft containers. The upper deck is partially

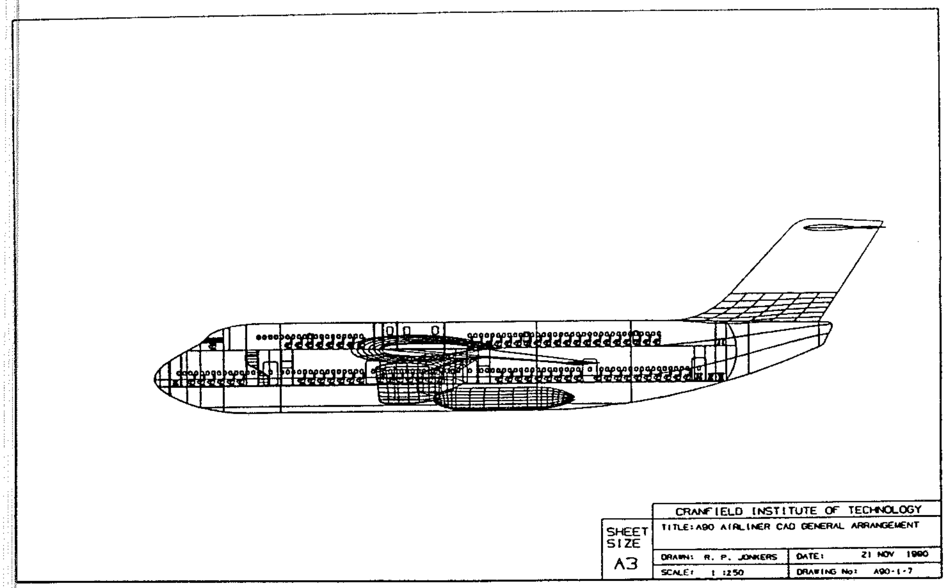


Figure 4.

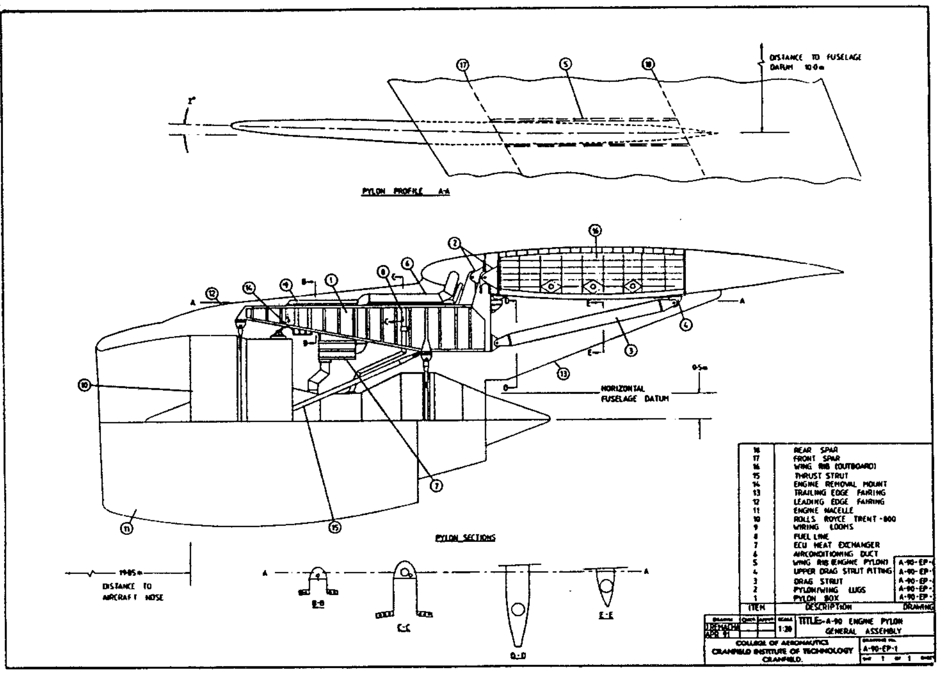


Figure 5.

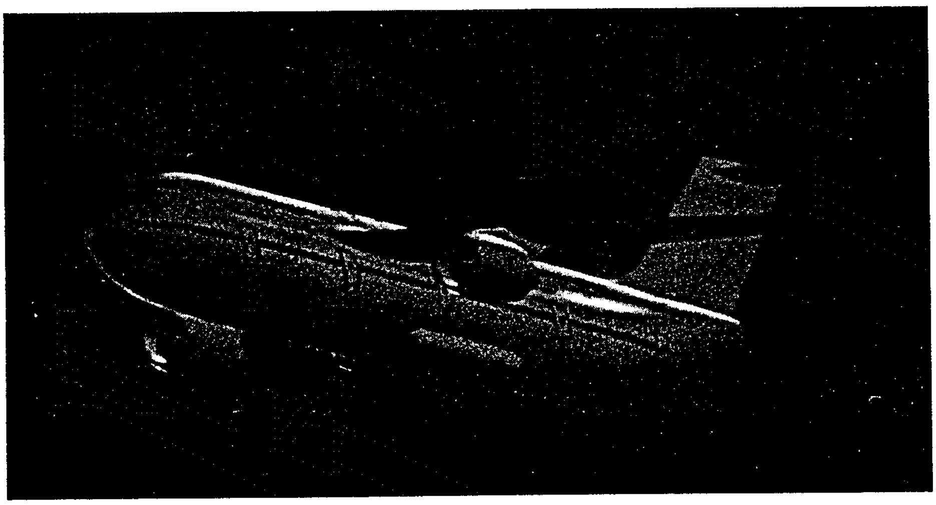


Figure 6.

divided by the upper-surface of the wing, but there is sufficient space for emergency transit between each half of the deck and access to the over-wing exits.

This arrangement thus combines the low interference drag of a mid-wing and the structural efficiency of a high-wing.

Other advantages of this layout were:

(i) Good ground clearance for the under-wing pods of the 10 ft + diameter engines. (This was the primary reason for this choice.)

(ii) The fuselage is closer to the ground because of less severe engine clearance problems. This eases cargo loading, passenger loading, and emergency passenger evacuation. The low fuselage facilitates the conversion of the aircraft to a military transport role, with loading ramps.

(iii) Easier access for fuselage maintenance, lavatory servicing and galley replenishment.

(iv) Main deck passenger vision is improved, except directly next to engines.

The disadvantages of this layout, relative to the more usual low-wing layout were:

— The ditching properties are not as good. This would be an extremely rare event, and the upper-deck over-wing exits should alleviate or eliminate this problem.

— The high-wing arrangement leads to fuselage mounted main landing gears. Those are installed in fuselage blisters, with added weight and drag. Such a big aircraft, even with a low wing, however, would still require one or two fuselage main-legs.

Tail Configuration

The mid/high wing location made a fuselage mounted tailplane unattractive due to down-wash. A high T-tail was chosen and mounted in such a position as to minimise deep stall problems. This arrangement led to the advantage of increasing the tailplane moment-arm, thus reducing tailplane size. The tailplane also acts as an end-plate, and increase in effectiveness. The disadvantages of this choice are those of increased fin and rear fuselage loads due to asymmetric tailplane lift, and maintenance access to a fin some 18 metres (60 ft) above the ground!

The latter problem was reduced by designing an internal maintenance ladder forward of the fin front spar, where the width was some 0.8M (2 ft 6 inches) at the intersection with the tailplane.

Landing Gear

The nose unit has a conventional twin wheel, forward retracting configuration. There are four fuselage pod-mounted main units, each with a four-wheel bogie.

Systems

Conventional avionic systems are used, but the "active" variable camber flaps require a fast acting flight control system. Fibre-optic signalling was chosen. The large passenger capacity required most of the engine bleed air to feed the environmental control system. Electro-impulse de-icing was used and most secondary power was produced electrically.

Dimensions and Performance

Table 1 gives the leading dimensions of the aircraft, whilst table 2 shows component mass targets, together with predictions based on detailed design.

The Manufacturers Equipped Mass was estimated to be some 5 tonnes lighter than the target, but uncertainties led to the

TABLE 1 — A-90 LEADING DIMENSIONS AND MASSES	
Wing Span	57M (187 ft)
Wing Span — Folded	40M (131 ft)
Gross Area	361.94M^2 (3896 ft^2)
¼ Chord Sweep	30.0°
Aspect Ratio	8.98
Supercritical aerofoil t/c = 14% Root, 10.2% MAC, 8% TIP	
Anhedral	3.0°
Overall Fuselage Length	59.3M (194.5 ft)
Maximum Width	6.56M (21.5 ft)
Height to tailplane	18M (59 ft)
Passenger Capacity (Mixed)	500
Passenger Capacity (All Tourist)	620
Powerplant	RR Trent 800 series
All-up Mass	211075 KG (466,923 lb)
Normal Fuel Mass	44500 KG (98,018 lb)

TABLE 2 — A-90 COMPONENT MASS ESTIMATES AND TARGETS

COMPONENT	EST. MASS (KG)	TARGET
Wing Group-Structure (inc. actuators)	20790	17920
Fuselage Structure	28315	31554
Fin and Rudder (inc. actuators)	1934	1200
Tailplane & Elevators (inc. actuators)	1180	1020
Undercarriage	8420	7855
Pylons	2160	2100
STRUCTURE	62799	61649
ENGINES, POWERPLANT STRUCT & ACCESS	14008	15509
Fuel System	1324	1215
Flying Control System	1395	1551
Hydraulics	32	1411
Electrical System	1680	3350
APU	260	230
Inst. & Avionics	1100	1120
De-ice	397	830
Fire Protection	80	620
Furnishings	7100	7100
Environmental Control System	1423	2078
Paint	180	180
SYSTEMS & EQUIPMENT	14971	19685
Manuf Equipped Mass	91778	96843
MEM Tolerance	7002	1937
Crew & Provisions	3690	3690
Seats, Emergency Equipment Pax Service	11800	11800
Nom OEM	114270	114270
2% Mid Life	2285	2285
Pallets & Containers	2520	2520
OPERATING EMPTY MASS	119075	119075
500 Passengers and Baggage	47500	47500
Fuel at Above Payload	44500	44500
MAX ALL UP MASS	211075	211075

decision to increase the MEM tolerance to 7.6% rather than the 2% required by the Association of European Airlines. This left the all-up mass unchanged.

Performance checks were made and produced a payload-range curve which indicated that the aircraft would exceed the specification requirements, giving a 500-passenger range of 2260 N miles, rather than the required value of 2000 N miles.

The economical cruise Mach No was predicted to be 0.83 with high speed at 0.86. The optimum performance over the 2000 mm range was cruise at M = 0.81 at 37,000 ft altitude.

It was possible to meet the specified all-up mass take-off field length of 8,300 ft at ISA conditions, but more power would increase climb gradient after the failure of one of the very large engines.

The landing field length increased to 7,750 ft. This is still reasonable performance, but the specified performance could be achieved by the use of more powerful auxiliary flaps.

The aircraft meets the runway LCN requirement of 65 and exceeds the internal space requirements for passengers.

Trans-Atlantic or trans-Continental flights of 3,500 N miles should be possible with 345 passengers.

A simple cost prediction method was used, which gave a first cost of $85 M (1990), based on a production run of 500 aircraft. The method probably underestimated the cost of the areas of new technology involved. Direct cost estimates will be made in the near future.

Conclusions

A case has been made for the development of 500 seat class, short haul airliners.

The A-90 project aircraft has been designed in considerable detail and has the potential of meeting mass, cost and aircraft requirements. It should exceed the range target of 2000 N miles with 500 passengers or carry 620 passengers 1700 N miles or 345 passengers for 3500 N miles.

The novel shoulder wing arrangement gives good engine clearance and has considerable flexibility for civil or military cargo operations. Ditching characteristics should be adequate, but research is required in terms of emergency evacuation.

The twin engine arrangement is feasible on such a large aircraft, but leads to potential problems with the provision of bleed air and secondary power. These were resolved by careful system design.

Practical schemes were produced for the deployment of variable camber flaps. They offered aerodynamic benefits and increased operational flexibility at the expense of increased complexity. Their effectiveness was increased by using them for gust and manoeuvre load alleviation, using fibre optics signalling. These designs should be continued and attempts made to quantify their mass, aerodynamic and direct operating cost characteristics further.

The fuselage cross-section was chosen so that it could be stretched to accommodate some 1000 passengers. It is unlikely that 3 or 4 engines would then be required.

The project provided a realistic environment in which students learned how to design practical components, work as a team and present their results orally, and in written theses. The theses contained some 200 engineering drawings, produced by traditional and CAD methods. Some 40 theses have been published, giving some 6000 pages of description and anlysis.

Students have been given "hands-on" experience of the use of many modern computer techniques, such as CAD, Finite Element Analysis, Composite Materials Analysis as well as a wide range of dedicated analysis programs. They have researched up to date aeronautical technologies such as fibre-optics, all-electric aircraft, and advanced materials. These activities will provide information of use to other members of the aerospace community.

Students were drawn from many countries in the world, indeed the only continent not represented was South America.

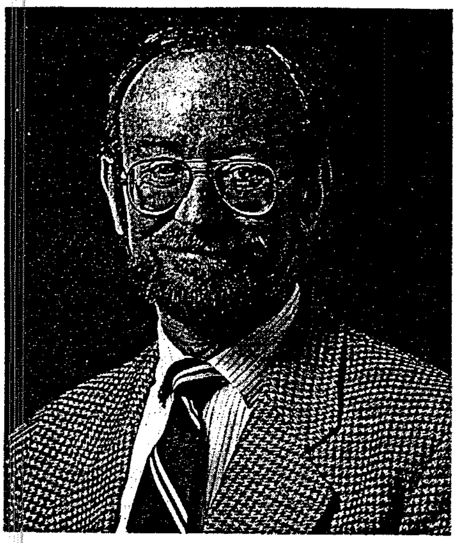
These students will reach senior positions within their countries and, hopefully, benefit aerospace activities throughout the world.

Reference

1. 500 Passenger Short-range Airliner 90. Project Specification. DES 9000. Dr J. P. Fielding. July 1991 Cranfield Institute of Technology.

The T-91 Advanced Trainer Project

by Dr John Fielding, Head of Design, Structures & Systems Group



Dr John Fielding

Project Background

Cranfield teaches Aircraft Design in a practical way, using the group design project as the major element of the course. We choose to design a wide range of aircraft types, as regular readers of AEROGRAM will know. It was decided this year to attempt the design of an advanced military training aircraft.

The BAe Hawk and Dassult/Dornier Alpha Jet are very successful advanced training aircraft, but their designs date back some 20 years. They have been up-dated during this period, but cannot fully utilise technological advances made since their inception. It was decided to investigate the design of a new aircraft for use from the year AD 2000. Discussions were held with Industry and Government representatives, which led to the following specification:

The Design Specification

Aircraft Operation Modes

- Advanced Flight Training
- Fighter Lead-in Training
- Air Combat Training
- Close Air Support
- Interdiction Missions
- Auxiliary Intercepter Fighter

Performance Requirements

i) Max clean aircraft Mach No should be 0.9, straight and level, Sea Level I.S.A. MD should be 1.2 at Altitude.

ii) The aircraft should be able to achieve a sustained 'g' level of 7 at SL, ISA at a Mach No 0.65, clean at 60% of internal fuel.

iii) The aircraft should have sufficient endurance to perform three refulled 45 min training sessions with a 20 min reserve.

iv) The ferry range should be 2000 n.miles on internal fuel.

v) The take-off ground run should be 1800 ft (550 m) at max training mass. The landing ground run shall be 2300 ft (700m). Both conditions to be at ISA, SL. The runway LCN should be better than 15.

vi) The ground-attack payload should exceed 3250 RG and be mounted on three stations per wing, and fuselage stations. An internal cannon should be fitted. Typical payload would be 5/6 × 277KG Cluster Bombs + 2 ASRAAMs + Gun.

General Requirements

The aircraft should be single-engined to reduce its cost to £6M (1991). Its life-cycle cost should be some £350,000 per year. Cost considerations suggest that the aircraft should not be supersonic except in a dive.

The aircraft should have better cockpit layout, avionics, and Reliability and Maintainability than current aircraft.

The aircraft should have a tandem seating arrangement.

Group Project Activities

The design process started with the conceptual design of the aircraft by members of staff, in the summer of 1991. The Cranfield group project is unique in the level of staff preparation, allowing scope for more detailed work by students than in group projects elsewhere. This work was summarised in Reference 1 which was given to 23 students in October of that year. Each structure student was given responsibility for the detail design, stressing and fatigue analysis of components such as the forward fuselage, outer wing, tail, etc. Some students designed mechanical systems such as fuel, flying controls, engine installations, etc. More global design tasks were performed by other students in the areas of cockpit layout, avionics installation, reliability and maintainability, aerodynamic performance and cost estimation.

The project was managed to a demanding eight-month programme by means of weekly project meetings, where students reported progress, received advice and instructions for subsequent work. The most important function of these meetings was that of a forum where design conflicts were resolved.

One of the dangers of individual responsibility is that of parochialism. The student designing, say, a portion of fuselage learns a great deal about that, to the exclusion of the rest of the aircraft. The group project meetings go some way to reducing this problem in that each aspect of the whole aircraft design is discussed in turn in project meetings. We had some very lively discussions about interfaces between wing and fuselage attachments, together with their effects on air intakes, fuel system, etc! Sub-groups were formed to convert the author's aerodynamic, geometric and mass information into structure loads, CAD models, etc.

The knowledge gained during lectures, project meetings and discussions with members of staff was augmented by information from aircraft manufacturers.

Vital information on the project engine was given by Rolls-Royce and realistic information was received from avionic systems manufacturers. An extremely useful group visit was made to RAF Wyton, where Hawk Aircraft were minutely examined.

This visit was closely followed by one to British Aerospace Brough. The high-light of this was a tour of the extensive Hawk and Harrier production lines.

The programme ended in May, 1991 with the submission of detailed project theses which contained descriptions of the designed components, supporting analyses, drawings, CAD plots, and Finite Element results.

The design was also used by some 20 Flight Dynamics students, who successfully simulated the aircraft's handling characteristics. This activity presages further integration of teaching activities. It is hoped that, in the future, students will be able to "fly" the project design in Cranfield's Flight Simulator, during the design evolution, so that handling characteristics will be part of a "Closed-loop" design process.

Description of the Final Design

General

A photograph of the CAD model is shown in Figure 1. In order to meet the above specification, the aircraft is of simple layout with a moderate aspect ratio supercritical section wing. The modest wing loading, powerful flaps and high thrust to weight ratio gives good manoeuvrability and field performance. Low cost and good maintainability requirements led to the choice of a moderate by-pass turbo-fan engine for low fuel costs. The high wing and underslung, partially buried engine were chosen to give good access to both the engine and the avionics.

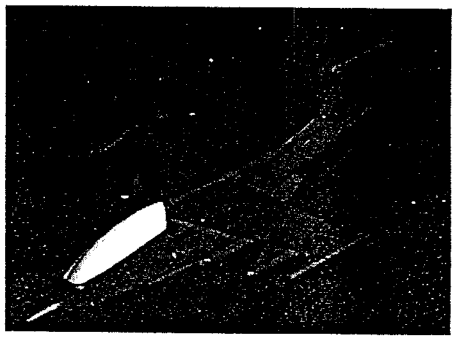


Figure 1. CAD Model of T-91

Wing

The wing has a moderate aspect ratio and sweep of 5 and 22° respectively. No leading-edge devices are used but a single slotted flap is used to improve take-off and landing performance. ASRAAM missiles and launchers are fitted to the wing-tips and two stores station pylons are used per wing. These act as fairings for the outboard flap tracks. The baseline wing design has two spars and integrally machined skins, made from conventional light alloy. A parallel composite design was performed for the outer wing with projected mass savings of some 20%. Conventional carbon-fibre ailerons were designed.

The Fuselage

Conventional light-alloy construction was used. The bulk of the fuselage has a "mass-boom" layout because of the large number of structural cut-outs. Considerable attention was given to battle-damage tolerance, at some cost in terms of complexity. Figure 2 shows the side view of the aircraft, high lighting the good access for

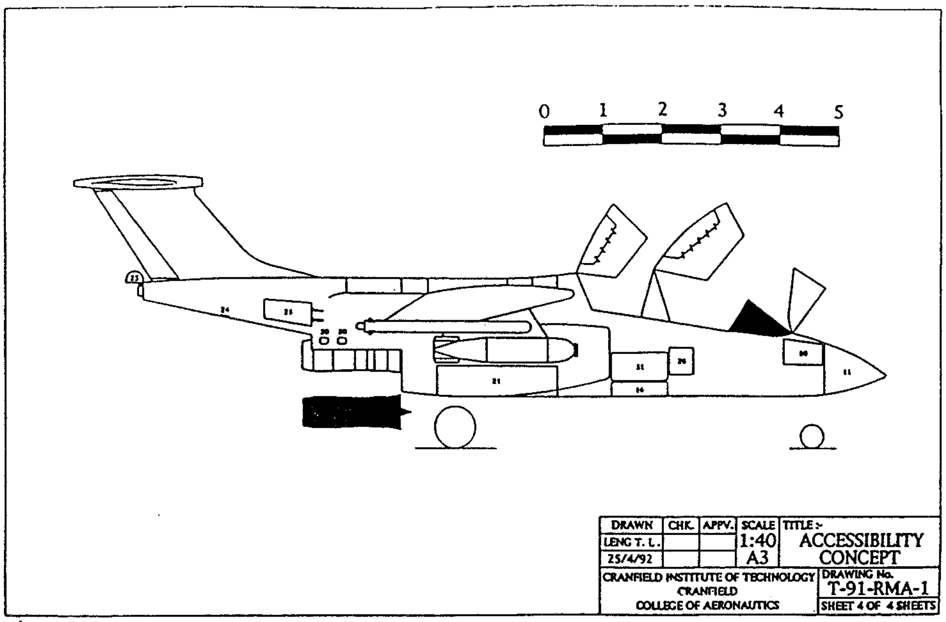


Figure 2.

The baseline design had a fixed-incidence tailplane constructed from light-alloy and a composite elevator. An alternative single piece composite all-flying tailplane was also designed with a 15% mass saving. Figure 3 shows the lay-ups designed for the composite rudder.

Systems and Installations
The aircraft uses a specially project-designed Rolls-Royce engine with a Sea Level static thrust of 29.26 KN. Its moderate by-pass ratio gives good fuel consumption and a cool exhaust, but limited the aircraft's service ceiling, relative to the Hawk. The air intake was designed, as were the engine mounts, venting and fire suppression system. Maintainability predictions suggests an engine-change time approximately one quarter of that of the Hawk.

A schematic drawing of the fuel system is shown as Figure 4. This is relatively complex, because of the high fuel capacity required for the mission requirement. Some fuel tank battle damage protection has been incorporated.

The main landing-gear retraction was extremely difficult geometrically, but a suitable design was arrived at by making use of a CAD system. The author's initial idea of the carriage of two fuselage-mounted bombs was rejected. Bomb fin clearance and C.G. limitations led to the use of a single bomb. The nose landing gear retracts forward and incorporates a steering mechanism. A flight control system was designed, the pilot controls of which were incorporated into the full-scale mock-up.

engine and avionics maintenance. The aircraft is fitted with an internal 25mm ADEN cannon, so that the transition between trainer and ground attack roles is facilitated. This reasoning also led to the use of separate cockpit canopies. It is envisaged that in the ground attack role, the rear seat, instrument panel and canopy are removed. They would be replaced by a drop-in module with extra attack avionics, and be covered by a light weight fairing, in place of the canopy. A full scale mock-up was made of the forward cockpit. This was checked out by our test pilots and design modifications were made. Airbrakes, a brake parachute system and chaff and flare systems were designed for the rear fuselage.

Tail Unit
Initial studies used a low-set tailplane, but the short rear fuselage dictated by the engine location led to severe downwash problems. A high-tee tail was chosen, although subsequent aerodynamic computer modelling suggested that a cruciform tail would have been possible.

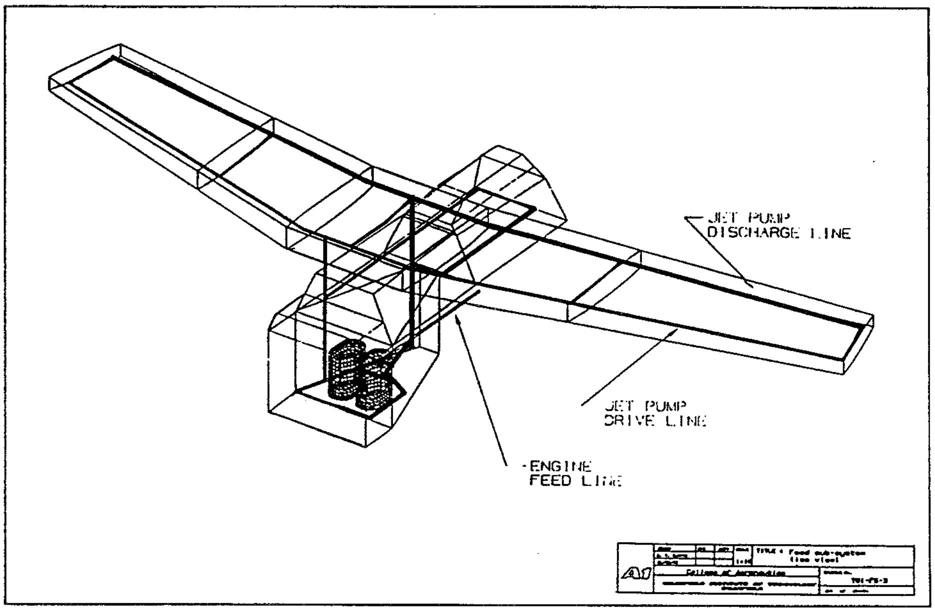
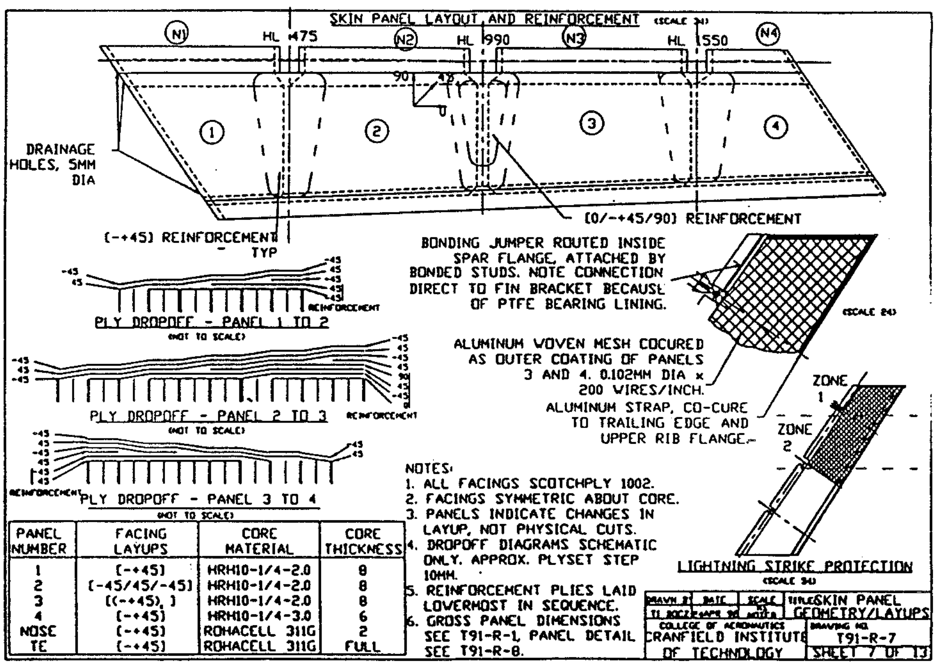


Figure 4. Fuel System



PANEL NUMBER	FACING LAYUPS	CORE MATERIAL	CORE THICKNESS
1	[-+45]	HRH10-1/4-2.0	8
2	[-45/45/-45]	HRH10-1/4-2.0	8
3	[(-+45),]	HRH10-1/4-2.0	8
4	[-+45]	HRH10-1/4-3.0	6
NOSE	[-+45]	ROHACELL 31IG	2
TE	[-+45]	ROHACELL 31IG	FULL

Figure 3. Rudder Design

Extensive maintainability and reliability calculations were performed, and fed into an operation simulation computer model. The results of this showed that the aircraft should provide very effective ground attack capability.

The aircraft nose was sized to allow the use of an attack radar or weapon aiming devices. The fin bullet provides space for radar warning receivers.

Predicted Performance and Costs

The work in the 23 project theses went a considerable way towards producing realistic component masses. Stressed items were based on adequate material volume and thus mass was

TABLE 1 – MASS BREAKDOWN	
Components	*Mass (kg)*
Centre Wing	182
Outer Wing (inc. Flaps and Ailerons)	376
Fuselage (inc. Airbrake and P/P Struct)	880
Tailplane and Elevators	83
Fin and Rudder	103
Main Undercarriage	220
Nose Undercarriage	75
Total Structure	1919
Engine, inc. Accessories	428
Total Powerplant	428
Fuel System	166
Flying Control	164
Hydraulics	61
Electrical Power	331
Avionics (Trainer)	255
Anti-Ice	39
Fire Extinguishing	49
Environmental Control	74
Paint	10
Ejector Seats	180
Installed Cannon	176
Fuselage Ejector Release Units	60
Systems and Equipment	1565
Pilots	180
Contingency	85
Basic Operating Mass	4177
Max. Internal Fuel	2665
Normal Training Mass	6842
Training Spec Payload (4 x BL755, 2ASRAAM, AMMO)	1326
2 Pylons, 2 Extra ERUs, 2 Launchers	164
Additional Payload	547
Fuel with spec. and additional payload	2186
Maximum All Up Mass	8400

predicted, with allowances for fasteners, etc.

The author made an error concerning engine mass, during the conceptual design process. It was too late to re-cycle the entire design process, so the difference was carried forward as an extra contingency which could have been used as the design evolved or traded for further payload. Table 1 shows the results of the final mass estimates, which gave a basic operating mass some 500 kg below the initial target. This has been fed into an increased payload of 1873 kg with maximum fuel load, for the ground attack mass.

The T-91 was the first group project to benefit from the development of an aerodynamic panel model as part of the design process. Figure 5 shows the panel model and some of the predictions of spanwise airload. The model was particularly useful for chordwise loading on the wing and asymmetric loads of the tailplane. These were fed into the aircraft loading actions and hence into the structural design process. The model applicability was limited to low subsonic performance, but gave indications of where detailed geometry changes could improve performance.

Table 2 shows the specification performance targets, the T-91 predictions and available figures for the BAe Hawk 60 and Hawk 100 aircraft. The latter two aircraft were the closest aircraft to the requirements of the training and ground attack roles of the T-91. The T-91 figures incorporates the 500 kg mass reduction in basic operating and training masses mentioned above. Hawk figures were obtained from the open literature, from which it is not known if DEF STAN field performance factors have been used. T-91 figures incorporate them.

It can be seen that the maximum speed and range requirements have been met, the latter comfortably exceeding Hawk figures. The sus-

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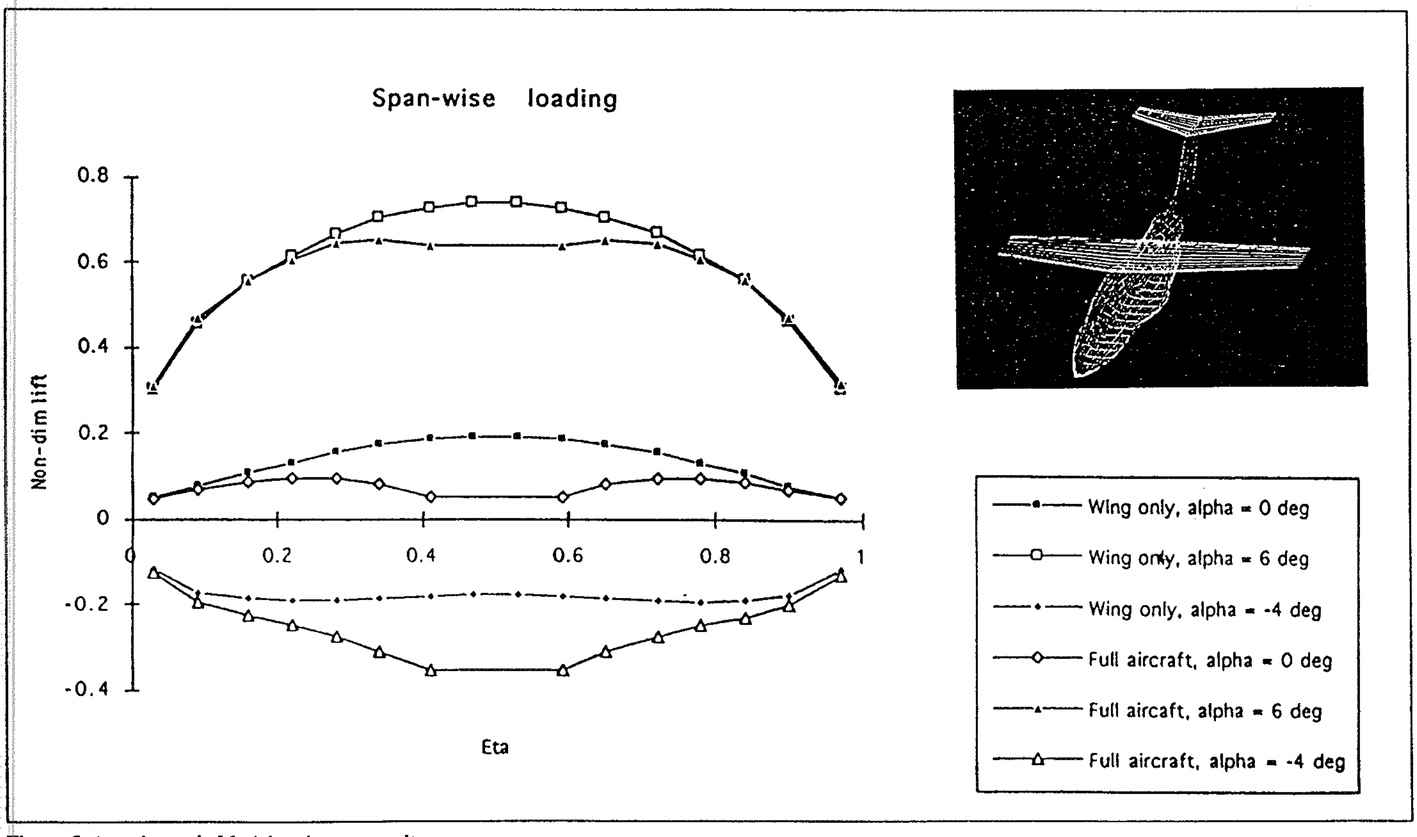


Figure 5. Aerodynamic Model and some results

continued from page 11

TABLE 2 – PERFORMANCE COMPARISON				
	Specification	*T-91*	*Hawk 60*	*Hawk 200*
Max Clean SL Mach No	0.9	0.89	0.88	0.85
S.T.R. M = 0.65 S.L. 60% Fuel	7.0 'g'	5.8 'g'	6.5 'g'	6.5 'g'
Training Mass T.O. Ground Run	550 m	1030 m	550 m	1585 m
T.O. to 15m		1400 m		2134 m
landing ground run, max landing training mass	700 m	770 m	524 m	555 m
Ferry Range (Int. Fuel)	2000 NM	2000 NM	1313 NM	482 NM
Max Payload	3250 kg	≃ 3000 kg	3100 kg	3500 kg
First Cost 1991	£6M	£6M at 110 A/C £5M at 175 A/C		
D.O.C.	£350 K PA	£380 K PA (Trainer) £300 K PA (G.A.)		

tained turn performance was disappointing, but could be improved by the use of combat flap, 60% of T-91 fuel is considerably more than 60% of Hawk fuel, which affects the S.T.R.

The take-off performance was significantly worse than the target, but is probably quite close to that of the Hawk, which was the intention of the specification.

Landing performance is close to target and could be improved by more effective brakes. The maximum payload is close to target if further strengthening was designed into the wing pylons and local structure.

Simple cost estimates showed that the aircraft should meet first-cost targets with a production run of 110 aircraft, and be £5M at 175 aircraft. Direct operating costs were predicted to be close to the target.

Conclusions

The choice of a relatively simple aircraft configuration, together with a large number of students led to a considerable amount of detailed design work. Many of the assumptions made in the conceptual design phase were substantiated.

The design met many of the performance and cost targets and has the potential of being a true multi-role trainer/attack aircraft with much less modication than existing aircraft. The cost of this has been a deeper forward fuselage to accommodate the gun and attack avionics, which are not necessary for the majority of training missions. The large internal fuel capacity and fuel efficient engine contributed to the low operating costs. This has penalised the high altitude performance of the aircraft.

The overall conclusion, however, is that the T-91 has the potential to become a cost-effective trainer/attack aircraft.

The integration of aerodynamic panel modelling has added a new dimension to the evolution of Cranfield's group project teaching system and further enhancements will follow.

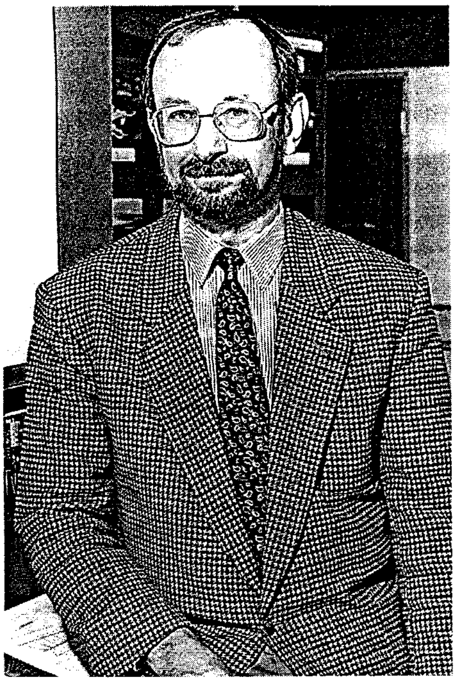
The group project fulfilled its primary aim of providing realistic design environment for the education of aircraft designers.

Reference

1. Advanced Training Aircraft – T-91 project specification. Dr J P Fielding, Mr H Smith, DAeT 9101, Cranfield Institute of Technology, July 1992.

The E-92 – an Entry-Level Executive Jet Project

by Dr John Fielding, Head of Design, Structures and Systems Group, Acting Head, Department of Aerospace Technology



Dr John Fielding

PROJECT BACKGROUND

The College of Aeronautics has a practical approach to the teaching of Aerospace Vehicle Design. Students are awarded an MSc degree if they have proved that they have the ability to produce workable, realistic designs in which all of the major problems have been addressed. This is assessed by means of annual group projects in which relevant aircraft types are studied. Our group project is unique by virtue of the amount of preparatory work done by staff before work is started by the students. All other known design projects start with the students being given the aircraft specification. They then perform a conceptual design, leaving little time available for detailed design. With the Cranfield method, this work is done by the staff, thus enabling the students to start much further down the design process. They thus have an opportunity to get to grips with preliminary and detail design problems, and become much more employable in the process. The Cranfield project method also allows students to use modern design tools such as CAD, finite elements, laminate analysis and aerodynamic modelling.

We choose to design a wide range of aircraft types, as regular readers of AEROGRAM will know. It was decided this year to design an executive jet. Such aircraft have an important role to play in the World market for aircraft. The need for executive aircraft has been satisfied by designs ranging from turboprop aircraft, to large high-subsonic aircraft such as the Gulfstream IV. Cessna and Swearingen recognised the need for entry-level executive jets by the development of their Citationjet and SJ-30 designs. Their aim was to produce new aircraft with a purchase price similar to that of the Beech King Air, but with greatly enhanced speed and comfort. These designs were made possible by the advent of the cost-effective, quiet and fuel-efficient Williams/Rolls FJ44 engine. The current Cranfield Design is pitched between the Citationjet and SJ-30 in terms of performance, but will utilise significant amounts of advanced composite materials in its construction. This should lead to lower mass despite the more generously sized cabin interior. The wing utilises a modestly forward swept wing to encourage natural laminar flow to save fuel.

THE DESIGN SPECIFICATION

Interior Layout

There should be provision for 5-6 passengers with comfort standards equivalent to airline First Class passengers. The aircraft should be capable of single-pilot operation, but a co-pilot's seat is required. There should be beverage, baggage and toilet accommodation superior to the SJ-30. The fuselage should have a door capable of loading a spare engine.

Performance

The following figures are based on ISA, sea level conditions.

(i) The high speed Mach no. = 0.75
economical Mach no. = 0.72

(ii) NBAA, IFR range with 3 passengers and 1 crew should be greater than 1800 miles (3245km)

(iii) Max operating altitude = 43,000 ft (13.1km)

(iv) FAR take-off balanced field length to be less than 3300ft (1005m)

(v) FAR landing distance at max landing mass to be less than 2600ft (792m)

Cost

The acquisition cost shall be no more than $3.5M US in 1994.

GROUP PROJECT PROGRAMME

The design process started with the conceptual design of the aircraft by members of staff, in the summer of 1992. This work was summarised in Reference 1 which was given to 25 students in October of that year. Each structures student was given responsibility for the detail design, stressing and fatigue analysis of components such as the forward fuselage, outer wing, tail, etc. Some students designed airframe systems such as fuel, flying controls, engine installations, etc. More global design tasks were performed by other students in the areas of flight deck layout, avionics installation, reliability and maintainability, aerodynamic performance and cost estimation.

The project was managed to a demanding eight-month programme by means of weekly project meetings, where students reported progress, received advice and instructions for subsequent work. The most important function of these meetings was that of a forum where design conflicts were resolved.

One of the dangers of individual responsibility is that of parochialism. The student designing, say, a portion of fuselage learns a great deal about that, to the exclusion of the rest of the aircraft. The group project meetings go some way to reducing this problem in that each aspect of the whole aircraft design is discussed in turn in project meetings. We had some very lively discussions about interfaces, particularly in the forward fuselage area. Figure 1 shows a computer aided design (CAD) model of this very crowded area. A suitable compromise was agreed between students responsible for fuselage structure, rudder pedals, nose landing gear, electrical power, avionics and flight deck layout.

Sub-groups were formed to convert the staff's aerodynamic, geometric and mass information into structure loads, CAD models, etc.

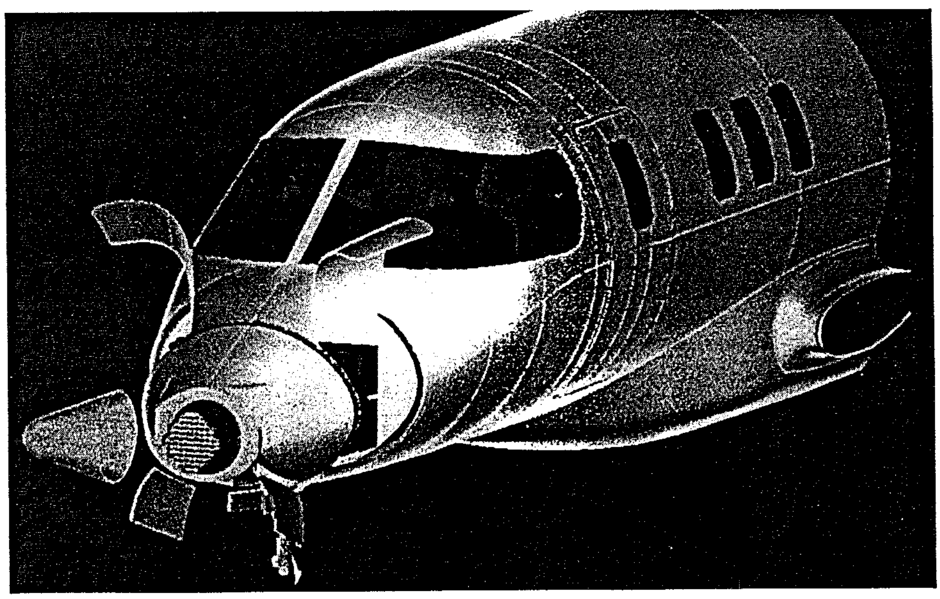


Figure 1. CAD model of forward fuselage

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The knowledge gained during lectures, project meetings and discussions with members of staff was augmented by information from aircraft manufacturers.

Vital information on the project engine was given by Rolls-Royce and realistic information was received from avionic systems manufacturers. An extremely useful group visit was made to Luton airport, where MAGEC's aircraft maintenance was examined. This visit was followed by one to British Aerospace, Chester. The highlights were close examinations of the BAe 800 and 1000 production lines and those of the Airbus wing assemblies.

The programme ended in May, 1992 with the submission of detailed project theses which contain descriptions of the designed components, supporting analyses, drawings, CAD plots, and Finite Element results.

The students made a verbal presentation of their work to a group of external examiners and Industrialists.

The design was also used by some 20 Flight Dynamics students, who successfully simulated the aircraft's handling characteristics. This activity presages further integration of teaching activities. It is hoped that, in the future, students will be able to "fly" the project design in Cranfield's Flight Simulator, during the design evolution, so that handling characteristics will be part of a "Closed-loop" design process.

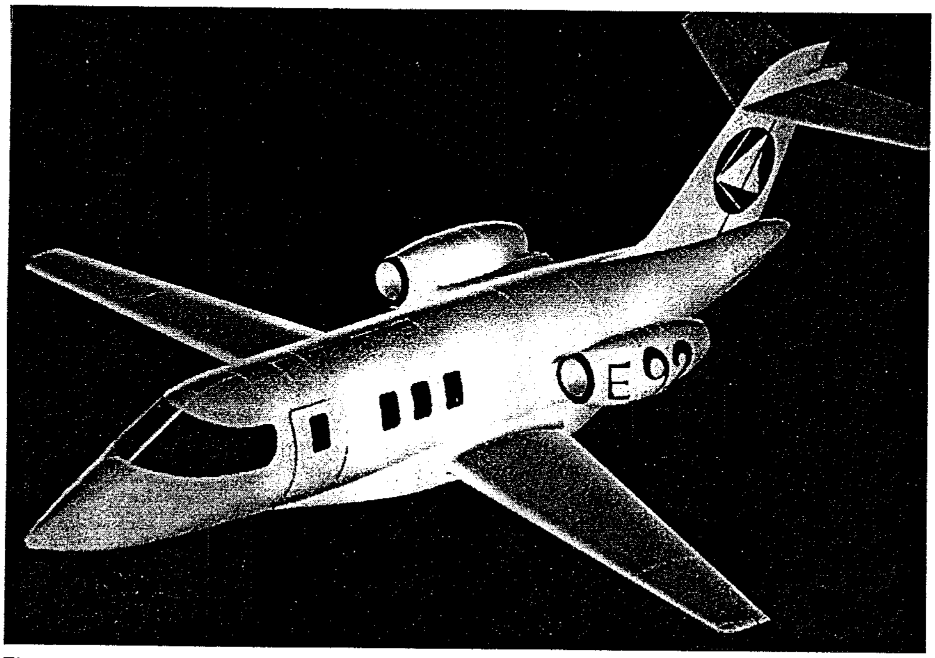

Figure 2. E92 surface model

DESCRIPTION OF THE FINAL DESIGN

The aircraft was designed using state-of-the-art materials, the majority of the structure being made from aluminium alloys, with some composite components.

Figure 2 shows a shaded image of the Computer generated surface model of the project. The surface model was generated using EDS Unigraphics software.

Wing

A modest sweep forward combined with advanced laminar flow wing sections enable Mach numbers in the region of 0.75 to be achieved. The aspect ratio is 8.0 and there is sufficient fuel tankage in the wing and fuselage at spec. payload for a range of 1800N miles with reserves. The high aspect ratio improves fuel burn and airfield performance. Double-Slotted Fowler flaps, moderate wing loading, spoilers and the high aspect ratio give adequate field performance.

The absence of slats, the forward sweep wing, the aerofoil sections and small chord should allow a significant percentage of natural laminar flow.

The particular laminar-flow section used has a very high zero-lift pitching moment. This was aggravated by the fuselage shape, giving significant trim drag, which would negate the effects of the drag reductions from laminar flow. The fuselage was reshaped to limit this effect, but it is unlikely that Cranfield will use the section again. The wing structure was designed by two teams, one with a composite, and one with metal construction.

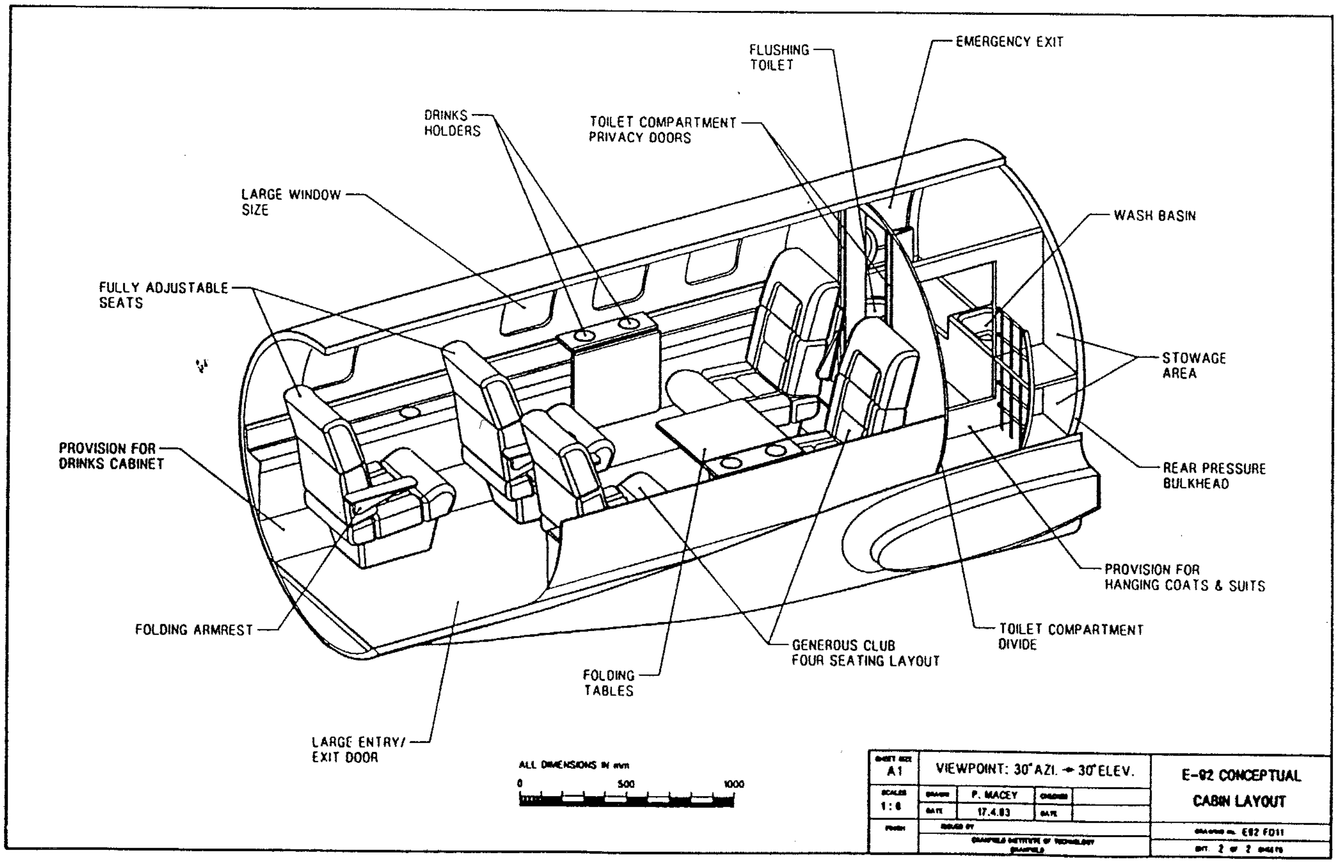

Figure 3. E92 conceptual cabin layout

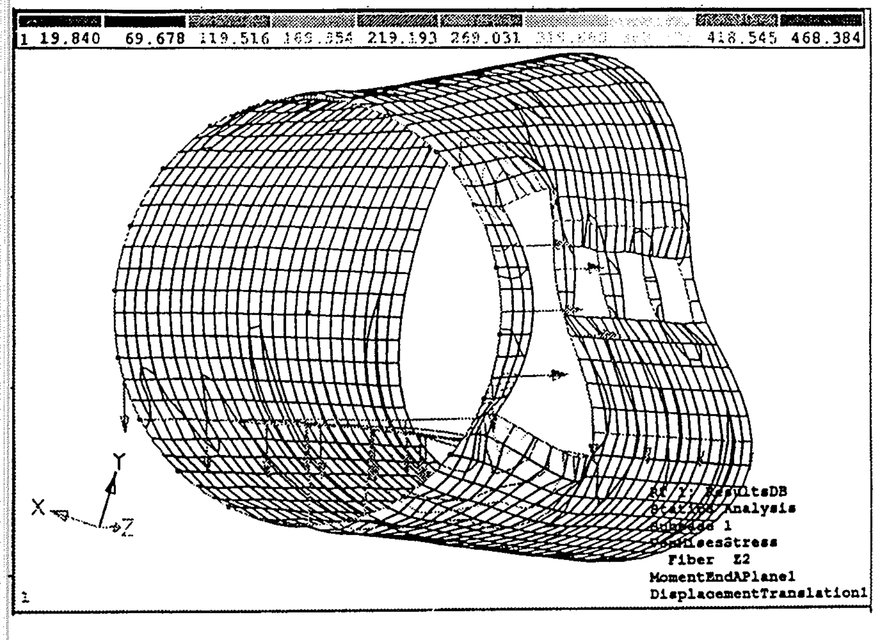

Figure 4. Exaggerated deflections of centre fuselage finite – element model

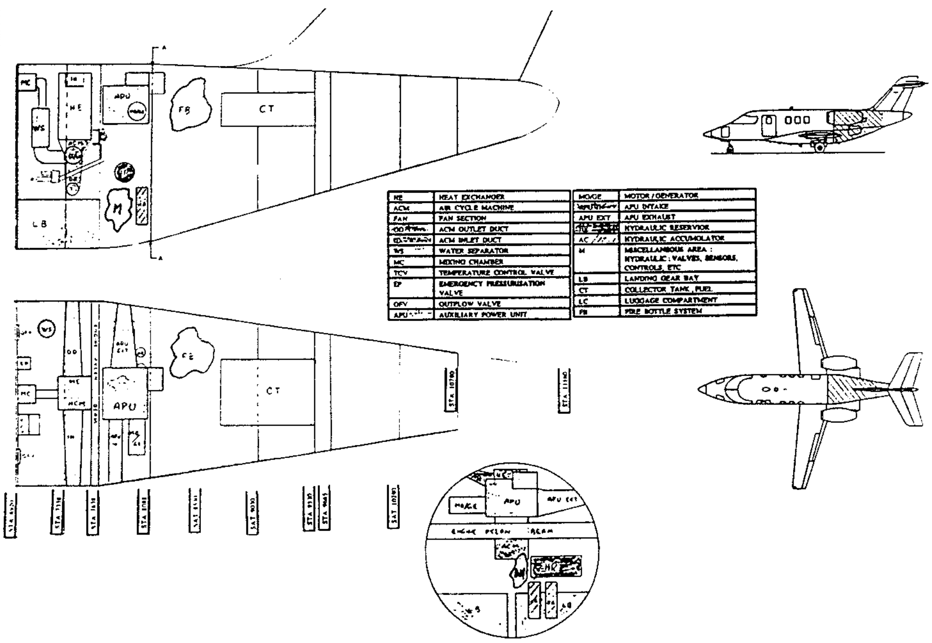

Figure 5. Rear fuselage equipment bay

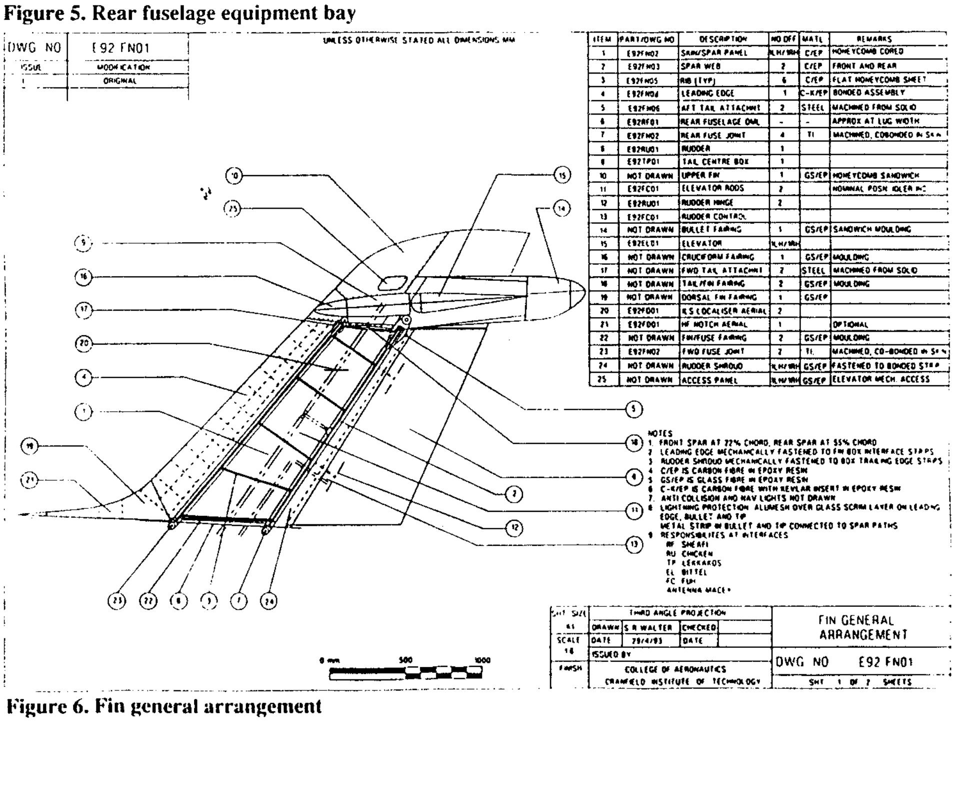

Figure 6. Fin general arrangement

Finite-element models are made using the NASTRAN system and showed that the modest forward-sweep of the wing did not result in aeroelastic problems.

Fuselage

The cross-section is generous for this class of aircraft, with a recessed aisle to give more headroom to move round the cabin. The baggage/toilet compartment is behind a privacy bulkhead, above the wing carry-through structure.

The interior is shown in Figure 3. The environmental and flying control system components run under the seat arm-rests and under the floor.

The toilet compartment is rather restricted for large passengers, and some re-design will be necessary. The fuselage structure is of the conventional aluminum semi-monocoque type. Figure 4 shows an exaggerated – deflection finite – element model of the forward fuselage. The passenger door and emergency exit doors cut-outs required reinforcements to maintain structural continuity. The rear pressure bulkhead also acted as the wing rear-spar pick-up. The area aft of the bulkhead was the primary equipment bay. The environmental control system hydraulics and electrical power systems were designed in considerable detail. These systems occupied the equipment bay, together with a rear fuselage fuel tank and space provision for an optional auxiliary power unit. The main landing gear retracts under the forward part of the equipment bay, the engine pylon front spar passes through it, and the baggage compartment is under the rear part of the equipment bay. (Figure 5).

Powerplant

The aircraft uses a pair of rear fuselage mounted Williams/Rolls-Royce FJ44 engines. They are mounted high on the fuselage to minimise wing interference effects.

The engine nacelles use easily-opened panels to ease engine maintenance. The engine pylon front spar passes through the fuselage to limit fuselage frame bending moments, whilst the lower-loaded rear spar is broken at the fuselage side, to facilitate equipment-bay access.

Tail Unit

The aircraft utilises a cruciform tail arrangement. This takes the tailplane above the jet efflux and increases its moment arm, due to the sweepback of the fin. This arrangement does not have as severe "rolling due to sideslip" effect as does the high Tee arrangement.

Figure 6 shows the general arrangement drawing of the fin. This was designed to be constructed of carbon-fibre composite material. The component was analysed by using Cranfield's laminate analysis programs and subsequently checked using finite-elements. A simple dynamic fin-tail analysis showed that some redesign would be necessary to improve dynamic structural stability. The tailplane was designed in conventional aluminium alloys and utilised a machined centre-box.

The high speed of the aircraft led to the use of mechanical assistance to the flight control system. Set-back hinges and either servo or balance tabs are used on the elevator, rudder and ailerons.

Landing gear

Single wheels are fitted to each main leg which retract inboard into the fuselage fairing. Several alternate retraction schemes were investigated, making use of the kinematics module of the CATIA CAD system. The nose leg uses twin wheels and retracts forwards into the fuselage nose. The layout of the units can be seen in the general arrangement drawing (Figure 7).

Predicted Performance

Table 1 shows the target masses for the major aircraft components. Shown alongside are the predictions that were made after the detailed designs had been completed.

The targets had been set using an empirical mass estimation program. The correlation between the targets and predictions is very good, considering the fact that the E-92 is very small, relative to the empirical database used in the program. Figure 8 shows the predicted payload-range for the aircraft. This was produced after considerable analysis, the production of aerodynamic computer models and consideration of the effects of intake efficiency, bleed and power off-takes. It shows that the aircraft could meet the range targets at a high-speed cruise Mach number of slightly less 0.72 and considerably exceed it at Mach 0.58. The calculations used pessimistic power off-takes and neglected the expected drag benefits of natural laminar flow.

The predicted FAR landing distance was 80 ft. better than the target of 2,600 ft.

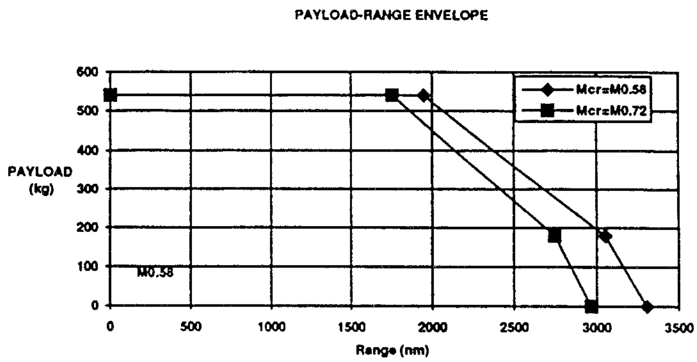

Figure 8. Payload – range envelope

TABLE 1 – MASS BREAKDOWN

COMPONENTS	TARGET MASS (KG)	PREDICTED MASS (KG)
WING (INC. AUXIL. SURFACE STRUCTURE)	278	287
FUSELAGE (INC. PAINT)	413	444
FIN (INC. RUDDER)	60	61
TAILPLANE (INC. ELEVATOR)	37	70
UNDERCARRIAGE	172	145
STRUCTURE	960	1007
ENGINES	404	404
POWERPLANT STRUCTURE NACELLES & PYLONS	153	119
POWERPLANT	557	523
FUEL SYSTEM	57	133
FLYING CONTROL SYSTEM	72	86
HYDRAULICS	55	53
ELECTRICAL SYSTEM	259	180
INST. AND AVIONICS	179	140
DE-ICE	57	57
FIRE PROTECTION	14	14
FURNISHINGS (INC. SEATS, GALLEY ETC)	290	290
ENVIRONMENTAL CONTROL SYSTEM	72	82
CONTINGENCY	110	117
SYSTEMS	1165	1152
BASIC EMPTY MASS	2682	2682
CREW AND PROVISIONS	189	189
OPERATING EMPTY MASS	2871	2871
2 PASSENGERS AND BAGGAGE	180	180
FUEL AT ABOVE PAYLOAD	1479	1479
MAX ALL-UP MASS	4530	4530

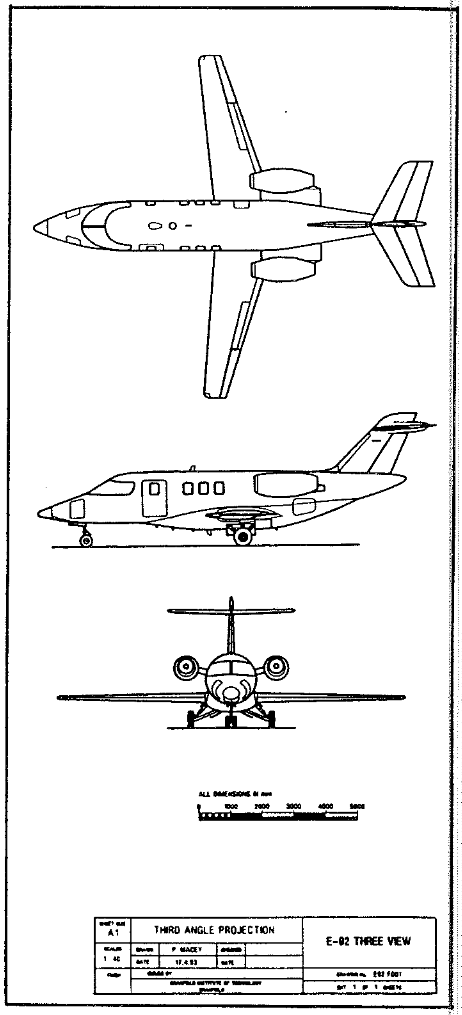

Figure 7. General arrangement

The maximum weight take-off balanced field length was predicted to 3,750 ft, which was a considerable degradation, relative to the target of 3,300 ft. The target could be reached by improvements to the flap system or a slight increase in engine thrust.

The target acquisition cost of $3.5 million, U.S. should be achieved on the basis of a production run of 300 aircraft. The direct operating cost should be $4.45 U.S. per aircraft nautical mile.

Conclusions

The design program fulfilled its main aim of providing a powerful means of educating aircraft designers. The use of a challenging project was a means of investigating many of the problem areas of executive aircraft and produced some good detailed design work.

The aircraft that was designed showed considerable promise but required further work to confirm the performance predictions, and to evaluate its operating costs more fully.

The use of a modestly swept-forward wing is a viable solution for this class of aircraft in both layout and aerodynamic terms. The configuration placed considerable demands on the ingenuity of the main landing-gear designer, but a good solution was produced.

REFERENCE

1. Entry-level Executive Jet E-92. Project Specification. Dr. J. P. Fielding, Mr. H. Smith, D.AeT. 9200, College of Aeronautics, Cranfield University, July 1993.

Two Design Projects for the Price of One! – Alternative Large Military Cargo Aircraft Designs

by Professor John Fielding, Head, Department of Aerospace Technology

Professor John Fielding

Introduction

Regular Aerogram readers will be familiar with Cranfield's method of aircraft design education and of the importance of the annual group design projects. We have usually had a single group of some 15-25 students, working as a team, with staff supervision and involvement. Numbers above 20 tend to become rather unwieldy, so the continuing increase in student numbers has become a problem, and an opportunity! The 93/4 project has been the first to use this opportunity by designing two alternative versions of the same aircraft with separate design teams, each with some 15 students and 3 staff. This approach involves more staff preparation and supervision time, but the results more than compensate for this.

Other aspects of the MSc course in Aerospace Vehicle Design remain as before, in that the aircraft conceptual designs are performed by staff, prior to the course commencement. This enables the students to start further down the design process than at other Universities. They thus have an opportunity to get to grips with preliminary and detail design problems, and become much more employable in the process. The Cranfield project method also allows students to use modern design tools such as CAD, finite elements, laminate analysis and aerodynamic modelling.

The subjects of Cranfield projects are chosen for their relevance as applied research into configurations of current interest, such as this year — future large military cargo aircraft.

European Air Forces have a general requirement for a new, multipurpose large aircraft. Whilst the major need is for a replacement of the Lockheed C-130 Hercules, it is envisaged that the aircraft should be capable of fulfilling other roles, such as anti-submarine maritime patrol and tanker missions. Requirements were based on what was known about the European Euroflag Aircraft. In the basic freighter role the aircraft is required to be capable of carrying a 20 tonne payload over a range of some 5500 km and be able to operate from relatively short, semi-prepared strips. Over shorter ranges the payload requirement is 30 tonnes with sufficient dimensional clearance to accommodate an Aerospatiale Super-Puma helicopter.

The field length requirement is for emergency operation from a 900 m strip at reduced all-up mass, and with some relaxation of the normal margins. The 900 m does not include distances to and from 15 m height.

The normal cruising speed requirement is for an improvement on the M = 0.56 of the Hercules, but fuel economy is more important than a high subsonic Mach number. This indicates a cruising speed of some M = 0.7 at 10 km altitude, a requirement which may be met by either turbo-fan or advanced turbo-propeller engines. It was by no means immediately clear which of these is preferable and hence two versions of the project were proposed:

F-93A — Wombat — with turbofan engines (BMM/Rolls Royce BR715/58)

F-93B — Gemini — with turboprop engines (Scaled Rolls Royce RB509/18)

Group Project Programme

The design process started with the conceptual design of the aircraft by members of staff, in the summer of 1993. This work was summarised in Reference 1 which was given to 30 students in October of that year. Each student with a structural component was given responsibility for the detail design, stressing and fatigue analysis of components such as the forward fuselage, outer wing, tail, etc. Some students designed airframe systems such as fuel, flying controls, engine installations, etc. More global design tasks were performed by other students in the areas of flight deck layout, avionics installation, reliability and maintainability, aerodynamic performance and cost estimation.

The project was managed to a demanding eight-month programme by means of parallel weekly project meetings for each team. Students reported on progress, received advice and instructions for subsequent work. The most important function of these meetings was that of a forum for multi-disciplinary design synthesis and added to the team-building process.

Sub-groups were formed to convert the staff's aerodynamics, geometric and mass information into structure loads, CAD models, etc.

The knowledge gained during lectures, project meetings and discussions with members of staff was augmented by information from aircraft manufacturers and visiting lecturers.

Vital information on the project engine was given by Rolls-Royce and realistic information was received from avionic systems manufacturers. An extremely useful group visit was made to RAF Lyneham where Hercules maintenance was examined. This visit followed one to Marshall's of Cambridge. We saw the prototype powerplant installation for the new C-130J aircraft and examined heavy maintenance of Hercules and Tristar aircraft. Senior Marshall's designers provided a design forum for students' questions.

Figure 1 gives an indication of the inputs to, and outputs from, the project design project.

The programme ended in May, 1993 with the submission of detailed project theses which contain descriptions of the designed components, supporting analyses, drawings, CAD plots, and Finite Element results.

The students then made a verbal presentation of their work to a group of external examiners and Industrialists.

Description of the Final Designs

Figure 2 shows a shaded image of the Computer generated surface models of both projects.

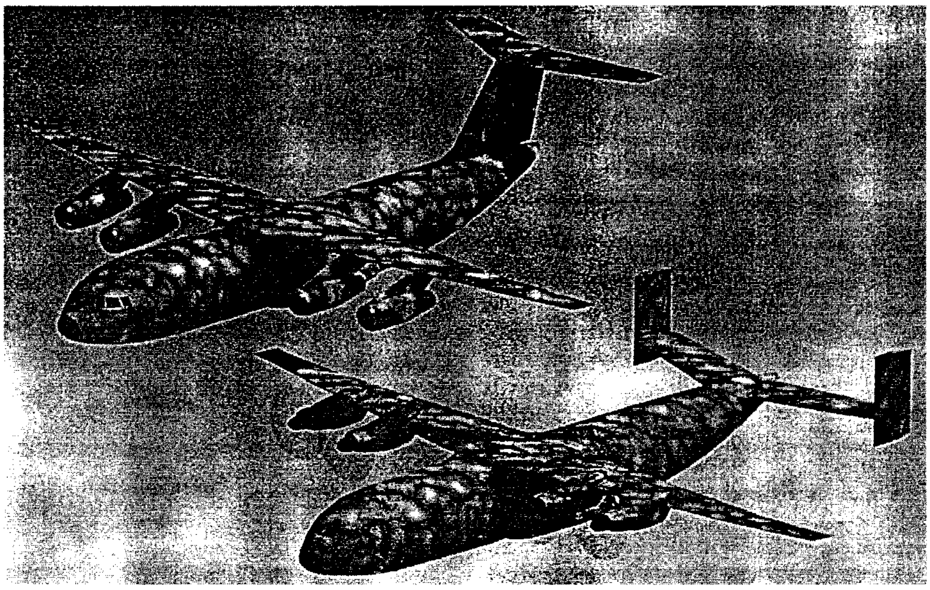

Figure 2. Computer models of both versions of the F-93

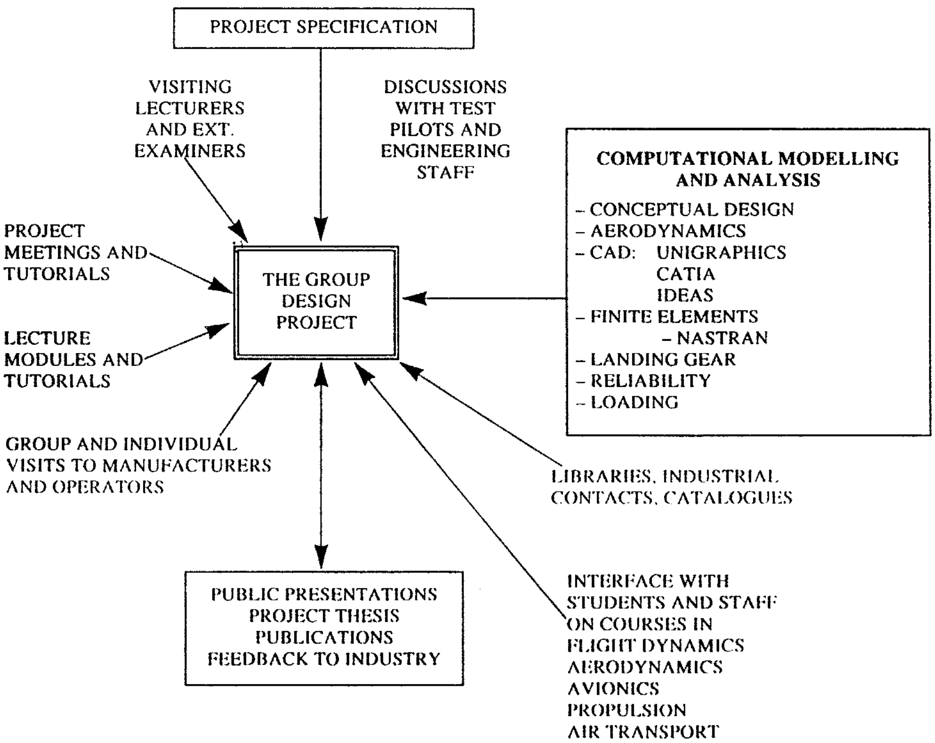

Figure 1. The Principal Inputs into the MSc Group Design Process

The surface models were generated using EDS Unigraphics software.

Both aircraft had the same target gross take-off mass, but the turbo-fan Wombat had a lower empty mass, but more fuel capacity. The external shapes were identical for both projects in terms of fuselages and wings. The main differences were the propulsion systems tail units and main landing gears. The structural loads, however, were unique to each aircraft and were sufficiently close to provide a check on calculations.

The aircraft were designed to use state-of-the-art materials, at the discretion of the students concerned. It was envisaged that the majority of the aircraft would be constructed of aluminium alloys with some use of composite materials. The assumed mass savings associated with these materials were:

Components	*Mass Saving Rel. to Conventional Aircraft*
Fuselage	5%
Wing	10%
Nacelle	10%
Tail	10%
Undercarriage	0%
Pylon	0%

Configuration

A high wing arrangement was implied by the need for paratroop and supply dropping operations together with a low floor line for ease of freight handling. The various roles envisaged for the aircraft dictate the need for pressurisation.

The low-pressure main landing-gear was retracted into large lower-fuselage blisters. These allow the use of adequate track, but do not interrupt the cargo bay. The turbo-fan aircraft uses a conventional high tee-tail, whilst the turbo-prop aircraft uses an H-tail. The latter should reduce rear-fuselage torsion loads, at the expense of slightly increased aerodynamic drag. Figures 3 and 4 show the general arrangement drawings of the aircraft.

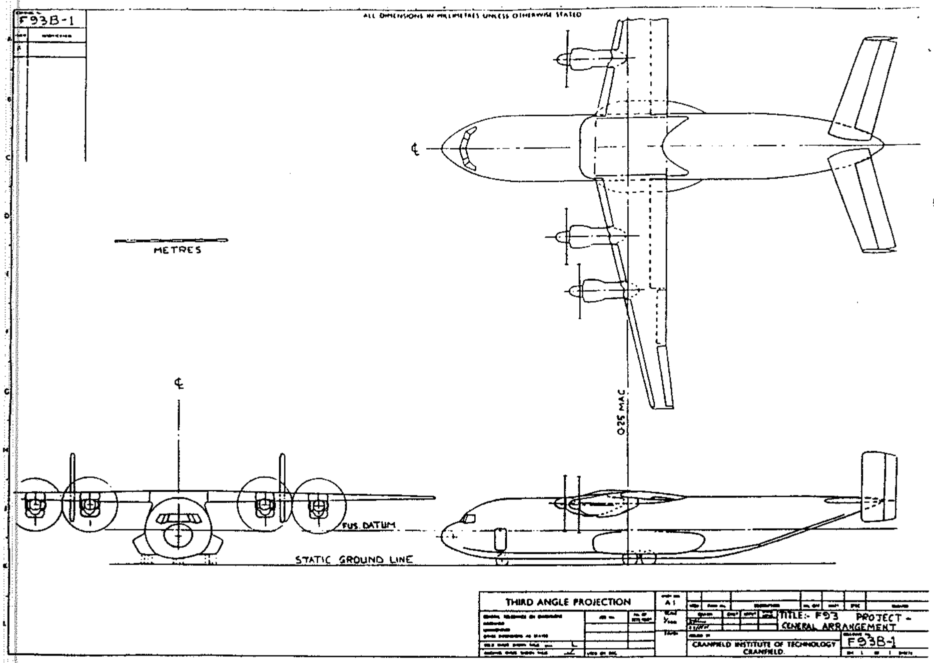

Figure 3. General Arrangement — Turbo-fan Version

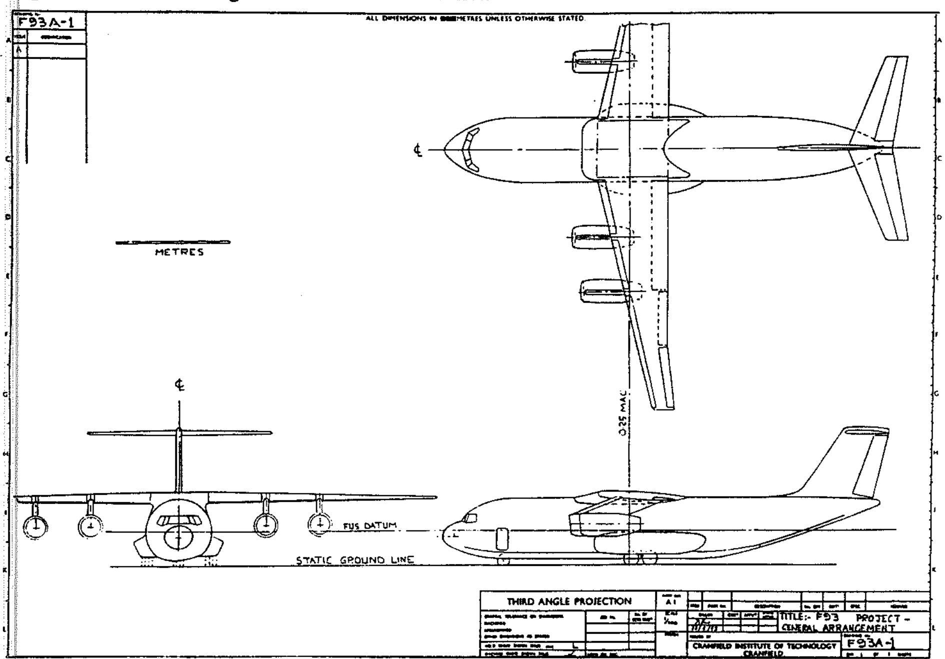

Figure 4. General Arrangement — Turbo-prop Version

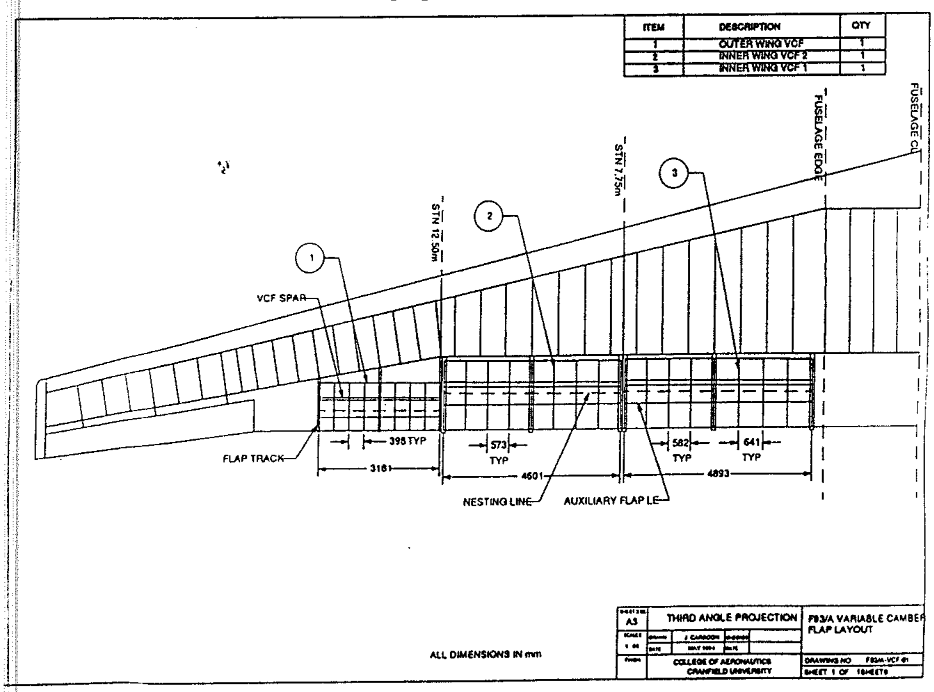

Figure 5. Variable-Camber Flap Layout

Wings

Although the sweepback angle is low, the use of an advanced aerofoil section enables Mach numbers approaching 0.75 to be achieved before significant compressibility drag rise is encountered. The high aspect-ratio of eleven is a result of the short field take-off requirements combined with long range. An unusual feature of the planform is the extent of the unswept trailing edge which covers 75% of the span. This enables the use of unswept trailing edge flaps and gives a possibility for practical application of variable camber. Nominally full span leading edge slats are also used.

Figure 5 shows the arrangement of the variable-camber flaps of the Wombat. Successful design schemes were produced at the expense of some complexity. Separate studies have shown a fuel burn improvement of some 5% for such flaps, but D.O.C. improvements were small for this type of operation. The VC flaps, however, give a great deal of operational and family-growth flexibility.

Powerplant and Vertical Wing Location

Apart from its operations advantages, the high wing improves lift and enables the use of alternative powerplants without change of layout.

Figure 6 shows the neat nacelle arrangement for the turbo-prop powerplant.

Fuselage

The fuselage cross-section is basically circular, except for an increased radius of curvature below the floor line. This enables the loading height to be about one metre above the ground. The nominal floor width of 3.6 m and maximum internal height of 4.5 m are combined with an unobstructed freight hold length of 22 m (to rear end of ramp door). The resulting freight hold volume is over 300 cu. m, or some 160 cu. m for loading to 2 m height. The combination of the ramp loading door and upper rear door enables full utilisation of the freight hold. The unusually large height is dictated by the Super-Puma requirement, but does have a secondary merit of enabling air dropping clearance to be achieved without increased external height of the rear fuselage.

The large rear-door apertures posed significant strength and stiffness problems for the rear fuselage designers. The NASTRAN finite-element structural analysis system was used extensively sometimes slowing down a CRAY super-computer! Figure 7 shows the floor-fuselage interaction model.

Systems

The fuel system consists of three tanks per outer-wing and a centre-wing tank. This complexity resulted, to some extent, from consideration of the effects of rotor-disk burst. The turbo-prop aircraft had little available bleed air, so electro-impulse de-icing was used for the intakes. Conventional hot air anti-icing was used on the turbo-fan version.

The environmental control system utilises two fuselage blister mounted ECS packs. The blisters also accommodate an auxiliary power unit.

Alternative electronically signalled and fibre optic flight control systems were designed.

Landing Gear

The conventional nose landing gear was modified on the turbo-fan aircraft to incorporate a hydraulic motor drive. This increased the axle and bearing sizes, but would allow slow reverse motion of the aircraft up a specified ramp.

Alternative retraction mechanisms were designed for the main landing gears of both aircraft. The four-wheel main bogies allow 22 passes at a CBR = 8 for a 90,000 kg aircraft mass, thus meeting the requirement for operation from semi-prepared airfields. The low location of the fuselage removed the need for "kneeling" landing gears but required the use of stiff spring characteristics for adequate ground stability.

Table 1. Geometry and Performance of Large Transport Aircraft

Characteristics	F93A/B		C-130J	An-70
Overall Length	39m		30m	40.25m
Wingspan	46.1m		40m	44m
Freight Bay Vol	281m³		111m³	305m³
Maximum AUM	101500kg		79830kg	130000kg
Maximum Fuel Load	37750kg	40000kg	28540kg	
Maximum Payload	30000kg		20000kg	35000kg
Cruise Mach No.	0.7	0.7	0.56	0.58
Max. Take-Off Distance	1363m	1363m	1573m	1800m
Max. Landing Distance	1157m	930m	838m	-
Rate of Climb at Sea Level	19m/s	23.2m/s	9.65m/s	-
Rate of Climb at 10km	8.6m/s	5m/s	-	-
Range with 20000kg Payload	7050km	7200km	3917km	-
Range with 30000kg Payload	3277km	4555km	-	4000km
Ferry Range	8919km	10186km	8750km	-

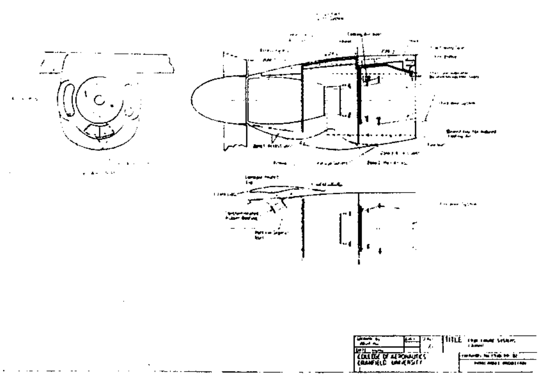

Figure 6. Turbo-prop Engine Nacelle

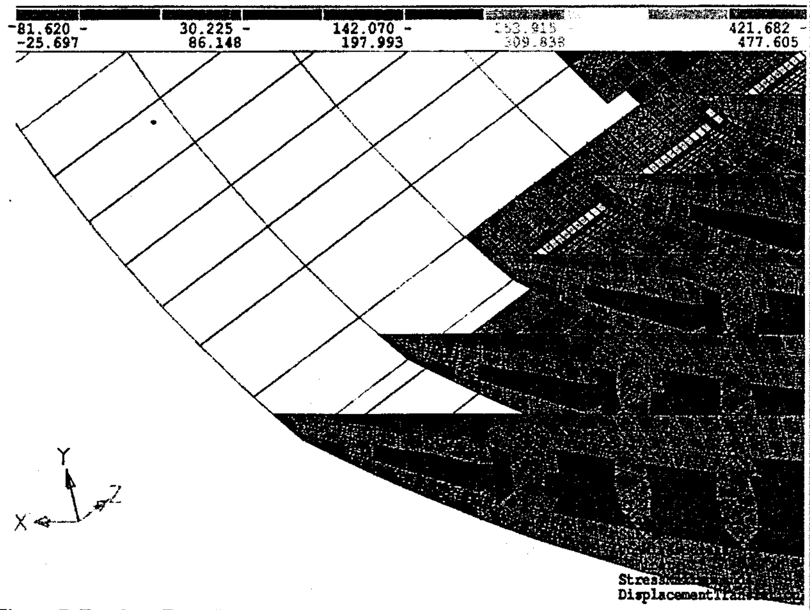

Figure 7. Fuselage Floor Finite-Element Model

Predicted Performance

Table 1 shows a comparison of the predicted dimensions, masses and performance of both versions of the F-93, the C130J and the Antonov AN-70. Performance data were not available for the EUROFLAG aircraft. It can be seen that the F93 aircraft have significant advantages in payload/range, speed and cargo volume, relative to the C130J, but the F93 is larger and more expensive. The Antonov is a very capable aircraft, but is considerably heavier than the F-93 and has a significantly lower cruise speed.

Clearly the F-93 is an attractive aircraft in terms of performance and capability, but it is likely to be expensive.

Relatively simple cost estimates were performed for the F-93 aircraft and the predicted Unit costs varied between $80 M US and $50 M US for 50 and 400 aircraft, respectively. It was thought that these are rather optimistic results and that more accurate predictions should be made and that a cost-benefit analysis be performed to compare competing aircraft types.

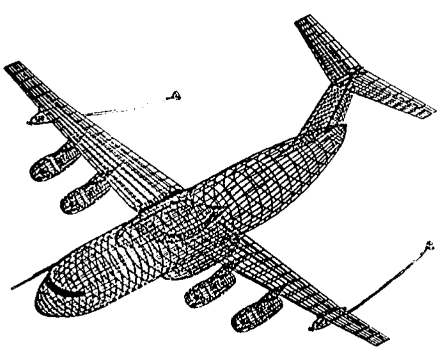

Figure 8. Flight Refuelling Version

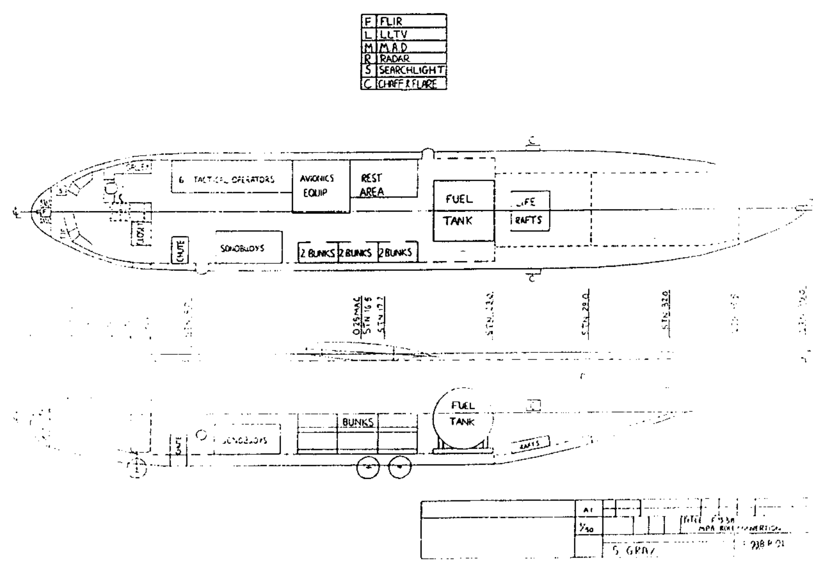

Figure 9. Maritime Patrol Version

A-94

600+ Seat Long-range Airliner Projects

by Professor John Fielding, Head, Department of Aerospace Technology

Professor John Fielding

THE PROJECT PROGRAMME

Many Universities use group design projects as powerful means of pulling together aeronautical teaching programmes in realistic applications of design integration. Design is largely taught by "doing" it. This has been Cranfield's Policy since 1946, but its design course is unique in the magnitude of the student, staff and equipment resources used in the projects. These allow much more detailed studies than elsewhere and provide useful research investigations. It is important that these resources are well-spent in investigating relevant aircraft design topics, and a large airliner was chosen as a suitable topic. It was felt that such an aircraft could be a major element in the alleviation of the chronic and worsening congestion at many of the World's airports. The most important requirement, however, was to provide a means of safe, comfortable travel at cost some 20% lower than current values. The current study was an extension of the earlier A-90 500 seat short - haul project.

It was decided to study developments of the A-90 family on the long-range market because, according to current forecasts, air traffic will more than double by the year 2011. The growth in the Asia/Pacific region is forecast to be 7%. P.A. Taiwan, South Korea, Malaysia and Indonesia are intending to join the established neighbours in Japan, Singapore and Hong Kong as the global business point of the 21st Century. Hence, the interest in Ultra High Capacity Aircraft. The project specification was drawn up following discussion with British Aerospace Airbus Limited and followed a study by students and staff.

Two project teams were formed in October 1994. Each comprised 14 MSc students and three members of staff. The red team designed a laminar-flow version of the aircraft, whilst the blue team designed a more conventional version. Figure 1 shows a computer generated image of the aircraft configuration which was common to both teams with small changes in masses and dimensions.

The students were each allocated the responsibility for the detailed design of a major part of the aircraft. These responsibilities took the form of a major structural component, such as the forward fuselage, a flying control surface or a mechanical system such as fuel, environmental control, propulsion, landing gear or the active control system. Each student was expected to act as designer, structural engineer and draughtsman for his or her component.

The project was managed to an exacting eight month programme by means of the weekly project meetings where students reported on progress, received advice and instructions for subsequent work from the staff project team. The most important role of the meetings, however, was that of a forum where design compromises were resolved and students gained an appreciation of the problems being encountered on other part of the aircraft.

The knowledge gained during lectures, project meetings and discussions with members of staff, was augmented by several valuable visits. No design programme would be complete without a visit to a company operating the type of aircraft similar to that being designed. A visit was therefore made to Monarch Airways' maintenance hangar where minute examinations were made of Boeing 767 aircraft which were undergoing maintenance. Individual students visited factories which were particularly relevant to their design specialisations.

A valuable visit was made to the British Aerospace factory at Chester where Europe's longest wings are built. These are for the Airbus A-340, but would be dwarfed by those of the A-94 with interesting manufacturing problems!

The project ended in May 1995 with a public presentation of the result and submission of project design thesis including drawings. Some 25,000 design-hours were spent on the project and led to interesting results.

THE A-94 SPECIFICATION

Capacity

- 600 mixed class passengers at 34"/32" pitch with comfort standards at least as good as those of the Boeing 747.
- One attendant's seat per 35 passengers with sufficient galley space per passenger of $0.025m^2$
- One toilet per 50 passengers.
- The flight deck shall be designed for a two-person crew.

Performance

- 600 passenger, mixed class, and bag payload range shall be approximately 7300 nautical miles with 200 nm diversion and hold at 1500 ft for 30 minutes.
- The maximum design cruise speed will not be less than 340kt. CAS.
- Maximum cruise altitude should be at least 41,000 ft.
- Maximum certificated runway for maximum all-up mass take-off is 11,000 ft at ISA sea level + 15°C conditions.
- The FAR landing distance at maximum landing mass should not exceed 700 ft at ISA sea level + 15°C conditions.
- Runway loading should not exceed that of a Boeing 747-400 at ramp mass.

A-94 DESCRIPTION

Wings

A modest sweepback combined with a supercritical wing section enable Mach numbers in the region of 0.86 to be achieved. The aspect ratio is 8.4 and there is sufficient fuel tankage at spec. payload for a range of some 7300 miles with reserves. Double slotted flaps, low wing loading and leading edge devices should enable field performance targets to be met for the blue version, whilst the variable camber flaps in conjunction with a Hybrid Laminar Flow Control system should enhance the cruise performance for the A-94 Red version.

Figure 2 shows the plan view of the wing of the red version. The wings are mainly constructed from aluminum-alloy with considerable use of composite materials.

Fuselage

The double-bubble fuselage permits twin-aisle, 10 abreast seating on the main deck, and six on the upper deck. Passenger baggage is stored under the cabin floor. The seating arrangements are as in the specification but an alternative layout accommodates some 750 passengers at 32" seat pitch. A quick-change version can accommodate twin rows of 8ft x 8ft containers. Figure 3 shows the fuselage centre-section which is largely designed to use aluminum-alloy construction.

Powerplant

The configuration consists of a low wing with 4 pod mounted Trent powerplants. The engine nacelles form part of the Hybrid Laminar Flow Control systems on the A-94 Red Version.

The wing laminar-flow system provides suction to the upper leading edges by means of dedicated compressors driven by the secondary power system.

Tail Unit

The aircraft utilises an all-moving fuselage mounted tail. Trim is obtained by tailplane movement whilst control is provided by the elevators. This powerful arrangement is necessary to trim out the large pitching moments produced by the wing high lift devices.

Landing Gear

Such large aircraft led to the expected problems with landing gear. The lighter red aircraft utilised the main gear arrangement

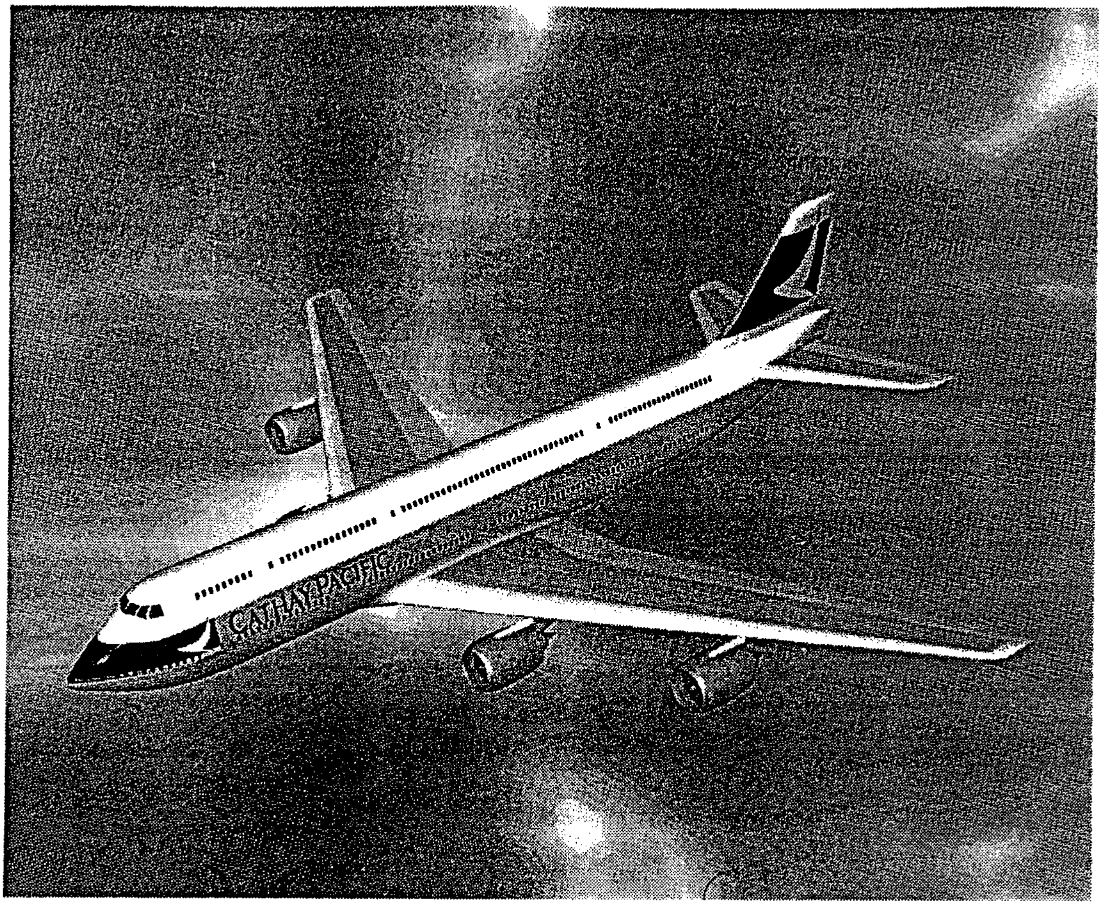

Figure 1. A-94 general configuration

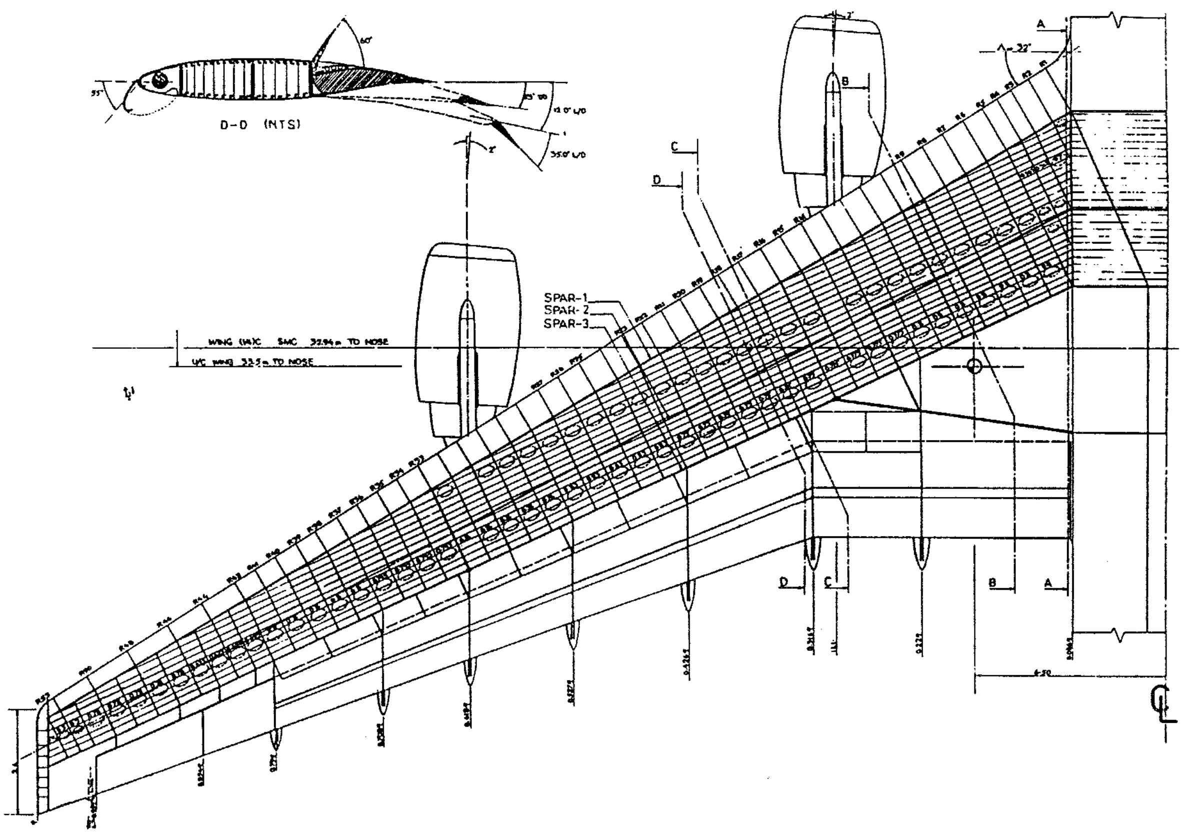

Figure 2. "Red" aircraft wing

of figure 4 with four six wheel bogies. The heavier blue aircraft used five main gears each with four wheel in-line axle nose gear bogies. Both aircraft use a four wheel in-line axle nose gear.

Operational Aspects

The aircraft both use generally conventional avionic and airframe systems, albeit of higher capacity than current aircraft. The exceptions were the system associated with laminar-flow and variable-camber flaps.

Maintainability and reliability prediction showed that the aircraft should meet targets and have a dispatch reliability of better than 97%.

Table 1 shows a summary of aircraft dimensions and masses. These indicate, along with other high-capacity aircraft studies, that such aircraft will have a significant impact on the airport environment. This includes passenger and cargo handling and maintenance but also impacts emergency evacuation. Figure 5 shows an initial scheme for escape slide deployment, but further research is required.

Performance, Costs and Lessons Learnt

Figure 6 shows the payload/range predication for both aircraft and a version of the blue aircraft with winglets. It can be seen that the latter aircraft meets the requirements but the others are slightly deficient. The red laminar-flow aircraft was effectively a modified turbulent design and full benefits of new technology can only be realised if the aircraft is optimised with the new technologies at the conceptual design phase. Independent research at the College of Aeronautics has shown significant benefits from aircraft optimised to take account of laminar-flow and variable camber.

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

The aircraft suffered from significant trim drag penalties at normal centre of gravity conditions. Flight dynamics students suggested flight control system modification to correct this, but an easier solution would be to move the wing forward on the fuselage on the next design iteration.

A large half-aircraft wind tunnel model was tested to investigate the wing fuselage fillet region. Flow visualisation tests were performed but these need to be continued.

An interesting lesson learnt was the cargo volume limitations posed by this class of aircraft. A consequence of double-deck aircraft is the reduction in the cargo baggage container capacity relative to the number of passengers carried. 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.

The following table shows the number of under deck LD3 containers that may be carried by some wide-body aircraft:-

Type	No. of LD3s	No. of Passengers/Container
Airbus A340-300	32	9.2
Boeing 747-400	30	14
Cranfield A-94	26	23

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.

Air cargo carriage is increasing at a higher rate than that for passengers, so the large aircraft may seem a retrograde step in this context. The large aircraft, however, could be modified to combi or dedicated all-cargo aircraft to alleviate this problem. Under-deck and main deck cargo could be handled as for the 747, but upper deck cargo would be more difficult. It would be possible to use 'igloo' standard containers on the upper deck, and a nose docking-port to aid loading and unloading. The docking-port could also be useful for maintenance access.

Conclusions

The A-94 project was a detailed study of a type of aircraft of current interest. It showed that such an aircraft is feasible and should meet market requirements, although a 20% D.O.C. reduction is difficult to achieve. New technologies such as laminar-flow and variable-camber flaps are potentially rewarding but care must be taken to integrate them into a fully optimised conceptual design.

Such aircraft pose significant problems for airport interfaces, but these are solvable and the cost savings should make changes worthwhile.

The A-94 projects provided realistic environments in which students learned how to design practical components, work as a team and present their results orally and in written theses. The theses contain some 200 engineering drawings produced by traditional and CAD methods. Some 30 theses have been published, giving some 4,000 pages of description and analysis.

Students have been given "hands-on" experience of computer techniques, such as CAD, Finite Element Analysis, Composite Materials Analysis as well as a wide range of dedicated analysis programs. They have researched up-to-date aeronautical technologies such as active control, all-electric aircraft, and advanced materials. These activities will provide information of use to other members of the Aerospace Community. Students were drawn from many counties in the World, indeed, the only continent not represented was South America. These students will reach senior positions within their countries and, hopefully, benefit aerospace activities throughout the world.

Table 1

SPECIFICATION DIMENSIONS AND QUANTITIES FOR THE A94:

The blue Aircraft has been designed as a "conventional aircraft", using current materials and systems. The Red Aircraft has been designed to incorporate advanced materials with high technology features such as hybrid laminar-flow on the wings and engine nacelles and variable camber flaps on the wing.–

Wing		
Gross Wing Area	672m² Red	688m²
Span	75.15m 76m	
Aspect Ratio	8.4 Both	
Quarter Chord Sweep	30° Both	
Tailplane		
Gross Area	185m² Both	
Span	6m Both	
Aspect Ratio	10.3 Both	
Fin		
Nominal Area	125.7m² Both	
Effective Aspect Ratio	1.786 Both	
Fuselage		
Length	69m Both	
Maximum Width	6.56m Both	
Maximum Height	7.76m Both	
Main Cabin Length	57m Both	
Powerplant		
Engines	Rolls Royce Trent 877 Both	
Sea Level Static Thrust	356.2 kN Both	
Masses		
Maximum Take-Off	506,548 kg Red	519,689 kg Blue
Maximum Payload	67,500 kg Both	
Maximum Volumetric Fuel	230,000 kg Red	236,000 Blue

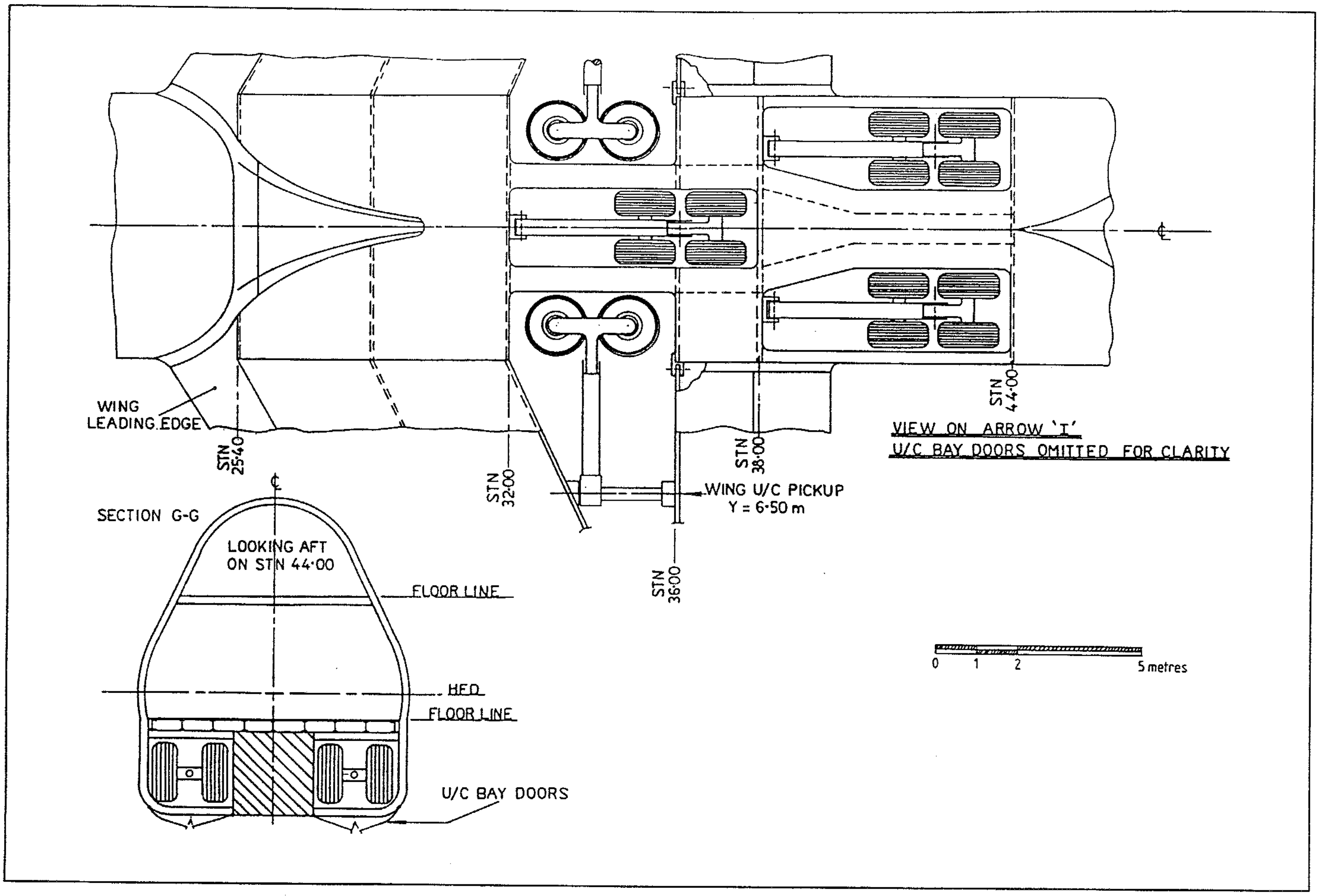

Figure 3. Centre fuselage of the "blue" aircraft

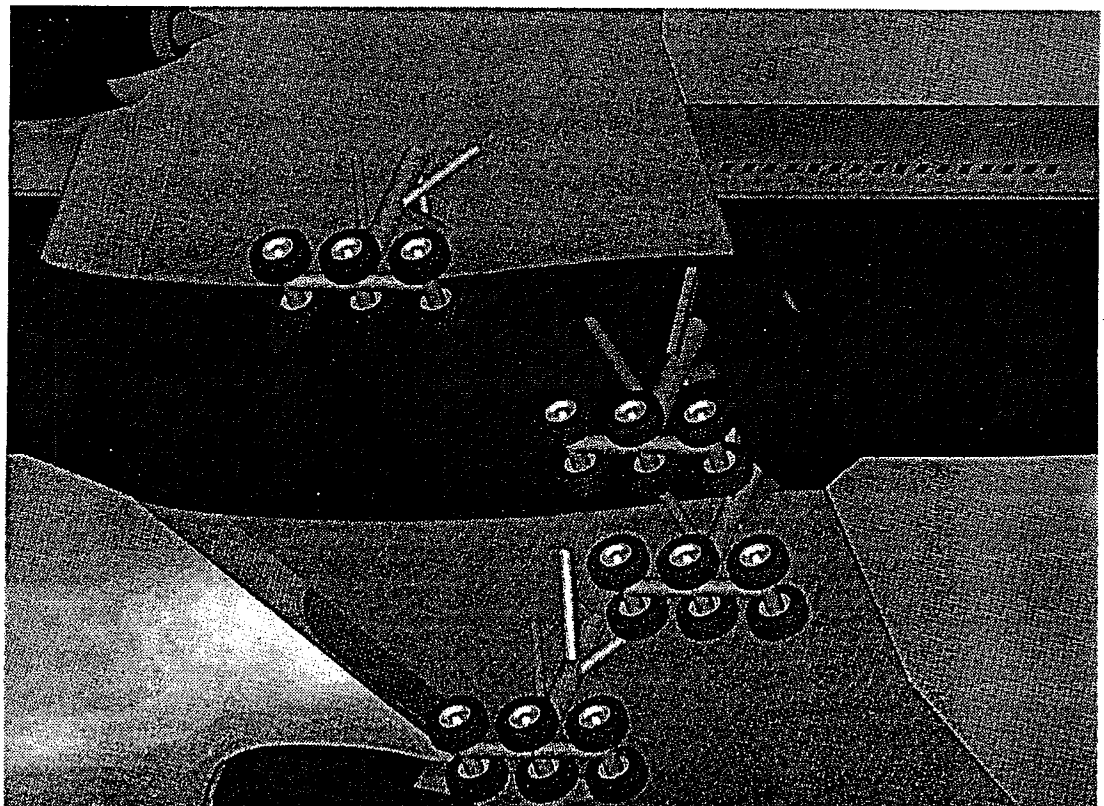

Figure 4. Main landing gear of the "red" aircraft

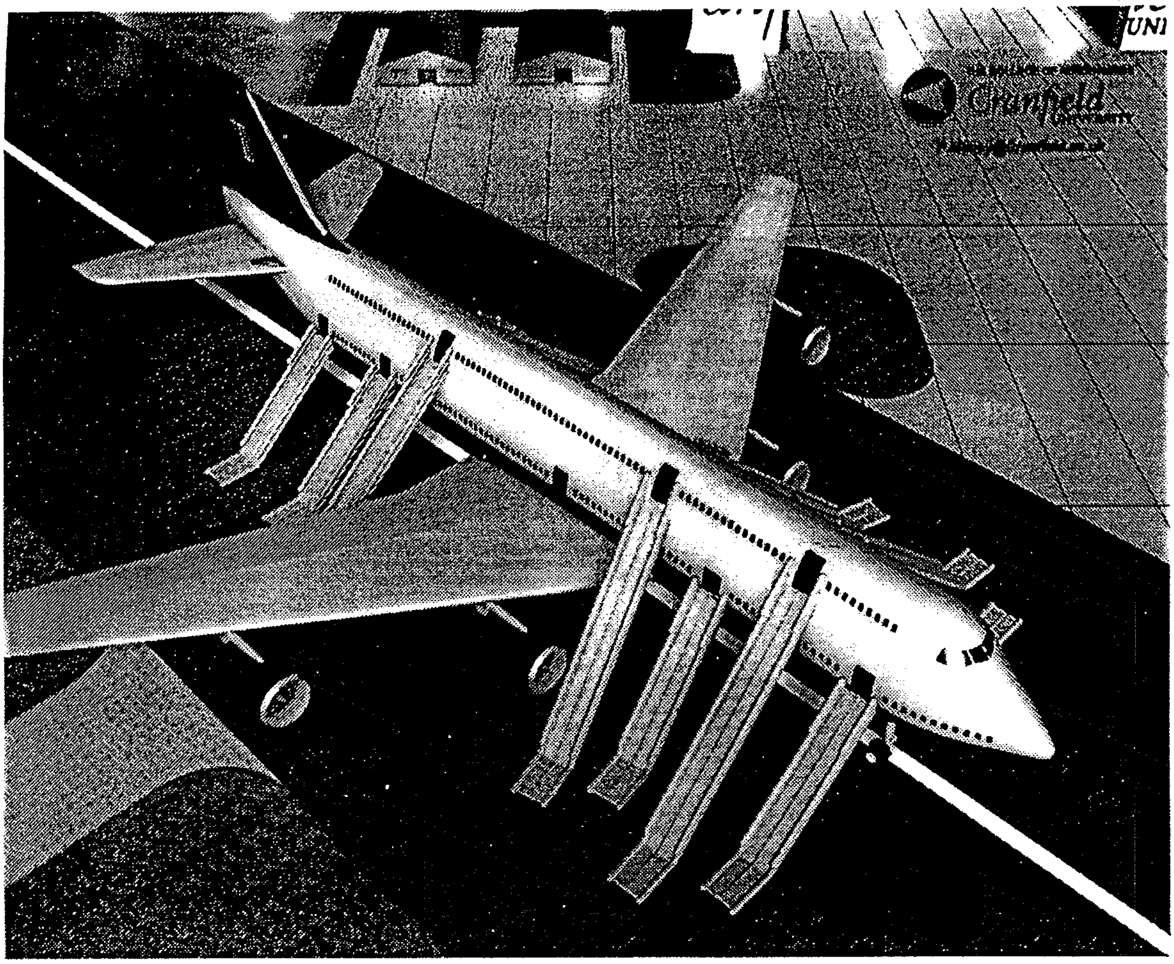

Figure 5. Emergency evacuation slides

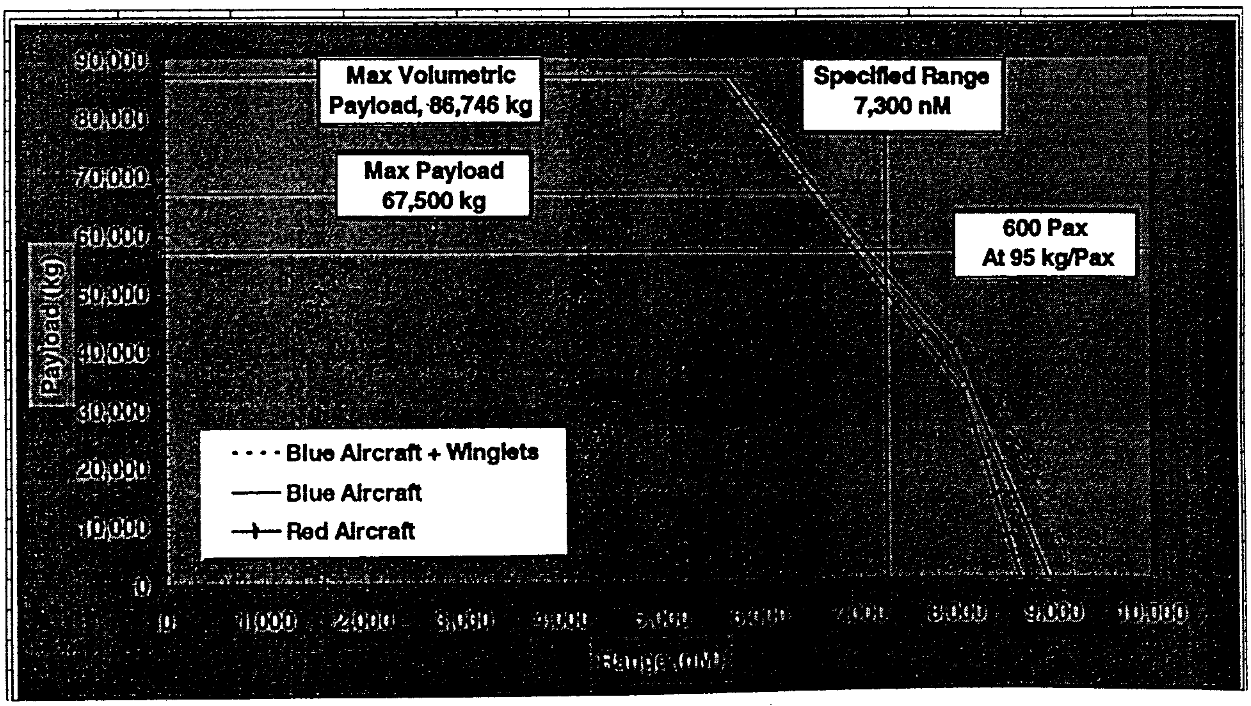

Figure 6. Payload-Range diagram

DAeT 9500/ 1

College of Aeronautics

AEROSPACE VEHICLE DESIGN

ADVANCED SHORT TAKE-OFF VERTICAL LANDING COMBAT AIRCRAFT

S-95

PROJECT SPECIFICATION (Issue 1)

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Prof D Howe
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Dr R I Jones

August 1995

1. INTRODUCTION

There has been varied interest in Vertical Take-Off and Landing (VTOL) and Short Take-Off and Vertical Landing (STOVL) combat aircraft concepts over the last 30 years. The latest development in this area being the joint US/UK ASTOVL programme, which would result in a supersonic successor to the Harrier. Furthermore, the amalgamation of the ASTOVL project with the Joint Affordable Strike Technology (JAST) programme which envisages a family of modular aircraft to address a diverse range of roles for the USAF, USN, US Marine, RN and possibly the RAF. Within this programme the ASTOVL variant would be a 'minimum change' version of the conventional Take-Off and Landing (CTOL) variant.

In the 1994-5 academic year Mr M Rosa [1] performed an initial project design which forms the basis of this years Aerospace Vehicle Design (AVD) group project.

2. SPECIFICATION

The aircraft is defined by the requirement implied by two basic roles that it is intended to fulfill, by a series of point performance requirements and by a number of basic structural design requirements.

2.1 Design Missions

2.1.1 Offensive Support Mission

i) Warm-up, taxi (5 minutes at ground idle), short take-off and climb to 80 m height

ii) Accelerate to Mach 0.6

iii) Outboard cruise at 80 m and M = 0.6 for 130 nm

iv) Penetration at 80 m and M = 0.8 for 60 nm

v) Fire 4 Maverick missiles at 80 m and M = 0.9 over 2 minutes

vi) Subsonic combat (four 360° turns at M = 0.9, sea level fire 2 ASRAAMs and expend ammunition)

vii) Egress at 80 m and M = 0.8 for 60 nm

viii) Return cruise at 80 m and M = 0.6 for 130 nm

ix) One minute hover out of ground-effect followed by a vertical landing with 5% internal fuel remaining on entering the hover. (Assume an instantaneous transition into the hover)

2.1.2 Offensive support weapons load

4 x AGM-65 Maverick
2 x AIM-132 ASRAAM
1 x 20 mm M61 A1 Vulcan gun with 400 rounds of ammunition

2.1.3 Air superiority mission

i) Warm-up, taxi (5 minutes at ground idle) and short take-off

ii) Accelerate and climb to Best Cruise Altitude and Mach number (BCAM)

iii) Cruise at BCAM for 235 nm

iv) Accelerate at maximum power to M = 1.5 at 30,000 ft

v) Supersonic combat at M = 1.5 and 30,000 ft (fire 2 AMRAAM then one 360°, 3g sustained turn)

vi) Subsonic combat at M = 0.9 and sea level (two 360° 8 g sustained turns, firing 2 AMRAAMs, 2 ASRAAMs and expanding all ammunition)

vii) Minimum fuel climb to BCAM

viii) Return to base at BCAM for 235 nm

ix) One minute hover out of ground-effect followed by a vertical landing with 5% internal fuel remaining on entering the hover. (Assume an instantaneous transition into the hover)

2.1.4 Air superiority weapons load

2 x AIM-132 ASRAAM
4 x AIM-120 AMRAAM
1 x 20 mm M61 A1 Vulcan gun with 400 rounds of ammunition

2.2 Point Performance Requirements

i) Level flight performance

M = 1.1 at sea level (Max. reheat)
M = 1.2 at 11 km (Max. dry)
M = 1.6 at 11 km (Max. reheat)

ii) Sustained turn rates

16 deg/sec at M = 0.5 and sea level
11 deg/sec at M = 0.9 and sea level
12 deg/sec at M = 0.9 and 6 km altitude
8 deg/sec at M = 1.2 and 6 km altitude

iii) Instantaneous turn rate

22 deg/sec at M = 0.55 and 3 km altitude

iv) Specific Excess Power

150 m/s at M = 1.4 and 9 km altitude
300 m/s at M = 0.9 and sea level
190 m/s at M = 0.9 and 6 km altitude

v) Field performance

Short take-off ground roll of 125 m on dry concrete at ISA + 15°C, full internal fuel and weapons load appropriate to mission, zero wind conditions.

Vertical landing at the landing mass appropriate to the mission at ISA + 15°C and in head winds from zero to 10 m/s.

2.3 Structural Design Requirements

Design maximum speed, V_D	386 m/s EAS
Design maximum Mach No., M_D	1.8
Limit normal manoeuvre factors at Combat Mass	+9 and -3
Ultimate factor	1.5
Bird impact at sea level	1.8 kg at 260 m/s
Design vertical landing velocity	4.45 m/s
CBR of 8 for 100 passes at design landing mass	

2.4 Avionics Fit

Integrated communications, navigation and identification
Inertia navigation system & GPS
Controls and display
Radio altimeter
Digital computers
Airborne radar
Weapon Management System
Radar warning system
2-18 GHz jammer
Chaff and flare dispensers

2.5 General

The aircraft will have a blended wing body configuration designed to minimise the radar cross-section and hence increase survivability. The demanding performance requirements of this vehicle preclude the incorporation of an internal weapons bay and hence all weapons, other than the gun, will be carried semi-submerged.

Due consideration shall be given to reliability and maintainability to minimise the life cycle cost.

3. CONFIGURATION AND DESIGN REQUIREMENTS

The general arrangement drawing is shown in figure 1.

3.1 Wing and Canard Foreplane

An unstable close coupled canard arrangement was chosen to give improved lift characteristics in take-off, landing and manoeuvres.

Wing leading and trailing edge devices improve take-off and conventional/short landing performance and can also be employed to optimise lift/drag in combat.

Figure 2 depicts the wing and canard geometries. The leading and trailing edges have been aligned to help reduce the aircraft radar signature.

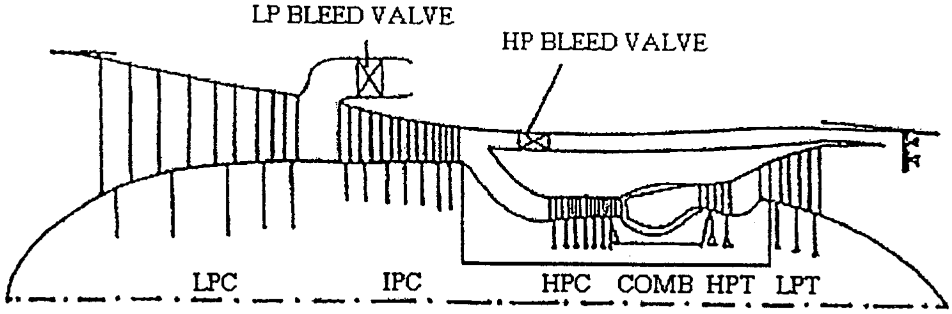
3.2 Powerplant

The engine is the, Cranfield developed, Selective Bleed Variable Cycle Engine (SBVCE) [2]. This dual cycle turbofan provides adequate thrust for both vertical lift and supercruise phases.

The engine has 2 modes of operation - low pressure (LP) and high pressure (HP). In the LP mode, designed for low Mach number, the LP bleed valve is open while the HP valve is closed. LP bleed air is fed forward to the cold (front) nozzle giving a vectored thrust capability and hence the engine acts as a low BPR turbofan.

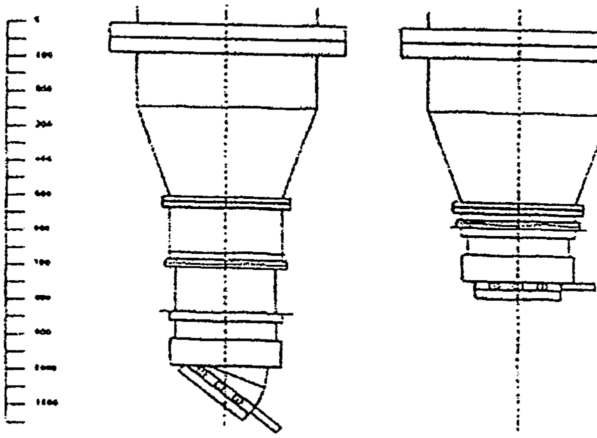
In the HP mode, designed for high Mach number, the HP bleed valve is now open with the LP valve closed. No vectored thrust is available, BPR is reduced, and the engine acts as a 'leaky' turbojet with lower mass flow but increased specific thrust. The afterburner is available in this mode.

The mode change over is pilot selectable and will usually occur around sonic conditions.



Schematic of the Selective Bleed Variable Cycle Engine

Details of the engine geometry are shown in figure 3, which also depicts the rear nozzle. A schematic of the Allison Telescopic Vectoring Nozzle, which may form the basis of the front nozzle, is shown below:-



3.3 Fuselage

The forward fuselage contains the pilots ejector seat surmounted by a reasonably large canopy for good visibility. Most of the avionics bays are just fore and aft of the cockpit with low mounted side intakes beneath. Also to the rear and below of the cockpit are the gun and ammunition separated by the forward nozzle.

The centre/rear fuselage houses the powerplant, either side of which are the weapon pallets which carry the semi-submerged weapons.

The aft fuselage is bifurcated, by the engine rear nozzle, into a twin boom arrangement.

The complex blended wing-fuselage geometry is intended to reduce the radar signature whilst maintaining good aerodynamic performance. Tentative suggestions for initial cross section geometries are given in figure 4.

3.4 Fins

The twin boom arrangement leads to a twin fin configuration. The fins are canted outwards to help reduce the radar signature of the aircraft.

3.5 Undercarriage

The landing gear uses a conventional tricycle arrangement. The twin wheel nose leg retracts rearwards. The main gear legs rotate as they retract rearward, to stow the wheel at an angle to the horizontal. This permits some of the volume above the weapon pallets to be utilised. Figure 5 gives indication of the landing gear geometry.

3.6 Radar Signature

Whilst it is not intended that the aircraft be in the Very Low Observable (VLO) category, attention should be given to radar signature. Radar Absorbent Material (RAM) and Radar Absorbent Structure (RAS) being applied where appropriate, subject to the availability of literature on these technologies.

3.7 Reaction Control System

The reaction control system is required to trim the aircraft in the hover mode and during transition to and from normal forward flight over the anticipated c.g. range. The system will also be required to provide adequate control of the aircraft at low speed.

3.8 Fuel System

An initial fuel system layout is given in figure 1. During flight it will be possible to schedule fuel usage and/or pump fuel to manage the c.g. position to best aerodynamic advantage. It is likely that the system may be refined further by optimising the tank locations.

3.9 Design Requirements

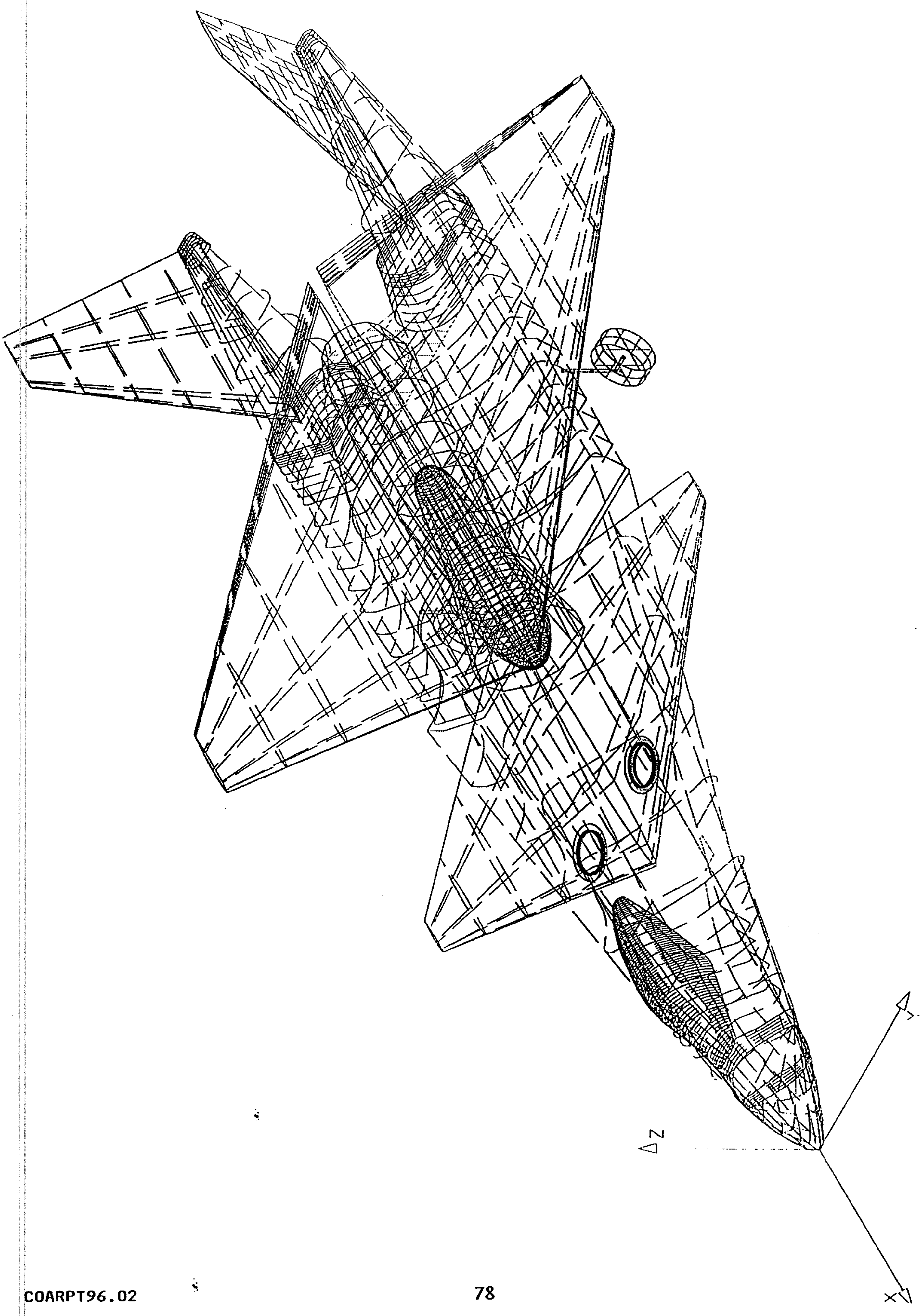
The aircraft is to be designed to meet the military requirements as specified in DEF STAN 00-970.

The maximum take-off mass is 19,000 kg. The undercarriage design vertical velocity of descent is 4 m/s.

The airframe life is 6,000 hours with fatigue damage specified in figure 6.

Figure 7 shows the flight speed envelope for the aircraft.

Where appropriate, the design of components should allow for reliability requirements shown in table 1.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