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Graduate Aircraft Design Education*

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Cranfield University believes that the best way to learn about design is to do it, and that group design projects are a very powerful means of providing practical experience. This is not unique, but what is unique is the practical detail achieved in the MSc course. Cranfield's approach is to invest at least 3 man-months work by staff in the preparation of each project, before it is presented to the students. This defines the aircraft's shape, aerodynamics and mass, and is equivalent to work done by Project Officers in industry. Students who wish to perform their own conceptual designs may do so for their individual research theses which are the other main activities of the MSc course. Some 25 students are allocated the responsibility for the design of a major part of the aircraft. These responsibilities take the form of a major structural component, a flying control surface or a mechanical system such as fuel, or the flying control system. Reliability, maintainability, performance and cost are overall design topics also studied by students. This paper describes the design of an entry-level executive jet, as an example of the group design project. The paper also describes the other elements of graduate education at Masters and Doctoral level.

INTRODUCTION

AIRCRAFT design is a synthesis of many disciplines, each of which must be understood and correctly applied to achieve the correct balance essential for optimum performance. It always involves compromises between the requirements of the different disciplines involved, and the perspectives of the specialists concerned.

Figure 1 shows sketches of aircraft designs that might be produced by engineers from different disciplines. A competent aircraft designer must know enough about those specialisations so that he or she will be able to balance them to arrive at a whole aircraft optimum design, rather than one that may be optimum from, say, a structural or aerodynamic viewpoint. The judgement required to achieve this balance requires a practical design approach that has been the hallmark of aircraft design teaching at Cranfield since the Aircraft Design course was established as one of the original Cranfield graduate courses.

This occurred in 1946, when the College of Aeronautics was founded on a site some 50 miles north of London. The original College had it's own well-equipped airfield and fleet of research and teaching aircraft. These facilities formed the bedrock of Cranfield's practical aeronautical activities and have been enhanced by the acquisition of progressively more modern aircraft and other facilities. Cranfield's original objective was to provide a world-class school of post-graduate aeronautical teaching and research. The College expanded into many other areas of engineering, science and management studies and received it's University Charter in 1969, under the name of Cranfield Institute of Technology. The name was again changed in 1993, to Cranfield University, to counter some misunderstanding in the UK, as to what was an Institute of Technology. The College of Aeronautics remains in existence as one of the major schools on the Cranfield Campus.

The title of the Aircraft Design course was changed to become 'Aerospace Vehicle Design', to reflect an expansion into the field of spacecraft design. The basic tenets of the aircraft design education process, however, remain those described by the Author's predecessor, Professor D. Howe [1], namely:

1. The properly equipped designer must be able to achieve a correct balance between synthesis and analysis and so achieve an optimum result in the most economic manner.
2. He/she must be aware of the importance of working through the task to the final details.

The need for a balanced outlook and almost intuitive approach to a problem has often given rise to the assertion that good designers are born, not made. There may be some truth in this but extensive training is essential in the context of a complex technology, and correct teaching can exploit the latent potential of design ability.

A student must have a broad and deep understanding of both theory and practice before he/she is capable of tackling design work effectively. The continuously expanding frontiers of aeronautics imply that text books rapidly become outdated, even if they exist at all. Therefore the staff must find ways of keeping up to date and at the same time not lose sight of fundamentals and real practice. George Bernard Shaw once wrote that 'those who can, do, but those who can't, teach'. To instruct in design effectively one must both 'do and teach' and ideally the student should 'do' as well! The course structure and environment at Cranfield have been built up to enable this to be achieved.

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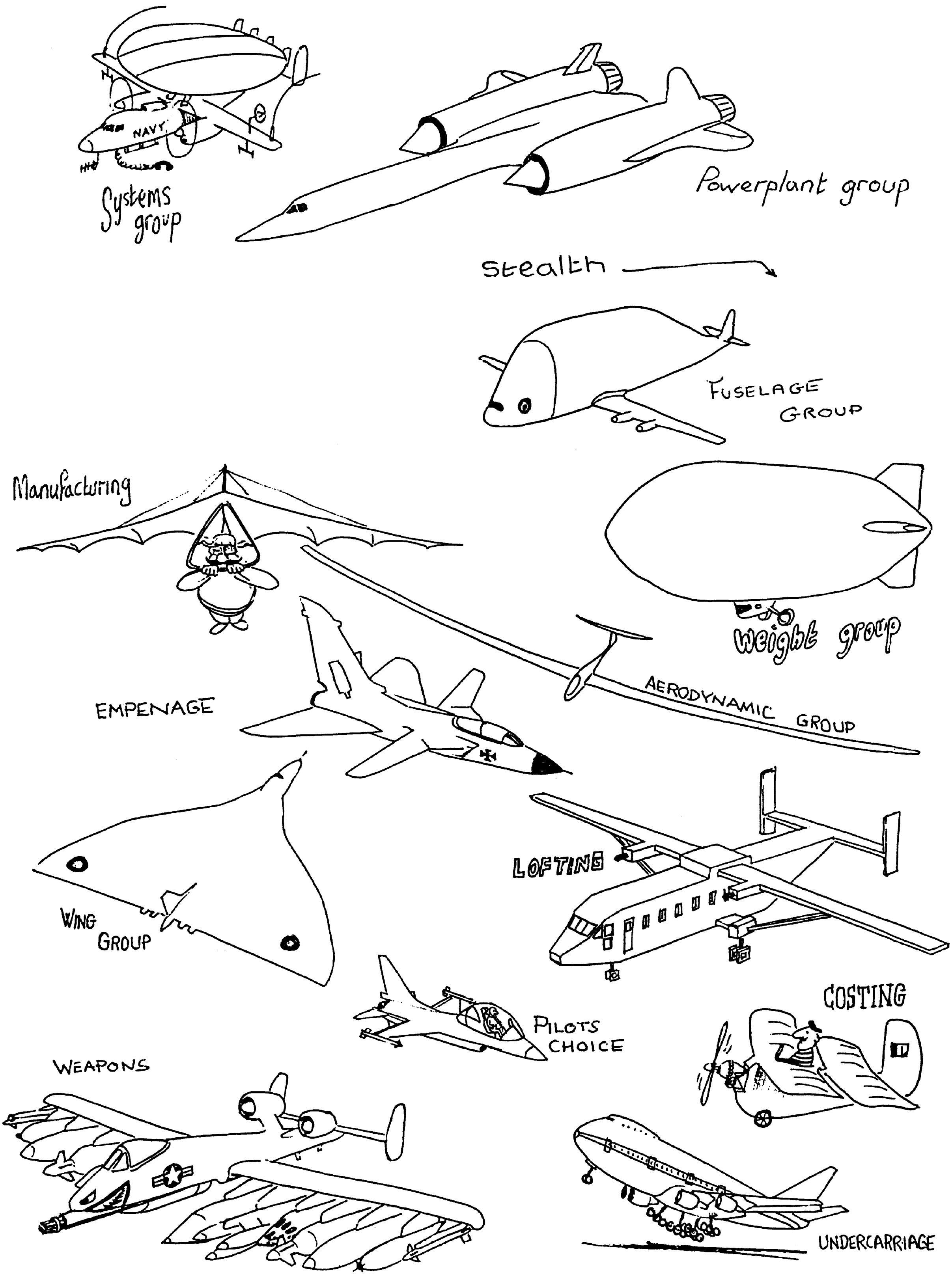

Fig. 1. Aircraft that could be produced by specialists with differing design priorities.

This philosophy has been proved to be sound, and has not changed since 1946, although the means of achieving those aims use modern tools, as will be shown later.

COURSE STRUCTURE

Figure 2 shows a summary of the Cranfield graduate aircraft design courses, the main one

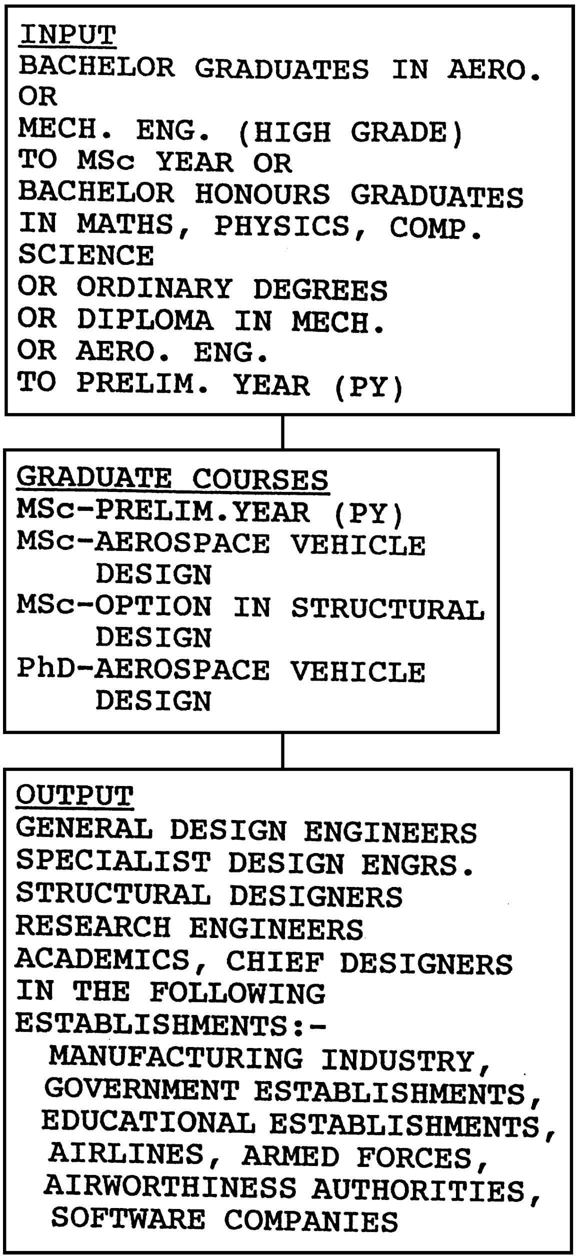

Fig. 2. Cranfield aircraft design courses.

being the 12-month MSc Course in Aerospace Vehicle Design. This is an intensive course and requires a high input standard in terms of prospective students' qualifications and experience. The usual entry is a good-class honours degree in Aeronautical or Mechanical Engineering, preferably with a number of years of post-graduate experience. Indeed, our average students' age is in the late 20's. Many students have degrees in such subjects as Physics, Maths or Computing and wish to convert to an aeronautical engineering course. These students can attend the preliminary year course (PY) and then progress onto the 12-month MSc course. The preliminary year course is also used by some lower-qualified aeronautical graduates, or students with relevant engineering diplomas. Preliminary year students usually form the core of the design team in the MSc year.

An MSc course option in Structural Design also exists. This differs from the General Design option in that students follow lectures and perform research most relevant to that subject. Rather than participating in the group design project, a more extensive individual research topic is performed and examinations are taken on the lecture material. A 3-year part-time version of the aerospace vehicle design course was introduced in February 1995.

An increasing number of students are following the PhD course. Some of these are recruited after completing the MSc course, but the majority come directly from other Universities, or from Government or industrial establishments. Most of the PhD students are members of the Conceptual Design Research group and activities include:

- The development of multivariate design synthesis and optimisation methods for canard delta, agile fighter, A/STOVL, UMA, Supersonic Transport and laminar-flow aircraft.
- Multidisciplinery preliminary design methodologies for conventional transport and blended wing/body aircraft.
- Investigation of configurational aspects of advanced airframe systems.
- The development of methods to improve the reliability, maintainability and survivability of civil and combat aircraft.

Other PhD students are studying topics in the structural design areas, particularly in the use of composite material structures.

LECTURE COURSES AND LABORATORY WORK

The preliminary year

The preliminary year is intended as an introduction or refresher in aeronautics, and is pitched at the final year undergraduate level. There are lecture courses in areas such as Maths, Computing, Structural Analysis, Aerodynamics, Aeronautical Engineering, Electronics, etc. These are augmented by laboratory work and the most important feature—individual design projects. Students will complete three progressively more complex design projects during the year. They will perform conceptual and detail designs, which are then stressed, and reports produced. The first project might be a relatively simple mechanism, the second a fuselage frame and the third a complete flying control surface. Students are taught, and use, computer-aided design and computer structural analysis tools.

The MSc year

The lecture programme is carried out over two, ten-week terms, in parallel with the group design project (see below). The lecture syllabus has a large mandatory core, with some options, depending on student interests. The total lecture hours vary between 240 and 300 hours in the following subjects:

General and project design:
Design for operation—including noise, V/STOL, airports, reliability, maintainability and weapon systems;
Initial aircraft design;
Design of major components;
Computer-aided design;
Loading actions.

Structural aspects:
Aerospace structural considerations;
Structural stability;
Finite-element methods;
Structural optimisation;
Fibre reinforced plastics;
Fatigue and fracture;
Structural dynamics;
Aeroelasticity.

System and allied areas:
Aircraft systems;
Control engineering;
Aircraft avionics systems.

Additional subjects:
Aircraft accident investigation;
Fixed wing aircraft performance;
Theory of flight.

The final topic is another unique feature of Cranfield Courses. Students are given lectures in aircraft performance, flight mechanics and flight test methods, and then complete eight flight tests in the College's own specially-equipped Jetstream aircraft (Fig. 3).

The theoretical knowledge is thus reinforced by flying *in* the aircraft during the flight-test manoeuvres and is then further reinforced by on-board flight data acquisition, and subsequent analysis. The latter activity has been recently enhanced by the incorporation of a Cranfield-designed on-board computerised data acquisition and display system.

Students, however, only act as flight-test engineers; they do not actually fly the aircraft. This deficiency has been remedied by student light aircraft flight test experiments in the College's two-seater Beagle Pup aircraft. Each student undertakes two flights in the aircraft. The Cranfield pilot demonstrates and tutors the student in level flight, climbs, turns and descents. The student then flies the aircraft in the second flight and conducts a simple flight test experiment, associated either with performance or flight dynamics.

These flying activities are expensive, but are part of the course and contribute significantly to the development of a well-rounded design engineer.

Fig. 3. Jetstream flight test 'classroom' aircraft.

INDIVIDUAL RESEARCH INVESTIGATIONS

These may be theoretical and/or experimental and are drawn from a range of topics related to the course and suggestions by the staff, sponsors or students themselves. Members of staff are appointed as research supervisors for each student within a few days of the start of the academic year. There is a close relationship between student and supervisor, reflected by the average student/staff ratio of around 9:1.

The experimental research is aided by the aircraft, some 20 windtunnels, an extensive structural test laboratory, metalwork workshops and a composite component fabrication laboratory.

There is a powerful computer facility with networked PCs, workstations and mainframe computers.

The research investigations comprise 45% of the MSc students' final marks and are assessed by research theses.

Topic areas are similar to those performed by the conceptual design research group, mentioned above, but extend to conceptual design, structural design, fracture and fatigue, composite structures and advanced airframe systems.

THE MSc GROUP DESIGN PROJECT

Background

The Cranfield 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. The group design project is undertaken by all the aerospace vehicle students and is a major feature of the MSc course, accounting for almost half of the final assessment. Each year the students work in teams on the design of a project aircraft. A substantial part of the airframe, a system, an installation or performance aspect, is allocated to each student as his or her own responsibility.

The aircraft chosen as the subject for the work are representative of types of current interest to industry. They usually incorporate some feature which extends the bounds of existing practice, as an applied research activity. This excites the interest, enthusiasm and ingenuity of the students and forces the staff to keep up to date.

Civil and military aircraft are investigated in alternate years, so that the whole of the industry is catered for. Recent examples of design projects included large and small business jets, a number of medium-sized jet transports and a 500-seat short-haul airliner.

Figure 4 shows the project programme for the last aircraft, the A-90 which is typical of all projects. Military aircraft include basic and advanced trainers, close-air support aircraft, an advanced tactical fighter, V/STOL supersonic strike aircraft and military transports.

Figure 5 shows a typical drawing from the T-91 trainer maintainability CAD model. The 1986/7 project saw the design of a two-stage to orbit space launcher, which is shown in Fig. 6 [2].

The remainder of this article gives a brief description of the E-92 executive jet project, as an example of a civil aircraft project.

THE E-92 EXECUTIVE JET PROJECT

Project background

It was decided to design an executive jet in 1992/3, as 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 piston aircraft, to large

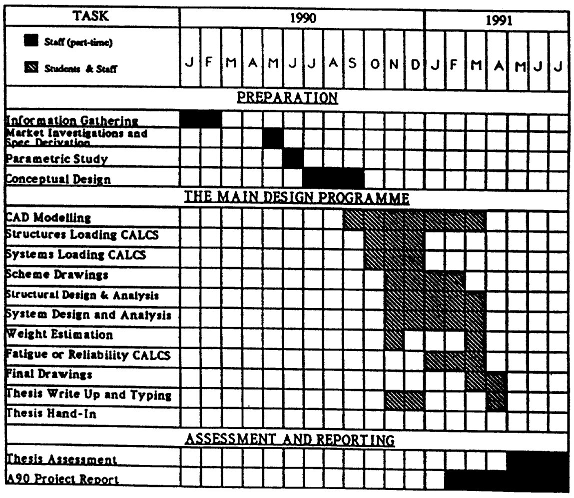

Fig. 4. The A-90 programme timescale.

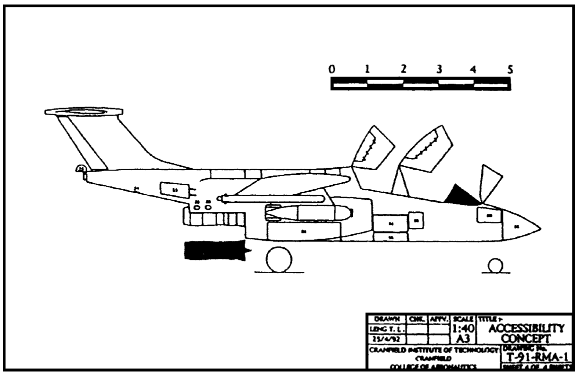

Fig. 5. T-91 Trainer—some maintainability features.

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 turbo-prop 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 Cranfield Design was pitched between the Citationjet and SJ-30 in terms of performance, but would utilise significant amounts of advanced composite materials in its construction. This should lead to lower mass despite the more generously sized cabin interior.

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 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.

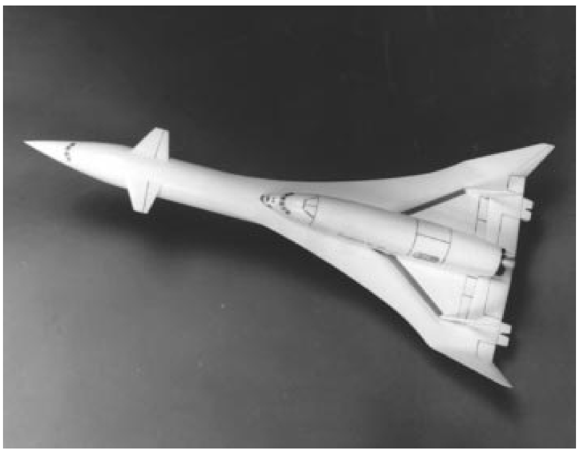

Fig. 6. SL-86 space launcher.

- High speed Mach No. = 0.75;
- Economical Mach No. = 0.72;
- NBAA, IFR range with 3 passengers and 1 crew should be greater than 1800 miles (3245 km); Max operating altitude = 43,000 ft (13.1 km);
- FAR take-off balanced field length to be less than 3300 ft (1005 m);
- FAR landing distance at max landing mass to be less than 2600 ft (792 m).

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 early 1992. This work was summarised in Reference 3 which was given to 25 students in October of that year. Each structures student was given responsibility for the detailed 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. There were some very lively discussions about interfaces, particularly in the forward fuselage area.

Figure 7 shows a computer-aided design (CAD) model of this very crowded area. A suitable

Fig. 7. E-92 forward fuselage.

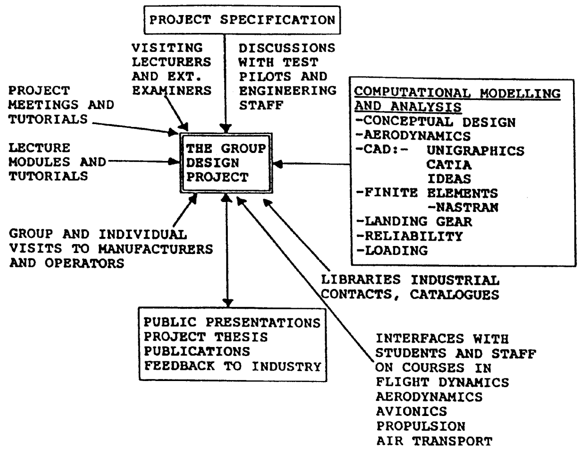

Fig. 8. Inputs into the group design project.

compromise was agreed between students responsible for fuselage structure, rudder pedals, nose landing gear, electrical power, avionics and flight-deck layout.

The knowledge gained during lectures, project meetings and discussions with members of staff was augmented by information from aircraft manufacturers. (See Fig. 8 for project inputs).

Vital information on the project engine was given by Rolls-Royce and realistic information was received from avionics 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, 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 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.

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 9 shows a shaded image of the computer-generated surface model of the project. The

Fig. 9. E-92 surface computer model.

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 the specified payload for a range of 1800 nautical 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 initial fuselage shape, giving significant trim drag, which would negate the effects of the drag reductions from laminar flow. The fuselage was re-shaped 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.

Finite-element models were 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 Fig. 10. The environmental and flying control system components run under the seat armrests and under the floor.

The toilet compartment is rather restricted for large passengers, and some re-design will be

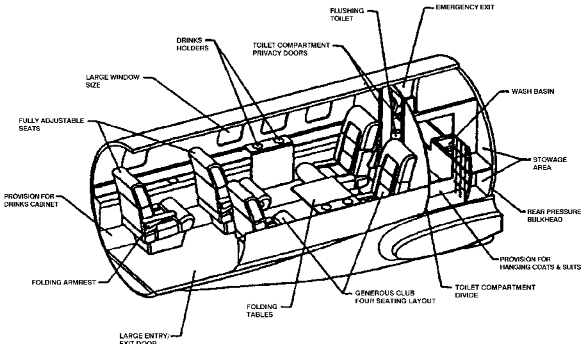

Fig. 10. Fuselage interior.

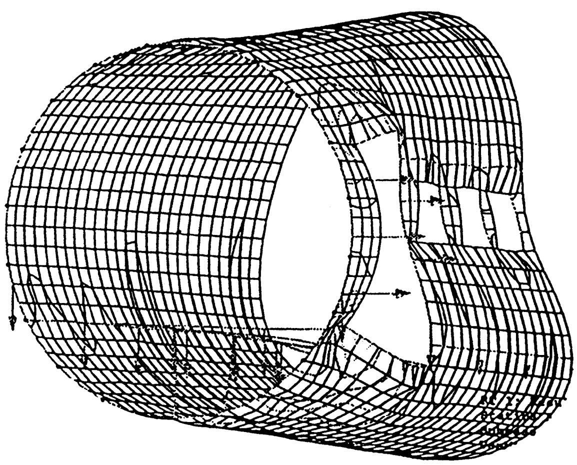

Fig. 11. Forward fuselage finite-element model.

necessary. The fuselage structure is of the conventional aluminium semi-monocoque type.

Figure 11 shows an exaggerated deflection finite-element model of the forward fuselage. The passenger door and emergency exit door 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 and the engine pylon front spar passes through it. The baggage compartment is under the rear part of the equipment bay.

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 sweep-back of the fin. This arrangement does not have as severe 'rolling due to sideslip' effect as does the high T arrangement.

The fin 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 finail 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. Setback 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, Fig. 12.

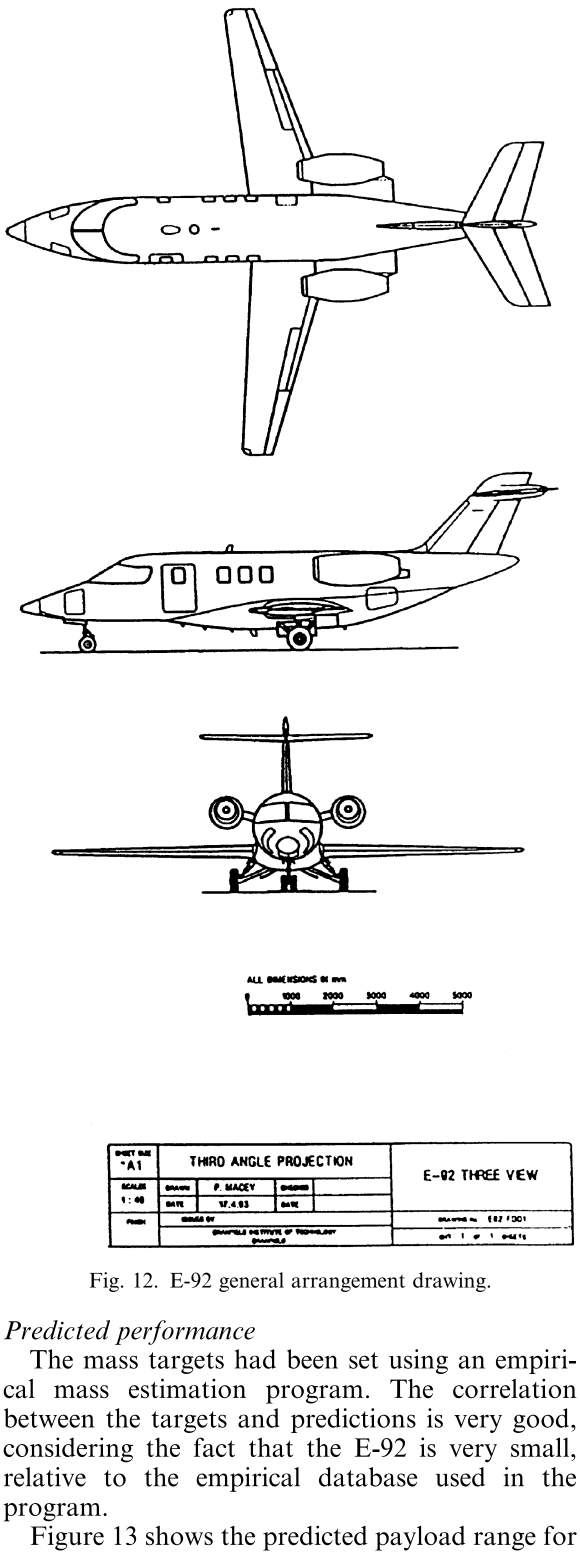

Fig. 12. E-92 general arrangement drawing.

Predicted performance

The mass 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 13 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.

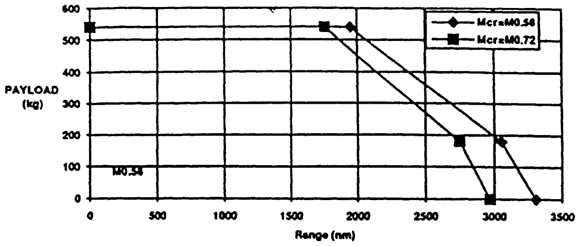

Fig. 13. E-92 predicted payload—range diagram.

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

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 $3.5m US should be achieved on the basis of a production run of 300 aircraft. The direct operating cost should be $4.45 US per aircraft nautical mile.

E-92 PROJECT 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 problems 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.

Results of Cranfield's design education process

Student entry to the Cranfield course is of a very high standard and the concentrated post-graduate courses add significant value to the graduates' education and design experience. The group projects and associated studies provides a realistic environment in which students learn how to design practical components, work as teams and present their results orally, and in written theses. The theses from a typical project contain some 200 engineering drawings, in total, produced by traditional and CAD methods. Some 30 project theses are published, each year giving some 4000 pages of description and analysis, in addition to a similar number of individual MSc research theses.

Students are given hands-on experience in computer techniques, such as CAD, finite-element analysis, composite materials analysis as well as a wide range of dedicated analysis programs. They have flown as flight test engineers in the College's Jetstream aircraft, and have themselves flown the Beagle Pup aircraft. They have researched up-to-date aeronautical technologies such as fibre-optics, all-electric aircraft, and advanced materials. These activities provide information of use to other members of the aerospace community.

The students' individual research thesis work, at Masters and Doctoral level, provide significant applied research in aircraft and structural design. These are published, and provide new ideas for the industry.

The major output, however, is the output of highly-skilled, rounded design engineers who reach high positions, world-wide, in the aircraft industry, airlines, academia, Air Force and Government Regulatory and Research Departments.

The lecturing, group project and research activities are very demanding of faculty members' time and require very low student/staff ratios. The extensive laboratory, computing, and flying activities are also expensive, but the positive results of Cranfield's design education speak for themselves.

There are many chief designers who are Cranfield aircraft design alumni. The Cranfield approach, started in 1946, continues and is continually being improved.

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Prof. John Fielding had 12 years industrial experience as both an engineering apprentice and design engineer at Hawker-Siddeley Aviation. In 1975 he joined Cranfield as an ARB Research Fellow and is now Professor of Aircraft Design and Head of the Air Vehicle Technology Group in the College of Aeronautics. He is responsible for research and

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