# LOAN DOCUMENT

PHOTOGRAPH THIS SHEET

AD-A277 806

DTIC ACCESSION NUMBER

LEVEL

INVENTORY

1

AGARD-CP-547

DOCUMENT IDENTIFICATION

Nov 93

Approved for public release; Distribution Unlimited

DISTRIBUTION STATEMENT

HANDLE WITH CARE

| ACCESSION FOR | |
|---|---|
| NTIS GRA&I | ☒ |
| DTIC TRAC | ☐ |
| UNANNOUNCED | ☐ |
| JUSTIFICATION | |
| | |
| | |
| BY | |
| DISTRIBUTION/ | |
| AVAILABILITY CODES | |

| DISTRIBUTION | AVAILABILITY AND/OR SPECIAL | |
|---|---|---|
| A-1 | | |

DISTRIBUTION STAMP

DTIC ELECTE MAR 3 0 1994 S C D

DATE ACCESSIONED

DATE RETURNED

94 3 16 018

DATE RECEIVED IN DTIC

94-08489

REGISTERED OR CERTIFIED NUMBER

PHOTOGRAPH THIS SHEET AND RETURN TO DTIC-FDAC

DTIC FORM JUN 90 70A

DOCUMENT PROCESSING SHEET

PREVIOUS EDITIONS MAY BE USED UNTIL STOCK IS EXHAUSTED.

LOAN DOCUMENT

AGARD-CP-547

AGARD-CP-547

# AGARD


ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT
7 RUE ANCELLE 92200 NEUILLY SUR SEINE FRANCE



**AGARD CONFERENCE PROCEEDINGS 547**


# Recent Advances in Long Range and Long Endurance Operation of Aircraft

(Les Progrès Récents dans le Domaine des Opérations Aériennes à Longue Distance et de Longue Durée)

*Copies of papers presented at the Flight Mechanics Panel Symposium, held in Kijkduin (The Hague), The Netherlands, 24th—27th May 1993.*

NORTH ATLANTIC TREATY ORGANIZATION


Published November 1993

*Distribution and Availability on Back Cover*

AGARD-CP-547

# AGARD

ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT
7 RUE ANCELLE 92200 NEUILLY SUR SEINE FRANCE

**AGARD CONFERENCE PROCEEDINGS 547**

# Recent Advances in Long Range and Long Endurance Operation of Aircraft

(Les Progrès Récents dans
le Domaine des Opérations Aériennes
à Longue Distance et de Longue Durée)

Copies of papers presented at the Flight Mechanics Panel Symposium, held in Kijkduin (The Hague), The Netherlands, 24th—27th May 1993.

North Atlantic Treaty Organization
*Organisation du Traité de l'Atlantique Nord*

# The Mission of AGARD

According to its Charter, the mission of AGARD is to bring together the leading personalities of the NATO nations in the fields of science and technology relating to aerospace for the following purposes:

— Recommending effective ways for the member nations to use their research and development capabilities for the common benefit of the NATO community;

— Providing scientific and technical advice and assistance to the Military Committee in the field of aerospace research and development (with particular regard to its military application);

— Continuously stimulating advances in the aerospace sciences relevant to strengthening the common defence posture;

— Improving the co-operation among member nations in aerospace research and development;

— Exchange of scientific and technical information;

— Providing assistance to member nations for the purpose of increasing their scientific and technical potential;

— Rendering scientific and technical assistance, as requested, to other NATO bodies and to member nations in connection with research and development problems in the aerospace field.

The highest authority within AGARD is the National Delegates Board consisting of officially appointed senior representatives from each member nation. The mission of AGARD is carried out through the Panels which are composed of experts appointed by the National Delegates, the Consultant and Exchange Programme and the Aerospace Applications Studies Programme. The results of AGARD work are reported to the member nations and the NATO Authorities through the AGARD series of publications of which this is one.

Participation in AGARD activities is by invitation only and is normally limited to citizens of the NATO nations.

The content of this publication has been reproduced
directly from material supplied by AGARD or the authors.

Published November 1993



ISBN 92-835-0726-6

*Printed by Specialised Printing Services Limited*
*40 Chigwell Lane, Loughton, Essex IG10 3TZ*

# Preface

Over the past few years, the use of aircraft in what can be termed long range and/or long endurance operations has proved to be a successful use of military resources. Operations such as tactical strikes mounted from bases thousands of miles away, to the use of long endurance patrol aircraft over either the battlefield or the maritime environment demonstrate the ability now contained in the NATO operational forces. The use of military airlift to position forces where they are most needed clearly is another operation where the range and endurance of the aircraft are pivotal to the success of the operation.

Technologies which improve the range and endurance of aircraft have seen considerable advances over the past ten years. Aircraft design for these features has matured considerably while the procedure of air-to-air refuelling has made global deployment and 24+ hour operations a reality. While not generally perceived as long range aircraft, the possible range and endurance of fighters (both subsonically and supersonically), V/STOL aircraft and even rotorcraft have improved considerably over the last generation of vehicle design.

With the current requirements to fly farther and longer, this Symposium was conceived to summarize the latest technological advances in the various fields which in a combined manner define the range and endurance of airborne vehicles. The Symposium was divided into four specific elements:

- airframe design technologies, including aerodynamics and structures,
- propulsion technology,
- the human factors problems associated with these types of missions and,
- air-to-air refuelling technologies and procedures.

The Symposium was opened by two Keynote Addresses, the first by M.Gen Breeschoten of the Royal Netherlands Airforce which described a military perspective on long range and long endurance operations, and the second by Burt Rutan of Scaled Composites Inc. which described the variety of technological and human challenges involved in the record breaking flight around the world of the Voyager aircraft.

# Préface

Au cours des dernières années, le déploiement de l'aviation pour des missions dites à longue distance et/ou de longue durée a été une réussite du point de vue de l'utilisation de ressources militaires. Des opérations telles que les frappes tactiques lancées à partir de bases éloignées de milliers de kilomètres de la zone de l'objectif, ou le déploiement d'avions patrouilleurs à longue distance soit au dessus du champ de bataille, soit en milieu maritime, montrent les capacités actuelles des forces opérationnelles de l'OTAN. L'emploi du pont aérien militaire pour positionner les forces de façon optimale fourni un autre exemple d'une opération où l'autonomie et l'endurance de l'aéronef sont cardinales pour la réussite de la mission.

Les technologies susceptibles d'apporter une amélioration du rayon d'action et de l'endurance ont progressé considérablement au cours de la dernière décennie. La conception des avions dans ce domaine a connu un développement significatif, tandis que la technique du ravitaillement en vol a permis le déploiement global vingt quatre heures sur vingt quatre. Bien que traditionnellement, ils ne soient pas considérés comme des avions à grand rayon d'action, la distance franchissable et l'endurance des avions de combat (tant en subsonique qu'en supersonique), des avions V/STOL et même des aéronefs à voilure tournante se sont améliorés au cours de la dernière génération.

Pour tenir compte de la tendance actuelle d'aller plus loin, et plus longtemps, ce symposium a été organisé pour faire le point des dernières avancées technologiques réalisées dans les différents domaines et qui, combinées, concourent à définir le rayon d'action et l'endurance des véhicules aériens. Il compte quatre parties:

- les technologies entrant dans la conception de la cellule, y compris l'aérodynamique et les structures
- les technologies de propulsion
- les problèmes associés au facteur humain dans ce type de mission
- les technologies et les procédures du ravitaillement en vol.

Deux allocutions ont été prononcées en ouverture du symposium. La première, qui a été donnée par M.Gen. Breeschoten du Royal Netherlands Airforce, a porté sur les perspectives d'avenir pour les opérations à longue distance et de longue durée, et la seconde, par Burt Rutan de Scaled Composites Inc. a fourni la description des différents défis, humains et technologiques, présentés par le vol record de circonscription du globe effectué par l'aéronef Voyager.

# Flight Mechanics Panel

**Chairman:** Professor L.M.B. da Costa Campos
Instituto Superior Tecnico
Pavilhao de Maquinas
1096 Lisboa Codex
Portugal

**Deputy Chairman:** Dipl.-Ing. H. Wünnenberg
Head of Flight Mechanics
Dornier Luftfahrt
D-88039 Friedrichshafen
Germany

## TECHNICAL PROGRAMME COMMITTEE

Mr S.W. Baillie
Flight Research Laboratory
Institute for Aerospace Research
National Research Council
Montreal Road
Ottawa, Ontario K1A 0R6
Canada

ICA J-M. Duc
Directeur
Affaires Internationales
O.N.E.R.A.
29, avenue de la Division Leclerc
92322 Châtillon-Sous-Bagneux
France

Mr K. McKay
Assistant Manager EFA Aerodynamics
Aerodynamics Department (W310P)
British Aerospace Defence Ltd.
Military Aircraft Division
Warton Aerodrome
Preston, Lancs. PR4 1AX
United Kingdom

## HOST NATION COORDINATOR

Captain (Rtd) Ir L. Sombroek
c/o National Aerospace Lab (NLR)
Netherlands Delegation to AGARD
P.O. Box 90502
1006 BM Amsterdam
The Netherlands

## PANEL EXECUTIVE

Mr M.K. Foster

**Mail from Europe:**
AGARD—OTAN
Attn: FMP Executive
7, rue Ancelle
92200 Neuilly-sur-Seine
France

**Mail from US and Canada:**
AGARD—NATO
Attn: FMP Executive
Unit 21551
APO AE 09777

Tel: 33(1)47 38 57 70
Telex: 610176 (France)
Telefax: 33(1) 47 38 57 99

## ACKNOWLEDGEMENT

The Flight Mechanics Panel wishes to express its thanks to the National Authorities of The Netherlands for the invitation to hold this meeting in Kijkduin (The Hague), and for the facilities and personnel which made the meeting possible.

The Flight Mechanics Panel also wishes to thank the Aerospace Medical Panel, the Fluid Dynamics Panel, the Propulsion and Energetics Panel as well as the Structures and Materials Panel for their valuable contribution.

La Commission du Mécanique du Vol tient à remercier les Autorités Nationales des Pays Bas pour leur invitation à tenir cette réunion à Kijkduin (La Haye), ainsi que des installations et du personnel mis à sa disposition. La Commission du Mécanique du Vol remercie également la Commission de Médecine Aérospatiale, la Commission du Dynamique des Fluides, la Commission de Propulsion et Energetiques, ainsi que la Commission de Structures et Matériaux pour leur précieuse collaboration.

# Contents

# TECHNICAL EVALUATION REPORT

by

F. MARY
23, Rue de la Croix du Val
F-92190 MEUDON
FRANCE

## 1. SUMMARY

This report reviews the lectures presented at the 82nd Flight Mechanics Panel Symposium on "Recent Advances in Long Range and Long Endurance Operation of Aircraft". The purpose is to analyse the various papers and try to make a synthesis of the subject, setting it in the scope of the present World aeronautical as well as political and economical environment. Though the initial prospect was a military one, in the frame of AGARD and for the benefit of the NATO Forces, civil transport and scientific applications have also been taken into consideration. An attempt is made to propose some recommendations for the future activities of the Panel.

## 2. BACKGROUND

Technologies and techniques which contribute to improve the range and endurance of aircraft have considerably progressed over the last ten years. However, very little was devoted to this topic in the past of the Panel, even in such symposia as "Improvement of Combat Performance for Existing and Future Aircraft" (April 1986) and "Progress in Military Airlift" (May 1990).
But the changes in Eastern Europe and the evolution in the World political situation resulted in a new challenge for the NATO Forces : in place of a well identified threat to which a strategy had been tailored for years, they have now to get prepared for types of conflicts not well defined, neither in form nor in location. Happening at a moment when the World Economy slowdown imposes drastic reductions in military expenses, this means that the existing (or even reduced) military forces must be used as efficiently as possible. An extended range is among the ways to improve this efficiency. It was the motivation of the Pilot Paper n° 195 (a summary of which is appended to this report), proposed to the Panel and eventually implemented in this symposium.

## 3. INTRODUCTION

The 82nd Symposium of the AGARD Flight Mechanics Panel was held in the Hague, the Netherlands, from the 24th to the 27th of May 1993. More than 100 participants were registered, representing 12 of the 16 NATO Nations.

The goal of this symposium was to review the various means available to extend the range or endurance of aircraft in all categories and to induce progress by discussion between the various parties involved.
Insufficient range of various categories of Western military aircraft was evidenced in such conflicts as Tchad, Falklands, etc. This prompted the writing of the Pilot Paper n° 195, the validity of which was eagerly confirmed by the Gulf War. Therefore the initial purpose of this Pilot Paper was essentially military, but the subject turned out to be of interest for the civil transport and scientific communities as well, which considerably extended the scope of the papers presented at the Symposium.
As suggested by the Pilot Paper, the contribution of other Panels was requested; papers were presented by the Structures and Materials Panel (SMP), the Fluid Dynamics Panel (FDP), the Propulsion and Energetics Panel (PEP) and the Aerospace Medical Panel (AMP).
The symposium comprised 2 keynote addresses and 26 papers, broken down into four sessions:

SESSION ONE. AIRFRAME DESIGN FOR LONG RANGE AND ENDURANCE.

SESSION TWO. PROPULSION SYSTEM CONCERNS FOR LONG RANGE AND ENDURANCE OPERATIONS.

SESSION THREE. THE HUMAN FACTORS SIDE OF THE PROBLEM.

SESSION FOUR. AIR TO AIR REFUELLING.

*Technical Evaluation Report on Flight Mechanics Panel Symposium on 'Recent Advances in Long Range and Long Endurance Operation of Aircraft', May 1993.*

It is not attempted to make abstracts of the papers themselves, but the questions and discussions related to the subjects are summarized.

## 4. HIGHLIGHTS

From the evaluator's stand point and due to the interest they raised at the Symposium, the following lectures are considered outstanding and recommanded to the time-limited reader :

- Second keynote address from Burt Rutan (if paper is available in the Proceedings) for the mix of professional experience and pioneering spirit shown in the "Voyager" project.

- Paper 5 for the comprehensive review of the present status and perspectives in the airlift area, including Eastern programmes.

- Paper 6 showing how to reduce dramatically the production costs of the weight-saving composite structures, thus allowing to carry a higher fuel load.

- Paper 7 showing how to reduce drag by natural and artificial boundary layer control.

- Papers 11 and 13, showing, each in their domains, that in the very competitive civil transport area, every detail improvement is worth being considered to reduce drag or fuel consumption.

- The whole Session three (Papers 15 to 18) for its outstanding presentation of the importance of human factors in long duration flights and of means to reduce their effects on the crews.

- Papers 21, 23, and 24, for a review of the status and prospects in Air Refuelling.

## 5. TECHNICAL PROGRAMME

### 5.1 Keynote addresses

To introduce the symposium, two very different lectures were provided, the first one considering the military aircraft in the present World political perspective and the second one telling of a "Round the World" record flight. The interest that both Speakers raised in the floor set up the spirit of the symposium.

With his long experience as a military and test pilot as well as due to his present position of Head of Operations at the Royal Netherlands Air Force Head-Quarters, the first Speaker was well qualified to introduce the subject on the military side. His views on the changes in the World political and economical situation, and their consequences on the NATO strategy were based on firsthand information. The main feature of future likely conflicts is to have no specific features, in terms of opponent, type of threat and location. Under these conditions, defining, preparing and organizing forces is difficult. One thing is certain: the importance of long distance intervention. As an example, in the Gulf War, some operations were impaired by the limited number of tankers. In addition, the Defense budgets in the NATO Countries have lost their priorities and are shrinking. The lecturer elected to draw, from these conditions, tentative general specifications for the future NATO aircraft of all types, pointing out, among others, the particular aspects concerned with long range or long endurance.

With the second Speaker, this was a completely different picture. The earnest military realities were forgotten. A pioneering spirit, of the eighties vintage, allied to a first class scientific and technological knowledge resulted in the design and building of a wonderful and fragile aircraft that flew round the World non stop. Humour was always present in the presentation of this story, which did not prevent Burt Rutan emphasizing how every technical choice was "long range minded"; and reading the paper shows that the technical conflicts were many, including the human factor aspects of the pilots' accomodation.

A film presented the main phases of the aircraft building and of the flight tests. But the most impressive part was the take off for the record flight, when the fuel overloaded wing scraped its tips on the runway for many hundred feet before leaving the ground and eventually lost both winglets at the beginning of the flight. The film showed that the risk of failure was not zero but one understand that the safety margin assessed was not that bad.

As a conclusion, the Speaker indicated that what could appear as a mere technical challenge and a sport feat would have more positive fall out (the Raptor project was mentioned). Of course, many of the technical solutions should be adapted or redesigned, for safety and reliability reasons, but the dedicated spirit of simplicity and invention will still be there.

### 5.2 Airframe Design for Long Range and Endurance

This first session comprises 10 papers, spread over one and a half day. It is therefore divided into two subsessions which do not differ technically. It is a mix of analyses, overviews, technological developments and programme descriptions, which reflect the multiple facets of the subject, depending on the areas concerned: civil transport, military aircraft, unman-ned air vehicle (UAV), research aircraft, etc.

In Paper 1, the subject is not very different from the second keynote's one, but it is treated in a more conventional manner and for a UAV. It is still a paper project whose parametric study is cost oriented. A lot of various missions, civil and military, are planned for this vehicle, the size and shape of which results from the need to carry an ADI radar antenna. The choice of a four engine configuration could be explained by the availability of relevant powerplants and the ability to operate at low weight on two engines. Concern appeared in questions from the floor about the uncommon configuration of two fuselages with no tail interconnections: is the structure stiff enough ? what about the flying and handling qualities ? were the stability and manoeuvrability on the ground assessed ? one question tried to compare the structural weight with Voyager's one, but this comparison is biased because of the different load factors, safety coefficients, etc.

Paper 2 is a similar parametric study. It reviews all kinds of missions that a HALE-UMA (read: High Altitude Long Endurance - UnManned Aircraft) can fulfill, in the civil and military areas, in some cases as a complement of satellite and aircraft surveys. Though a drawing of the vehicle is displayed, the study does not seem to have got into detailed design, as far as structure and systems are concerned. A review of the possible propulsion systems resulted in the choice of 2 supercharged reciprocating engines, allowing a symmetrical one engine operation at low weight. But comparing the powerplant with that of paper 1, one finds a much better weight coefficient, in spite of a more ambitious cruise altitude (82,000 ft in place of 65,000ft) which would probably require a more sophisticated supercharger and heat-exchanger system.

Paper 3 is in the very opposite corner of the picture: it speaks of supersonic transport and Concorde is used as a reference throughout the lecture. A traffic survey, primarily on maritime airways requires a minimum range of 6,000 km (approx. 3,250 nm), for which Concorde is short-legged. The market survey for a supersonic transport with enough range seems optimistic but could well depend upon the World economics situation. A complete review of the main features (aeodynamics, structure, propulsion, temperature control, etc) and of the specific airworthiness requirements (sonic boom, NOx, noise in the airport areas, etc) is illustrated with the "Alliance" project. One may only regret that this paper was not presented, in a synthetic perspective, as a "struggle for range".

Paper 4 deals again with another corner: surface effect. Preliminary aerodynamic studies, information from Russia and flight experience on several aircraft converge: surface effect at high speed reduces drag and smoothes ride.
From these findings, the Author devises a variety of large military vehicles capable of a wide range of speed and altitude and even of being operated from the water. These vehicles could fly very long routes, partly at high altitude, partly in the surface effect. Curiously enough, no mention is made of the powerplant that could operate efficiently in all this range. In the same way, little was said on civil applications, which would probably raise problems of passenger transfer, weather comfort, traffic, etc.
Questions focused on manoeuvrability, change in configuration, efficiency, rough sea, etc.
Apparently much research and study remains to be done before any development could be launched.

Paper 5 was a last minute offer to replace a cancelled paper. It is an overview of a Symposium held in Strasbourg, France, on "the Future of Large Capacity Multipurpose Aircargo Fleets", with the participation of Eastern and Western Countries. It emphasizes the importance of long haul in the civil cargo traffic (5,000 km on average). It is also the opportunity to recall the impressive airlift operation of Desert Shield/ Desert Storm, a precious indication on future needs in airlift fleets.
A large array of super-airlifters was displayed.
As a complement, two films were presented: one about two very long range Russian airlifters and the other on the Airbus Super Transporter (AST), derived from a standard long range Airbus A300-600 with an enlarged fuselage diameter to carry oversized cargo.

Paper 6 deals with design and manufacture. Indeed, with composite structures, design and manufacture are tightly integrated as this paper will show. Composite is a way to save structural weight dramatically (15 to 20%) for the benefit of fuel load, if production is not too expensive. It is not the case for large complex parts, for which, until now, prepreg fiber tapes had to be laid by hand. A new process has succeeded in laying tapes on complex parts, automatically and along optimized orientations.

Compared production rates are very spectacular: 0.3 kg/h by hand vs 9 kg/h with this process.
The interest raised was reflected in the number of questions about the present limits of the process, which is still in development for improvement:
- does it apply to deformable parts or to vibrating parts ? the answer is yes;
- how is delamination taken into account ? by empirical formulas, since the phenomenon is still not well known; but, in other respects, buckling was already implemented.
This contribution of the SMP was very much appreciated.

Paper 7 is also an interesting contribution from another panel (FDP). Turbulent flow generates more drag than laminar flow; thence the interest to shift the transition as far downstream as possible. On a given airfoil, a theoretical analysis (with many formulae!) allows one to assess to what extent the natural laminar flow could be maintained. This is markedly confirmed by windtunnel tests and flight tests. However, for wing sweep angles higher than 30°, in order to extend the laminar flow as far downstream as possible, it is necessary to add a suction device, which needs a negligible amount of bleed air from the engines. In addition, the leading edge must be kept very clean and a decontamination (liquid oozing) device must be installed. A first estimate gives a 15% fuel saving for a fully equipped airplane. To conclude this very clear and methodic lecture, it was indicated that the prospect was promising enough to plan equipping a new corporate airplane.

Paper 8 is an interesting demonstration of an original use of airplane's flight characteristics. It could be summarized as endurance maximalization through "relaxed" (saw-toothed) altitude profile. The secret is to use the powerplant in its better efficiency part of the flight envelope (low speed) to gain altitude and then "sail" down at idle with flaps extended in optimal position. This very clever flight profile raises but one question: what for ? It is hard to imagine civil airplanes using such flight plans and still harder to see combat aircraft missions adapted to this profile, except perhaps for recovery in case of fuel shortage, though it was not indicated whether the range was also improved.

Paper 9 is the mere description of a helicopter, the 3 engined EH 101, where the Author put emphasis on its long range capabilities:
. possible flight on 2 engines only,
. all-weather equipment,
. ergonomy (low vibration level),
. air refuelling (yet to be flight tested).
For the time being, military customers are the Royal Navy and the Canadian Navy. It is worth mentioning that blades are foldable for carrier underdeck storage.

Paper 10 is another aircraft description. Still a paper project, Eurofar is a tilt rotor aircraft. The formula adds to the helicopter capabilities the extended range and speed of an airplane. Unlike helicopters, transition allows keeping the cabin floor level. A very vivid presentation followed by a lot of questions:
. rolling take-off ? yes, like helicopters ( 50 m),
. why are the engines not tilted ? for better ground margin, better IR cancellation in military operation and better turbine burst containment for civil airworthiness,
. autorotation ? less efficient than on an helicopter, due to the high disk loading and to the wing screen,
. noise in the cabin ? better than in some turboprop aircraft: the propellers are far enough from the fuselage and their cruise rpm is 20% less than at take off, thus avoiding any sonic effect at the blade tips.

### 5.3 Propulsion System Concern for Long Range and Long Endurance Operations

This session, prepared in cooperation with the PEP, has the same diversity as the previous one: two papers tell mainly of transport airplanes, the other two of HALE aircraft.

Paper 11 deals with civil transport aircraft (though it applies to other categories as well). In this domain, harsh competition leads to various airplane types being very close to each other, as far as performance and direct operating costs are concerned. Therefore, any design solution or detail adjustment that may result in an even small improvement in drag or in better ride comfort is valued, if the corresponding development and production cost is affordable. In addition, the CFD (Computational Fluid Dynamics) has reached such a quality in simulating airplane aerodynamics that it can now tackle the problem of airflow over large and complex parts (if not the whole) of a big airplane at the project level, allowing to adjust and compare various solutions before detailed design is launched and without time and cost expenses in windtunnel tests. Even if these goals were not much emphasized in the lecture, particularily for the purpose of range improvement, this is the target of the three examples which are very clearly presented in this paper.

It is more convenient to follow up with Paper 13, written in the same spirit, but from the engine manufacturer's point of view. The Author has elected not to speak about the optimal thermodynamic cycles and other theoretical ways to perform long range, but to tell of some aspects of the design know-how that allows these performance to be constant and reliable, showing at the same time some of the key points in the architecture of modern large turbofans and confirming that experience and common sense are still good arguments.
He explained what seems to be a contradiction, for these sophisticated engines, between a search for longer life cycles and shorter times between inspection. For the combat aircraft, he also pointed out how much the engine hot part life was depending on the high power setting time in a mission, rather than on range.
He ended up with some hints on the "special vehicles" (very high speed ones) for which cooling is a very challenging problem.

We now come back to two HALE papers. Paper 12 is a comprehensive overview of all the possible solutions to power such vehicles, for which altitude and loiter time are selection key parameters. For the time being, the turbocharged reciprocating engine is the most efficient, the performance of the turbocharger-heat exchanger system becoming determinant as altitude increases. But the Author leaves the choice open, depending on the mission.
As for fuel cells, they are very promising, but are prone to stay promising still for some time.

Paper 14 seems an application exercise of Paper 12. The powerplant described is intended for a high altitude research airplane (up to 24,000 m / 79,000 ft) where turbocharging is a challenging problem. The chosen concept is truly original, promising and probably not too expensive. The design is described with many details. Indeed one would have traded off some of them for hints on systems necessary on a manned aircraft: hydraulics, electricity and above all the air-conditioning system, with its probable adverse effects on the powerplant efficiency.
In answer to a question about pump cavitation, tests were conducted down to 30mb without any cavitation problem.

### 5.4 The Human Factors Side of the Problem

This session, fully prepared by the AMP, is very consistent. The four Authors seem to be accustomed to work together and produced papers quite complementary to one another. For many engineers in the floor, it was the first opportunity to hear of new matters they would have to take into consideration in the future, in the conception and design of manned aircraft.

Paper 15 reviews the various types of fatigue and describes the main causes of fatigue for the long range crew members, after a survey on transport airplane pilots. In the characteristics of the cockpit atmosphere, it is noteworthy that relative humidity is very low, lower than in many deserts. Heavy workload is a source of fatigue, but lack of workload (during long haul flights) may impair alertness. Night flight, ozone concentration, noise, mild hypoxia, etc were also examined, as well as jet lag, which creates difficulties for the crews to get asleep during layovers. Displayed charts raised some surprise and concern: among the sleeping aids, alcohol is by far the most used.
In the conclusions, not only does the Author recommend the flight planning staffs to take the various causes of fatigue into consideration, but he also advises the individual pilots to plan their rest times according to their own capabilities.

Paper 16 completes the preceeding one by a survey of the regulations of various airworthiness Authorities on flight time limitation with two pilots crews and augmented crews. In addition, an investigation was conducted on true airline flights, aiming East or West, with qualitative questionnaires to the pilots. The results are: fatigue is mainly influenced "by the duration of wake time since the last sleep" so that the flight time is not so determinant as is a combination of time "on duty" + night flight + jet lag + accumulation. Thence, conclusions are not very different from those of the previous paper: prevent excessive duty time and provide for adequate rest periods and sleep patterns. It points out the benefit of small naps.

Paper 17 derives its findings from another live experience: American airlift crews during the Gulf War. These crews worked in very poor conditions with inadequate, if any, resting or sleeping facilities. Due to the heavy transport needs, an experiment was conducted with several of them to see whether it was possible to extend the monthly flight time from 125h to 150h. The results were not those expected. First the investigators pointed out the very adverse conditions of comfort, both in the airplanes and on the ground. They confirm the benefit of naps and, above all, they concluded that the way pilots spent the recent days (duty, flight, rest, sleep,...) was more important than the cumulative flight time of the past month.

The paper suggests to use the DFDR (Digital Flight Data Recorder) to try to establish a correlation between pilot's log and abnormal behaviour (on an anonymous basis, of course). A way to answer the remark from the Author to introduce his lecture: when an aircraft crashes for structural failure, many investigations and researches are conducted; if it is for human failure, nothing is done.

Last of the session, Paper 18 describes the study of two main causes of fatigue: jet lag and sleep deprivation, through the use of a test battery which mesures psychomotric reactions. These tests have permitted to define a day pattern of better sleeping efficiency and confirmed the benefit of naps. But, still more important, it was used to assess the effects of various means to combat fatigue, with emphasis on drugs, specially one which seems to have no adverse side effects. However, its use is recommanded for urgent cases in exceptional military operations only and, by no means, by civil aircrews.

This remarkable session was concluded by an interesting round-table with the four Authors discussing on the following subject:

"Should the operations be adapted to crew capacities, or capacities adapted to operations ?"

Whenever it is possible the first part of the alternative is recommended. The Authors were unanimous to insist that use of drugs to adapt the crew capacities to operations should be strictly limited to urgent military cases. Ethics forbid using such means to make champions or robots.
From the floor, a question asked whether, in war time, a specific medication could facilitate the adaptation of combat pilots to the fighting environment. Apparently no study had been done on that subject and the Authors could give no answer.
For the civil aircrews at layovers, in addition to jet-lag, they are confronted with difficulties to sleep during local activity hours. Moreover, mainly among young crew members, layover time may be a bit heavy loaded. In these cases, soft methods are recommanded: education, a hygienic way of life, some physical activity and, if possible the days before flight, a progressive adaptation to the local time to come. Another question asked whether physical fitness would improve the capacities in the cockpit ? This problem is on the agenda of the working group, but it does not seem that the lack of physical fitness impairs these capacities (neither does smoking!).

### 5.5 Air-to-Air Refuelling

This session is the one which best fits with the original Pilot Paper. It is military and consistent by nature. Of the eight papers, only one does not deal with AAR, though its matter still concerns additional fuel (it replaces a cancelled paper on AAR).
Nothing new in the systems themselves, except for some details, but emphasis was on operation with recent conflict experience. With the Gulf War, NATO Countries became aware of some weaknesses in their refuelling capabilities (already slightly apparent at the Lisbon Symposium in May 1990 "Progress in Military Airlift") and of interoperability problems between the different Air Forces.

Paper 19 deals with the development of a dedicated external fuel tank (EFT) which extends considerably the range of the combat aircraft concerned, compared to the existing standard EFT. The paper gives an idea of the important flight test programme necessary to qualify the aircraft equipped with this new EFT, principally in combination with other external stores which can raise surprises, mainly in flight dynamics and flutter.

Paper 20 tells of the development of the flight refuelling of a new combat aircraft for the French Air Force. It makes obvious the differences that can occur in operation behind different tankers: behind a KC 135 equipped with BDA (Boom-Drogue Adapter), easy approach, touchy fuelling position holding; behind a Navy combat / tanker aircraft: tricky approach (basket whirling in the engine wake), easy holding. However the outstanding handling qualities of the aircraft facilitates the manoeuver. With the quick engine response to throttle movement, pilots prefer docking with throttle than with airbrakes.
The lecture was completed by a very good film which showed clearly the various phases of the manoeuvers from different sight points (receiver and side aircraft).

It is convenient to review both Papers 21 and 24 together. They were presented by the same cooperating teams and deal with tightly connected subjects.
The first Paper draws from the Gulf War experience to devise specifications for a future tanker and indications on the operation of a future tanker fleet (During "Desert Storm", more tankers would have been welcome!).
Emphasis was put on timing and interoperability which was seriously impaired in Desert Storm

by the lack of compatibility between the "Boom and Receptacle System" on the one side and the "Probe and Drogue system" on the other side, even if the BDA has slightly improved the situation. The development of multipoint tankers is recommanded to improve flexibility, interoperability and rapidity of operations.
The second paper gets into more details of the refuelling operations to compare both systems and see how they could be best used in coordination, assuming a multipoint tanker is developed. As regards this matter a review is made among the existing or future civil airplanes or military airlifters, derivatives of which could be the successors to the KC-135.
A question was raised about the compared safety and reliability of both systems. The answer (given by a boom user) is that the boom and receptacle system seems to have better ratings. It is probably the result of a longer and wider experience.
It is curious to notice that an assumption is made implicitly: a complete air superiority. It was true in the Gulf War, but in case it were not, it would probabiy need changing operation strategy ( scattering or concentrating ?) and in any case it would still more favor the fastest refuelling solution.

The Author of Paper 22, a member of the US Navy, is on the hose-drogue side. The Navy has the only aircraft type capable of both means of refuelling in the same flight (though not at the same time): the KC-10. The paper starts with a review of the various airplanes used for refuelling by the US Navy and Marine Corps and recalls the improvements brought to both systems: BDA (Boom Drogue Adapter), wing pods, lengthened hose, variable geometry drogue (to adjust drag to the refuelling speed, for instance for helicopter purpose). But the main subject of the paper deals with flight dynamics related to the wing pods. The airflow behind the wing pod, where the receiver is flying, is asymmetrical and conditions could be critical for the latter. So, before launching a multipoint tanker programme, a detailed flight investigation was decided, the results of which are displayed in very clear diagrams in the paper.
A good review of the state of the art.

Paper 23 presents a very methodic and logical process to define a future tanker fleet:
- review of mission needs,
- survey of candidate airplanes,
- functional requirements,
- measures of effectiveness, including secondary mission capabilities,
- fleet size and life cycle cost evaluation.

For every candidate airplane, an assessment is conducted of the necessary enhancements, to be injected in the life cycle cost process.
The paper ends with an interesting review of technology requirements, where, for the first time in this symposium, one learns of a tentative enhanced automatization of air refuelling:
- automatic rendez-vous,
- automatic hook-up,
- higher transfer rates, etc.

Paper 25 tells how the Royal Netherlands Air Force selected two DC-10 as tankers. Those aircraft would have a peace time duty: to reduce noise around air bases in Netherlands, the fighter aircraft have to practice over the North Sea and therefore have to be air refuelled. Among the requirements, the candidates should be used aircraft, proven tankers and capable of being used as airlifters, the whole at least cost. The modification definition was that of existing KC-10, except for the rear operator's station, found too expensive because of the structural modifications; it would be replaced by a palletized "Remote Air Refuelling Operator" station, in front of the cabin, with video control. This solution is claimed as being already used on a B-707, but one may wonder whether its development, for two DC-10 airplanes only, would not cost more than the standard version.
Many questions were raised, among which:
- accuracy of remote 3D viewing ? claimed as precise as direct view,
- night operation ? was already experienced (elsewhere), so there is good confidence; if necessary, provision is made for IR lighting,
- are two KC-10 not too much an AR capacity for the RNLAF ? agreements were already taken with other NATO Nations; moreover, so many other missions have already been planned that the Author wonders whether time will be left for the refuelling missions !!!

In the last Paper 26, the Author describes the rather different solution elected by the Royal Canadian Air Force. Five C-130 H from the airlift fleet are being converted for air refuelling capability. They are fitted with two wing pods (hose drogue system). The cabin conversion from tanker to airlifter configuration takes 4 h. The main tanker task is to refuel two types of combat aircraft, and this is the challenge, because of the compared flight envelopes. Flight tests already conducted have defined the refuelling flight envelopes, which are not very large, specially with one of the fighters. Once again, the stability of the drogue basket is found a problem.
Further flight tests are being conducted.

## CONCLUSIONS

Comparing the proposed list of topics, given in the Pilot Paper, with the agenda of the Symposium, one finds that a large part of the aims was reached and even that, with the contribution of the civil transport and scientific communities, the scope was still extended.
In the airframe and powerplant sessions, the contribution of civil transport design reached its target with matters which could be easily extended to military aircraft.
However one can regret that the "Influence of aircraft stores on range" was not dealt with.
Nor were, in the Propulsion session, the important "Multiple design point" and the "Fuel choice".
In the other sessions, the subjects were very much influenced by the present World situation or by recent events.
The interesting and coherent session on "Human factors", drew a lot of experience from the Gulf War.
This event was also of great concern for all Air Forces which were engaged in the conflict, because of the need to extend the range of combat, airlift and tanker fleets which had not been planned for that purpose. It was reflected in the subjects: all were mainly concerned with reinforcement of tanker fleets or definition of their future requirements. But, frustratingly enough, nothing was said about foreseen technical improvements in refuelling, save for one or two lines in a chart.
The appearance of Unmanned Air Vehicles, for military and civil uses, explains why several papers were devoted to HALE (High Altitude Long Endurance) projects, with one or two non conventional solutions.
Finally this Symposium was somewhat more interesting than the agenda could suggest. It is a pity that attendance was somewhat low, but the same phenomenon appeared rather consistently in many other international meetings in that period, which seems to be a consequence of the present dull economic situation.

## RECOMMENDATIONS

Among its large scope of interest, the Panel will probably not devote another symposium to "Long Range and Long Endurance" for some time. Though it is a very important feature for all types of airplanes, the means to deal with it are rather different from one category of aircraft to another. In addition, it is difficult to treat this topic independently from other features like speed, altitude, etc. It would perhaps be more advisable to include this matter in symposia dedicated to specific categories of aircraft, like, in the past, "Progress in Military Airlift" (May 1990) or "Improvement of Combat Performance of Existing and Future Aircraft" (April 1986).
As for new systems and techniques like automatic rendez-vous or automatic hooking, they could well be dealt with in one of the frequent symposia on flight tests.
From a wider point of view, it could happen that the Panel organizes a symposium on the impact of the changes in the World situation on the characteristics and operation of aircraft in the NATO Air Forces. This would be an opportunity to assess the importance of long range for both combat aircraft and airlifters.

# ANNEX TO THE T. E. R.

------------

## SUMMARY OF PILOT PAPER N° 195

----------

*A Pilot Paper is an internal working document of the Flight Mechanics Panel, through which any Member of the Panel may make a proposal for a future activity of the Panel (symposium, lectures series, printed matter, etc). The paper is studied in committee, amended if necessary and, if considered appropriate by the Panel at its Business Meeting, is accepted as part of its activity programme. Due to its internal nature, it is not relevant to publish this Pilot Paper in full, but an extract with the salient features is given below.*

Over the past years, long range and long endurance have proved to be very useful in operations. In the same time, technologies which improve these features have developed.

For these reasons, it was found timely to summarize the various aspects of these performance areas, which are different, according to the aircraft types. The contribution of other Panels was highly recommended.

The resulting suggested programme was as follows:

- Session 1.- Airframe Design for Long Range and Endurance.
  - optimization of airframe configuration for higher cruise efficiency,
  - structural techniques to increase the payload weight fraction of aircraft,
  - the weight savings provided by non-conventional (ie "not aluminum") airframe structures,
  - techniques to improve the boundary layer 'character' on airframes in the cruise configuration,
  - advances in the design and carriage of aircraft stores.

- Session 2.- Propulsion System Optimization.
  - techniques to more efficiently integrate propulsion systems in the airframe,
  - advances in technologies which directly improve engine efficiency (ie materials that withstand higher temperatures, etc),
  - the tradeoff between pure performance requirements and cruise efficiencies (the multiple design point problem),
  - considerations of problems caused by longer flight times (ie cooling, lubrication, etc),
  - fuel choices to enhance range and endurance and the associated tradeoffs.

- Session 3.- The Human Factors Side of the Problem.
  - the aircrew performance implications of extended operation times,
  - airframe design features which limit the aircrew performance degradation,
  - cockpit and cockpit systems design with aircrew fatigue in mind.

- Session 4.- Air-to-Air Refuelling.
  - design studies of aircraft for modification to enable air-to-air refuelling,
  - the tradeoffs between air-to-air refuelling (controlled pod versus drogue and boom),
  - the technique of receiver-tanker rendezvous and tanker protection,
  - design of airframes as tanker aircraft,
  - other techniques to increase vehicle effective range (ie forward staging bases).

------------------

# KEYNOTE ADDRESS 1

## OPERATIONAL REQUIREMENTS

by

**Major-General W. Breeschoten**
Director of Operations, RNLAF
135 Binckhorstlaan
2516 BA The Hague
The Netherlands

Ladies and Gentlemen, when I looked at the subject of this symposium: 'Recent advantages in long range and endurance operation of aircraft", and noticed the issues of the associated sessions: "Air frame design, propulsion concerns, human factors and air-to-air refuelling"', I considered it appropriate to discuss with you the source of all these subjects: the operational requirements. I therefore decided to talk about the requirements I, as an operator, would have, if somebody asked me what a future fighter aircraft should look like, in view of the new roles we have to fulfill in NATO. I will not restrict myself to those requirements directly related to long range and endurance, but I will also mention some requirements which may impact the foreseen solutions for the long range and endurance problems.
The end of the cold war means for us in Europe the end of the preparations for a war of which a large number of factors were assumed to be known. The threat and the allies were well-known and called for only one scenario. The military strategy and doctrine therefore hardly ever changed and hence plans and requirements were more or less stable. And maybe the most important of all, the military budgets were secure and allowed for regular, qualitative improvements of aircraft and weaponry meaning a growing defense budget. Those really were enjoyable times for military planners in Western Europe. Their plans indicated that the airwar would be fought over own, familiar terrain, which for most NATO-countries was close to own territory. Many diversion fields were available in case the home base could not be reached anymore.

Aircrew training was virtually unrestricted and could take place right over the expected combat area. Targets were well-known and hardly ever changed. Aircraft and helicopters were designedconcentrated on manoeuvrability, payload and survivability. Those were enjoyable days for aircraft designers. Lucky enough we were never forced to execute the operational plans.

Today we face a totally different situation. The old and familiar threat suddenly has disappeared and its place has been taken by a bundle of unknowns. Unknown new threats and new scenarios asking for unknown new strategies, doctrines, requirements, training methods and aircraft design. With the end of the cold war one thing immediately became clear: the chances that the next air war would have to be fought in and over the familiar nato territory became unlikely. Although the outbreak of a major conflict still has to be taken into account, the focus of our political leaders is aimed at participation in multinational peace-keeping and peace-enforcing operations in support of resolutions of the united nations.

For the European NATO countries this means out-of-area operations with a limited number of forces. Of course there will always be a requirement for a so called main defense force, but it is difficult to calculate the required quantity in forces when the scenario's are unpredictable. Especially in our democratic systems, political issues that require reprioritisation of financial resources in the short term are more important than a long term insurance against worst case scenario's. Giving a lower priority to defense budgets in favor of other financial requirements is in the current situation fully understandable. If this is a wise decision can only be proven in the future when we are history.

*Presented at an AGARD Meeting on 'Recent Advances in Long Range and Long Endurance Operation of Aircraft', May 1993.*

According to current national plans the number of fighter aircraft in the central region will for instance be reduced with about 50%.

At the same time the political will to support peace keeping and peace enforcing operations all over the world has increased. The result of this shift in the use of military power at large distances from their home base and in difficult to predict scenario's, requires an increased flexibility. The Gulf conflict, cambodia, and Bosnia-Hercegovina are just some of the places where the Royal Netherlands Air Force participated in operations. This indicates that the geographical area, in which our air force may have to operate, has expanded quite drastically since the cold war. This means that also our Air Force has to prepare itself for out-of-area operations. Contingency plans have to deal with the performance of swift deployments and have to have sufficient flexibility for the necessary adjustments for the specific area of operations.

As future conflict areas are unknown, future threats are also unknown. The strict division of western aircraft and air defense systems on one side confronting eastern systems on the other side no longer have to be true. It is more likely that future opponents will possess a mix of western and eastern weapon systems. It even is possible that during conflicts operations have to be flown against an adversary with the same weapon system. It is therefore uncertain what level of sophistication the weapon systems of the adversary will be. This level can range from poor to highly sophisticated.

Operations with fighter aircraft are likely to be conducted from airbases located at a significant distance from the operations area. These airbases may differ considerably from the home airbases with regard to runway length, available arresting gear, danger of fod. It is very likely, that (due to the lack of airbases in the theater) airbases will have to accommodate a larger than usual number of aircraft.

Like in the Gulf it may take months before hostilities break out. After arrival, flying operations will then consist of air policing operations along and/or across the border. The theater commander therefore will initially require mainly fighter aircraft to fulfil this role. However, once hostilities break out, more and more fighterbomber aircraft will be required and the role of fighters will mainly consist of escorting fighterbomber aircraft to the target area, or even better, will be able to switch roles from defensive to offensive operations. In another scenario it mat just be the other way around.

Peace keeping and peace enforcing operations are conducted right under the eyes of the media (and therefore the public). This implies that collateral damage and losses to civilians have to be kept to a minimum. Chances of fratricide have to be kept to a minimum as well. All participating aircraft should be well protected against air defense systems.
In air combat a positive identification will dictate the range at which air-to-air missiles can be deployed. Visual identification may be required in all cases like in the current situation over Bosnia-Hercegovina. But BVR identification capabilities should be available and improved. For air-to-ground operations we need the capability to provide accurate target information. Fighterbomber aircraft will have to hit targets with sufficient accuracy. This will reduce the number of sorties required to destroy a selected target and at the same time will reduce collateral damage. Real-time transfer of targetdata from platforms like AWACS, ELINT, JSTARS and space based systems to fighters and fighterbombers is possible right now. Last month the USAF fired the first anti-radiation missile from a F-16, using target information gathered by a stand-off platform and transferred in flight to the F-16. This means that the requirement to have sophisticated on-board sensors in all aircraft that have to deliver ordnance, in the future, can be

reduced.
Certain basic own capabilities will be required, but the more expensive systems, or systems that take a lot of space or cause large weight penalties can be put in systems like AWACS or JSTARS or even space based systems. Of course the problem then arises that one becomes dependend on the organisation that controls these off-board sensors. From a military point of view that strengthens the requirement to maintain NATO, because, apart from the USAF, only within NATO all these resources will be available and hopefully interoperable.

Our F-16 will have a true multi-role capability after the mid life update program has been completed. The disadvantage of the current generation aircraft is their range and endurance capability and their radar cross section. This is caused by their basic design and the fact that ordnance, fuel and, in some cases like our F-16, active ECM have to be carrried on outboard stations. Another problem is the vulnerability for guns at altitudes below 10000 feet.
This vulnerability is reduced considerably when operations at low altitude can be performed at night. Of course there are weapon systems in the current inventories that can do these things, but they are available in small numbers only and especially designed to operate in a certain specified role.
An example is the F-117 of the USAF.
The range and endurance restrictions of the current generation of airplanes is partly solved by the capability to refuel in the air. The problem, however, is the required nr of tankers when an operation of a somewhat larger scale has to be executed and the vulnerability of these assets. The operations in the Gulf have shown that the number of tankers required versus the number available very often restricted the operational planners.
Since the development of new aircraft becomes more and more expensive, while the number of aircraft required decreases, it makes more sense to concentrate in the future on the development of a true multi-role aircraft. Not just an aircraft which can perform well in one role and is capable of conducting other roles. No, an aircraft which is capable to achieve well in the air-to-air, air-to-ground and reconnaissance roles.
The discussion about the further development of the YF-22, the AX and in the future the MRF or just forget the YF-22 and the AX and concentrate on MRF for both USAF and NAVY also points in this direction.

A multirole aircraft should be relatively cheap, have enough endurance and inherent aerodynamic capabilities to fulfil the air defence role. This would mean an internal fuel capacity to stay on station for about 4 to 5 hours. Of course, this would give also more range for the offensive role. The radar cross section should be kept to a minimum, which means internal carriage of armament, internal ECM and external fuel tanks only to deploy over very long distances. Due to the increased accuracy with which conventional weapons can be delivered, a reduction of the number of weapons that internally can be carried is acceptable. Although an external carriage capability to increase the number of weapons carried should be available in certain scenario's where radar cross section is not a player anymore.

To prevent FOD when operating from less than optimum airbases particular constraints are placed on the position of the engine intakes or we have to install systems to prevent FOD like the Russians do. To assure short stopping distances the installation of a dragchute may be required. Because airbases in the operation theatre are probably congested with aircraft, maintenance and repair facilities will be limited. Aircraft systems should have extensive self-test and system monitoring capabilities to limit the Apart from airframe design, vectored thrust will play an important part acquiring these capabilities.

Experiences in the F-22 program show very positive effects of two dimensional thrust vectoring.

Modern means of communication and data gathering wil increase the amount of antennas on the airframe. Antennas for various datalinks, global positioning system, active missile warning receivers and interogators will be added to the already existing antennas. Some systems will require multiple antennas to achieve a good coverage. This inevitably will cause drag penalties. The development of antennas that can be blended in with the aircraft skin are therefore also important.

The question single versus two men crew is the next question to be answered. With the developments in avionics and advanced computer programs that will help the pilot in his decision process tremendously, a single seat will be capable to perform the majority of tasks and therefore, according to me, will be acceptable and more affordable for those countries that will have to replace their F-16's in the future. However, for more complex tasks (like for instance laser designation at night) the possibility should exist to accomplish these tasks from two seat aircraft. An important factor here is that extra room needed for the second seat should have no impact on fuel quantity and hence range, but should be found by other means (by for instance a reduction of the amount of internal carried weapons).

The choice between a single and a two engine version is another subject for debate. Ideally speaking it should be possible to develop a multi role fighter in a single engine and a two engine version. In that case each country could select the type which would fit its requirements. I immediately admit, that this is easier said than done. The amount of engines required is a major factor in aircraft design and the question can be raised how much commonality in the design would be achieved and, if therefore, a multi version design appraoch would prove to be beneficial.

The single engine version will be cheaper but will have a slightly higher peace time attrition. For the smaller air forces this most probably will be acceptable.
Also an air force that needs large quantities, like the USAF, may go for the single engine version. The US Navy most probably will require the two engine version. All this requires a modular approach and a lot of common sense of all participating parties.

I must admit that these requirements for a theoretical fighter aircraft are a very simple approach to a very complex problem since i left out variables like interests of national industries maintaining enough flexibility in the industrial base the risks involved in too many eggs in one basket etc. But maybe the economic realities will drive us into the direction of more commonality within nato and force us to use economies of scale more and more.
Until we have an airplane with enough inherent range and endurance, the requirement for air refueling capability will continue to exist.
I think there will always be a requirement for airrefueling, only the number of tankers required may be reduced due to future developments. The capacity in Europe, however, is limited. The RNLAF has bought two DC-10 airplanes that will be converted to tankers with a boom system next year. They will be the only two tankers in Europe that can refuel for instance F-16 aircraft of which there will be more than 600 in the European inventories the coming decades.

During this symposium I understand you will discuss the technologies that will make improvements in the future possible.

Ladies and Gentlemen. I just covered some of the operational requirements for a theoretical new multirole aircraft. I realize that my contribution to this symposium did not solve any of the range and endurance problems, on the contrary, I just added a few.

I wish you a fruitful and pleasant symposium and I hope you will have a chance to enjoy your visit to the Netherlands.

# KEYNOTE ADDRESS 2

# VOYAGER MILESTONE: NON-REFUELED FLIGHT AROUND THE WORLD THE DESIGN APPROACH

by

**Burt Rutan**
President
Scaled Composites
Hangar 78 — Airport
Mojave
California 93501
United States

The Voyager aircraft, which now hangs in the National Air and Space Museum, was designed to accomplish a feat that many aerospace people thought was out of reach. This brief article outlines the design philosophy showing how that feat was accomplished.

With the singular goal in mind of global non-refueled flight, I initially planned to design the Voyager for a range well in excess of that required. This may seem to have been an impossibility, since the world distance record, held for over 20 years by the B-52H bomber was only one-half the earth's circumference. I ruled out trying to modify any existing design or to use any existing aircraft components. More than anything I had done before, this would be a very special aircraft, with a specific design point-optimizing range with no other generic compromises.

The basic parameters I used for the design task were the following:

- Ability to just barely takeoff from the world's longest airport, the 3-mile runway at nearby Edwards Air Force Base, California.
- Two crew (Dick Rutan and Jeana Yeager) to allow crew to sleep and share duties. A total weight of 350 pounds would include their food and water for the entire trip.
- Absolutely minimum cabin size to maximise the range of the aircraft. Crew comfort was not considered to be a major issue. They would only have to do the flight once!
- Two engines, to allow staging of power during the flight. The cruise power during the last stages of the flight with nearly all the fuel gone would be less than 15% of that needed for the heavy weight takeoff. Engines are not efficient at these low power settings, so by shutting off the larger of two engines several days into the flight, the important last day would have the remaining engine running with at least 35% rated power for an acceptable efficiency.
- The engines and propellers would be "off-the-shelf" standard units with a long history of reliability so there would be no new developments which might add risk and cost.
- Only the bare minimum of equipment was to be installed. Any non-essential weight would shorten range.
- The structure would have to be extremely light and still be buildable by our small team.
- Risks would be taken. For example, there would be no protection from a possible lightning strike which could destroy the structure.

The Breguet range equation which defines the maximum range of any airplane is a simple calculation using several assumed constants regarding the efficiency of the engine and propeller, the efficiency of the aerodynamic configuration of the airplane, and the portion of the takeoff weight that is fuel. Specifically:

$$\text{Range} = K\left[\frac{\text{P.E.}}{\text{SFC}} \times \frac{L}{D} \times \text{Ln}\left(\frac{\text{TOW}}{\text{LW}}\right)\right]$$

Where:

Range = statute miles
P.E. is propeller efficiency = thrust horsepower per engine horsepower
SFC is engine efficiency, specific fuel consumption — lb/HP • hr
$\frac{L}{D}$ is airplane aerodynamic efficiency: lift-to-drag ratio
TOW is takeoff weight = landing weight + fuel weight
LW is landing weight
K is a constant = 375 to normalize the units.

Let's now dissect this equation to discover how I was able to achieve over twice the range of any previous record aircraft. First, by my ground rule of using existing reliable aircraft engines and propellers, I planned no significant improvements on the first term.

For the airplane efficiency, I would use a slender wing with extremely long span to distribute the weight lightly and evenly to achieve minimum aerodynamic drag due to lift. The wing and fuselage would be carefully shaped to optimize their contours to minimize aerodynamic drag due to skin friction and local air pressures. The result would be an airplane efficiency (L/D) of between 32 and 40, depending on how precise the wing shape could be maintained, to achieve laminar flow. Extensive laminar flow over wings is rare, since even slight imperfections or insect strikes cluttering the leading edges will trip the flow to the turbulent condition, greatly increasing drag.

The L/D of normal light planes ranges between 9 and about 17, with the slickest airliners around 20 to 24. However, I was to set no records here, since high performance sailplanes (devoid of engine installations and other drag-producing protuberances) are able to achieve L/D values over 50.

The last term of the Breguet range equation is where the Voyager was to be significantly better than any airplane previously built. My initial goal was to achieve a fuel weight of 80% of the takeoff weight, a very ambitious goal, especially for an airplane with long slender wings. Long wings mean high bending loads requiring heavy wing spars for adequate strength and stiffness. The 80% fuel fraction would guarantee adequate range even if laminar flow were not achieved.

My initial design attempts were to lay out a slender fuel-filled flying wing to distribute all the fuel weight along the span. This did not work because the proper size wing did not have enough volume to hold the fuel. Clearly, most of the fuel would have to be external to the wing. Placing the fuel in an enlarged fuselage would significantly increase the wing structural weight. The slender, long wing was too weak and flexible to support the large mass concentrated at the center.

The solution was obvious. I would have to distribute the "external" fuel spanwise along the wing. A slender wing is very weak and flexible in bending and extremely flexible for twisting loads. It was clear that, to support large fuel masses along the span, the slender wing would have to have some help. The breakthrough was my unusual configuration of the Voyager. Two wings, the canard in front and the long wing at the back, support the fuel-laden "booms" with their relative bending stiffness. The fuel was adequately supported without depending alone on the torsional stiffness of a single slender wing.

The key to the remarkable range of the Voyager lies in the ability to build the structure extremely light, and to not burden the airplane with unnecessary weight. The structure would weigh only 9% of the takeoff weight of the airplane. One pound of weight saved on the structure would allow the airplane to carry an additional pound of fuel without compromising its takeoff performance. That pound of fuel would carry the Voyager as much as eight miles. On the other hand, one pound of fuel added to the takeoff weight would carry the airplane only two miles and would reduce the takeoff performance.

To achieve an extremely light structure, the Voyager was fabricated with graphite epoxy materials. The wing spars were laminated in hand-made steel molds and cured under pressure at the Hercules autoclave in Salt Lake City. The rest of the airplane was built right in our small shop by hand laminating the pre-impregnated graphite fibers in a sandwich form (two thin, hard skins separated by a lightweight Nomex honeycomb material). After lamination, this sandwich material was compressed with a vacuum bag and cured at 250°F using a home-made oven. This resulted in an extremely stiff, light structural configuration. Nearly all the Voyager components (wing skins, ribs, fuselage skins, bulkheads) were fabricated in this way.

During 1983 and 1984, when the Voyager was built at my small shop, the program was a secret. It was not supported by volunteers as it was during its flight preparation. The majority of the fabrication of the airplane was done by three people, Bruce Evans (who had built an all-composite homebuilt aircraft) and the crew, Dick Rutan and Jeana Yeager.

When the airplane initially flew, it was not equipped with the specific engines required for world flight, nor with any of the expensive navigational gear which would be required for world flight. It was initially flown "bare bones" in order to carefully measure its capability so that I could, based on actual flight test data, specify the world flight powerplant configuration. Before the aircraft flew, I had thought the takeoff gross weight would be more than 11,000 pounds and the engine sizes would be 180 horsepower on the front and 125 horsepower on the rear. This would provide good margins on the range performance required for world flight. However, during flight tests it was determined that the structural flexibility of the airplane was a more serious problem than had been anticipated. As we flew the aircraft with more and more fuel, serious problems were seen with the turbulence response and with the stability characteristics of the airplane. Above 9,000 pounds gross weight appeared to be extremely risky. This was a serious problem which threatened the success of the program.

The solution lay not in stiffening the structure nor in changing the airframe, but in breaking an original ground rule of using only fully developed engines. Teledyne Continental Motors was developing a new water-cooled aircraft engine which would have as much as 7% better specific fuel consumption than standard aircraft engines could achieve. While 7% does not seem like a large margin, it was clear that if that margin could be achieved, the airplane could be flown around the world with considerably less fuel, thus eliminating the need to takeoff at more than about 9,500 pounds.

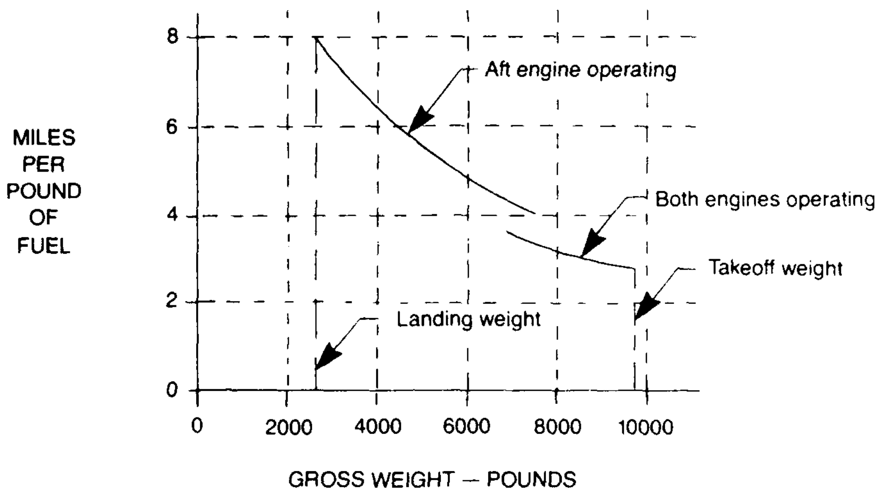
The new 9,500 pound takeoff weight goal allowed me to use a 140 horsepower engine in the nose and the efficient water-cooled 110 horsepower engine in the tail. Thus reconfigured, flight test data and calculations of the efficiency of the new engines showed that world flight capability still existed with the lower weight configuration.

As the program entered its second phase and was turned over to Dick and Jeana for world flight capability development, it was clear that the challenges to develop new aircraft systems were considerably more significant than under the original ground rules. The first-ever flight of the new water-cooled engines occurred on the experimental Voyager aircraft. Uncertificated propellers were also selected and resulted in some hazardous tests because they failed during evaluation. Re-equipped with a more standard propeller configuration, but with new propeller blade contours designed by John Ronez, my consultant who also designed the airfoils for the Voyager wings, the aircraft was ready for the world flight in December 1986.

The graph below summarizes the measured overall efficiency of the Voyager aircraft. These flight test data overcome the deficiencies of the Breguet equation, in that the "constants" which in reality are variables, are all measured together for a true range prediction. For example, engine and propeller efficiency vary with altitude and speed. Also, the best speed for optimum L/D is not always flown due to winds. The area under this curve is range, in miles. At world flight takeoff, at a gross weight of 9,700 pounds, the Voyager carried 73% of its weight in fuel, well down from my original goal of 80%.

A nine day flight, fraught with every conceivable contingency of weather, turbulence, tail winds and head winds tends to be a great averager. The performance of the Voyager actually turned out to be within one percent of its prediction. The additional aerodynamic drag, which was experienced because the wing tips were damaged scraping on the runway during takeoff and the loss of approximately 100 pounds of fuel through a leaky fuel cap, reduced the range to a point where only 1.5% of the takeoff fuel remained (18 gallons) when the aircraft landed at Edwards Air Force Base.

In 1981, when we were planning the program, we had no idea of the extent of its difficulty and risks. An interesting question to ask is: "If we had come up short, would we have had the courage to try again?"




VOYAGER EFFICIENCY

# HIGH ALTITUDE LONG ENDURANCE AIRCRAFT DESIGN STUDIES

by

**V.B. Venkayya and V.A. Tischler**
Wright Laboratory
Wright-Patterson Air Force Base
OH 45433-7552
United States

## ABSTRACT

This paper presents the results of structural optimization studies made on a High Altitude Long Endurance (HALE) aircraft at Wright Research and Development Center (now Wright Laboratory) during the late eighties. The purpose of this study is to investigate the feasibility of developing a ultralightweight airframe that can operate at high altitudes for extended periods of time in order to provide continuous reconnaissance, surveillance, communications and targeting functions. A variety of structural concepts and material studies were made prior to settling on a twin boom very high aspect ratio wing airframe. The wing and fuselage structures are made of truss substructures covered with skins, both made of high strength, high modulus, lightweight composite materials. Extensive structural optimization studies were conducted in order to obtain a lightweight structure. The large size of the aircraft drove the design to a stiffness critical structure.

## INTRODUCTION:

During the late eighties and early nineties a number of government agencies and industries made preliminary design studies on unmanned aircraft for operation at very high altitudes for an extended period of time as an inexpensive means for continuous reconnaissance, communications and targeting functions. The Wright Laboratory (WL), then called the Wright Research and Development Center (WRDC), conducted a preliminary design study on a version of HALE (High Altitude Long Endurance Aircraft) during 1988 and 1989. The WRDC team was made up of engineers from aerodynamics, structures, materials, controls, landing gear and propulsion.

At present satellites and manned aircraft are the primary means for high altitude reconnaissance and surveillance. However, these systems can only provide continuous coverage for a few hours at a time. In contrast unmanned high altitude long endurance aircraft can provide continuous coverage for long periods (several days) of time. Recent advances in sensor resolution, propulsion systems, advanced structural concepts, materials, controls technology and modern avionics can provide a high degree of reliability for the autonomous flight of the unmanned aircraft. Some of the key requirements of a HALE aircraft are high aerodynamic efficiency, minimum weight (both structural and nonstructural components), minimum power for maximum endurance, robust controls and a variety of advanced subsystems. An adequate wing surface and an efficient airfoil configuration are essential for low subsonic flight at high altitudes. The low air density and slow speed may not provide adequate lift or control power to stabilize the aircraft. In addition, the airspeed must be sufficient to overcome high altitude winds. Lightweight structures are necessary in order to maximize the mission payload. A variety of high stiffness/high strength and lightweight composite materials are available for HALE applications. However, they need to be tested for environmental stability at high altitudes. The severity of the ozone environment at high altitudes may be detrimental to organic composites. In addition, the application of modern optimization methods in structural design can significantly enhance structural, aerodynamic and control efficiencies while minimizing the weight. They in turn can reduce the power requirements. A variety of propulsion systems such as turbocharged engines, chemical fuels (hydrogen), solar power, beamed microwave energy and nuclear isotope power must be considered in order to obtain a high degree of propulsion efficiency.

*Presented at an AGARD Meeting on 'Recent Advances in Long Range and Long Endurance Operation of Aircraft', May 1993.*

emphasis on its long range capabilities:
. possible flight on 2 engines only,
. all-weather equipment,
. ergonomy (low vibration level),

goals were not much emphasized in the lecture, particularly for the purpose of range improvement, this is the target of the three examples which are very clearly presented in this paper.



Environmental conditions such as wind, hail and icing play an important role in the safe operation of HALE aircraft. The total payload must include the needed redundancy for weather related extension of the mission.

The primary mission of the HALE aircraft is reconnaissance and surveillance. The military mission is for the detection and tracking of low observable targets including aircraft surveillance for the protection of air and ground forces and the Navy fleet. The civilian mission may include search and rescue, drug interdiction, ocean mission fisheries patrol, mapping, atmospheric sampling, etc. The payload and mission profile of the aircraft were derived from the Air Defense Initiative (ADI). Two ADI radar antenna sizes were considered for the HALE application. The smaller antenna is 50 ft long and 7 ft high, while the larger one is 70 ft long and 16 ft high. Total budgeted weight of the two antennas are 4125 lbs and 14400 lbs respectively. The mission profile for the HALE aircraft is shown in Fig. 1 (Ref. 1). The HALE structural design optimization, which is the main focus of this paper, is based on high strength, high modulus composite materials. Details of the structural design study were documented in references 1-3.

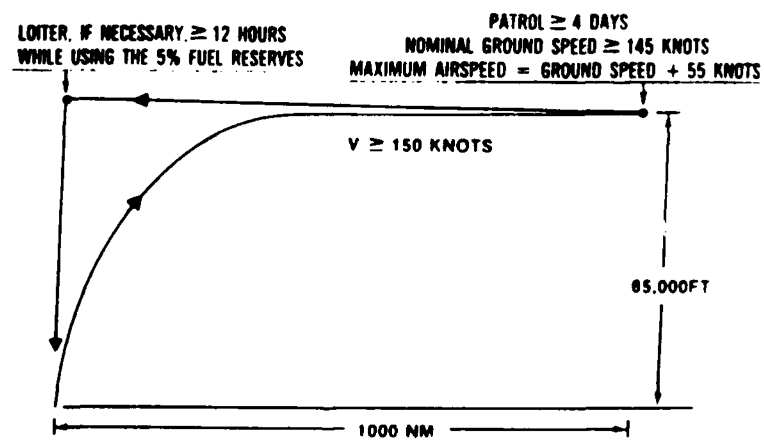
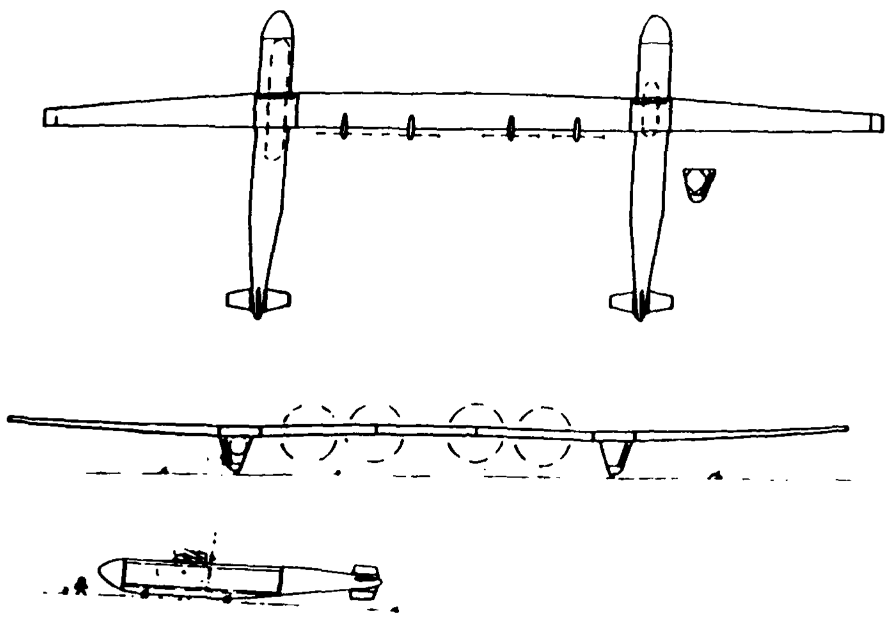



Fig. 1 HALE ADI nominal mission profile

## HALE AIRCRAFT CONFIGURATION

A twin fuselage configuration was selected for this study, and it is shown in Fig. 2. A number of performance and economic advantages were cited for the twin fuselage vehicle over the conventional single fuselage concept: (1) sharply reduced aircraft/payload interference, (2) reduction in wing weight due to the load (bending moment) alleviation between the fuselage segments, (3) reduction in overall landing gear weight etc. The rotating propellers, in particular, reflect signals to the antenna and cause interference. The antennas on the outboard side of the two fuselages could significantly reduce the interference problem due to reflection from the propellers as well as from the wing.



Wing Span = 270 ft

Aspect Ratio = 30

TOGW    H-8a 18000 lbs.  H-8B 25000 lbs

Fig. 2  HALE H-8B point design

However, one of the major drawbacks of a twin fuselage plane with a connection only at the wing (no connection at the tail) is that the demand on the flight control system would be severe in order to maintain the fuselages alignment with control twist only. The wing twist control is important to maintain the "optimum" lift distribution along the wing span. However, it is much easier to control the wing-angle-of attack variation along the span in a twin-fuselage configuration. Fig. 3 shows the bending moment variation along the wing span for a twin fuselage and a single fuselage configuration. By appropriate selection of the spacing of the two fuselages the severity of the wing bending can be reduced by as much as 50%. The reduction in wing bending moment allows for a lighter wing structure. However, any increase in fuselage weight will be more than offset by a reduction in wing and landing gear weights. Another advantage of the twin-fuselage configuration is the increased volume available for payload which mainly consists of radar antennas and fuel. The fuel in this case is likely a hydrogen fuel.

Basically two aircraft configurations were considered in this study. Both were twin fuselage aircraft as shown in Fig. 2. The two fuselages were connected only along the wing. The power plant consisted of four engines in push propeller configuration mounted on the center wing. The two configurations, called H-8A and H-8B, differ only in the total takeoff weight and the number of days of endurance. The H-8A is the lighter of the two (18000 lbs versus 25000 lbs takeoff weight). Correspondingly the H-8B is intended for a six day mission compared to a four day mission for the H-8A. The fuel requirements are about 50% for the H-8A compared to the H-8B. There is little difference in the structural arrangement of these two configurations. A patrol altitude of 65000 ft and a true airspeed of 200 knots were considered to be an optimum combination for mission utility, endurance and radar performance.

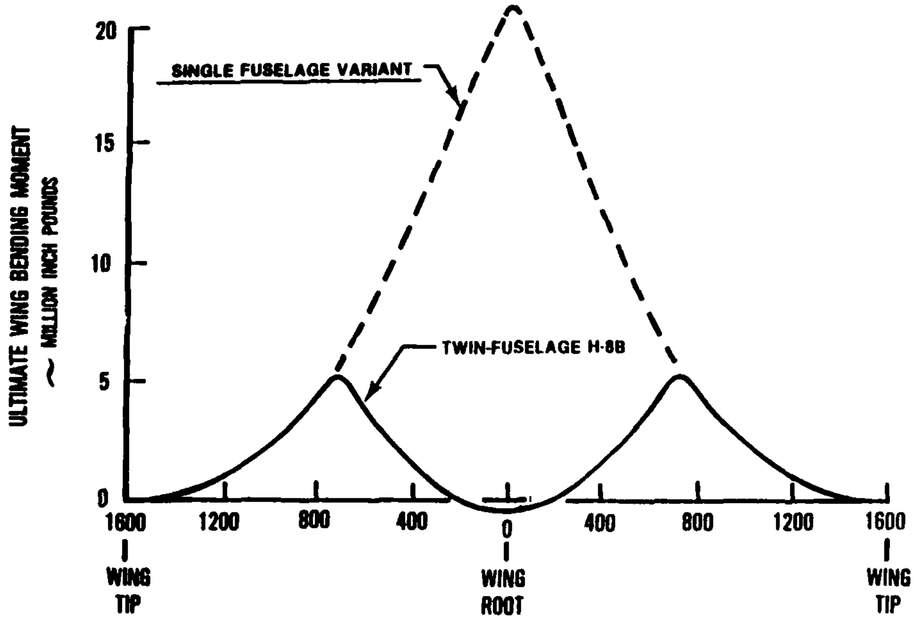



Fig 3. HALE ultimate wing bending moment comparison

The physical dimensions of the two HALE aircraft are summarized in Table 1.

Table 1. The Physical Dimensions of the Two HALE Aircraft

| Aircraft | H-8A | H-8B |
|---|---|---|
| Payload | 18000 lbs | 25000 lbs |
| Endurance | 4 days | 6 d s |
| Wing Span | 270 ft | 270 ft |
| Wing Aspect Ratio | 30 | 30 |
| Air Patrol Altitude | 65000 ft | 65000 ft |
| True Airspeed | 200 knots | 200 knots |
| Fuel Wt | 3500 lbs | 7400 lbs |
| Fuel | Hydrogen or JP4 | Hydrogen or JP4 |
| Material | T50 (T40) | T50 (T40 |

## WING AND FUSELAGE INTERNAL STRUCTURE

Lightweight and adequate stiffness are the two important considerations in the design of a HALE aircraft structure. The wing design is primarily governed by wing deflection, twist and aeroelastic stability. Antenna performance is very sensitive to fuselage deflections. In essence both the wing and the fuselage designs are stiffness and weight driven. It is obvious that lightweight graphite composite materials offer the best opportunity for high performance at reasonable cost. New composite materials exhibit high strength, high modulus and the fatigue resistance necessary in HALE applications. A bonded graphite epoxy structure is the prime candidate in this HALE design. However, thermoplastics are seriously considered, even though they are more expensive. Nevertheless, they may offer a better advantage when all the cost drivers such as manufactureability, repairability and toughness considerations are considered. Material properties used in this study for T50 (baseline) and T40 graphite epoxy systems are shown in Table 2.

Table 2. Materials Properties

| | T-50 | T-40 |
|---|---|---|
| Longitudinal Tension | | |
| Strength (10**3 psi) | 105.5 | 235.0 |
| Modulus (10**6 psi) | 35.0 | 25.0 |
| Poisson's Ratio | .28 | .33 |
| Longitudinal Compression | | |
| Strength (10**3 psi) | 70.0 | 125.0 |
| Modulus (10**6 psi) | 35.0 | 25.0 |
| Transverse Tension and Compression | | |
| Strength (10**3 psi) | 2.6 | 5.0 |
| Modulus (10**6 psi) | 1.06 | 1.50 |
| Inplane Shear | | |
| Strength (10**3 psi) | 4.6 | 7.0 |
| Initial Modulus (10**6 psi) | .84 | 1.0 |

Notes:
-- Strengths are 50% of dry, room temperature values for graphite/epoxy.
-- T-50 and T-40 are fiber designations.
-- Properties based on Union Carbide ERL-1962 resin and 62% fiber by volume.

The preferred structural concept for this HALE study is a graphite composite truss substructure covered with a layered composite skin of the same material. The wing structural concept is shown in Fig. 4. It is a multispar and multirib structure made of graphite composite tubes, with wing skins made of a 0°, 90°, ±45° (quasi-isotropic to start) layup. The spar caps and rib caps are acting as both the truss members and the wing skin panel boundaries. The entire wing box was constructed of bonded graphite epoxy (or peak/thermoplastic) components. The rib and spar caps were 1.0" channels (inside dimension). The vertical diagonal members were 1" square tubes (outside dimension). The tubes would be inserted into the channels and bonded to the inside of the channel walls at the joints. The baseline leading and trailing edges utilize prepeg Kevlar cloth and graphite epoxy skins and a Nomex honeycomb core. The leading edge uses sandwich skin, and the trailing edge uses a full depth honeycomb.

The stiff substructure breaks the wing skin into a number of panels semirigidly supported at all four sides. The spacing of the spar and rib trusses is governed by the wing skin thickness failure in a panel buckling mode. If the trusses are spaced too far apart, the skin needs a honeycomb core support in order to stabilize the panels.

• STRUCTURAL ARRANGEMENT

• TRUSS STRUCTURE - SKIN COVER - WING

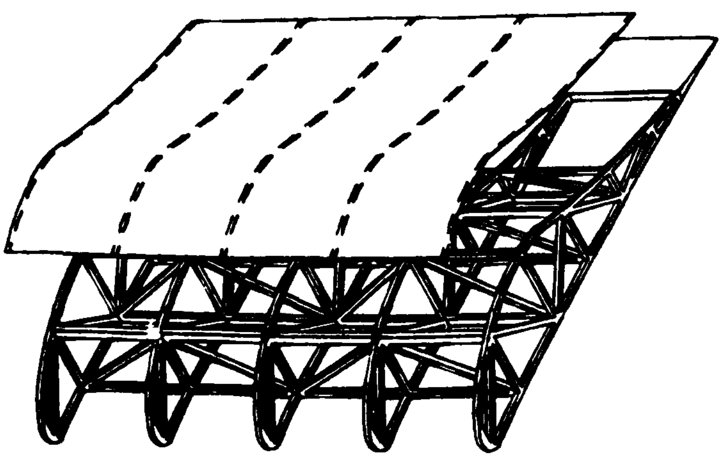


Fig. 4 Wing internal structure

In addition, the pressure load on the wing skin can deform it sufficiently to alter the airfoil shape and the airflow over the wing. The choice of the wing skin layup as well as the spacing of the trusses are airfoil and configuration dependent. The wing twist control and panel stabilization considerations may dictate a larger percentage of ±45°. A rib spacing of 2.0 ft was selected in order to prevent the spar caps from buckling as columns.

A thin (0.002 in) Tedlar coating of the composite structure is recommended as a protection against ozone, ultraviolet radiation and moisture. Minimum gage thickness for the wing skin is specified at 0.021", the honeycomb face sheet at 0.0105 in and 0.1 sq.in. for the tube and channel cross-sectional areas.

The fuselage structure is also a graphite composite structure covered with the same skin as the wing. The cross-section of the fuselage, Fig. 5, shows the truss skin arrangement. The fuselage is very lightly loaded during all phases of the mission, and it was established that a minimum gage structure is adequate. In order to establish the adequacy of the construction, extensive testing at the coupon, component and full scale level is necessary. In addition a local buckling analysis of the panels and columns is necessary. Buckling considerations may add additional material at selected locations.

# • STRUCTURAL ARRANGEMENT

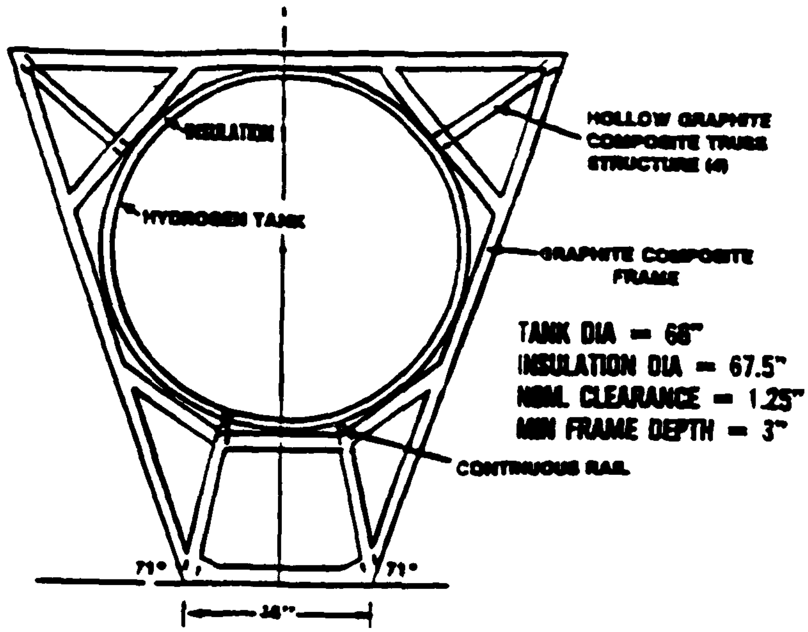



Fig. 5 HALE H-8B fuselage cross-section

An estimated weight summary of the H-8B aircraft is given in Table 3.

Table 3. H-8B Weight Summary

| | weight lb. | | wing station in. | |
|---|---|---|---|---|
| Structure | 5900 | | 707 | |
| Wing | | 3400 | | 720 |
| H-tail | | 180 | | 731 |
| V-tail | | 90 | | 731 |
| Fuselage | | 1830 | | 722 |
| Landing Gear | | 200 | | 720 |
| Nacelles | | 200 | | 318 |
| Propulsion | 6055 | | 646 | |
| Motors | | 144 | | 319 |
| Gear Boxes | | 197 | | 319 |
| Propellers | | 461 | | 319 |
| Fuel Tanks | | 1204 | | 720 |
| Compressors | | 121 | | 720 |
| Scrubbers | | 312 | | 720 |
| Accessories | | 607 | | 720 |
| Stacks | | 1238 | | 720 |
| Inverters | | 253 | | 319 |
| Radiators | | 911 | | 695 |
| Heat Exchangers | | 607 | | 720 |
| Equipment | 1375 | | 528 | |
| Avionics - fwd | | 250 | | 720 |
| - aft | | 100 | | 720 |
| Electrical - wing | | 719 | | 353 |
| - fuse | | 156 | | 720 |
| Actuators - fwd | | 50 | | 720 |
| - aft | | 100 | | 720 |
| Fuel | 7400 | | 720 | |
| Payload | 4270 | | 761 | |
| Radar | | 2700 | | 762 |
| IFF | | 70 | | 762 |
| Communications | | 100 | | 762 |
| IRST | | 400 | | 750 |
| Antenna Support | | 1000 | | 762 |
| TOGW | 25000 | | 695 | |

High lift and low drag coefficients are critical for high altitude, low subsonic and long endurance flight. The LC111A airfoil was considered the most appropriate candidate to satisfy the requirements. It is a thick airfoil which can easily accommodate the high bay composite lightweight structure. Comprehensive aerodynamic and wind tunnel test results are also available for the LC111A airfoil. See Fig. 6.

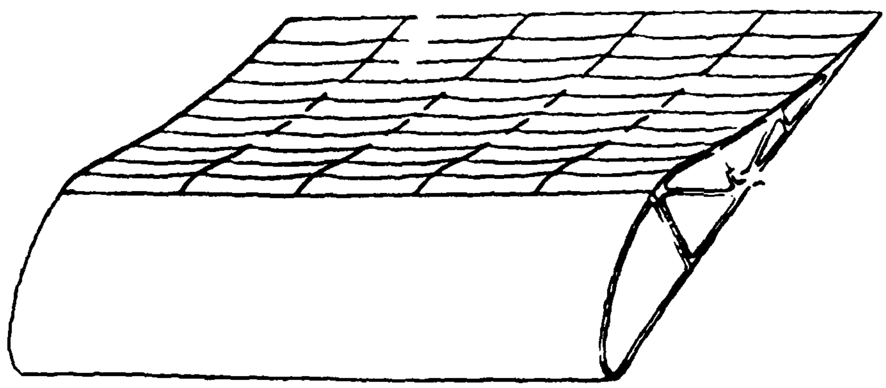


Fig 6. Airfoil section

## HALE AIRCRAFT LOADS

The aircraft is designed for effective static loads, and the loads analysis was performed on the wing and fuselage separately. The loading conditions are summarized in Table 4. (Ref. 2).

Table 4. Loading Conditions Summary

| LOADING CONDITION | DESCRIPTION |
|---|---|
| 1 | Ultimate Positive Lift - full fuel |
| 2 | Ultimate Positive Lift - half fuel |
| 3 | Ultimate Positive Lift - empty fuel |
| 4 | Ultimate Negative Lift - full fuel |
| 5 | Load 1 + Differential Tail Loads (+ve on one tail and -ve on the other) |
| 6 | Load 4 + Differential Tail Loads, but opposite to Load 5 |

The ultimate load factors were calculated as follows:

$$Cl_{nom} = W / ((q_{max}) \times (S))$$

$$LLF = (uaf) \times (Cl_{max} / Cl_{nom})$$

$$ULF = (n) \times (LLF)$$

where

$Cl_{nom}$ = nominal lift coefficient (level flight)

$Cl_{max}$ = maximum lift coefficient (stall condition)

W = aircraft weight

n = factor of safety (1.25 for up and away flight)

$q_{max}$ = maximum dynamic pressure

uaf = unsteady aerodynamics factor (1.25)

S = wing planform area

LLF = limit load factor

ULF = ultimate load factor

An unsteady aerodynamics factor was used to account for the instantaneous higher-than-stall lift. An elliptical spanwise pressure distribution was assumed. The chordwise lift distribution was interpolated from wind tunnel pressure data from the L1003M airfoil at the stall angle-of-attack (14°). Actual test data matched the theoretically predicted distribution at -10°. A theoretical distribution and an actual test data showing a stalled condition were available at -15°. Some typical pressure distributions are shown in Fig. 7.

The inertia loads for the flight condition were calculated using the mass distribution shown in Table 3. The fuselage bending moment diagram is shown in Fig. 8.

A number of auxiliary computer programs were written to transfer the aerodynamic and inertia loads data to the structural grid points. One of these integrates the wing pressure data and assigns the load to structural grid points. The other program transforms the shear-moment-torque diagrams to equivalent gridpoint loads. The third program is for the computation of equivalent EI and GJ properties (beam properties) of the composite wing and fuselage components for use in the control system sizing. It first computes the line of the elastic axis (connecting shear centers) with a complete finite element analysis of the wing box with a plate-rod elements model, and then determines the EI and GJ properties. This program needs further testing and validation.

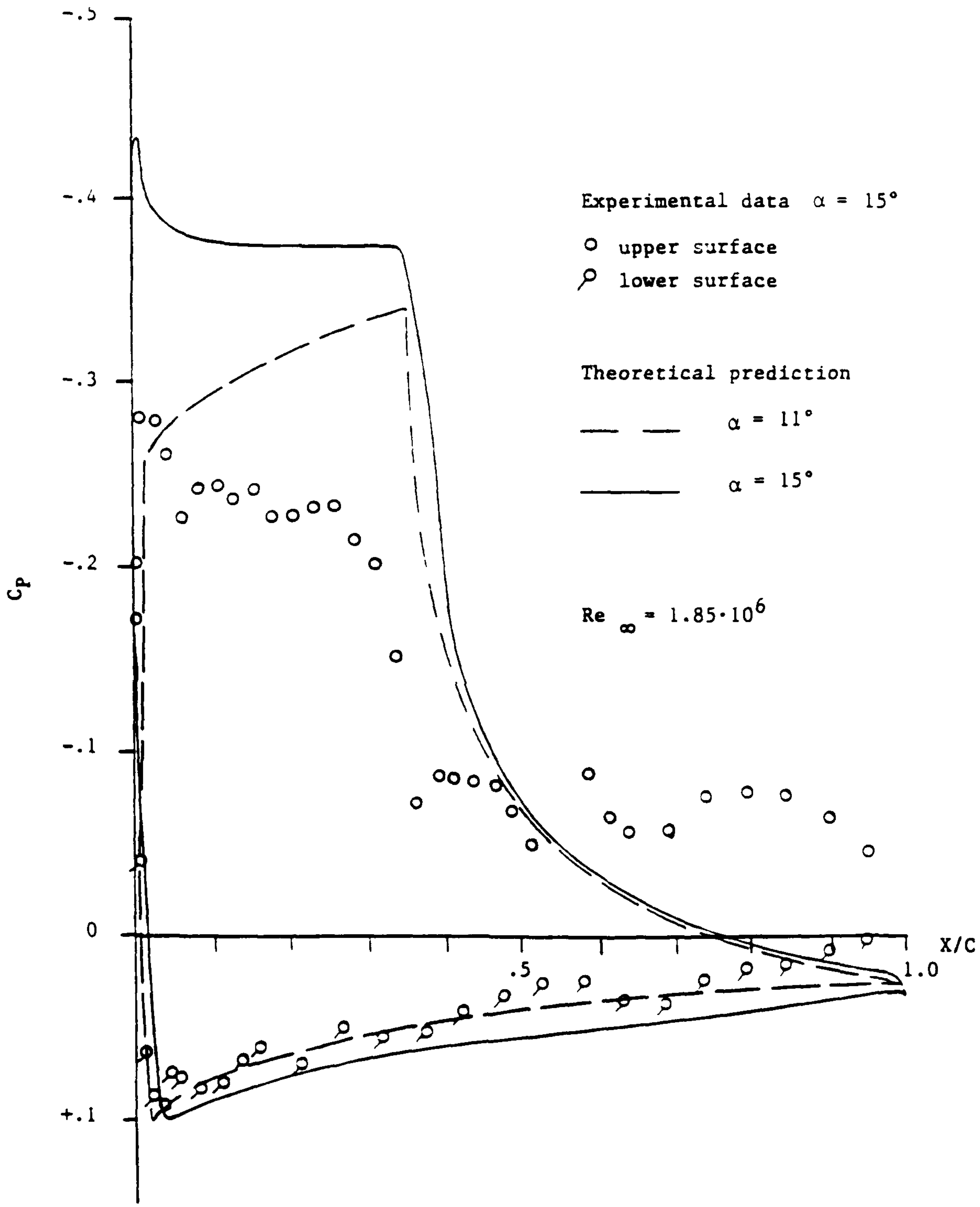



**Figure 7. Airfoil chordwise pressure distribution**

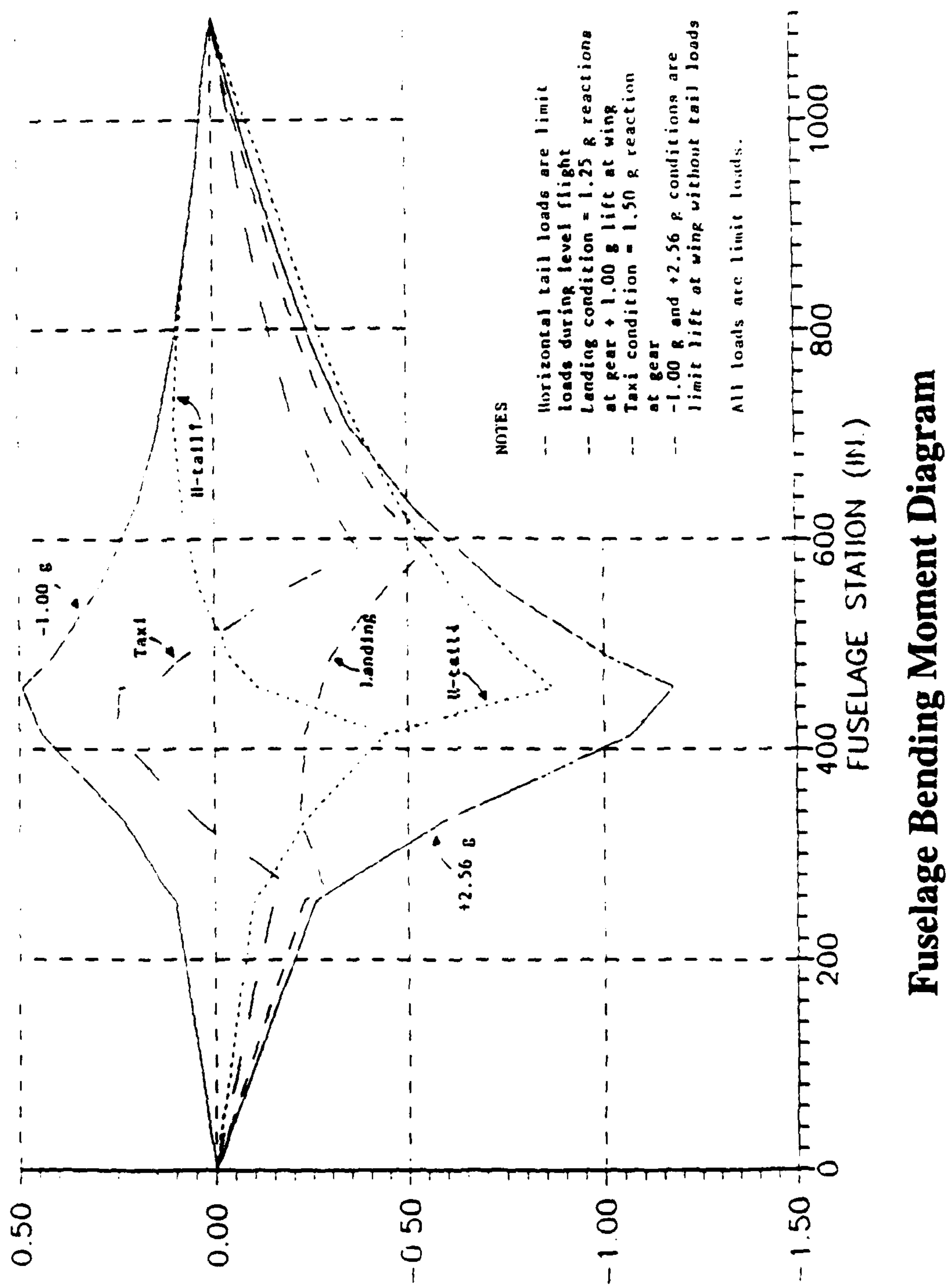



**Figure 8** **Fuselage bending moment diagram**

## STRUCTURAL ANALYSIS AND OPTIMIZATION

The primary analysis and optimization program used in this study is called OPTSTAT (Ref. 4). It is an in-house structural optimization program based on an optimality criterion. It is intended only for the design of structures subjected to static loads. The structural element resizing algorithm in OPTSTAT is based on (Ref. 4).

$$A^{\upsilon+1} = A^{\upsilon} \left[ \sum_{j=1}^{p} C_j \, e_{ij}^{\upsilon} \right]^{1/2}$$

where

$A^{\upsilon+1}$ - Design variable vector in the $(\upsilon + 1)$ cycle.

$A^{\upsilon}$ - Design variable vector in the previous cycle.

$C_j$ - Weighting parameters approximated from the Lagrangian multipliers.

$e_{ij}$ - Strain energy density function in the $i^{th}$ element corresponding to the $j^{th}$ design condition.

$\Sigma$ - The summation is on the number of design conditions.

The design variables are the sizes of the structural elements.

The same resizing formula (with some modification) is used to determine both the overall thickness of the element, and the percentage of fibers corresponding to each direction in the elements. The advantage of this simple but approximate resizing formula is that it allows OPTSTAT to complete the design very rapidly, even in the presence of thousands of variables. In most cases it does not take more than five or six cycles. The program supports only triangular and quadrilateral membrane elements (for wing skins), the shear panel for spars and ribs, and rods for the spar caps, rib caps and posts.

## RESULTS OF THE HALE STUDY

Numerous wing optimization studies were conducted in connection with this HALE design study. They included many trade studies with different composite materials. The results of the most promising study is included in this paper. The structural weight summary and the wing tip displacements corresponding to the first four loading conditions are given in Table 5.

Table 5. HALE Study Results

# H-7 - H-8 WING COMPARISON [ 0,90,+45 ]$_s$

min. size = .021

T-50 (50 % ALLOWABLE STRENGTHS) ply thickness = .002625

WEIGHT

| ITERATION | TOTAL WEIGHT | | SKIN WEIGHT | | ROD WEIGHT | |
|---|---|---|---|---|---|---|
| 1 | 3266. | 2489. | 2628. | 1999. | 638. | 490. |
| 2 | 964. | 886. | 504. | 433. | 460. | 453. |
| 3 | 603. | 538. | 343. | 279. | 260. | 259. |
| 4 | 639. | 728. | 336. | 364. | 303. | 364. |
| 5 | 679. | 643. | 349. | 334. | 330. | 309. |
| 6 | 678. | 599. | 353. | 287. | 325. | 312. |

Z - DISPLACEMENT

| NODE | LC#1 | | LC#2 | | LC#3 | | LC#4** | |
|---|---|---|---|---|---|---|---|---|
| 1 | 165.2 | 95.2 | 176.3 | 96.5 | 182.0 | 94.0 | -43.0 | -60.9 |
| 3 | 165.2 | 95.3 | 176.9 | 96.6 | 183.2 | 94.1 | -43.3 | -60.7 |
| 5 | 165.2 | 95.4 | 177.3 | 96.7 | 184.0 | 94.2 | -43.5 | -60.6 |
| 7 | 165.2 | 95.5 | 177.6 | 96.7 | 184.7 | 94.2 | -43.7 | -60.5 |
| 9 | 165.2 | 95.6 | 178.2 | 96.8 | 186.0 | 94.3 | -43.9 | -60.4 |
| 11 | 165.2 | 95.8 | 179.2 | 97.0 | 188.3 | 94.5 | -44.5 | -60.1 |
| | FULL TANKS | | HALF TANKS | | EMPTY TANKS | | FULL TANKS | |

The baseline structural concept was a six spar configuration with the spars at 10, 21, 28.5, 35, 47.5 and 70% locations, and they are shown in Fig. 9.

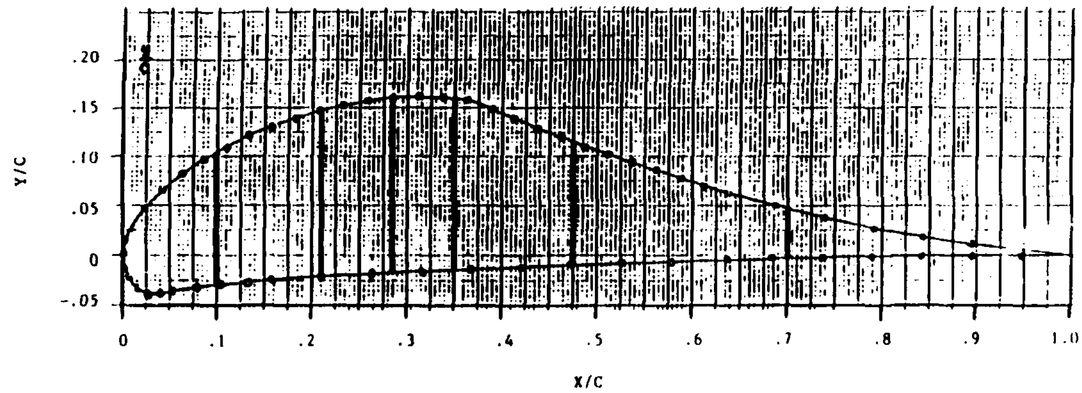



Fig. 9 Liebeck laminar rooftop

The six spar configuration was selected to assure against panel buckling and to maintain the airfoil shape under pressure load in the absence of honeycomb core support for the wing skins. Nevertheless, some of the strength optimized skin panels were buckling critical. An increase in the number of $\pm 45°$ layers solved the skin buckling problem. Table 6 contains the results of a number of design optimization studies (Ref. 2). This design study indicated that much of the HALE structure is governed by minimum sizes indicating that the structure stiffness is critical and not the strength. Table 6 also contains trade studies involving 3 and 6 spar wings, T40 versus T50 materials etc.

## SUMMARY AND CONCLUSIONS

This HALE study establishes the feasibility of designing ultralightweight structures for long endurance. The designs are primarily stiffness critical as opposed to strength. The vehicles are very lightly loaded and tend to be dominated by minimum gages for the structural elements. The advantage of structural optimization is that the final designs are relatively insensitive to changes in structural concepts. This is particularly true where the structure is governed predominantly by minimum sizes.

This HALE delineated the basic elements of the aircraft preliminary design process in a modern computer aided design environment. The modern structural optimization tools promote effective communication between the engineers on various subsystems. They enhance trade studies involving new materials and structural concepts. They can significantly reduce the cost and product development time while expanding the performance bounds.

interference. The antennas on the outboard side of the two fuselages could significantly reduce the interference problem due to reflection from the propellers as well as from the wing.



Table 6. HALE Wing Trade Study Results

| | | | weight (lb) | maximum vertical tip deflection (in) | maximum twist angle (degrees) |
|---|---|---|---|---|---|
| 6.1 | H-8A | (T-50) | 758 | +116/-115 | -0.6 |
| | H-8B | | 839 | +86/-54 | -1.5 |
| 6.2 | T-40 | (H-8B) | 767 | +248/-157 | -1.3 |
| | T-50 | | 839 | +86/-54 | -1.5 |
| 6.3 | Single | (T-40) | 981 | +279/-184 | -2.1 |
| | Twin | | 767 | +248/-157 | -1.3 |
| 6.4 | Single | (T-50) | 1340 | +135/-89 | -1.4 |
| | Twin | | 839 | +86/-54 | -1.5 |
| 6.5 | 1.0 | (T-50) | 839 | | |
| | 2.0 | | 1282 | | |
| | .54 | | 670 | | |
| 6.6 | 6-spar | (T-50) | 839 | +86/-54 | -1.5 |
| | 3-spar | | 583 (+128) | +112/-64 | -3.2 |
| 6.7 | [0,90, ±45] | (3-spar) | 583 (+266) | +112/-64 | -3.2 |
| | [±45] | | 944 | +100/-58 | +.4 |

Note:
- Maximum deflection and twist are due to ultimate load.
- Maximum twist angle is recorded for symmetric load cases only and is measured relative to aircraft centerline.
- Positive deflection is up and positive twist is pitch up.
- All trades performed on twin fuselage, 6-spar concept with [+45, 0, -45, 90]s skins unless otherwise noted.
- All weights shown are semi-span wingbox optimum weights. Weights do not include honeycomb, adhesive, coating, leading edge, trailing edge, or additional structure required for

attaching fuselages, propulsion system, etc., except the weights in () in 6.6 and 6.7 which are included for comparison purposes.

## REFERENCES


1. C. Patterson, "Unmanned High Altitude Long-Endurance Aircraft," AIAA/AHS/ASEE Aircraft Design, Systems and Operations Conference, AIAA 89-2011, Seattle WA, July 31 - August 2, 1989.

2. P. M. Flick and Maj. R. L. Hinrichsen, "Structural Design of a High Altitude Long Endurance Aircraft," WRDC-TM-90-333-FIBCC, October 1990.

3. P. M. Flick, "Composite Wing Box Optimization Using Design Variable Linking," WRDC-TM-90-334-FIBCC, October 1990.

4. V. B. Venkayya and V. A. Tischler, "OPTSTAT - A Computer Program for the Optimal Design of Structures Subjected to Static Loads," TM-FBR-79-67, June 1979.

# TECHNOLOGICAL CHALLENGES OF HIGH ALTITUDE LONG ENDURANCE UNMANNED CONFIGURATIONS

R. Bargetto, R. Spezzaferro

Preliminary Design Department
Alenia Aeronautica
Corso Marche 41
10146 Torino, Italy

## 1. Summary

This paper presents the conceptual work performed in Alenia during the recent years for defining some possible configurations for military and civil HALE (High Altitude Long Endurance) aircraft capable of carrying very different kinds of payloads and with mission durations ranging from one to two days.
Also in relation to the aircrew fatigue implied by such a long flight time, they all have been conceived as UMA (UnManned Aircraft), achieving in that way a significant reduction of mass and complexity, withstanding the maturity of automatic control system.
The aeromechanical aspect of the configurations (i.e aerodynamics, propulsion, structures, systems, weights and performances) will be discussed in detail considering that HALE-UMA type of aircraft have to face some technical challenges in many fields generated by the rather demanding requirements in terms of payload and endurance.

## 2. Introduction

In recent years the interest for some quite innovative civil roles has considerably grown all over the world. This fact is due to the increased concern that is spread all around the industrialized world for earth resources, high atmosphere sampling and environmental problems monitoring that is promoted in particular by some organizations in order not to destroy biological equilibrium of the world.
On the other hand from the military point of view the necessity has emerged of efficiently performing peacetime long range surveillance and intelligence gathering in risk areas.
These missions up to now have been only performed by special versions of already existing large and expensive military aircraft that are not particularly suited to these new tasks.
As it will be evident from the following paragraphs both these role categories can be efficiently performed by aircraft capable of very long duration missions at outstandingly high altitudes.
In those conditions the presence of the crew on board implies heavy penalties to the configuration in terms of weight and basic system complexity.
Moreover it must be also highlighted that for manned HALE aircraft the long mission duration determines heavy consequences on aircrew fatigue thus requiring frequent crew turnaround with the associated costs.

## 3. Possible HALE-UMA requirements

At the beginning of 1990 ALENIA decided to explore this new area, trying to identify the basic requirements for such new types of aircraft, looking at all possible applications for both civil and military roles.
Before describing in some detail the conceptual studies performed it is better to have a brief survey of the tasks they have to cope with, and the suitability of HALE-UMA to perform them with high effectiveness in comparison with more conventional aircraft and in a cooperative scenario with satellite based system.

### 3.1 Civil tasks

Civil versions can have a wide spectrum of applications ranging from earth monitoring, support to emergencies and many others by assuring a service that can be exploited only at much greater costs with satellites or that cannot be effectively accomplished at all with any other existing means.

#### 3.1.1 Earth monitoring

In this role HALE-UMA aircraft can be considered first of all as a valid alternative to satellites that have been used for this kind of applications for many years since they can cover some specific needs in a more efficient way.
In fact, beside the better resolution achievable with aircraft in comparison with satellites due to the much lower flight altitude it is also important to stress that an airplane can be vectored in whatever zone is needed to survey in short time and it can perform the monitoring continuously for a period of one or two days if this is required.
During this time a continuous data link with control station on ground is maintained or acquired informations are stored on board for eventual processing.
On the other hand satellites are bound to predetermined position in space or can perform only periodical passages over the zone to monitor with a forced time lag between two consecutive observations.
In any case these kinds of aircraft and the already existing satellites can also be used together to enhance the effectiveness of the whole system.
The sensors already used in satellites, their spatial resolution and the time lag between two successive observation are summarized in table 3.1.1-1, while a possible use of a HALE-UMA aircraft teaming with satellites for this kind of applications is sketched in figure 3.1.1-1.

*Presented at an AGARD Meeting on 'Recent Advances in Long Range and Long Endurance Operation of Aircraft', May 1993.*

| SENSOR | SATELLITE | TIME INTERVAL | SPATIAL RESOLUTION |
|---|---|---|---|
| Imaging radiometer | Meteosat GOES GMS | 30 mins | 1 - 7 Km |
| AVHRR | NOAA 10 - 12 | 12 h | 1 - 7 Km |
| MSS | Landsat 5 - 6 | 16 days | 60 - 80 m |
| TM | Landsat 5 - 6 | 16 days | 30 m |
| HRV | SPOT | 12 h , 3 days | 10 - 30 m |
| SAR | ERS-1 JERS-1 | 3 days , 35 days | 30 m |

Table 3.1.1-1

| DISASTERS | INTERESTED AREA [$Km^2$] | SPATIAL RESOLUTION [m] | TEMPORAL RESOLUTION [min] |
|---|---|---|---|
| Floods | $10^3$ - $10^5$ | < 10 | 15 |
| Avalanches | $10^2$ - $10^3$ | 10 - 100 | 60 |
| Earthquakes | $10^2$ - $10^4$ | < 10 | 1 - 10 |
| Seaquake | $10^4$ | 10 | 1 - 10 |
| Volcano belch | $10^3$ - $10^4$ | < 10 | 30 |
| Woody fires | $10^2$ - $10^3$ | 10 | 15 |
| Sea/lake pollution | $10^3$ - $10^6$ | 10 - 100 | 30 - 60 |
| Air pollution | $10^3$ | 100 | 15 |

Table 3.1.2-1

**3.1.2 Support to emergencies**

In this role HALE-UMA aircraft may first of all be used to monitor areas hit by natural disasters.

In fact in case of such disasters it is vital for the people tasked of the assistance organization to have the most detailed situation awareness in the least time and to know precisely how the situation does evolve, in order to take the most suited action.

The usual natural calamities, the extension of areas involved and the required resolution in terms of space and time are summarized in table 3.1.2-1.

In this case we have to note that the time in which the situation evolves is in any case longer than 24 hour, thus imposing an heavy requirement in terms of patrol time.

In the case of performing this task with piloted aircraft huge cost implications for their acquisition and operation are to be taken into account.

It is important to stress that such task clearly cannot be performed by satellites considering their peculiar characteristics and in particular their inherent limitations in terms of time lag between observations that have been already described above.

**3.1.3 Other tasks**

An HALE-UMA can find applications in response to other needs nowadays being increasingly felt by the social communities all over the world.

The widespread attention to the levels of atmosphere pollution and to the ozone depletion has been enhanced by the awareness of the damages due to the today air transportation system and, in perspective, to be expected from the future supersonic transport presently under study.

Shifting to another problem area the devastations caused by drug diffusion have stimulated the perception of the need for a tighter control of such cultures and traffic.

The peculiar features of an HALE-UMA in terms of outstanding values of patrol time and altitude and the high resolution achievable using a SAR (Synthetic Aperture Radar) make this aircraft perfectly suited for some scientific applications like high atmosphere sampling and ozone measurement.

Furthermore, its difficult detectability from the ground and all weather capability enable it to stealthily monitor forbidden trades or some other illegal activities.

The latter of these roles is already being exploited by some models of existing aircraft but the high sensor resolution, long patrol time and payload weight capability of especially designed HALE-UMA aircraft can significantly enhance the efficiency of patrolling. On the other hand the former ones are up to now performed by balloons equipped by up to 1600 Kg of scientific apparatus but this sort of flying machines suffer from the fact that their track is almost completely driven by the atmospheric winds without any means of guidance.

**3.2 Military roles**

Military versions of HALE-UMA aircraft may be dedicated primarily to long range aerial surveillance, ballistic missiles launch detection and intelligence gathering.

A typical scenario in which such airplanes may operate is depicted in figure 3.2-1.

For almost all these military roles the extremely high patrol altitude, and the use of sensors with long range detection capability allow this type of aircraft to fly over friendly territory thus reducing in that way the probability of being exposed to hostile fire and consequently enhancing the effectiveness of the system; in any case the peculiar characteristic of being unmanned eliminates human hazard during real war operations.

**3.2.1 Long range surveillance**

HALE-UMA aircraft for long range aerial surveillance can be considered as a really low cost version of AWACS aircraft since they can carry a sophisticated high performance radar and have an extremely high loiter time in the order of one to two days at an altitude of about 20 Km.

Their characteristic of being unmanned also avoids the problems, weights and costs associated with the many crew members necessary to AWACS operations provided that the presence on board of an adequate ground data link be ensured.

**3.2.2 Surface target acquisition**

In this role the HALE-UMA with the use of a FTI/MTI (Fixed Target Indicator / Moving Target Indicator) radar can control ground movement of troops and support the attack operations performed by hostile aircraft.

Also in this case the high patrol time in the order of one day and altitude of about 20 Km do enhance the effectiveness of this kind of airplane configurations in comparison with today recce systems.

**3.2.3 Ballistic missile launch detection**

Ballistic missiles interception can be more effectively performed in the case of their early detection.

When considering the presently used systems it must be emphasized that the detection capability range of ground radars is limited by terrain morphology and AWACS or satellites are really expensive solutions.

On the other hand in a much less expensively way the enemy ballistic missiles at the moment of their launch can be detected by HALE-UMA aircraft equipped with infrared sensor enabling the activation of suitable countermeasures for their interception.

Particularly suited for this application are high loiter altitude and long endurance while payload is relatively small, as it is in the order of no more than 300 Kg.

**3.2.4 Intelligence gathering**

At present this task is only performed by special versions of allready existing large airplanes like U2/TR1, C130, C135 or by satellites with obviously heavy costs implications both in terms of acquisition, operations and maintenance.

Long endurance characteristic and adequate availability of quite high payload weight and volume make HALE-UMA type of aircraft extremely suitable for this application, also considering that pilot actions are really unnecessary during the mission, while fast deployability makes these airplanes also more suitable than satellites for this application.

**4. Technological challenges**

In order to start the preliminary sizing of the configuration it has been necessary to define the technological level required to be adopted for the aircraft.

The necessity to keep costs at a minimum imposed to reduce as much as possible weights and dimensions of the aircraft thus forcing the designers to adopt the most advanced technical solutions.

On the other hand these solutions have to be all achievable at present without a big investment in research and development that would increase cost itself, so that in many cases they appear to be quite conventional.

**4.1 Aerodynamics**

From the aerodynamic point of view the configuration of any HALE-UMA is heavily conditioned by requirements of high aerodynamic efficiency.

As well known, the most relevant aerodynamic endurance parameter for propeller driven aircraft is $E^*C_L^{1/2}$; from this the necessity arise of flying at quite high values of lift coefficients even higher than those of maximum efficiency.

At such high lift coefficient values the wing sections have to maintain laminar flow over substantial wing chord fractions at low values of Reynolds number.

In order to cope with this need a conceptual trade-off had been done between wing sections ranging from 12 to 19 % that demonstrated the overall superiority of the thinner one, also considering the relatively high values of local Mach numbers in the design condition.

A brief survey of this trade-off results is represented in figure 4.1-1 in which it is evident that the achievable efficiency with the 12 % thick wing section is about double with only a roughly 12 % increase of wing weight and 20 % decrease of maximum lift coefficient.

In order to keep also lift-induced drag at a minimum it is mandatory to use the highest possible value of aspect ratio compatible with present tecnological

limits, illustrated in figure 4.1-2.
A value of 40 has been chosen thus imposing also very demanding structural requirements to ensure an adequate wing stiffness to prevent flutter and aileron reversal phenomena.
The maximum efficiency and the drag breakdown relevant to typical military and civil aircraft in comparison to HALE-UMA configuration are represented in figure 4.1-3 and 4.1-4.
These diagrams evidence the really superior aerodynamic performance of this kind of aircraft that are more comparable to sailplanes from this point of view being their aerodynamic efficiency from 1.5 to 3 times that of civil and military aircraft respectively, also taking in account the extremely low value of design Reynolds numbers that promote usually a drag increase.
Furthermore, being the radiators drag a significant fraction of the whole parasitic drag owing to their dimensions caused by the extremely low air density, the feasibility of surface heath exchangers will also be investigated.
In fact preliminary calculations have shown that this improvement to the baseline configuration can decrease its zero lift drag by about 5 %.
These radiators could be positioned over not heavily stressed surfaces like fin torsion box panels in order to avoid piping failures and liquid leakage due to wing flexing.

### 4.2 Propulsion

At the very beginning of the conceptual phase a trade off has been performed with the aim of defining the most suitable propulsion system for this kind of airplanes flying at extremely high altitudes and relatively low speeds.
This study only considered engine types that are at present technologically feasible without any important development work.
Thus we excluded from the start all the really exotic propulsion system like nuclear, solar/battery, liquid oxygen and others that are from one standpoints very appealing but that would have certainly required heavy investments in terms of time and money for their development.
With these assumptions this study considered only reciprocating, turboprop and turbojet engines.
It resulted that without any doubt the old fashioned turbocharged reciprocating engine is the most efficient solution from the point of view of the total propulsion weight (engine plus fuel) in the range of speeds and altitudes required for that sort of aircraft.
One of the decisive factors for this choice is the thrust lapse ratio of turbojet and turboprop in comparison to flat rated reciprocating engines that is illustrated in figure 4.2-1.
From this figure it is evident that in order to obtain the réquired thrust of only 50-60 Kg in the loiter condition at 25 Km it is necessary to intall for example a turbojet engine capable of a static, sea level thrust of 20 times greater i.e. about 1100 Kg, with a weight in the order of 250 Kg instead of a reciprocating turbocharged engine of about 100 HP with a total weight of about 210 Kg comprising all the accessories.
What is more important is the worse specific fuel consumption of turbojet and turboprop in comparison to reciprocating engines that produces a fuel flow from 1.4 to 2.5 times greater as illustrated in figure 4.2-2.
In conclusion the total propulsion weight obtained considering engine plus the fuel required for a 24 hours endurance time may be evaluated in about 600 Kg, 1000 and 1300 Kg for reciprocating, turboprop and turbojet engines respectively like illustrated in figure 4.2-3.
In any case it is important to stress that the turbocharged reciprocating engines considered are required to be flat rated up to the loiter altitude of about 20 or 25 kilometres: this fact imposes a noteworthy challenge to the propulsion system manufacturer, the pressure ratio of the turbocharger unit being roughly above 20 to 1 or 40 to 1 respectively as it is possible to see in figure 4.2-4.
This last requirement is satisfied by using two or three stages of turbocharging with intercoolers between each stage and before feeding the engine.
The propeller also must be designed to achieve an efficiency in the order of 90 % by using sections and blade shapes especially suited to the range of Reynolds and tip Mach number attainable in flight.
The propellers considered have fixed pitch and are driven by a variable gear reduction unit because this solution has been considered preferable to the most usual variable pitch propeller taking in account the single, extremely well defined design condition of the configuration.
In fact for this kind of airplane it is mandatory to feature an extremely high propulsion efficiency in the loiter condition and just an adequate thrust in the take off and climb condition.
Therefore the necessity is avoided of having high propulsion efficiency in many points of the flight envelope that is peculiar to and achievable by a variable pitch propeller, obtaining in that way a reduction of the weight, complexity and cost of the whole propulsion system.

### 4.3 Structure

From the structural point of view the main challenge is to build the wing structure stiff enough to avoid flutter and aileron reversal conditions in all the flight envelope with the least weight considering the extremely high value of aspect ratio chosen to improve aerodynamic efficiency.
On the other hand the design flight conditions, namely low Mach and Reynolds numbers, promote the adoption of rather thick wing sections alleviating in that way the structural problems.
In order to choose the material for the primary structures a conceptual study has been performed whose results in terms of strength and stiffness referred to the weight are briefly summarized in

figure 4.3-1.
This study considered aluminium alloys, fiberglass and graphite epoxy reinforced fiber and demonstrated that by far the latter is the most suitable structural material when strength and stiffness are required with the least weight, being their characteristics almost more than 2.5 times greater than those of the other materials.
Moreover it is mandatory to prevent wrinkling of wing surfaces that would destroy the laminar flow over the wing, and then the adoption of graphite composite material becomes mandatory.
Considering the present state of the art and the low values of load factor and dynamic pressure imposed to that sort of aircraft, a specific weight of about 10 $Kg/m^2$ referred to the planform surface is considered feasible for a wing structure using high strength graphite epoxy fibre.
This represents a weight target that is from 4 to 5 times less with respect to modern civil and military aircraft wings as it is illustrated in figure 4.3-2.
Total predicted structural weight savings versus composite material usage is depicted in figure 4.3-3 as it resulted from previous statistical studies.

### 4.4 Systems

The main challenges concerning systems are generated by the peculiar characteristic of this sort of configuration of being unmanned.
In particular the avionic and communication system must be capable of performing the following tasks:

- navigation
- control of flight
- ground and satellite communications
- data exchange between all the on board devices

During each mission the flight will be autonomously controlled by the airplane itself in all the phases but the take off and landing that on the contrary can be remotely controlled by a human pilot located in a ground station.
This does not imply that future UMA cannot be autonomously landed by MLS (Microwawe Landing System) connected with an autolanding system, whose know-how can be derived by the experience gathered from manned aircraft.
Autonomous flight phases may be programmed before the take off or reprogrammed during the flight from the ground in order to overcome particular events or emergencies not foreseen before.
The on board computer must be able to perform the continuous monitoring of all the flight parameters (incidence, heading, speed, altitude ecc.) and to generate input signals for flight controls.
In addition it is necessary to install on board a data-link system highly integrated with the other navigation, communication, control and payload systems and capable to transmit to the ground the flight parameters and to receive input signals for the direct control of flight and for the mission reprogramming.
Taking into account the large distances implied, the data-link system needs to be operated through satellite channels.
For what concerns the other systems they don't pose particular challenges; it is just worth to say that, as the dynamic pressure is quite low and the speed of actuation is not particularly demanding, flight controls can be of all electric type.
In this case total power generation has to be provided by starter generators driven by the engines that must also be capable of providing enough power also in case of engine/generator failure.
In order to cope with the event of total power generation loss a reserve battery has to be installed in order to perform a safe return to home base.

## 5. Preliminary sizing

Assuming the above illustrated technological levels, a trade off study of a typical HALE-UMA configuration has been performed allowing the definition of the total take-off weight, empty weight and fuel weight for different values of payload weight and loiter duration.
Loiter durations of 1, 2 and 3 days with payload weight ranging from 300 to 1700 kg have been considered.
These values have been defined to cover the possible aircraft requirements to perform all the tasks illustrated in the preceding paragraph.
The mission profile used for this study, typical for an HALE-UMA aircraft, is composed of the following phases:

- Take off
- Climb to loiter altitude
- Cruise of 1000 Km to loiter area
- Loiter at a speed not lower than 180 KTAS
- Return cruise
- Descent
- Landing with 5 % reserve fuel

Mission fuel and other weights have been calculated with the classical and well known methods of preliminary sizing using aerodynamic, propulsive and structural parameters consistent with the assumed technology levels that have been previously described and some statistical relationships derived from the limited amount of data pertinent to this class of aircraft.
In figure 5.-1 the results of this analysis are illustrated in terms of take-off weight versus loiter duration and payload weight, while a sensitivity study of the loiter duration relevant to a typical HALE-UMA configuration is presented in figure 5.-2.
This plot had been obtained by varying the main aerodynamic and propulsive parameters in order to assess the influence on the most relevant aircraft performance of each technology level variation with respect to the assessed value .
This preliminary sizing proved the feasibility of an

HALE-UMA aircraft with a reasonable level of complexity, costs and dimensions consistent with already existing technological capability; it led the way to the subsequent configuration definition and detailed dimensioning already in progress.

### 6. *Selected configuration*

On the basis of the preliminary sizing and trade off studies illustrated in the previous paragraph a rather detailed configuration layout definition of four different version of HALE-UMA aircraft has been performed.

All these four configurations have different payload weights, dimensions and loiter durations and are conceived to perform some of the tasks defined before, both military and civil.

Interest is now focused on the last one and the description of its requirement and general characteristics is presented in the following pharagraphs.

### 6.1 Requirements

The main characteristic of this configuration is its extremely enhanced payload modularity.

Thus it has been designed in order to have the payload housed in a pallet of about 3 $m^3$ of volume that is completely separated from the remaining airframe.

Therefore the aircraft can be easily reconfigured for different roles, both military and civil, in a very short period of time simply by changing the pallet, so that it can be considered a real all purpose configuration. This version is capable of loiter time in the order of one day with a pallet of 600 Kg at an altitude of 20 Km or at 25 Km if the payload is reduced to 100 Kg. In such a way both ground surveillance and scientific mission can be performed with a noteworthy capability.

### 6.2 General description

As stated in the previous paragraph the main feature of this configuration is its capability of carrying a pallet which can accommodate many kinds of payload for different roles and, what is most important from the configuration point of view, featuring different weights and dimensions.

Therefore, it is mandatory to position the payload with its centre of gravity coincident with that of the complete aircraft in order to avoid balance problems with payload change.

Moreover a twin engine solution has been chosen for safety reasons; in order to improve the compactness of the configuration the engines have been placed one in front of and the other behind the payload bay in a push pull arrangement.

This solution has been preferred to a more conventional one with two tractor engine nacelles over the wing and a separate fuselage for some reasons.

In fact, total airplane frontal area has been reduced, eliminating two extremely draggy items like isolated engine nacelles over the wing that have been replaced by only one integrated fuse containing the two engines, the payload and the systems.

Moreover total wetted area of the configuration has been reduced allowing a further decrease of drag and weight of the configuration.

Drag is also reduced by having the two propellers aligned on the same axis and thus only one stream tube, instead of two, spoiling wing laminar flow.

After this brief description of the reasons that have led to this configuration shape we can describe its peculiar characteristics.

The structural layout of the wing is based on a twin spar torsion box arrangement with sandwich upper panel and solid laminate lower panel, all made from high strength graphite epoxy reinforced fibre and that also forms the fuel tank in his central zone between the booms.

Roll control is obtained by means of ailerons located along trailing edge from the booms to approximately 60 % of wing span; this rather unusual arrangement is due to the need of reducing bending loads and of enhancing aileron reversal speed.

The ailerons are divided in sections, each about one meter long, connected to the others through a joint in order to avoid hinges jam when the wing deflects under flight loads.

At approximately 17 % of semispan two tubular, tapered booms are attached to the wing torsion box; they carry at their rear ends the empennages that are joined in order to exploit the mutual favourable aerodynamic interference.

The central fuselage is connected to the wing with four fittings and it carries the payload pallet, the engines with their turbochargers, the landing gear and the systems.

The landing gear is a bicycle type with auxiliary outriggers located on the wing for ground stability during taxiing that are jettisoned after the take-off phase.

This fact is basically due to the presence of a rather long payload bay that is located near the center of gravity on a small width fuselage compared to wing span that prevents the use of a more conventional tricycle type with the main legs housed in fuselage side pods.

The reciprocating turbocharged engines are flat-rated at 110 HP each up to the loiter altitude of 25 kilometres and drive two 4 m diameter fixed pitch propellers by means of a variable gear reduction unit.

The avionics and systems bay, located in the front fuselage forward of the pallet area, is closed by means of a large non structural panel with easily removable latches for better maintainability and serviceability

When speaking about systems it is worth to briefly deal with the avionic system, the flight control system and the electric system.

The latter provides the total power generation by means of two 6 KW starter generators, each driven by one engine, and a reserve battery in case of total power generation loss.

This solution has been preferred to the AC power generation with TRU (Transformer Rectifier Unit) in order to minimize total system weight and complexity. The conceptual layout of this system is presented in figure 6.2-1.

On the other hand the avionic system is composed by the navigation and control, data link, satellite communications and air data subsystems.

As far as navigation and control subsystem is concerned, it has to cope with the conditions of autonomous and remotely controlled flight and is composed by an inertial navigation unit, a GPS (Global Positioning System) and a NAFCC (Navigation And Flight Control Computer).

Considering the outstandingly flight time and the absence of crew, the navigation and control system requirements are really demanding in terms of reliability and integration with the other systems, both on board and on the ground.

The data link subsystem have to receive the input from ground station for the remote flight control and to transmit back all the flight parameters and the payload data; thus also in this case a great integration with the other systems is required.

The sketch of the avionic conceptual layout is depicted in figure 6.2-2.

For what concerns the flight control system, as anticipated in para 4.4 it has been conceived all electric in order to save total system weight and complexity, taking into account its not particularly demanding requirements in terms of power required and speed of actuation.

Weights and dimensions of this configuration and its three view are collected in table 6.2-3 and figure 6.2-4.

## 7. Ground support

The HALE-UMA system will be interfaced with two ground based control stations, dedicated to the payload and to the aircraft respectively and each one with different functions:

- to perform the processing of the data coming from sensors and to control the operations of the sensor itself
- to monitor the mission also interfacing with air traffic controllers, reprogramming the mission itself when necessary and to pilot the aircraft during the take-off and landing phases

For all the applications the ground station dedicated to payload monitoring will be interfaced with the appropriate central control station, both military or civil depending on the application that will be the end user of the data collected by the airplane during the mission.

Owing to the peculiar characteristics of certain of the roles envisaged it will also be extremely useful to locate these ground stations in containers installed on trucks to provide system mobility and fast deployment.

## 8. Conclusions

The preliminary design studies here described have verified the feasibility of HALE-UMA aircraft capable of flying at altitudes up to 25 kilometres with payload weight up to 1000 kilograms and loiter duration from 1 to 2 days at a distance of almost 1000 kilometres from the main base.

It has also been demonstrated that such an aircraft can be realized using technologies already affordable, although exploited at their highest level, without a huge investment in new researches that would increase costs and time schedule.

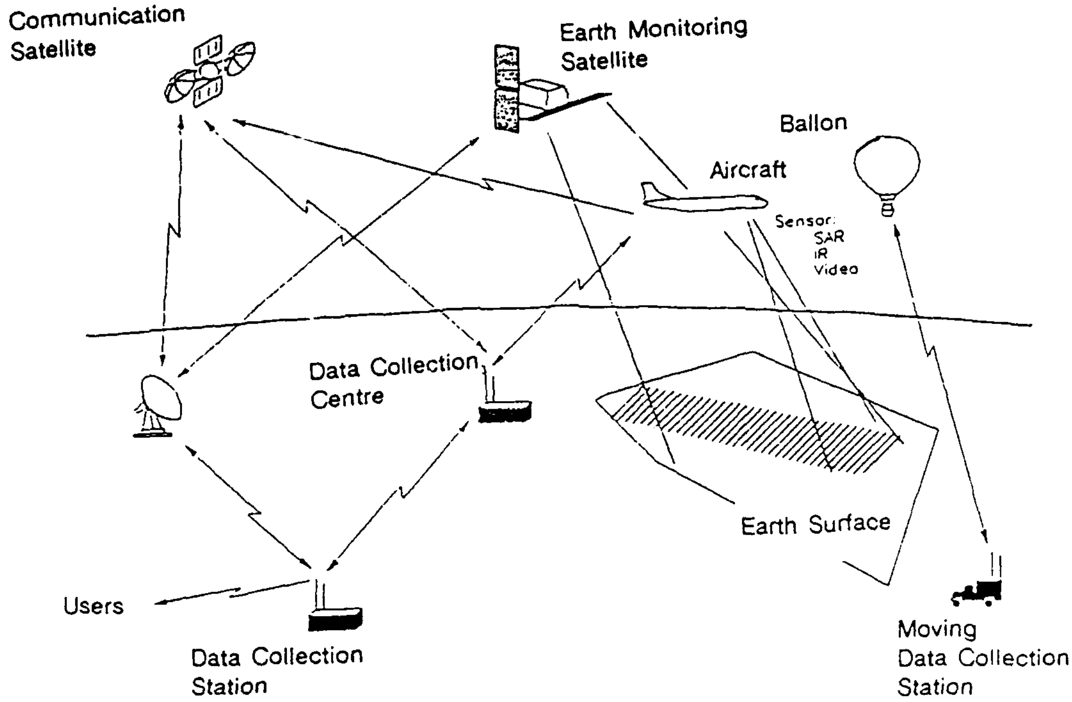



Figure 3.1.1-1

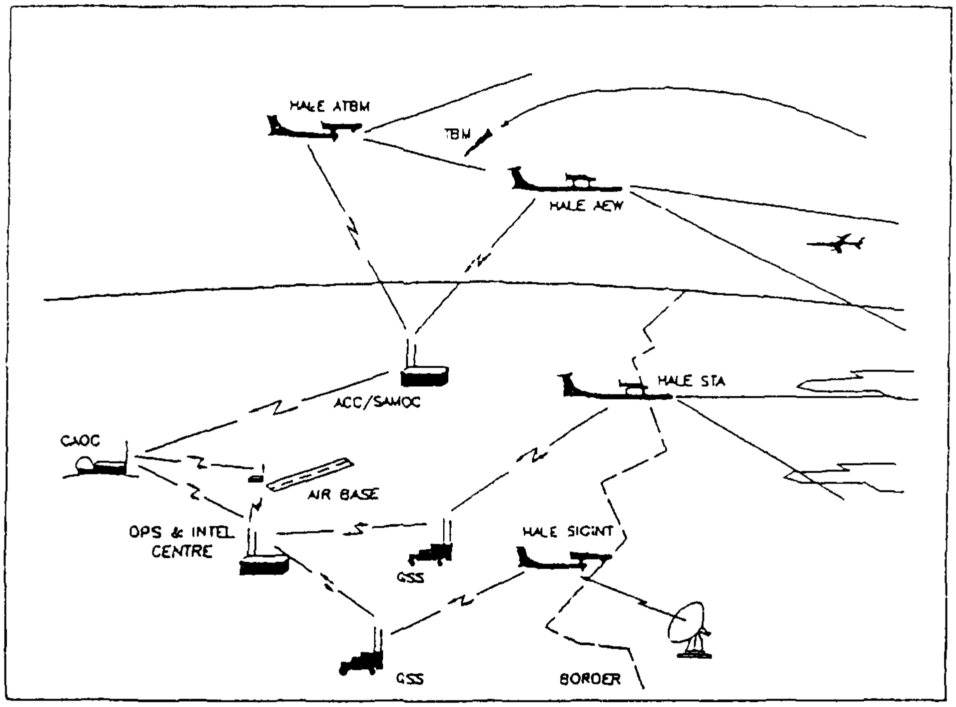



Figure 3.2-1

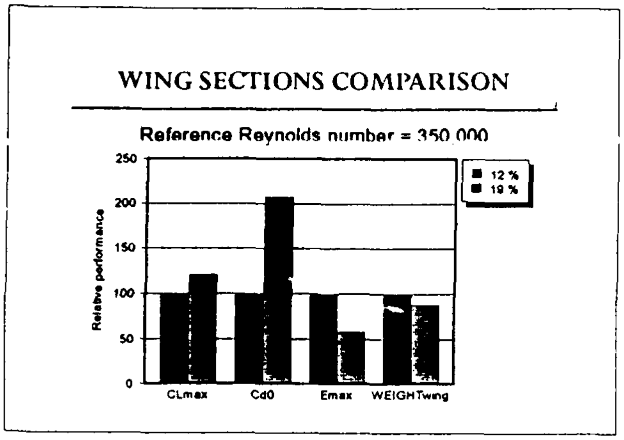



Figure 4.1-1

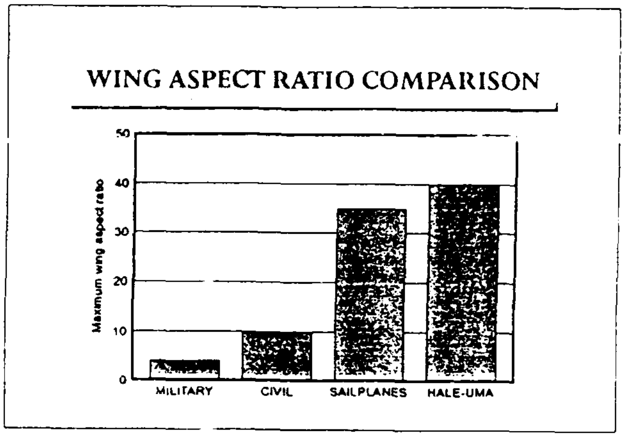



Figure 4.1-2

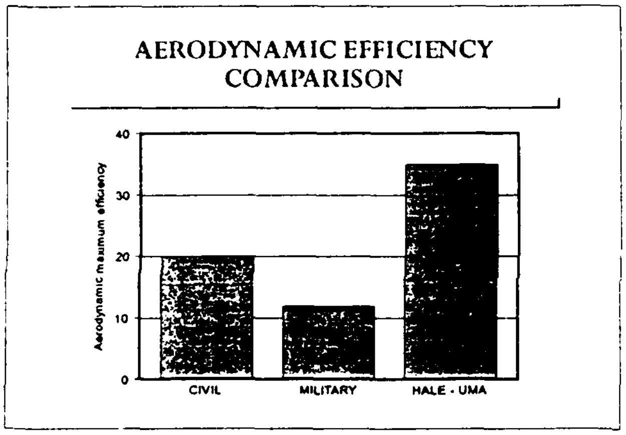



Figure 4.1-3

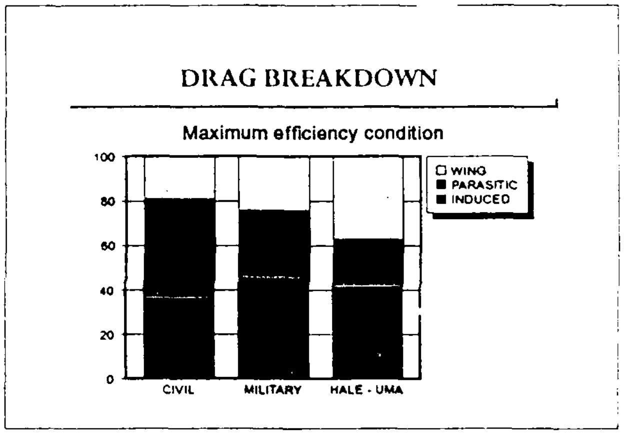



Figure 4.1-4

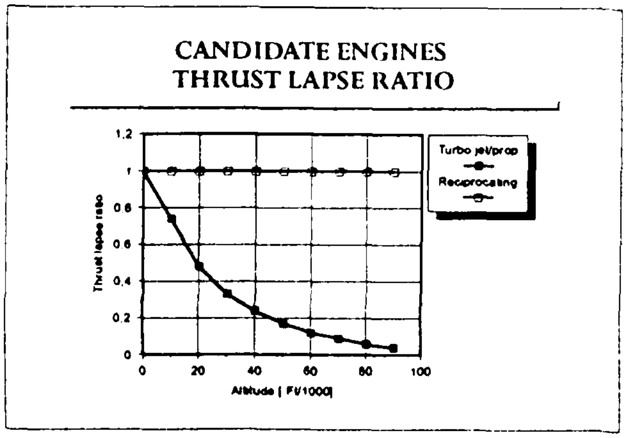



Figure 4.2-1

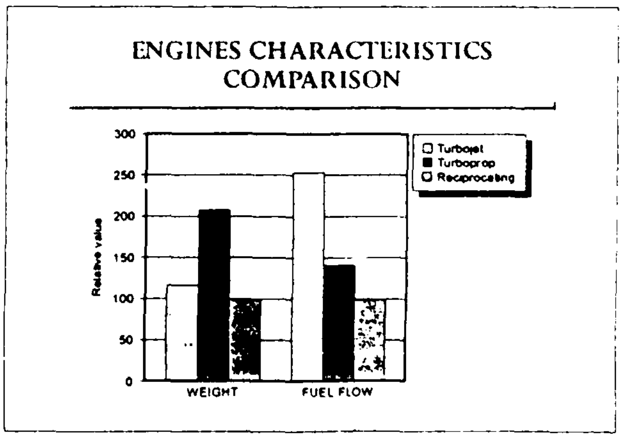



Figure 4.2-2

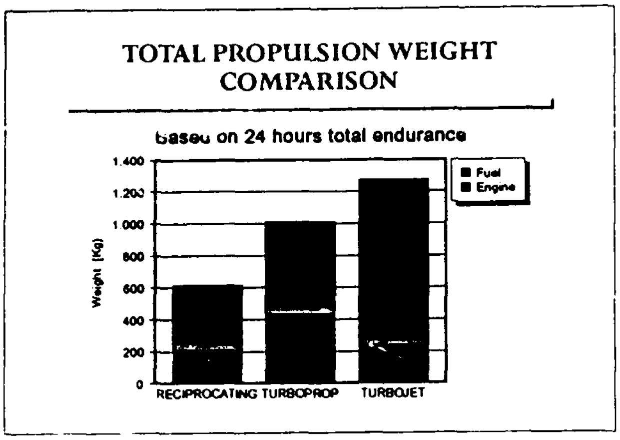



Figure 4.2-3

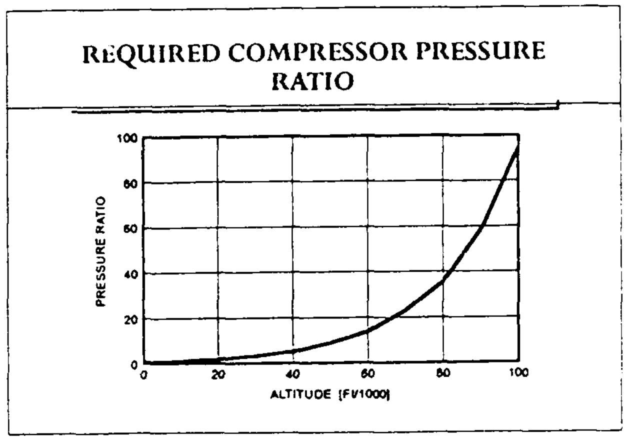



Figure 4.2-4

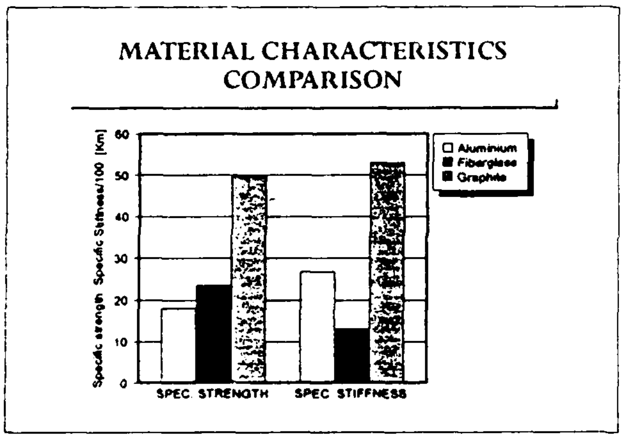



Figure 4.3-1

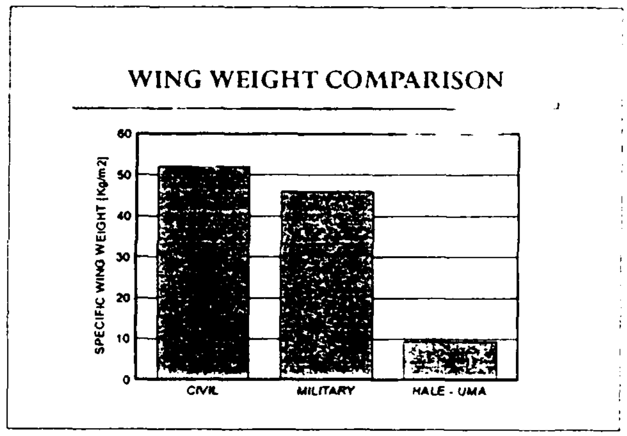



Figure 4.3-2

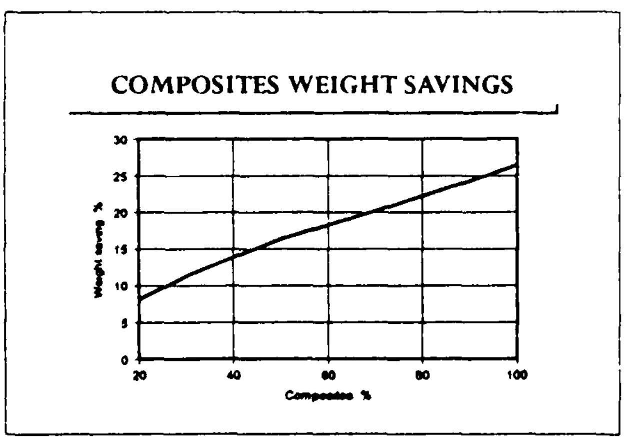



Figure 4.3-3

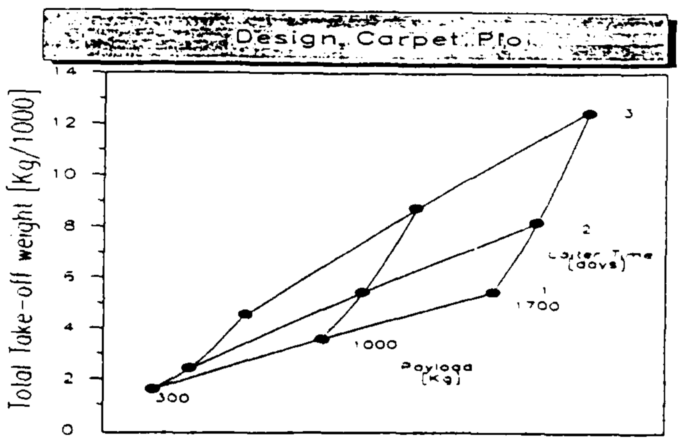



Figure 5-1

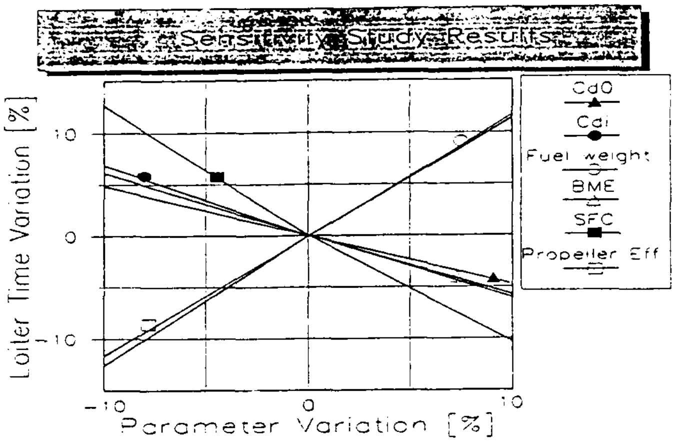



Figure 5-2

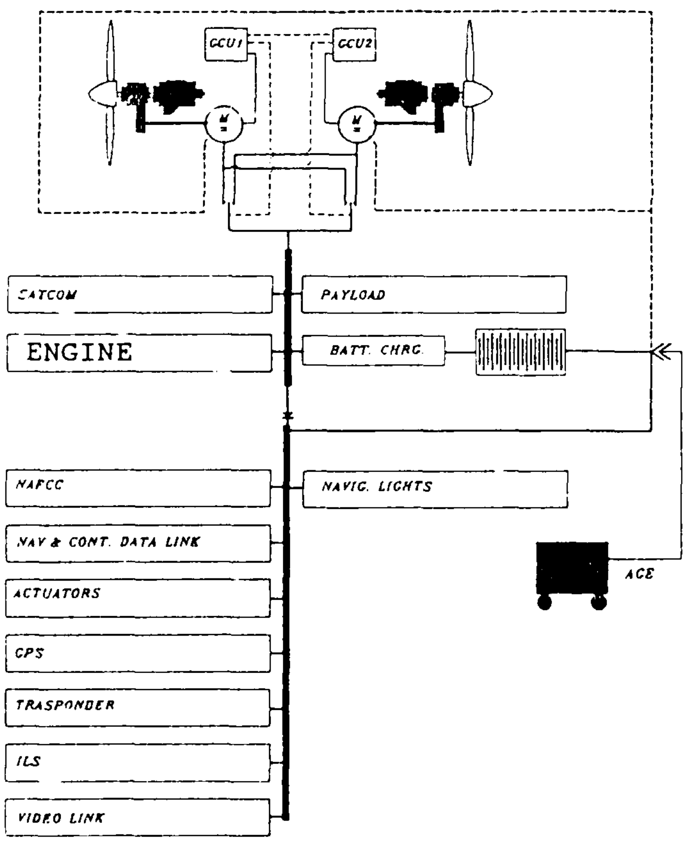



Figure 6.2-1

| | | |
|---|---|---|
| COMPLETE AIRPLANE | | |
| Wing span | 37.4 | [m] |
| Length | 11.5 | [m] |
| Height | 4.5 | [m] |
| Engine | 2 x TELEDYNE | |
| Power | 110 | HP |
| Propeller diameter | 4 | [m] |
| WING | | |
| Span | 37.4 | [m] |
| Area | 35 | [m$^2$] |
| Aspect ratio | 40 | |
| Medium thickness | 17 | [%] |
| Taper ratio | .325 | |
| HORIZONTAL TAIL | | |
| Span | 5.8 | [m] |
| Area | 3.48 | [m$^2$] |
| Aspect ratio | 9.7 | |
| Medium thickness | 15 | [%] |
| Taper ratio | 1 | |
| VERTICAL TAIL | | |
| Span | 2.4 | [m] |
| Area | 2 x 2.76 | [m$^2$] |
| Aspect ratio | 2.1 | |
| Medium thickness | 15 | [%] |
| Taper ratio | .53 | |

| COMPONENT | WEIGHT [Kg] |
|---|---|
| Structure | 607 |
| Propulsion | 463 |
| Equipment | 127 |
| Operating Mass Empty | 1222 |
| Payload | 600 |
| Fuel | 900 |
| Take off | 2722 |

Table 6.2-3

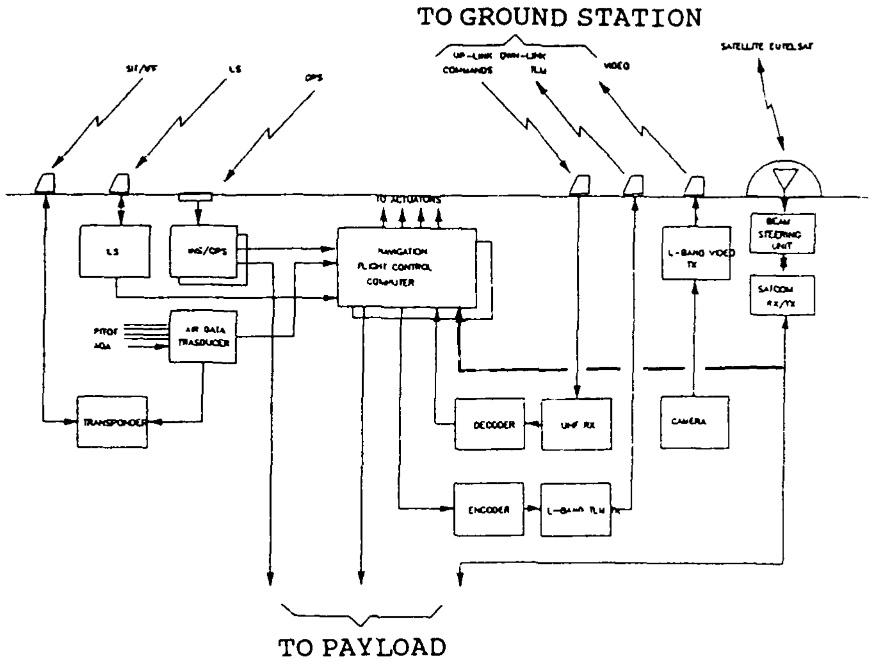



Figure 6.2-2

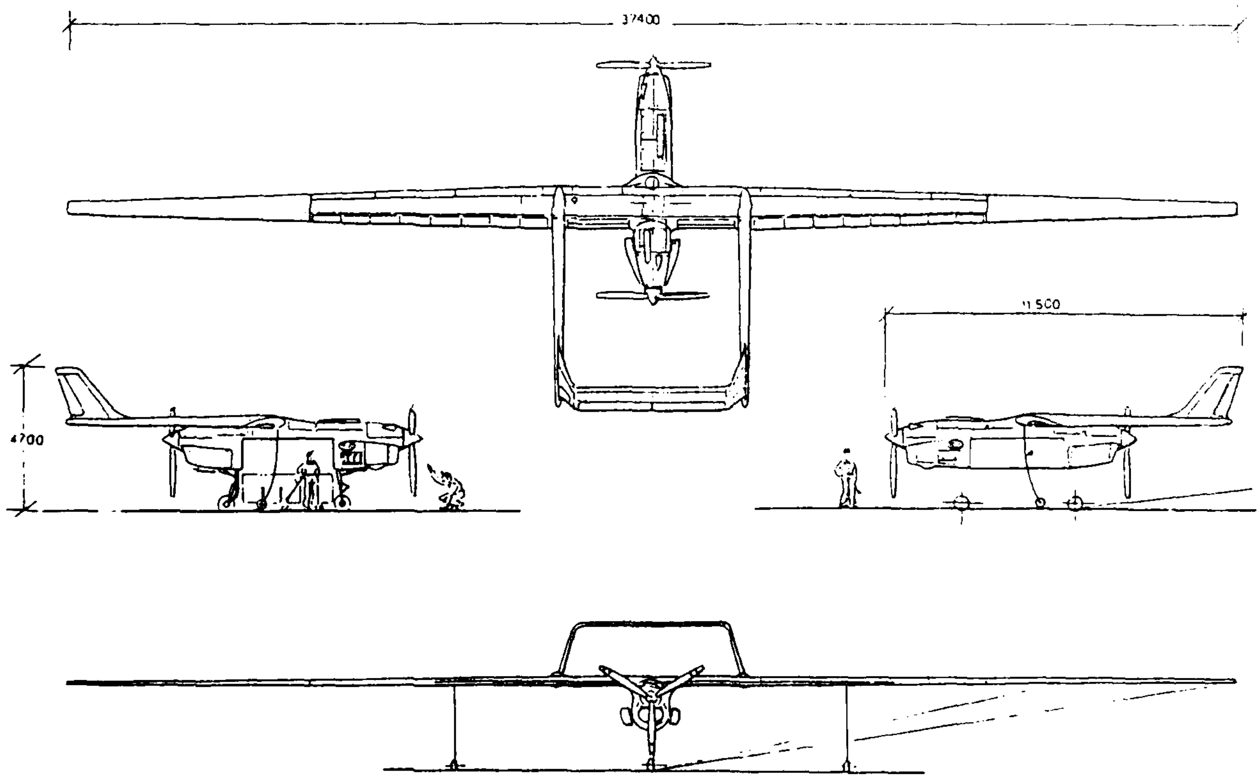



Figure 6.2-4

# Avion de Transport Supersonique Futur : un Défi Technologique pour le Vol Long Courrier

# Future Supersonic Commercial Transport Aircraft : A Technological Challenge for Long Haul Traffic

J-L. Galvani
Aerospatiale, Aircraft Division
316 route de Bayonne, 31060 Toulouse Cedex 03, France


## Abstract

Long haul traffic is a key sector that is constantly increasing. Since Concorde entry into service in 1976, it has tripled and will again double by the end of the century. There is no doubt that this long haul traffic development will create an increasing interest in high speed.
The entry into service of a HSCT will enable flight time to be divided at least by 2 on these long routes, and could capture 20% to 40% of the long range market.
To face up this future air transport landscape Aerospatiale, who jointly with British Aerospace has accumulated an unique experience in high speed transport with the Concorde programme , is studying a potential successor : the Alliance project cruising at Mach 2.

Due to the significant progress in technology already achieved or foreseen in the near future, the entry into service of a second generation supersonic transport can be envisaged as early as 2005. The success of this project is strongly linked to the capability of the aircraft and the engine manufacturers to provide the appropriate technology level to make the airplane environmently acceptable and economically attractive.
A significant effort in R & D is necessary to make available the challenging technologies : new materials, aerodynamics, propulsion...

Considering the level of investment required and the complexity of the problems to be solved, a close collaboration involving indutrial partners is necessary on a world wide basis.
This collaboration has already started. Following a long experience of bilateral cooperation, Aerospatiale and British Aerospace joined again in 1990 to study together a second generation supersonic aircraft around their respective concepts (AST and Alliance). Both partners are also cooperating with DASA, Boeing, Mc Donnell Douglas, the Japanese Industries, Alenia and Tupolev within an International Study Group.


## List of symbols

| | |
|---|---|
| CD | drag coefficient |
| MTOW | maximum take-off weight |
| Cs | Specific fuel consumption |

## 1. Introduction

Concorde, en service régulier depuis plus de quinze ans a désormais démontré la faisabilité technique du transport commercial civil et ceci en toute sécurité; ouvrant ainsi la voie à la prochaine génération d'avion supersonique.
Les progrès technologiques importants réalisables et la croissance du trafic long courrier au début du 21ème siècle, nous laisse envisager la possibilité de lancer un nouvel avion supersonique avec une entrée en service en 2005.

Toutefois, un effort important de recherche et de développement est nécessaire afin de préparer les technologies appropriées pour un tel projet.

Dans cette conférence, les perspectives d'un transport supersonique de seconde génération sont passées en revue. Cela inclut notamment le marché potentiel, les principales contraintes de définition et les études en cours à l'Aerospatiale. On rappellera les efforts de coopération en cours entre les principaux constructeurs aéronautiques mondiaux, en insistant sur la nécessité d'une coopération internationale pour le succès d'un tel projet.

## 2. L'acquis Concorde

Concorde reste le seul avion commercial supersonique en service aujourd'hui. Conjointement conçus et produit par British Aerospace et Aerospatiale pour la partie cellule, Rolls Royce et Snecma pour les moteurs, il a désormais démontré la faisabilité technique et la capacité opérationnelle du vol commercial supersonique.

La flotte Concorde, en service régulier sur 15 ans a accumulé plus de 160000 heures de vol en opération sur plus de 200 aéroports. Ceci d'une manière totalement sure et compatible avec le trafic subsonique et les contraintes aéroportuaires (Fig.1).

CONCORDE OPERATING STATISTICS (AS OF MAY 1992)

| AIRLINE | AIRCRAFT | DELIVERY DATE | FLIGHT HOURS | FLIGHTS |
|---|---|---|---|---|
| AF | F-BTSC | 1/6/76 | [illegible] | [illegible] |
| AF | F-BVFA | 12/18/75 | [illegible] | 4243 |
| AF | F-BVFB | 4/6/76 | 12084 | [illegible] |
| AF | F-BVFC | 8/3/76 | [illegible] | 3124 |
| AF | F-BVFD | 3/26/77 | [illegible] | 1012 |
| AF | F-BTSD | 9/4/78 | 8230 | 2746 |
| AF | F-BVFF | 10/24/80 | 7746 | 2812 |
| TOTAL AIR FRANCE | | | 84201 | 21298 |
| BA | G-BOAC | 2/13/76 | 10324 | [illegible] |
| BA | G-BOAA | 1/14/76 | [illegible] | [illegible] |
| BA | G-BOAB | 9/30/76 | 10874 | [illegible] |
| BA | G-BOAD | 12/6/76 | 10727 | [illegible] |
| BA | G-BOAE | 7/20/77 | [illegible] | [illegible] |
| BA | G-BOAG | 2/6/80 | [illegible] | [illegible] |
| BA | G-BOAF | 6/13/80 | 11294 | [illegible] |
| TOTAL BRITISH AIRWAYS | | | [illegible] | [illegible] |
| TOTAL FLEET | | | [illegible] | [illegible] |

figure 1

En plus de l'unique expérience pratique acquise par les deux sociétés, Concorde a permis de réaliser des avancées technologiques importantes dont ont pu bénéficié les programmes Airbus. Ainsi parmi les retombées, on peut recenser :

- les commandes de vol électriques,
- le contrôle du centrage par transfert de carburant,
- les lois complexes de pilotage,
- les freins carbone...

D'autres produits comme les avions subsoniques, devraient tirer les bénéfices du saut technologique réalisable grâce au développement d'un nouvel avion supersonique.

*Presented at an AGARD Meeting on 'Recent Advances in Long Range and Long Endurance Operation of Aircraft', May 1993.*

### 3. Le trafic long-courrier et le marché potentiel

Ce trafic a cru plus rapidement que l'ensemble du trafic aérien au cours des 20 dernières années, et tout conduit a penser que le besoin en échanges internationaux de biens et de personnes assurera la poursuite de cette évolution (Fig.2).

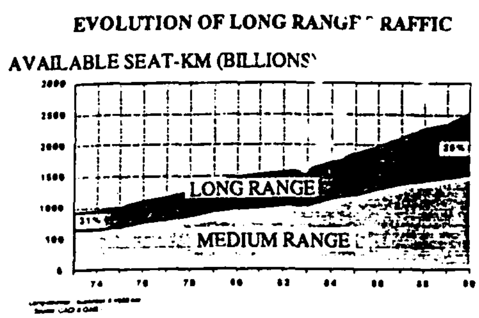



figure 2

Les prévisions réalisées montrent qu'avec une croissance de 5% le trafic long courrier devrait être multiplier par 2 entre 1990 et 2005 et par 5,5 entre 1990 et 2025, pour atteindre environ 400 millions de passagers par année (Fig.3).

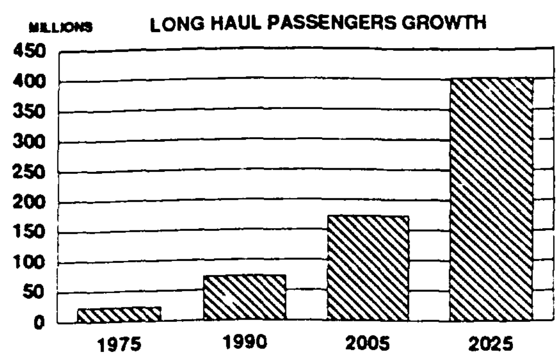



figure 3

La croissance devrait être particulièrement forte pour les pays asiatiques à fort potentiel de développement. Dont une conséquence est que près de 70% des vols long-courriers continueront à être effectués sur des trajets essentiellement océaniques. Ces routes étant fort bien adaptées pour le vol supersonique (Fig.4).

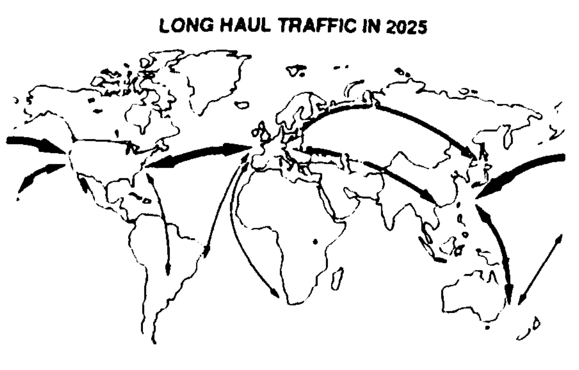



figure 4

Sur ces routes, l'avion supersonique offrira une réduction massive du temps de vol (50%) si l'on compare aux avions subsoniques. Ce gain en temps n'étant que faiblement affecté par le nombre de Mach de vol considéré (Fig. 5).

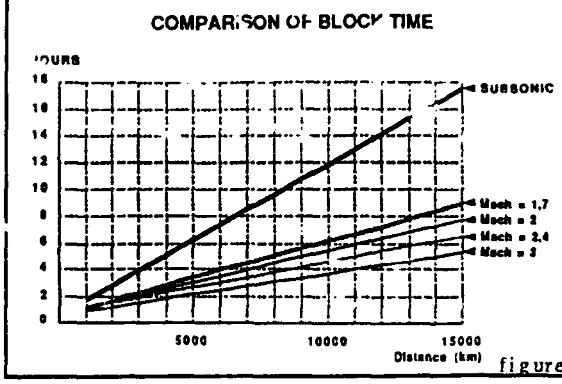



figure 5

Pour les routes dont une partie s'effectue au-dessus des terres, on considère que le survol de ces zones en supersonique restera interdit. Malgré tout, sur ces routes les paliers subsoniques ou les détours supersoniques nécessaires en opération n'affecteront que peu le gain en temps de vol comme l'illustre la figure 6.

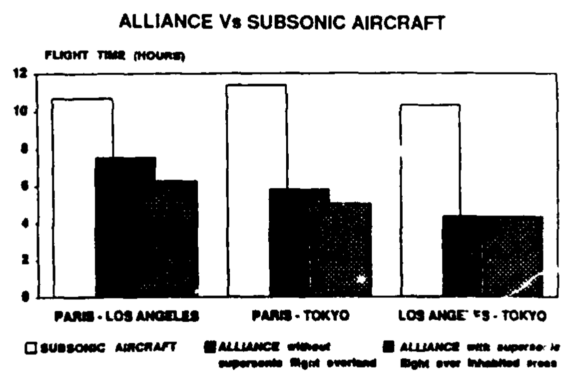



figure 6

La part du marché que pourra atteindre cet avion dépend du niveau économique réalisable en opération et du prix du billet. De nombreuses études sont en cours dans le monde pour comprendre l'élasticité du marché en fonction des différentes catégories de passagers et de la surcharge tarifaire appliquée.

En considérant les caractéristiques d'un avion de 250 - 300 passagers volant à Mach 2, le marché est estimé entre 500 et 1000 avions d'ici 2025 (Fig.7).

En complément de cette rapide analyse du marché, on peut envisager un effet "stimulus" du à la réduction du temps de vol identique à celui observé lors la mise en service de train à grande vitesse. Cet effet pourrait accroitre la part du marché de l'avion supersonique.

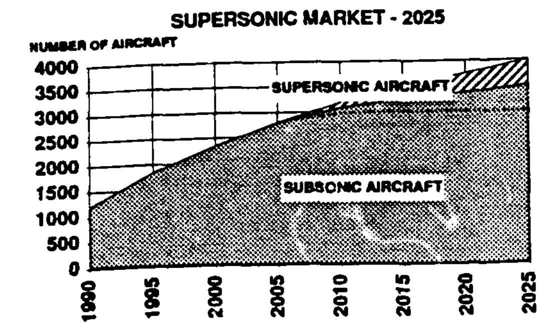



figure 7

## 4. Le supersonique et l'environnement

Tout en recherchant le succès commercial pour ce programme, on doit porter une attention particulière aux contraintes liées à l'environnement. Ce qui signifie le respect de toutes les réglementations en vigueur ou à venir concernant le bang sonique, les émissions moteur et le bruit autour des aéroports.

En projetant les progrès technologiques réalisables d'ici la fin du siècle, il semble possible de développer un avion qui n'aura pas d'impact significatif sur l'environnement.

### 4.1 Le bang sonique

En croisière supersonique, un avion produit une onde de choc qui peut se propager au sol, et crée une surpression qui peut sembler forte et gênante pour l'oreille humaine.
L'expérience Concorde a démontré que les populations n'acceptent pas cette nuisance sonore, et de fait le survol supersonique des terres est interdit dans la plupart des pays.
Le fait de dessiner un avion économiquement exploitable pour des niveaux de bang acceptable n'est pas réalisable avec les standards technologiques d'aujourd'hui. On considère donc pour l'ensemble des études en cours aucun survol supersonique des terres.

### 4.2 Les émissions moteur

Les quantités de gaz émises par les avions sont faibles par rapport aux rejets humains ou naturels, mais elles sont localisées en altitude et concentrées près des zones aéroportuaires.
Les résultats scientifiques montre que les composés d'oxydes d'azote (NO, NO2 aussi appelés NOx) joue un rôle important dans la chimie atmosphérique. Mais l'impact des NOx émis par une flotte d'avions supersoniques sur la couche d'ozone est incertain et est le sujet d'importantes recherches scientifiques à travers le monde.
Cependant, il sera indispensable d'obtenir un consensus international sur l'impact d'une flotte supersonique avant de prendre la décision de lancer le programme.
L'évolution technologique des moteurs montrent que l'on peut espérer une réduction importante du niveaux de NOx émis par les moteurs, qui peut atteindre 70%.
La sélection de l'installation motrice associé à un choix approprié de l'altitude de croisière (17 - 19 km), et du nombre de Mach, montre que l'avion vole à des niveaux inférieurs à ceux ou l'on trouve la plus forte concentration d'ozone et pour lesquels les temps de dispersion sont relativement longs (Fig.8).

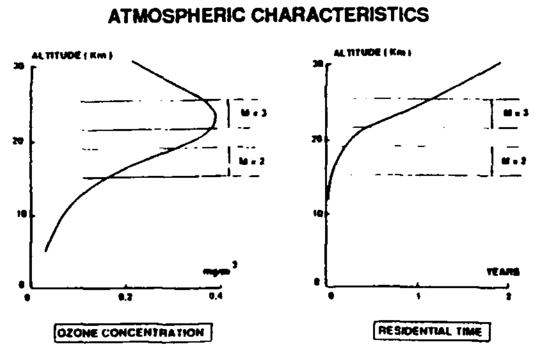



figure 8

### 4.3 Le bruit avion / moteur

Le futur avion supersonique devra être un bon voisin autour des aéroports.
Si l'on regarde la décroissance continuelle avec le temps des niveaux de bruit avion, un saut technologique important est à réaliser pour dessiner un avion qui ne fera pas plus de bruit que les subsoniques de la même génération. Il opérera à partir des aéroports et des pistes existants et ne devra pas excéder les niveaux de bruit réglementaires imposés par la FAR 36 Stage 3 (Fig.9).

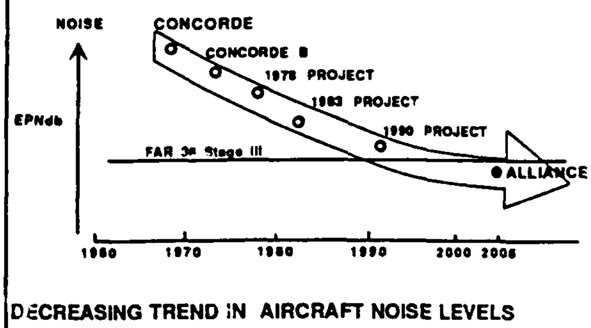



figure 9

Aujourd'hui de fortes pressions existent en Europe pour abaisser encore plus ces limites de bruit. Dans ce cas, des marges sont à prendre en compte pour la conception de l'avion et du type de moteur, de manière à prévenir une éventuelle modification de ces règlements.
Des technologies moteur très poussées, comme l'utilisation de nouveaux concepts (moteur à cycle variable) et des dispositifs d'éjecteurs sur les tuyères permettront de réduire la contribution principale du bruit moteur qui résulte de la vitesse d'éjection très élevée caractéristiques des moteurs supersoniques.
Cependant, du côté du constructeur les actions entreprises pour améliorer l'efficacité de la cellule (aérodynamique, masses) ou des modifications des procédures opérationelles pour les phases de vol à faible vitesse, montrent de bons espoirs pour contribuer à la réduction globale du bruit du couple avion / moteur.

## 5. La configuration Alliance

Les résultats des études de marché, les premiers contacts avec les compagnies aériennes et les différentes contraintes nous ont conduit à retenir une série d'hypothèses quant à la définition de la configuration de base : Alliance.

### 5.1 Les objectifs d'Alliance

Les objectifs d'Alliance sont résumés sur la figure 10.
L'avion est prévu pour transporter 250 passagers sur une distance de 10000 km, même si la mission comprend, au début et à la fin, d'importants segments subsoniques.

Ainsi, le rayon d'action spécifique unitaire (RASU) visé en subsonique, à Mach = 0,95, sera voisin de celui obtenu en croisière supersonique, de façon que cette partie du vol n'introduise pas de pénalité sur la consommation en carburant.

Notons que de bonnes performances en subsonique tendent également à réduire le niveau de bruit de l'avion à faible vitesse et la quantité du carburant nécessaire pour les réserves.

L'aménagement en trois classes doit offrir un confort pour le passager équivalent aux avions subsoniques dont les durée de vol sont voisines.
Les raisons du choix du nombre de Mach = 2,05 sont les suivantes : obtenir une productivité de l'avion suffisante sans accroître de manière trop significative la complexité technologique, les coûts associés à un nombre de Mach plus élevé, et l'impact des émissions sur la couche d'ozone.

**BASELINE MISSION REQUIREMENTS**

| | |
|---|---|
| PASSENGERS | > 250 ( 10% FIRST, 30% BUSINESS, 60% ECONOMY ) |
| SONIC BOOM | NO SUPERSONIC FLIGHT OVER INHABITED LAND |
| EMISSIONS | MINIMUM VALUE TO BE DEFINED |
| NOISE LEVELS | FAR 36 STAGE 3 |
| MAX CRUISE MACH NUMBER | 2.05 |
| MAX RAM TEMPERATURE | 127° C |
| RANGE | 5500 n.m ( at entry into service )<br>6500 n.m ( developed extended range aircraft at higher TOW ) |
| FUEL | JET A KEROSENE |
| RESERVES | 4 % Block fuel + 30 min. hold, 240 n.m diversion<br>+ 2 x 10 min. holds ( VC = 220 & 250 kt ) |
| OPERATION | NON SEGREGATED OPERATION FROM EXISTING AIRPORTS USING SUBSONIC AIRCRAFT |
| ECONOMICS | ACCEPTABLE INCREASE ABOVE SUBSONIC EQUIVALENT ( TO BE DEFINED ) |

figure 10

Pour ce qui concerne le rayon d'action, il parait prudent de ne pas fixer un objectif trop ambitieux pour l'entrée en service, notamment pour l'estimation des marges nécessaires pour la certification des niveaux de bruit. Au fur et à mesure de développements techniques ultérieurs, ce rayon d'action pourra être augmenter progressivement par une augmentation de la masse maximale au décollage.

### 5.2 Les caractéristiques techniques d'Alliance

La *figure* 11 montre l'évolution de la configuration d'Alliance depuis le début du projet en 1983. On notera aussi l'amélioration de la finesse en croisière qui passe de 8 à 10,5; avec notamment la modification de l'installation motrice par la séparation des fuseaux moteur, ce qui réduit considérablement la trainée.

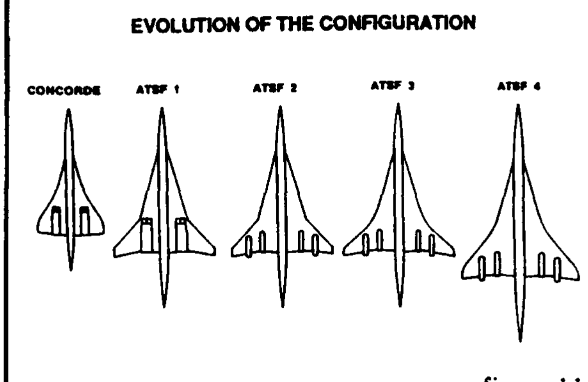



figure 11

#### 5.2.1 L'Aérodynamique du planeur

La configuration générale est fortement influencée par une exigence de finesse élevée dans toutes les phases de vol.

D'un côté, une finesse élevée est nécessaire pour de bonnes performances opérationnelles au décollage et à l'atterrissage, en respectant les limitations imposées par les normes de bruit; et une utilisation économique lors des paliers subsoniques. Ceci pouvant être obtenu grâce à l'utilisation de dispositifs de bord d'attaque.

D'un autre côté, une finesse élevée en croisière est un paramètre fondamental pour les performances globales de l'avion.
Ces différentes raisons nous ont conduit à choisir une grande surface voilure et une grande envergure (Fig.12).

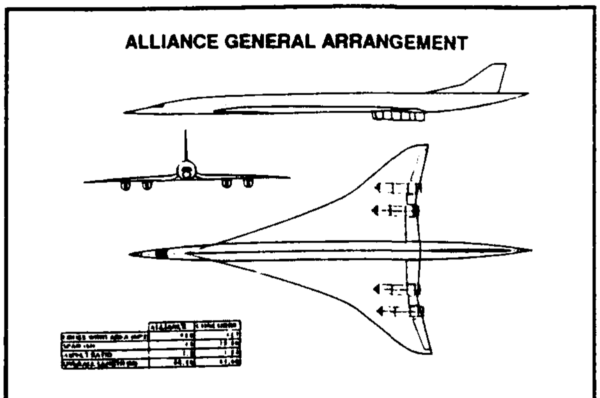



figure 12

Un certain nombre d'améliorations aérodynamiques ont été apportées au planeur (Fig.13) :

- un affinement de la pointe avant du fuselage;

- un changement de la forme en plan de l'extrémité voilure;

- une réduction du maître couple du fuselage;

- une optimisation de la cambrure et du vrillage afin d'améliorer la marge statique.

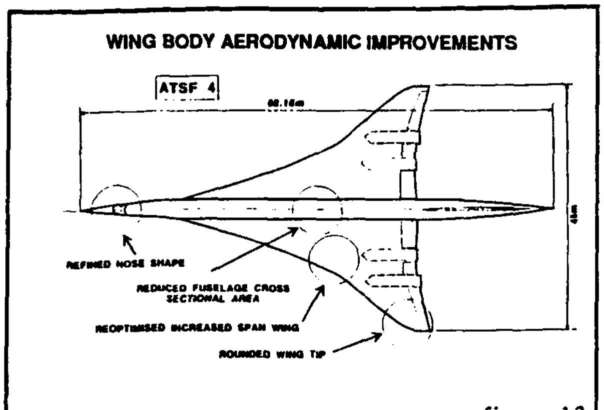



figure 13

**Affinement de la pointe avant**

Par modification de l'aménagement du cockpit initial (celui de Concorde), grâce à l'expérience acquise sur l'Airbus A320, il est possible d'affiner la forme externe de la partie avant d'Alliance.

La disposition des instruments et l'accès au poste sont améliorés sur Alliance, bien que la largeur du cockpit soit réduite de 150 mm et le plafond abaissé de 50 mm (Fig.14).

La répartition des aires de section droites est légèrement meilleure, qui se traduit par une diminution de la traînée d'onde, mais c'est surtout la discontinuité qui amène un gain, plus important que prévu de 100 $\Delta Cx = 0.0097$, équivalent sur une mission de 10000 km à un gain de plus de 500 kg sur la masse structurale ou sur la charge marchande.

Une attention particulière devra être porté sur l'état de surface de la pointe avant, de manière à réduire au minimum possible la traînée parasite associée aux imperfections de surface (bande pare-foudre, joints, sondes anémométriques et générateurs de tourbillons).

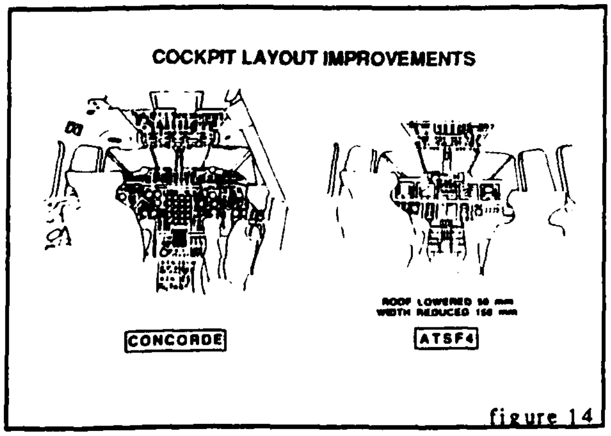



figure 14

**Dessin de la voilure**

La voilure d'un tel avion doit être mince (épaisseur relative voisine de 2%), légère, résistante aux charges statiques et dynamiques (rafales, manoeuvres, aéroélasticité, flottement...). La souplesse probable de la voilure et les déformations en vol doivent être prises en compte pour permettre d'assurer une forme dont la traînée sera minimale en croisière pour un centrage correct de l'avion.

La forme finale intégrera par contre toutes les contraintes de conception, telles que les chargements aérodynamiques, la répartition des réservoirs et des masses, l'échauffement cinétique, l'installation des systèmes...

De bonnes performances et qualités de vol à travers l'ensemble du domaine de vol (normal et périphérique)doivent être obtenus, notamment aux grandes incidences à faible vitesse, avec les marges nécessaires pour le contrôle de l'avion lors des passages en transsonique.

Sur Alliance, la forme initiale de la voilure ATSF1 résultant d'une importante étude théorique et d'une série de corrélations théorie / essais.
Les effets favorables d'augmentation d'envergure, prédits théoriquement et mesurés en soufflerie ont conduit à la forme voilure de l'ATSF3 (Fig.15).

Cependant, et bien que la finesse avion dans toutes les phases de vol aie été améliorée, il a été décidé de réduire l'allongement de la voilure Alliance par une diminution d'envergure; dans le but d'abaisser le poids structural de la configuration actuelle - ATSF4.

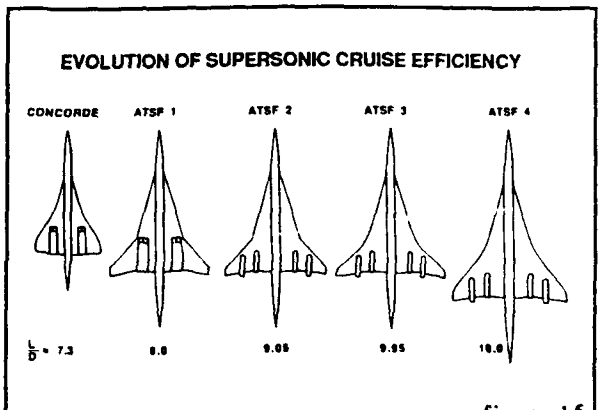



figure 15

Des petits gains supplémentaires ont été obtenus en arrondissant les extrémités de la voilure, et en optimisant la cambrure et le vrillage pour la croisière.
Alliance possède un onglet de voilure relativement épais, ce qui en plus de donner du volume pour les réservoirs, réduit la traînée d'onde de l'avion et permet de rétracter le train principal d'atterrissage constitué de trois parties vers l'avant, à l'intérieur du profil et du fuselage.
On évite de ce fait la pénalité de traînée et de masse qu'entraînerai la présence d'un carénage de train. L'absence de carénage ayant un autre avantage, en éliminant l'effet de masque par rapport à l'échauffement cinétique, et en réduisant le niveau des contraintes thermiques dans cette zone.
En effet l'allure de la répartition de sections droites contribue à minimiser la traînée d'onde de l'avion (Fig. 16).
La loi des aires optimale pour l'avion est réalisée en sculptant l'épaisseur voilure, permettant ainsi de conserver une section courante du fuselage constante.
Une intégration optimale des quatre moteurs séparés et de leur entrées d'air respectives devrait contribuer à minimiser la traînée d'installation et réduire la traînée totale de l'avion.

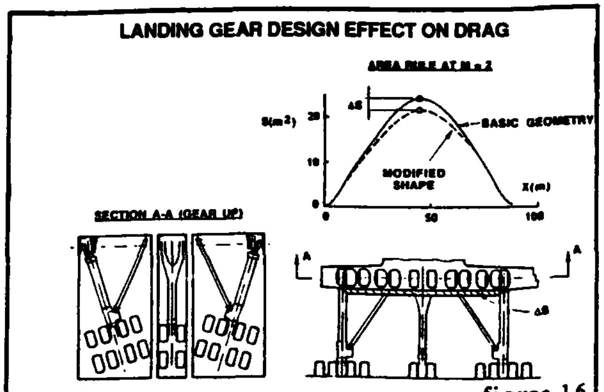


figure 16

Des gains supplémentaires nécessiterait l'utilisation d'une voilure laminaire avec contrôle de la couche limite, mais l'application possible d'une telle technologie à l'avion supersonique n'est pas envisagée à moyen terme.

### 5.2.2 Structures et Matériaux

Le prochain avion supersonique sera caractérisé par l'application de nouveaux matériaux et concepts structuraux, car toute réduction de masse structurale est importante pour l'amélioration des performances globales de l'avion. Ainsi des gains de l'ordre de 20% sont attendus par rapport aux technologies actuelles.
De manière à réduire les masses, les alliages de titane sont envisagées pour le caisson central de la voilure, ainsi que des alliages légers d'aluminium (fuselage). Par contre, la proportion de matériaux composites utilisés sera relativement plus importante que sur les avions actuels. Ainsi de nombreuses pièces ou ensemble structuraux seront réalisés entièrement en composites comme le radôme, la pointe arrière du fuselage, l'aile externe, la dérive, les surfaces mobiles, les trappes de train ... (Fig. 17)
Mais à cause des températures élevées rencontrées en vol, supérieure à 100° C sur la peau de l'avion, et de la durée de vie envisagée pour la cellule; une évaluation préliminaire des caractéristiques et des essais de qualification (vieillissement thermique, fluage...) sur différentes familles de composites sont en cours.

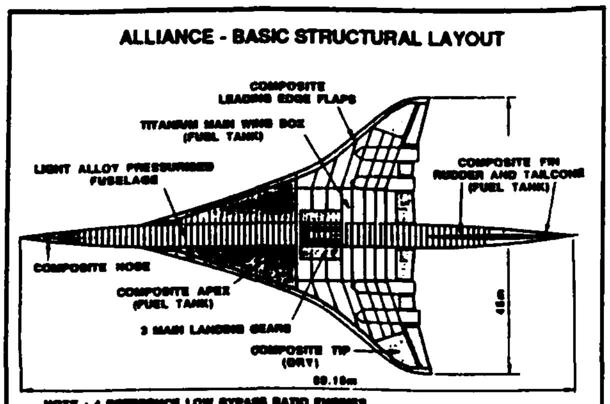


figure 17

### 5.2.3 Les Systèmes

Les systèmes de cet avion bénéficieront pleinement de l'évolution actuelle pour les avions subsoniques. Les commandes de vol et les systèmes pour le cockpit seront issus directement des dernières avancées technologiques disponibles au lancement du programme et incorporés sur l'avion.
Des développements spécifiques seront nécessaires, en particulier pour le système de contrôle des entrées d'air, pour les problèmes liés aux températures ambiantes élevées et à cause de la nécessité de diminuer l'encombrement des différents éléments : servocommandes, conditionnement d'air, systèmes de génération de puissance électrique et hydraulique.
Le carburant utilisé sera le même kérosène que pour les avions subsoniques. La température du carburant s'élevant au contact de la structure chaude et en raison des durée de vol élevée (5-6h), il faut prévoir dès le début de la conception une gestion du bilan thermique de l'avion.
Une caractéristique particulière de cet avion vient du fait que la masse importante de carburant stockée dans la voilure sert aussi de puits de chaleur efficace pour absorber l'échauffement cinétique de la structure.
La température maximale du carburant admissible à l'entrée des moteurs en fonctionnement normal est voisine de 150°C. Et si l'on considère l'évolution en cours de mission de la température du carburant à l'intérieur d'un réservoir situé près du bord d'attaque de la voilure, une comparaison avec Concorde montre qu'à condition de bien gérer l'utilisation des réservoirs, ce point est moins critique que sur Concorde (Fig. 18).

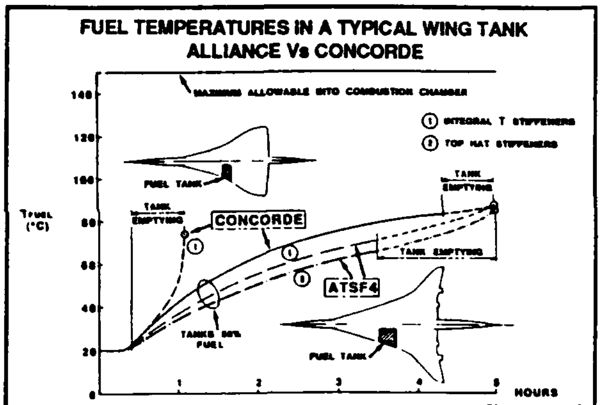


figure 18

### 5.2.4 La Propulsion

La viabilité de ce programme dépend fortement de la disponibilité en temps voulu d'un moteur devant répondre à plusieurs critères :

- une faible consommation spécifique en subsonique et supersonique pour des raisons économiques d'exploitation;

- des niveaux de bruit et d'émissions respectant les réglementations actuelles ou à venir;

- un développement en temps voulu des technologies nécessaires pour ce concept.

Le moteur Turbojet Olympus de Concorde, bien que donnant des performances en vol supersonique excellentes, a une consommation en subsonique et des vitesses d'éjection bien trop élevées pour une exploitation économique et les limitations de bruit actuelles.

### Les moteurs candidats

Pour répondre à ces objectifs, le concept de moteur à cycle variable est apparu chez les motoristes, qui ont suivi deux directions différentes (Fig. 19).

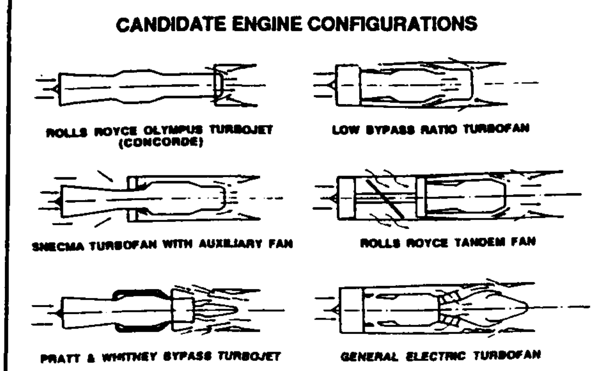


figure 19

Ainsi, en Europe, pour réduire le bruit SNECMA et ROLLS ROYCE étudie la possibilité d'ajouter au décollage une partie importante du flux secondaire au flux primaire d'un turbofan à faible taux de dilution. Dans ce cas les vitesses d'éjection sont faibles.

Aux Etats-Unis, PRATT & WHITNEY propose un monoflux ayant un système de by-pass autour des chambres de combustion et de la turbine, et un système d'éjecteur en aval de la turbine entraîne un débit important. GENERAL ELECTRIC propose un moteur double flux à cycle *variable*, muni d'un système qui inverse les écoulements chaud et froid à la sortie.

Pour ces deux moteurs sans leur dispositif d'éjection, la vitesse maximale d'éjection (définie par le rapport poussée / débit moteur) est deux fois plus élevée que celle des moteurs à soufflante secondaire.

L'installation sur Alliance de ces quatre types de moteurs est en cours d'étude.

### L'intégration motrice

Dans ce domaine, les interactions entre le constructeur et le motoriste sont cruciales, de manière à réaliser l'installation du moteur et le dessin de l'entrée d'air permettant un bon fonctionnement du moteur dans l'ensemble du domaine de vol et pour différentes conditions.

L'installation typique d'un moteur double-flux requiert de nombreux efforts pour obtenir une faible traînée d'installation. Le moteur externe est généralement le plus difficile à installer en raison de la faible épaisseur de la voilure a cet endroit, et du fait de la localisation des accessoires et systèmes au-dessus du corps du moteur pour éviter toute pénalité de traînée (Fig. 20).

Le principe retenu pour le dessin de l'entrée d'air est d'utiliser deux entrées d'air type Concorde disposées à la verticale et dos à dos. Ce qui permet de réduire la longueur de l'ensemble propulsif et d'améliorer la traînée (voir Fig. 15).

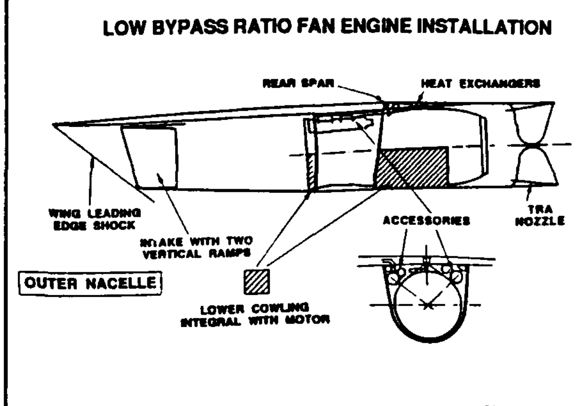


figure 20

### 5.2.5 Les Performances en mission

L'objectif de performances général est de transporter au moins deux fois plus de passagers que Concorde sur une distance deux fois plus grande, ce qui se traduit par une consommation par passager et par km de 45g/passager/km à comparer avec 100 g/passager/km pour Concorde.
Les coûts directs d'exploitation par passager et par étape sont au moins 50 % supérieur à ceux d'un avion subsonique. On peut remarquer que la vitesse est un facteur favorable sur la part relative des postes de maintenance, équipage (moins d'heures de vol), des charges aéroportuaires.
Mais, l'accroissement important du poste carburant pour l'avion supersonique, montre la très grande sensibilité des coûts directs d'exploitation à ce paramètre (Fig. 21).

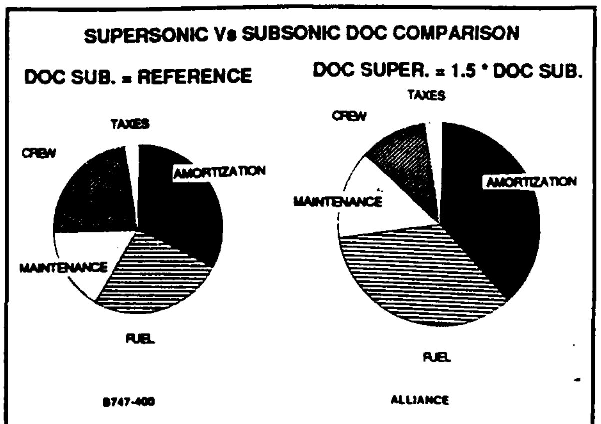


figure 21

**Possibilités pour l'amélioration des performances en mission**

En étudiant quelques caractéristiques de l'avion sur la mission nominale, on obtient les taux d'échanges suivant :

- $\Delta$MTOW = -1% ---> $\Delta$Carburant bloc = -2%

- $\Delta$Finesse = +1% ---> $\Delta$Carburant bloc = -1%

- $\Delta$Cs moteur = -1% ---> $\Delta$Carburant bloc = -1%

où - MTOW : Masse maximale au décollage

- Cs moteur = Consommation spécifique du moteur en croisière.

Ces valeurs montrent clairement que si des efforts sont menés dans différents domaines tels que les masses, l'aérodynamique, la consommation des moteurs, ils auront un impact significatif sur les performances et l'exploitation économique de l'avion.

## 6. La Coopération Internationale

Le succès du développement d'un programme d'avion supersonique sera basé sur une large coopération internationale pour les raisons suivantes :

- les coûts de développement et les risques élevés par rapport aux projets subsoniques;

- la nécessité de pénétrer le marché mondial et de collaborer avec les autorités officielles sur les questions de réglementations.

Aerospatiale consciente de cette nécessité est impliquée suivant deux axes de coopération privilégiés.

### 6.1 La Coopération avec British Aerospace

Grâce à la longue expérience de coopération bilatérale qui a débuté dès 1962, Aerospatiale et British Aerospace se sont retrouvés en 1990, pour étudier ensemble le futur avion de transport supersonique ensemble. En se basant sur des hypothèses de définition identiques les deux sociétés ont développé indépendamment deux configurations différentes : AST pour British Aerospace (Fig. 22) et Alliance pour Aerospatiale.
L'activité technique commune vise principalement à identifier pour chaque configuration les points techniques critiques et entreprendre les travail et les échanges nécessaires pour converger rapidement vers une configuration unique.

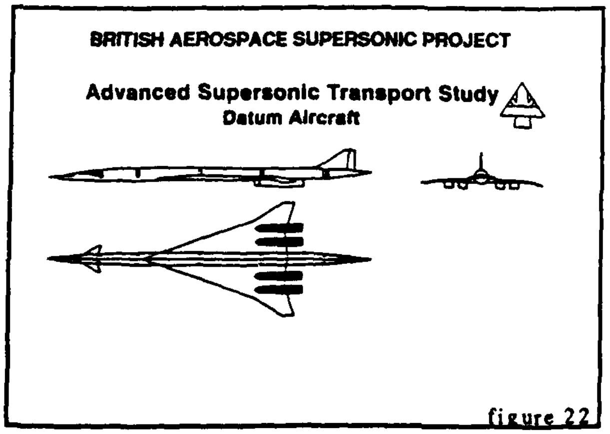


figure 22

### 6.2 Le Groupe International d'étude pour le transport commercial supersonique

Depuis mi-1990, British Aerospace, Boeing, Deutsche Airbus, Mc Donnell Douglas, and Aerospatiale ont commencé à coopérer sur le projet d'avion supersonique. Ce groupe étudie plus particulièrement les possibilités et les intérêts de mener un tel programme en coopération.
En 1991, Alenia, l'industrie Japonaise - JADC - et Tupolev se joint à ce groupe d'étude. Et les principaux aspects étudiés par ce groupe élargi sont les études de marché, les questions liées à l'environnement (bruit, bang sonique, émissions) et à la certification.

## 7. Conclusion

Il apparait probable à la lueur de cet exposé que dans la première décennie du 21ème siècle, le successeur de Concorde sera un avion de transport supersonique de seconde génération volant à Mach 2.
Le respect des contraintes et réglementations liées à l'environnement sera un point clé pour le succès du programme.
Les études sur la faisabilité technique conduites jusqu'ici sont encourageantes, et les améliorations nécessaires sont envisageables dans les quinze années à venir, notamment au niveau de l'aérodynamique, des matériaux, des moteurs...
En raison des coûts et des risques élevés de développement technologiques pour assurer une exploitation économique de l'avion et réussir à pénétrer le marché au niveau mondial, une coopération internationale étendue sera indispensable.

## 8. Références

1 *"Concorde successor: Mach 2 or Mach 5?"*
P. Picq
International symposium on Japan's National Project for a Super/Hypersonic Transport Propulsion System
Tokyo, Oct. 1992

2 *"Etude d'un avion de transport supersonique croisant à Mach 2"*
D. Collard
Symposium Européen sur l'Avenir du Transport Aérien à Grande Vitesse
Strasbourg, Nov. 1989

3 *"Second generation supersonic transport studies at Aerospatiale"*
D. Collard
RAe - Birmingham, Sept. 1992

4 *"Hypothèses de définition de la configuration Alliance"*
J-L. Galvani
Aerospatiale, Mar. 1993

# THE CASE FOR SURFACE EFFECT RESEARCH, PLATFORM APPLICATIONS & TECHNOLOGY DEVELOPMENT OPPORTUNITIES

**J. M. L. Reeves, C.Eng., MRAeS**
**Naval Air Warfare Center, (Aircraft Division)**
**Warminster, Pennsylvania 18974-0591**
USA

**1.0 SUMMARY**
In 1962, while walking to the Blackburn Aircraft Cafeteria at Holme-on-Spalding Moor, one sunny evening, the author became aware of the grass flattening ahead of him. Moments later, a Blackburn Buccaneer prototype flew overhead at over 500 knots. This was the author's first exposure to high speed surface ("ground") effect.

This paper commences by defining the conventional understanding of Surface Effect phenomenon and compares theories which show small reductions in drag occur above one span height above the surface. A discussion on reports of pilots who have flown their aircraft in surface effect ensues. From this, a broader understanding of surface effect is developed supported by low speed wind tunnel tests and Russian published technical documentation.

The author divides surface effect platforms or, perhaps, better described as Enhanced Performance Low Flying Platforms (EPLFP's) into three distinct categories. Potential applications of surface effect platforms are discussed based on the changing world, the evolving airline industry and airport constraints. Missions and specific mission examples are given. Reasons for the pursuit of rather large platforms ar[illegible]ed as are some of the major technical hurdles which will have to be overcome for them to succeed. Technology opportunities are discussed. A summary concludes the paper.

## 2.0 SURFACE EFFECT

This section discusses surface effect as generally understood, pilot reports of flying aircraft in surface effect, and an expanded understanding of surface effect based on both flight reports, wind tunnel results and Russian documentation.

### 2.1 Conventional Understanding of Surface Effect Phenomenon

When an aircraft nears a surface, a change occurs in the three dimensional flow pattern because the local airflow has an almost insignificant vertical component at the surface. Thus the surface becomes a restriction to the flow and alters the wing upwash, downwash and wing tip vortices reducing the induced drag and increasing lift. A smaller angle of attack is required near the surface to produce a given amount of lift versus that required in freestream conditions at altitude or roughly one span height above the surface. For the same angle of attack the induced drag is reduced, reducing the thrust required for a given lift and reducing the stall margin. When an aircraft gets close enough to a surface, the flow in the confined region beneath the wing and wake approach two-dimensional channel flow with known boundaries and known mass addition, coming from the flow tangency boundary condition on the lower surface. (The lift coefficient of the wing, with the upper surface neglected, is only a function of planform and shape of the wing lower surface, [Reference 1]). Based on Reference 2, the equation below gives the lift on the bottom surface, assuming two dimensional channel flow, as:

$$CLr = I_{0}^{1.0} \left( 1.0 - \left\{ \frac{\dfrac{h_{(te)} - delta_{(te)}}{\cos[alpha]}}{\dfrac{h_{(te)} - delta_{(x)} + (c - X) * \sin[alpha]}{\cos(alpha)}} \right\}^{2.0} \right) d(x/l)$$

where:

x = distance downstream of leading edge
c = wing chord
CLr = ram lift coefficient
delta (te) = boundary layer thickness @ trailing edge
delta (x) = boundary layer thickness @ "x"
I = integral
h (te) = trailing edge height above the surface
alpha = angle of attack
l = projected chord length = c * cos[alpha]
X = x/(cos[alpha])

This equation emphasizes, through the growth of the boundary layer, the importance of chord in generating ram lift in surface effect. When the trailing edge is at an infinitesimal distance from the surface, the velocity in the boundary layer must be equal to the freestream velocity. This suggests a change in the nature of the boundary layer. This equation also suggests, that, should the flow transition from laminar to turbulent, there will be a change in lift because of the difference in the thickness growth between the laminar and turbulent boundary layers.

The lift coefficient on the bottom surface should approach unity and the maximum lift coefficient on the top surface could approach 0.6.

$$CLtotal = CLu + CLr$$

where:

CLu = Lift of the Upper Surface

This suggests a maximum lift coefficient of about 1.6. Whether this can be increased with leading edge devices and trailing edge devices with boundary layer control (BLC) is uncertain.

The maximum obtainable lift coefficient is clearly a major issue. Current commercial airliners are able to achieve a CLmax of about 2.4 - 3.6 and have take-off speeds of between 125 - 165 knots depending on the type and weight of the airliner in question. The take-off of speed for a surface effect platform having maximum lift coefficient of 1.6 with the same wing loading as a Boeing 747-400 without a thrust augmented ram, would be of the order of 200 knots. To obtain a take-off speed of the same order as current commercial transport aircraft requires a wing loading of less than 80lbs/ft**2. The reduction of take-off and landing speeds of platforms in surface effect represent a major technical challenge and major opportunity for a research effort.

To estimate the drag associated with lift in surface effect, one of two theories are generally used for quick approximations along with an empirical formula developed by NASA (National Aeronautics and Space Administration). The latter are for wings without endplates. Figure 1 shows a comparison of the two theories, Wieselsberger and finite element (Brock and Houghton) in terms of percentage induced drag reduction as a function of height to span ratio. The NASA empirical formula (Reference 3) is not shown since it is only valid between h/b = 0.033 to h/b= 0.25. Note as with induced drag which is primarily a function of span:

$$CDi = \frac{K*CL*CL}{Pi*AR} = \frac{K*CL*CL*S}{Pi*b*b}$$

where:

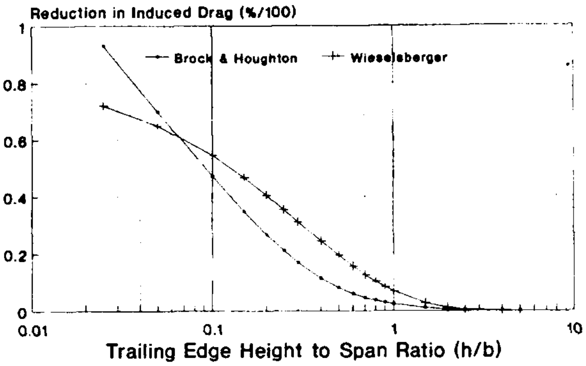
K = 1/e – Oswald Efficiency Factor
S = Wing Area
AR = Aspect Ratio
CL = Lift Coefficient
b = Span
Pi = 3.14159

the reduction in induced drag in surface effect as predicted by theory, is a function of span and height of the trailing edge above the surface only. An almost imperceptible induced drag reduction occurs at 5 span heights above the ground. As a span height above the ground is reached, the reduction in induced drag is 2.4% and 6.9% for the finite element theory and Wieselsberger theory, respectively. This could equate to a 1.2 to 3.5% reduction in total aircraft drag. At a trailing edge height to span ratio of 0.025 there is a significant discrepancy between both theories and also the NASA empirical equation for reduction in

*Presented at an AGARD Meeting on 'Recent Advances in Long Range and Long Endurance Operation of Aircraft', May 1993.*

drag in surface effect. The use of endplates can either increase or decrease the induced drag reduction. These theories underscore the importance of keeping the wing of a surface effect platform as close to the surface as possible. They also show that the real benefit of surface effect occurs when height to span ratios are less than 0.3. This has been confirmed by numerous wind tunnel tests and is of significance for waterborne platforms in particular.

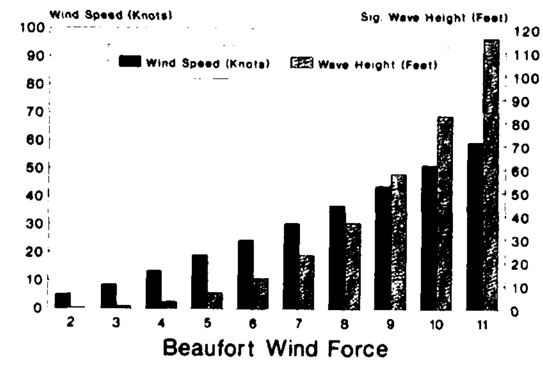
## Induced Drag Comparison
### Reduction In Surface Effect




1. Percentage Reduction in Induced Drag as a Function of Height above the Ground.

Assuming an amphibious or non-amphibious waterborne platform, if we use the Hovercraft/Hydrofoil rule of thumb that the maximum sea state is governed by the significant wave height and that the distance between the surface and the hard structure is equal to the significant wave height, we have the limitations shown in Figure 2 as a function of wind speed. For large platforms, an operating sea state of 6 may be required. This would give a keel to hard structure height of 15ft. For a 3,500,000lb platform a wing span of about 375 feet might be appropriate which gives a trailing edge height to span ratio of 0.05 for a clearance of 3.75 ft. A land based surface effect platform might have a height to span ratio of about 0.0375. This would give a reduction in induced drag of between 63% to 70% depending on the theory used. Thus, if a reasonable open ocean capability is to be obtained for a waterborne platform, flying in surface effect, the platform must be necessarily large.

## Sea State, Wind Speeds and Wave Heights
### Fully Arisen Sea




2. Significant Wave Height and Wind Speed versus Sea State

### 2.2 Pilot Reports

In 1989, Stephan F. Hooker, President of Aerocon Inc., presented a paper (Reference 4) in which he reported there was consistent evidence of surface ("ground") effect above one wing span and improved handling qualities for aircraft with low aspect ratio wings including the F-104 Starfighter and XB-70 Valkyrie. Pilot reports of aircraft flying in surface effect are quite numerous. For all the aircraft shown, Table 1, pilots have reported an improved ride quality at heights at or below 500 feet above the surface which equate to more than five (5) span heights above the ground. Generally, the delta winged aircraft were singled out as having the greatest improvement in ride quality. Six aircraft are of note in low level flight excursions.

## Flight In Surface Effect
### Conventional Aircraft

| Type | Country & Service | Speed |
|---|---|---|
| F-105D | U.S. Air Force | M•1.28 |
| B-58 | U.S. Air Force | M•1.05+ |
| F-106A | U.S. Air Force | M•0.92 |
| B-1B | U.S. Air Force | M•0.95+ |
| A-4 | U.S. Navy | M•0.7+ |
| A-3 | U.S. Navy | M•0.7+ |
| Vulcan B.Mk.2 | U.K. Air Force | M•0.5+ |
| Buccaneer S.Mk.1 & 2 | U.K. Navy/Air Force | M•0.85+ |
| Tornado | U.K. Air Force | M•0.85+ |
| Entendard IVM | Argentine | M•0.7+ |

Table 1

1. Flight in Surface Effect, Conventional Aircraft

### 2.21 Thunderchief, F-105D

The Thunderchief (Figure 3) was identified as having flown supersonically in surface/ground effect on video on the Discovery Channel in November of 1992. A follow-up conversation with the pilot confirmed that this was achieved on a relatively turbulent day with the use of afterburner from a dive from 15,000ft. A speed of 849 knots IAS (Mach=1.285) was attained over the range at Eglin Air Force Base in Florida. The pilot claimed that he flew below 50ft above the ground at the latter speed and that the aircraft was rock steady. Apparently, only two feet of the vertical tail was visible, the rest of the aircraft was immersed in shock waves. The maximum level flight speed of the Thunderchief is 810kts CAS or Mach=1.23 at sea level. The pilot stated that flying in surface effect desensitized the aircraft to thermal and wind turbulence.

3. Republic Thunderchief, F-105D

The Thunderchief has, perhaps, the highest allowable indicated airspeed at sea level of any aircraft that has reached production. This particular aircraft exceeded the speed and Mach number of a World Airspeed record held by a Navy F-4A Phantom, of Mach=1.2, 783.9kts at 328ft above the ground. According to the pilot, the F-105 Thunderchief and F-104 Starfighter gave the smoothest rides at high speeds.

The Thunderchief was powered by an afterburning and water injected Pratt and Whitney J-75 engine. As with all turbojet and low bypass ratio turbofans the thrust initially decreases and then increases through the high subsonic and supersonic flight regimes at sea level. Similarly specific fuel consumption has the same characteristic and with afterburner engaged will be in excess of 2.0 for sea level static conditions and subsonic, transonic and supersonic flight conditions. A rough estimate of thrust at the 849kts is between 30,000 and 34,000lbs and drag of the order of 35,000lbs in the clean configuration. For the flight in question in surface effect, no friction or form drag reduction would be expected because the wing would need to be less than 6ft off the ground. Additional analysis would be necessary to fully understand this particular event but it does seem there was a possible reduction in drag.

The Thunderchief used conventional ailerons for low speed control and five sections of hydraulically operated spoilers ahead of the flaps for roll control at medium and high speeds. All control surfaces were actuated by fully powered tandem jacks. It had an all-moving tailplane and the hydraulic system was a 3,000lb/in$^2$ in system.

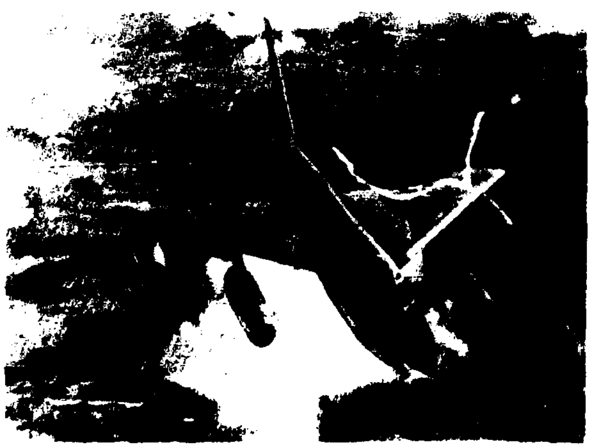
**2.22 General Dynamics/Convair Delta Dart, F-106**

On March 1, 1960, a Convair Delta Dart (Figure 4) flew a distance of 260 nautical miles at an average speed of 610 knots {Mach=0.92} at between 50ft and 300ft above the Southern California desert in turbulent air. Although a special automatic control damper system to improve ride quality was fitted specially for the flight, the pilot did not find a need to use it. It also carried empty external fuel tanks to increase its drag.


4. Convair Delta Dart, F–106

**2.23 General Dynamics/Convair Hustler, B-58**

On September 18, 1959, a General Dynamics/Convair B-58 Hustler (Figure 5) flew from Carswell Air Force Base, Texas, to Edwards Air Force Base, California, a distance of 1217 n.m. in precisely two hours at Mach 0.92 at heights below 500ft and as low as 200ft. According to Reference 5, the aircraft exceeded its performance predictions. At this speed the aircraft could not be heard until it was approximately at right angles to an observer and at two miles away from its flight path, its sound was barely discernable. The aircraft gave a smooth ride even in turbulent conditions. The pilot claimed that the flight was extremely comfortable with no problems regarding tunnel vision, mental or physical stress. The return trip was flown at 37,000ft for a total distance of 1052 n.m. in 2 hours and 3 minutes. The average speed was 610 knots on the outbound leg to Edwards Air Force Base and 510 knots on the return to Carswell Air Force Base. At the same Mach number, the aircraft flies about 80 knots faster at sea level.



5. General Dynamics/Convair Hustler, B–58A

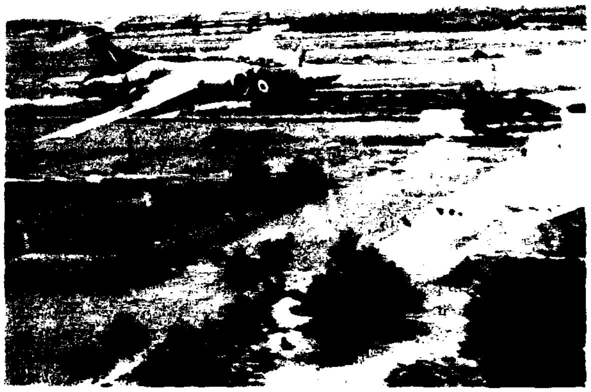
The B-58 was powered by four General Electric J79-GE-5B turbojets delivering a total of 62,000lbs of thrust with full afterburner for all four engines. The aircraft was 96 feet long, 31 feet high and had a wing span of 56 feet. The B-58 had a three man crew and had a maximum take-off weight of 163,000lbs and a maximum flight weight of 177,000lbs. At sea level the aircraft could go supersonic at maximum cruise thrust without afterburner. According to the pilots, the only indication that the Hustler was flying supersonic at sea level was the Mach meter. The aircraft was capable of Mach 1.05+ at full military power without afterburner. Its structural weight was a record low of 14% of the aircraft maximum take-off gross weight. This achievement was made possible by the extensive use of honeycomb sandwich panels.

**2.24 B-1B**

The smooth ride in a B-1B at 400ft above the ground and between 540 to 580 knots is noted in Reference 6. This occurs when the wings are at maximum sweep where, of course, the lift curve slope is reduced, significantly. However, the aircraft has an extremely high wing loading of about 245lbs/ft**2 which is likely to have more influence than the lift-curve slope.

**2.25 Blackburn Buccaneer S.Mk.2**

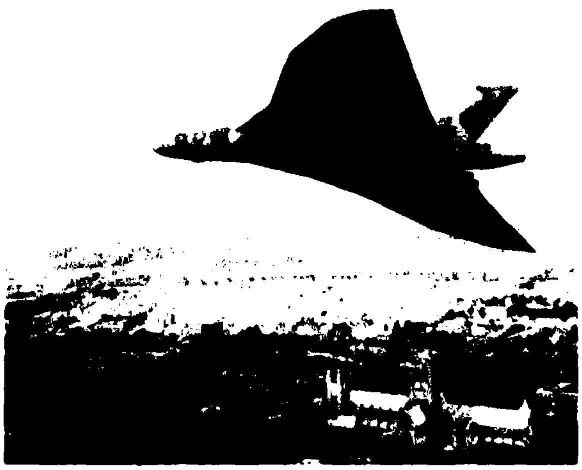
The Buccaneer (Figure 6) was designed as a true low level strike aircraft. Its operational requirement was influenced by the WWII experience of DeHaviland Mosquito aircraft which flew at extremely low levels on some missions. The Buccaneer's good ride quality at 580 knots at 100ft above the sea is mentioned in Reference 7. At this altitude pilots also execute maximum rate turns, so precise are the flying qualities of the aircraft.



6. Blackburn Buccaneer, S.Mk.2

**2.26 Avro Vulcan B.Mk.2**

The Vulcan (Figure 7) was designed to fly at high altitude at high subsonic speeds. At altitude, it could cruise at up to Mach 0.94. In order to achieve this, it was necessary to use a low wing loading of 56.5lbs/ft**2. The aspect ratio of the wing was 3.1. The aircraft achieved a rather remarkable lift/drag ratio of 17.5 at high subsonic speed. The bomber grossed about 224,000lbs and had a rather high empty weight/maximum take-off weight ratio of 60%. The aircraft set up a number of high subsonic speed records. Although the aircraft was supposed to have rather poor ride quality at low level, when it descended to extremely low level, the ride quality improved substantially. Except for the XB-70 Valkyrie and Concorde, it had the longest wing mean chord of any aircraft flying.



7. Avro Vulcan, B.Mk.2

**2.27 Pilot Report Summary**

From the foregoing it has emerged that flying closer to a surface appears to improve ride quality for all the aircraft mentioned. Perhaps, the most surprising improvement was that of the Vulcan bomber which seemed to be highly regarded in this respect together with the Buccaneer. The Buccaneer had over twice the wing loading of the Vulcan. Simple theory, which can only be used as a rough guide, expresses incremental normal force for a gust to be:

$$\text{Delta N} = \frac{\text{Rho} * \text{Kat} * \text{Ug} * \text{Vinf} * \text{dCL/dAlpha}}{2 * \text{W/S}}$$

where:

dCL/dAlpha = PI*AR/(1 + (((AR/2*cos(Lamda))**2)+1)**0.5)
Rho = Density of Air (slugs/ft**3)
AR = Aspect Ratio
Ug = Vertical Gust Velocity (ft/sec)
Vinf = Flight Velocity (ft/sec)
W/S = Wing Loading (ft/sec)
Kat = Attenuation Factor
Lamda = Leading Edge Sweep (degrees)

This leads to two interesting observations. The first is that the faster the aircraft is flying, the greater the gust load factor and, therefore, the rougher the ride. The second is that the higher the wing loading the smoother the ride. However, the Vulcan did not follow this trend.

Although aircraft of various types have flown at extremely low level, there is no data on these particular aircraft that confirms the ride quality trend. In surface effect, there is an increase in lift curve slope close to a surface, the theoretical maximum of 2Pi radians can be exceeded. This should suggest that the ride would become rougher rather than smoother in surface effect.

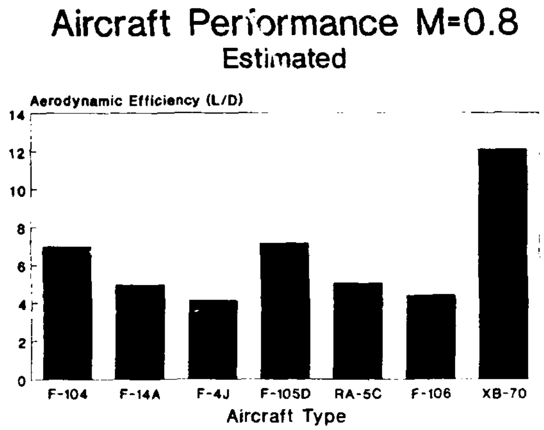
Again for these particular aircraft, there is little data to support the hypothesis that there is a drag reduction at subsonic, transonic and supersonic speeds when flying close to a surface. The main reason for this appears to be that either the pilots are too busy flying the aircraft or that it had not occurred to the pilots, flight test engineers and aerodynamicists alike, that a drag reduction occurs which could be shown through observing the fuel flow. In addition, it is doubtful, if any wind tunnel data exists on aircraft at subsonic, transonic and supersonic speeds showing changes in force and moment characteristics as a function of height above the surface. However, as discussed later in this paper, Russian data does exist which shows a reduction in profile drag and that drag due to lift reductions do occur throughout the high subsonic Mach number range.

If aircraft can fly low enough at transonic speeds, we can postulate that a drag reduction might occur on the basis of an analogy with the supercritical wing. At supercritical Mach numbers, a broad region of locally supersonic flow extends vertically. The region of locally supersonic flow usually terminates in a shock wave which results in much increased drag. The much flatter shape of the upper surface of the supercritical section causes the shock wave to occur further downstream and therefore, reduces its strength. Thus the pressure rise across the shock wave is reduced with a corresponding reduction in drag. However, the reduced camber/flatter profile of the upper surface results in a reduced lift coefficient which must be compensated by increased lift from the region of the airfoil aft of the shock wave. This requires a positive camber or the equivalent of positive flap deflection at the wing trailing edge. In surface effect we can obtain additional lift or redistribute the contributions to total lift of the upper and lower surfaces of an airfoil by flying closer to a surface. As we fly closer to a surface, the lift distribution on the airfoil changes, the lower surface providing more and more lift as height above the ground is decreased. By off-loading the wing upper surface, the local velocities on the upper surface of the airfoil are decreased and the drag of the wing is decreased.

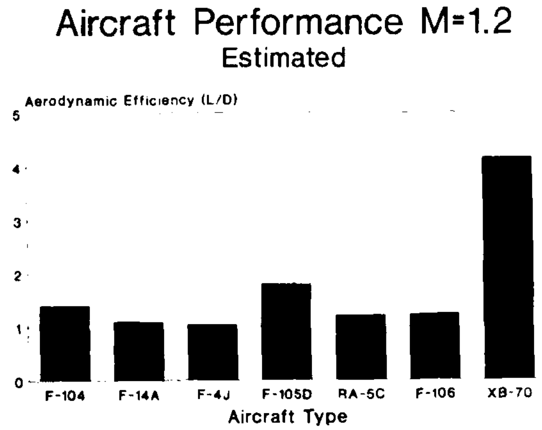
Finally, it is very clear that no special control system is needed for low level flight, and that there appear to be no unusual physical and mental problems associated with low level flight.

**2.3 Aircraft Performance Comparison at Low Level**

Figures 8 and 9 show the calculated L/D's for a number of aircraft at a Mach Number of 0.8 and 1.2, respectively, based on drag curves presented in Reference 8. These curves are not corrected for flying in surface effect. The purpose of them is to show, that, as perhaps expected, small delta wing aircraft are not as efficient as swept or straight wing aircraft at normal subsonic speeds. However, at very high subsonic M=0.92+, transonically and supersonically, they tend to be better or perhaps as competitive and significantly more maneuverable at low altitude. The French claim that in an assessment of maneuverability, the delta winged aircraft proved far superior (Reference 9). The Thunderchief F-105D and Starfighter F-104 were both reported as having extremely good ride quality at low level. Both had high wing loadings of 140 lbs/ft**2 and 143 lbs/ft**2, respectively versus the 68.1 lbs/ft**2 of the delta winged F-106. Aspect ratios ranged from a low of 2.31 for the F-106 to a high of 3.17 for the F-105. The Valkyrie with a wing loading of 81.78 lbs/ft**2 and wing aspect ratio of 1.75 had poor ride quality owing to its overly long nose ahead of the center of gravity. The nose essentially acted as a pendulum and control of the aircraft because of cockpit movement during turbulent landing conditions was said to be mildly challenging.




8. Aircraft Performance M=0.8

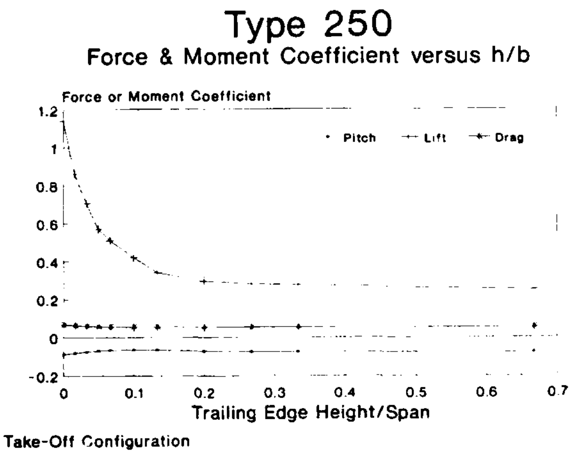



9. Aircraft Performance M=1.2

To obtain a low landing speed, delta winged airplanes require a significant wing angle of attack which usually makes visibility during take-off and landing unacceptable. The Concorde and Fairey Delta 2 solved this problem by using a drooping nose. Nevertheless, the reduced aerodynamic center travel, in and out of ground effect, and enhanced lift characteristics in surface effect suggests that the delta planform may be attractive for surface effect application, especially as the ram lift compensates for the high incidence normally required for take-off and landing.

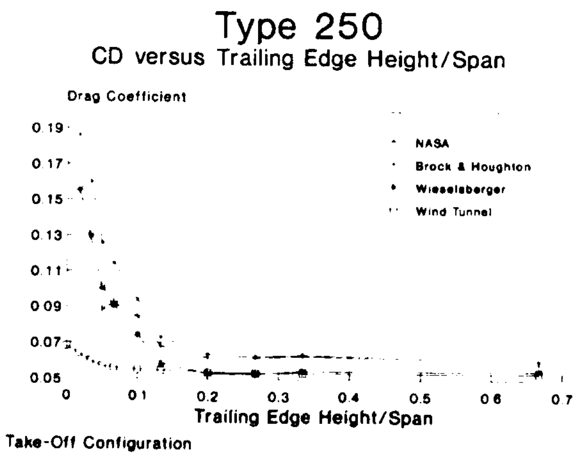
**2.4 Surface Effect. A Better Understanding.**

As has been mentioned above, one additional benefit of surface effect is increased ride quality which occurs at subsonic, transonic and supersonic speeds. Flying close to a surface clearly must have other effects. Because there is a pressure increase under a wing flying in surface effect, it seems clear that there are effects on the boundary layer. It also seems possible that there could be a reduction in form and perhaps in friction drag when flying close to the ground. Some of the aforesaid is supported by wind tunnel tests conducted on a ram wing in the U.K. in the mid 1960's. Although the tests were conducted in a low speed (150ft/sec speed) 4ft by 4ft tunnel with transition fixed on the model, some interesting trends have emerged. Figure 10 shows the pitching moment, lift and drag coefficients versus height for a wind tunnel model of a low aspect ratio AR=0.5, 60ft span, EPLFP in its take-off configuration. Of interest is the pitching moment curve which has a valley in it, the significant increase in lift coefficient once an h/b=0.15 is reached and the essentially constant drag coefficient even when the lift coefficient is increasing substantially. This shows that the Breguet range equation is not appropriate for this type of vehicle if we are cruising at CL's below 0.5.



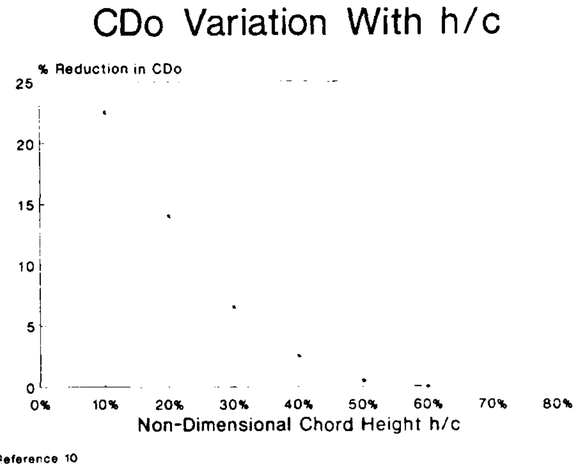

10. BL–250 CM, CL and CD versus Height above the Ground

Figure 11 shows the actual drag coefficient in the wind tunnel corrected to full scale size versus predictions. As can be seen theory seems to predict the drag coefficient reasonably well only to a non-dimensional height of (h/b) = 0.1666 or 10ft above the ground for this 60ft span platform. The Wieselsberger and Brock and Hougnton theories and NASA empirical equation results are shown. It is extremely difficult to offer an explanation. It could be a combination of form drag reduction, friction drag reduction and induced drag reduction. Reference 10, identified by Hooker in Reference 4, shows that there is a reduction in profile drag as a wing approaches the surface. This particular wing had a fixed angle of attack of 4.9 degrees. This was the only angle of attack analyzed. Although undersurface laminar flow was offered as a partial explanation, the authors were unable to establish how this mechanism works. Clearly, though, both friction and form drag reductions occurred. The profile drag reduction is plotted in Figure 12.




11. BL–250, CD vs Height above the Ground

A further report mentioned by Hooker in Reference 4 is Reference 11. This shows that there is a reduction in drag due to lift as the surface is approached even at high subsonic Mach numbers. Wave drag due to lift appeared to be absent at these Mach Numbers. The report also shows that the lift coefficient increases with Mach Number and likewise so does the pitching moment coefficient, indicating that the aerodynamic center moves aft as Mach is increased and height above the surface decreased. Similar trends, but not quite as significant, are shown for a wing and tail in Reference 12, also identified by Hooker in Reference 4. Here the effects of increased Mach and decreased height above the ground are not quite as significant. Although, the lift coefficient is likely to be low at high subsonic Mach Numbers, this is yet another beneficial effect of flying close to a surface or surfaces. The latter references suggest that surface effect, that is the height at which it is entered, is also a function of Mach Number. How aircraft shock waves impinging on a surface affect the performance and control of an aircraft is unknown.



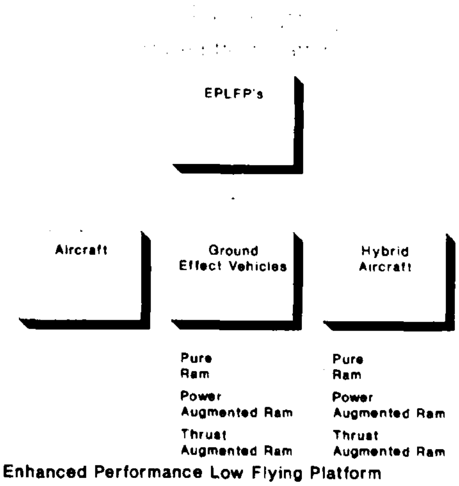

12. Reduction in Profile Drag versus Non–Dimensional Height above the Ground

Returning to the delta wing theme, Reference 13 suggests that the aerodynamic efficiency can be significantly increased by the use of vortex flaps and/or vortex plates. This allows Oswald efficiencies of up to 0.986 with 100% leading edge suction or induced drag factors down to 1.014 with 100% leading edge suction. In testing slender wings in ground effect, Reference 14 states that ground effect increases suction on the upper surface and pressure on the lower surface. This phenomena is unique to slender wings. In two dimensional flow on high aspect ratio wings for example, the suction is reduced owing to surface effects (Reference 15).

In summary, we can better define Surface Effect. Surface Effect deals with the aerodynamic, aeroelastic and aeroacoustic impacts on platforms flying within surface effect. The boundary of surface effect is a function of height above the surface. This height, itself, is also a function of Mach number.

### 3.0 SURFACE EFFECT PLATFORMS

Figure 13 defines three distinct categories of Enhanced Performance Low Flying Platforms.




13. EPLFP Family Benefitting From Surface Effect

Those land-based aircraft which have flown or do fly in surface effect rely upon relatively old technologies. With today's advances in computer electronics and sensor technology, flight of future aircraft close to the surface should pose few risks. Perhaps, flight at extremely low altitudes, where practical, should be encouraged because of the more comfortable ride, the less likelihood of being detected (flight below the optical horizon) and the lower acoustical signature and reduced fuel flows and therefore increased range and endurance. To be balanced against such a recommendation is the possible increase in crew work load, more likelihood of propulsion and airframe corrosion and perhaps decreased airframe fatigue life.

Ground Effect Vehicles are the total breadth of Russian efforts which are broadly categorized into amphibious and non-amphibious Ekranoplans and Dynamic Hovercraft. Although a number of articles have been published in the Western press, little is known of the Russian efforts. The press articles appear to be contradictory. However, various pictures and references to Russian Wing-in-Ground Effect platform development have appeared on Russian television news which is broadcast regularly on the cable networks around the U.S.A. Given the better understanding of Surface Effect, it is not surprising that development efforts are still underway even under the current Russian fiscal climate.

Hybrid aircraft are what could be classed as seaplane derivatives. The basic premise is that this is a platform with the capability to operate in surface effect and at high altitude when the need arises. This type of platform would have the capability of essentially being a ship or an aircraft. Because of the employment of surface effect technology it would be able to cruise efficiently at close to take-off speed, at a speed for best range of between 350 - 450 knots and to "dash" cruise at speeds above Mach=0.85. In addition, it would be able to fly at high altitude, perhaps up to 55,000ft at Mach numbers between 0.8 - 0.94+.

### 3.1 Potential Surface Effect Platform Applications

The following paragraphs discuss emerging constraints that may inhibit the use of large land planes. These constraints may be overcome by the development of platforms which operate from the sea. Although conventional land-based military aircraft clearly do operate in surface effect and can be designed to operate in surface effect, the major emphasis of the discussion is on the seaplane derivatives, platforms that operate from the sea.

### 3.11 The Changing World

As we look towards the future, we see an evolving new world which will undoubtedly result in territorial squabbles, disputes over raw materials and energy, and continued religious strife. Decreased defense budgets resulting from the political environment and economic environment, inevitably means fewer aircraft, ships, soldiers, less equipment, fewer foreign bases and a lack, perhaps, of overflight rights. This suggests less flexibility to engage in small conflicts and suggests the need for either presence and/or the ability to achieve a quick presence with adequate fire power from the sea to avoid bureaucratic delays associated with obtaining overflight and landing rights. Throughout the world there are only a limited number of airfields from which heavily laden bombers and transports can operate. Likewise, for ships there are a limited number of ports from which container and other large ships can operate. The accompanying chart, Chart 1, summarizes the world scene, emerging airline and airport trends, and ship port requirements/constraints.

### 3.12 Evolution in the Airline Industry

In terms of the airlines, there will likely be fewer carriers most of which may be multi-national. Communications and computer technology may decrease business travel significantly. Some airlines may only market, process people and freight and provide ground support equipment operators and maintenance. These carriers may wet lease aircraft which may enable leasing companies to buy more and larger aircraft of a single configuration thus reducing training demands and ultimately lowering life cycle costs. Quick redistribution of assets will assist in maximizing utilization. Thus, these companies may be able to match capacity to the market more easily. Finally, the scenario outlined will pose a major challenge to long term Military Airlift and how CRAF can be maintained in the future.

### 3.13 More Constraints on Airports

In the past, platform design has driven the design of terminal facilities. But, today, the issues of noise, emissions, land and channel

## THE CHANGING WORLD

### World Scene

- Changing World Order:
  - Major Economic Powers
    - Communities
    - Isolated Nations
  - Regional Economic Powers
- Reasons for Conflict:
  - Territory
  - Politics
  - Resources
    - Raw Materials
    - Materiel
    - Energy
  - Religion
- Overflying Rights
- Shorter Conflicts
- Quick Response to Threats

### The Airlines

- Fewer major carriers - most multi-national
- Communications and computer technology may reduce business travel, significantly
- Travel demands tied to economic cycles
- Airlines may only market, process people and freight, and provide ground support equipment operators and maintenance.
- International leasing companies provide wet leased aircraft.
  - Larger aircraft buys to a single configuration
  - Lower life cycle costs
  - Less training
  - Quick redistribution of assets to maximize utilization
  - Optimal capacity/market matching

### Airport Restrictions

- Stronger runways for hub operations (ULCA)
- Limited ramp and taxiway space for larger aircraft
- Airport access (road & rail)
- Major issue of environmental impacts:
  - Noise
  - Emissions
  - Land Reclamation
  - Local Ecology
- Local opposition to airport improvements:
  - Dallas/Fort Worth Major Legal Battle to Add 2 More Main Runways - 3 Years So Far! Cost of Improvement • $3,500 Million

ULCA • Ultra Large Capacity Aircraft

### Ship Port Requirements/Constraints

- American President Lines Panamax container ships require crane booms with 140ft reach. Few ports have capability.
- Ports have had to be rebuilt and/or relocated:
  - New York's container handling terminals now in New Jersey
  - London Port Authority cargo handled at Felixstowe 60 miles from London
- No standardization of facilities:
  - Keel clearance in ports
  - Deck boom clearances
- Ten identical vessels are rare
- Large container ships require 40+foot deep channels
- Environmental concerns:
  - Dredging
  - Exhaust emissions

Chart 1

The Changing World

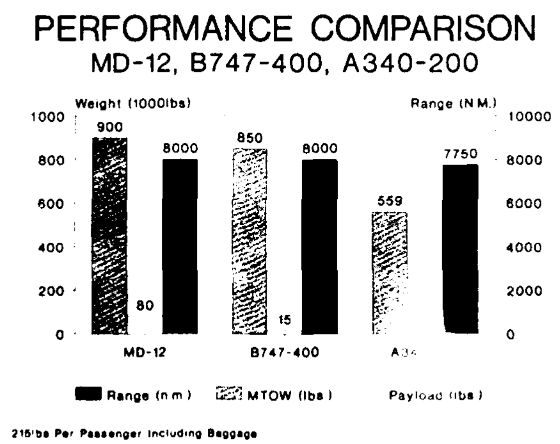
reclamation, and local ecology will restrict expansion and development of existing and future airports. Likewise, more constraints are likely to be imposed on military facilities.

Airport access may be restricted and there will likely limited ramp and taxiway space for large aircraft. This may force the Ultra High Capacity Aircraft of the future to be less efficient than current aircraft and may further add pressure to develop a High Speed Commercial Transport. For the heavier weight transports, fewer runways and less flexibility of dispersal will likely be the case. Events here and abroad show that political battles will stall improvements to existing facilities and perhaps prevent construction of new ones. For example, at Dallas/Fort Worth a major legal battle has raged foi three years to prevent the addition of two more main runways which when completed will cost a minimum of $3,500 Million.

**3.14 From The Sea**

Given the constraints mentioned in the paragraphs above, it seems inevitable that airborne power must come FROM THE SEA in the future. Today we look upon wars as being short and the time required to respond to threats as being equally short. This suggests that we need a means to be able to move large forces and their equipment around the world in a matter of days rather than weeks. In addition, it suggests that we should be able to position an overwhelming response on a threatmongers doorstep within hours and yet not be constrained by diplomatic bureaucracy for the use of foreign airspace for overflights and intermediate airfields for supporting tankers. The platform that would have the capability to station, perhaps, 500,000lbs of offensive payload off the shore of the coast of a threatmonger, would be a seaplane derivative. If Russian claims are correct about the reduction of profile drag in surface effect, and if this can be successfully integrated with the well known reduction in induced drag, a new extremely efficient platform could be developed which would have both future military and commercial value. A range of 10,000 nautical miles at 350 knots in surface effect may be a suitable goal.

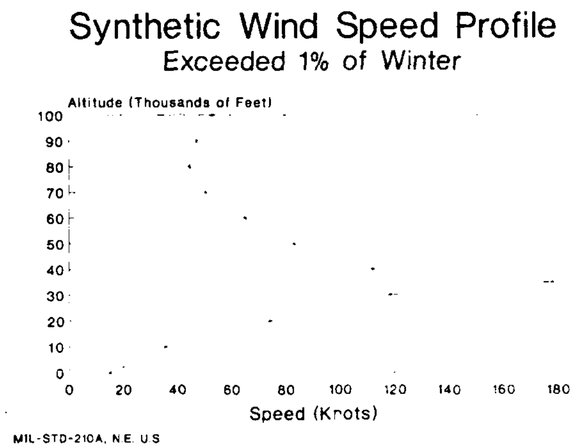
Figure 14 is a performance comparison (developed by McDonnell Douglas for Cathay Pacific Airlines) for two existing airliners and one projected airliner from Reference 16. As can be seen, for a range of about 8,000 nautical miles, a payload-to-weight ratio of less than 10% is to be expected. It is unlikely that much greater performance efficiencies can be achieved without significant technology breakthroughs.




14. Performance Comparison, MD-12, B747-400, A340-200

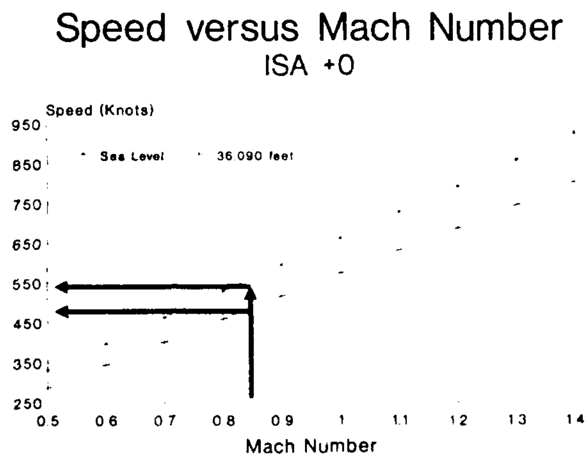
**3.15 The Seaplane Derivative**

L/D's of between 35 and 45 will be required of seaplane derivatives at a speed of 350 knots in order to attain a range of 10,000 nautical miles. At 500 knots, which would be more than competitive with the new generation of subsonic jets, an L/D of about 25 would be required. To attain these levels of aerodynamic efficiency, laminar flow, either natural laminar flow or augmented laminar flow control, will be required. Because the wetted area drag is a higher percentage for the large seaplane derivative, than with an aircraft flying at altitude, the potential benefits are greater. The use of laminar flow control and other drag reducing techniques should enable the wing loading to range between 50 to 75lbs/ft**2 thus maintaining acceptable take-off and landing speeds. Even with an aspect ratio of 2.5 wing, cruise altitudes of the order of 50,000 to 55,000ft with speeds approaching Mach 0.9 should be possible, although this might not be the most efficient altitude for cruise. However, at these altitudes, wind velocities tend to be less than at normal commercial aircraft altitudes (Figure 15), which can, on occasion, compensate for the more severe headwinds at lower altitudes. The figure shows the wind strength which will not be exceeded for 1.0% of the winter when they are the highest. The average wind strengths are of course much lower and the strengths are a function of the time of the year as well as location. For example, Reference 17, discusses wind strengths at various locations throughout the world. For New York, the average wind strength at 35,000ft is about 80 knots in winter reducing to about 35 knots in summer. In Tokyo, the average wind strength is 130 knots in winter versus about 35 knots in summer. Sea Level winds are about 20 knots in winter versus about 5 knots in summer for both locations.




15. Synthetic Wind Speed Profile

Cruise in surface effect offers one further advantage over high altitude flight. For a given design Mach number at altitude, for the same speed at sea level the Mach Number is lower (Figure 16). This can result in the aircraft flying, perhaps, out of its drag rise region. At low CL's, typical of sea level flight, the drag rise tends to be less than at high altitude.




16. Speed Versus Mach Number

To achieve the performance stated in the previous paragraphs, there are some significant issues for the larger type seaplane derivative. They are:

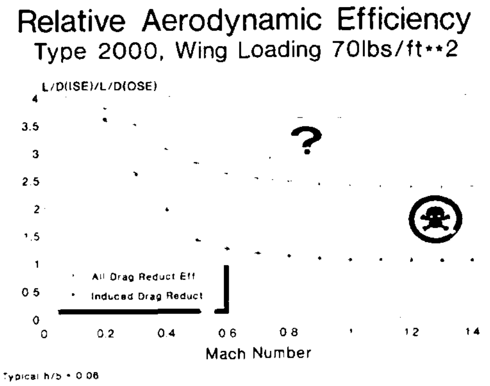
- o What is the maximum achievable L/D in surface effect at the speeds discussed? Can an L/D in surface effect be twice that of the L/D out of surface effect? If not, surface effect platforms, if they have a future, would be slow speed platforms (Figure 17).
- o Are the achievable L/D's sufficient to present an overall platform gain in range and endurance in spite of possible higher structural weight fractions for the sea level operation and higher engine specific fuel consumption than at high altitude?
- o Are corrosion and structural fatigue problems so severe as to drive up the structural weight fraction to an unacceptable level?

figure 4

observé lors la mise en service de train à grande vitesse. Cet effet pourrait accroître la part du marché de l'avion supersonique.



- o Are the operations and support costs unacceptable because of the primary mode of operation will be at sea level?
- o The role of the platform, that is whether it should be basically a sea sitter and occasional flyer or vice-a-versa and whether it should operate only from sheltered waters, will also have a major impact on the structural weight of the platform.
- o What is the minimum size of platform which is more cost effective than either land based asset and/or seaplane asset?




17. Relative Aerodynamic Efficiency

Given that the above issues can be resolved and/or there is significant military value for platforms designed to fly in surface effect because they possess unique capabilities, a matrix of mission applications for various types of platforms can be postulated.

### 3.16 Mission Matrix

Table 2 shows a mission matrix along with platforms which could be designed to operate in surface effect. Conventional aircraft would retain their high altitude capability. However, they would have an added extremely low level flight capability. They could be designed for low flight over appropriate terrain and expanses of water, perhaps down to one span height or less for improved ride quality, flight below the optical horizon, and increased range. This might suggest aircraft designs with mid to low wing fuselage locations. Sukhoi has proposed a next generation multi-role fighter, designated SU-37 which would have an estimated top speed of 813 knots and "good maneuverability near the ground and low radar visibility". The aircraft is designed to operate from unpaved runways and the wing and cross section are optimized for low level flight (Reference 18).

| Mission Area | Low Flying Conventional Aircraft | Seaplane Derivative (Amphibious) | Seaplane Derivative (Non Amphibious) | V/STOL TAR |
|---|---|---|---|---|
| Amphibious Warfare | + | + | - | + |
| Anti-Surface Ship Warfare | + | + | + | + |
| Anti Submarine Warfare | + | - | + | - |
| Command, Control & Communications | + | | + | |
| Electronic Warfare | + | + | + | + |
| Special Warfare | + | + | + | + |
| Logistics | + | + | + | . |
| Mine Warfare | + | + | | -- |
| Strike Warfare | + | + | + | + |
| Anti Air Warfare | + | -- | + | + |

Key
+ Recommended for Mission Area
Doubtful for Mission Area

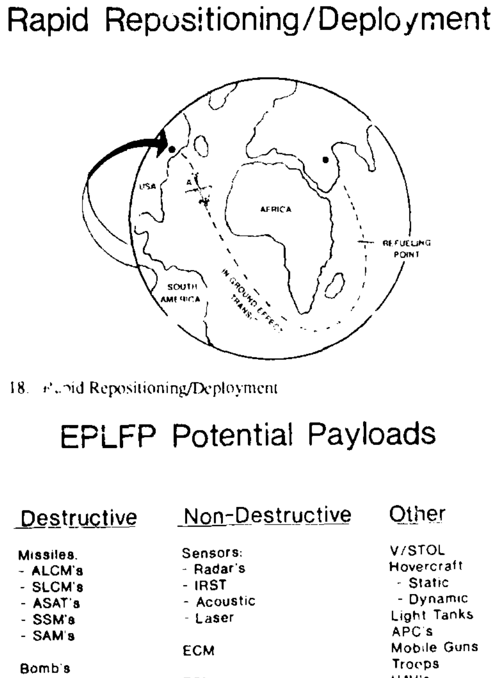
Table 2.

2. Mission Possibilities for Low Flying Platforms

The amphibious seaplane derivative would be turboprop powered and would use either a thrust augmented ram or power augmented ram to give it the amphibious capability. Because of the structural and drag penalties associated with this type of platform, it would generally be perceived as a short to medium range platform.

### 3.17 Seaplane Derivative Mission Examples

The large seaplane derivative as mentioned earlier would be the long range platform. It could carry up to 2,000 troops or 1,000 troops and some of their equipment over 10,000 nautical miles in surface effect without refuelling. If refuelled, it would be able to carry substantially larger payloads, of the order of 1,500,000lbs over 3,000+ nautical miles. Table 3 shows a list of potential payloads from which the payload complement of the platform can be made up to equal the platforms payload and volume capacity for a specific set of missions. For example, for this size of platform, it would be possible for it to fly from Camp Pendleton, California, at say 35,000ft to New York, refuel at New York and transit in surface effect, round Cape Horn and refuel from a submarine off the East Coast of Africa before proceeding in surface effect to the Middle East (Figure 18). In the Middle East it uses RPV's to acquire missile site targets and their radars, fires cruise missiles to eliminate the offending sites, uses RPV's to conduct battle damage assessment, disembarks 500 troops and equipment to demolish the remaining missile site infrastructure, recover the troops and returns by the sea to New York all in the space of about 100 hours. Alternatively it could accompany a carrier battle group, assist in suppressing attack from a small fleet of warships and then conduct a mining mission several thousands miles from the carrier and return to accompany the carrier within 24 hours. It would then ferry 1/3 of the carriers crew back to the U.S. to execute a crew change while replacement crew is already boarding the carrier from another seaplane derivative.




18. Rapid Repositioning/Deployment

EPLFP Potential Payloads

| Destructive | Non-Destructive | Other |
|---|---|---|
| Missiles. - ALCM's - SLCM's - ASAT's - SSM's - SAM's | Sensors: - Radar's - IRST - Acoustic - Laser | V/STOL Hovercraft - Static - Dynamic Light Tanks APC's |
| Bomb's - Smart - Dumb | ECM ESM Armor Protection | Mobile Guns Troops UAV's Fuel Spares Boats CTOL Aircraft |
| Torpedoes Guns Mines | | |

Table 3

3. EPLFP Potential Payloads

The V/STOL aircraft suggested in Table 2 would be a vertical take-off and landing aircraft which uses a thrust augmented ram to allow it to hover a few inches off a surface with much less thrust than required for vertical flight. In this way, the aircraft is capable of carrying a significantly greater payload and/or having much greater range or endurance.

### 3.18 Other Applications

Table 4 presents a list of other applications for surface effect platforms.

The large seaplane derivative would be a Navy's large missile carrier/launcher, mine layer and MCM platform, ASW platform and maritime replenishment platform.

## Service Applications?

**Coast Guard • Navy in Some Countries**

- Navy:
  - Large Missile Carrier/Launcher
  - Tactical Strike Reconnaisance (V/STOL)
  - Mine Layer/MCM Platform
  - ASW Platform
  - Maritime Replenishment
- AIR FORCE - Logistics Support (C-5B/AN-124)
- ARMY - Tank Buster (UAV or Manned)
- COAST GUARD - Law Enforcement/Rescue
- MARINE CORPS - *Amphibious Landing Craft*

Includes NAR and TAR EPLFP's

Table 4

4. Service Applications

The V/STOL tactical strike reconnaissance aircraft might be based on small carriers or amphibious assault ships. Using these ships as their main operating base, they might be selectively deployed to other fleet assets to make their presence less obvious. The other primary advantage of this type of VTOL aircraft is its ability to be operated from ship to shore to concealed dispersal points and operated at will against enemy lines without the need of tanker assets once a fuel supply has been established.

For an Air Force the same seaplane derivative would support planes such as the C-5's, and An-124's. The army might use relatively small vehicles which use the TAR to give them amphibious capability. Also, UAV's might be used flying only a few feet off the ground where terrain permits but not benefitting significantly from surface effect. A Coast Guard could use either amphibious or non-amphibious platforms for surveillance at altitude. Once a transgressor has been spotted, the platform would rapidly descend and give chase, land, board and apprehend the criminal/s. These platforms could also be used for search and rescue. For the coast guard role these platforms may need to be sea sitters, flying only occasionally.

For a Marine Corps, a medium range amphibious platform accompanying the battle group would perhaps be appropriate. With a cruise speed of 300 knots it would provide troop, equipment delivery and resupply. For special operations, a small version, which would also be amphibious, could be housed within the confines of ships with landing docks.

### 4.0 TECHNOLOGY OPPORTUNITIES

Technology development and enhancement opportunities applicable to all surface effect platforms are shown in Table 5. These could be treated as multi-national efforts. Most of the items are self explanatory. However, some major opportunities are discussed hereafter.

As mentioned in the early part of the paper, the maximum obtainable lift coefficient in surface effect is clearly a major issue. The reduction of take-off and landing speeds in surface effect depends on increasing the maximum lift coefficient, significantly, and, therefore, represents a major technical challenge and major opportunity for a research effort.

The major driver in achieving long range performance, because of the "costs" of flying at low level in terms of adverse structural weight and adverse propulsion efficiency impacts is aerodynamic efficiency. To achieve the L/D's which accommodate these penalties and still allow long range capability will require new aerodynamic research in the areas of analysis and testing perhaps extending to aerodynamic prototype platforms such as those for the Vulcan bomber. Areas of investigation would include wing planform, wing sections, endplate sections and placement, and interference drag investigations. These investigations should be done through subsonic, transonic and supersonic Mach numbers.

In terms of testing facilities there are concerns about the adequacy of both fixed ground board and moving belts in wind tunnels. In tow tanks, the speeds are inadequate to simulate full scale air dynamic pressure. Also, existing experimental facilities may not be able to simulate full scale Froude and cavitation numbers at the same time. To obtain more accurate data may require the design of development of a captured flight rig that might also solve the problems of testing over a wavy surface.

| Opportunity | Low Flying Conventional Aircraft | Seaplane Derivative (Amphibious) | Seaplane Derivative (Non-Amphibious) | V/STOL TAR |
|---|---|---|---|---|
| Aerodynamics | | | | |
| Lift Augmentation (T.O. & Landing | + | + | + | + |
| Testing Facilities | + | + | + | + |
| Configuration Integration | + | + | + | + |
| Thrust/Power Augmented Ram Integration | - | + | - | + |
| Flow Control | + | + | + | + |
| Hydrodynamics | | | | |
| Thrust/Power Augmented Ram Integration | - | + | - | - |
| Spray Effects | - | + | + | - |
| Hydrodynamic Load Alleviation | - | + | + | - |
| Propulsion | | | | |
| Environment | + | + | + | + |
| Bypass Ratio/Engine Cycle Optimization | + | + | + | + |
| Flight Controls | | | | |
| Autopilot | + | + | + | + |
| Fly-By-Wire | + | + | + | + |
| Special Device | - | + | + | + |
| Structures | | | | |
| Environment | + | + | + | + |
| Producibility | + | + | + | + |
| Smart Joints | + | + | + | + |
| High Strength to Weight Materials | + | + | + | + |
| Supportability | + | + | + | + |
| Sensors | | | | |
| Surface Contours | + | + | + | + |
| Collision Avoidance | + | + | + | + |

Key.
- \+ Development/Enhancement Opportunity
- \- Doubtful or No Opportunity

**Table 5.**

5. Technology Opportunity Research Areas

Three hydrodynamic areas are identified. The thrust augmented ram is the primary challenge to minimize hydrodynamic and aerodynamic drag during take-off. New or highly modified hulls need to be developed to reduce spray drag. Spray scrubbing may also create erosion depending on the construction of the fuselage. Hydrodynamic load alleviation may be achieved through the use of wedges on the fuselage and perhaps hydroskis. New hull designs could eliminate this problem.

New sensors will probably have to be developed and tied to the autopilot to successfully fly the platforms over both terrain and waves. Triplicated redundant flight controls and computers will be necessary to assure safety. Along with the flight control system, a collision avoidance system for sea and air traffic objects will need to be installed.

### 5.0 SUMMARY

Surface Effect or "ground effect" as it is more usually referred to was always considered as a low speed phenomena associated with the change in flow close to a surface. Academically "ground effect" was said to alter the wing upwash, downwash and wing tip vortices reducing induced drag and increasing lift. While this is true, it is now clear that there are other positive effects and these effects occur both at low and high Mach numbers.

Surface Effect might be better defined. Surface Effect deals with the the aerodynamic, aeroelastic and aeroacoustic impacts on platforms flying within surface effect. The boundary of surface effect is a function of height above the surface. This height, itself, is a function of Mach number.

Russian documents suggest that there are other drag reductions attributable to surface effect, namely profile drag and wave drag due to lift. However, the mechanism for these reductions is not clear. For the profile drag reduction, the possibility of laminar flow at least on the lower surface of a wing does exist.

Pilot reports indicate an improvement in ride quality as the ground is approached even at supersonic speeds. They also report that stability is good as is maneuverability. Aircraft which would be expected to have poor ride quality owing to their low wing loading also are reported as having good ride quality by their pilots. Analytical investigations and wind tunnel tests to confirm or deny this, currently, appear not to exist. The combination of a profile drag reduction and additive surface effects on wings of delta shape suggest that this may be an ideal planform for further investigation. The overall improvement of aerodynamic efficiency in surface effect of a delta wing and, also, the effects on the center of lift and pitching moment in and out of surface effect suggest that this might be the planform of choice for future large seaplane derivatives designed to fly in surface effect. Because of their conservative wing loadings, these seaplane derivatives may have the potential to fly at altitudes of 50,000 to 55,000ft.

Aircraft that have flown in surface effect are generally the older types with design histories dating back to the late 40's and early 50's. None appear to have experienced stability problems. Therefore it looks as though, if desired, present and future land based aircraft could easily be designed and equipped to fly at low levels.

Seaplane derivatives have the potential to offer sequential mission opportunities and a tactical freedom currently not available with any platform extant. Specifically, they offer ocean sitting capability, endurance cruise at 200 - 250 knots; extremely long range cruise at 350 - 450 knots for, perhaps, 10,000 nautical miles; high speed dash cruise at over 550 knots for, perhaps, 5,000 nautical miles; and the opportunity to cruise at over 35,000ft at Mach 0.85+ for 5,000 nautical miles. The tactical value of a platform which can sit in the sea, cruise as a normal ship or fly in any of four speed ranges cannot be overlooked.

To complete the family of Enhanced Performance Low Flying Platforms for potential development, we should include future land based aircraft with the capability to fly extremely low, amphibious seaplane derivatives which would have medium to short range capability and, last, but not least, future generations of the category of ground effect vehicles pursued by Russian technology innovators and engineers over the last three decades.

While there are major issues to be resolved, it is clear that more research in understanding and applying surface effect flight capabilities to future platforms is appropriate. Such research will offer, perhaps, multi-national opportunities in all aspects of air vehicle design and man/machine interface.

## 6.0 ACKNOWLEDGEMENTS

The author wishes to thank the Naval Air Warfare Center (Aircraft Division) Warminster, for permission to publish this paper. In particular he wishes to thank Dr. D. P. McErlean, Head of the Air Vehicle and Crew Systems Department, and Mr. L. O. Lehman, Director of the Air Vehicle and Technology Program Office for encouragement to write and publish this paper. Mr. R. Ackerman (Code 3021), deserves recognition for proposing some innovative scenarios in this paper for the use of seaplane derivatives. The author would also like to thank Captain E. D. Pope, Office of Naval Research, Washington D.C. for guidance on its content. In addition, the author would like to thank the U.S. Air Force Public Affairs Office, Washington, D.C., for the provision of the artist's rendering of Republic Thunderchief's in action, General Dynamics Corporation for provision of Delta Dart and Hustler data and video and, finally the British Aerospace Corporation for providing information on the Blackburn Buccaneer and the Avro Vulcan bombers. He also wishes to thank the anonymous test pilots, service pilots and crew of Air Force's and Navy's domestic and foreign and the U.S. Air Force Museum in Dayton, Ohio for their contributions to this paper.

Finally, the author would like to thank Mr. E. C. Lesoravage (Code 302), Mr. B. L. Cavallo (Code 303) and Mr. S. Greenhalgh (Code 6051) of the Naval Air Warfare Center, Aircraft Division, Warminster, Pennsylvania for their review and comments on the Draft Paper.

## 7.0 NOTE:

The views expressed in the paper are the personal opinions of the author and do not necessarily reflect those of the Department of the Defense, the Department of the Navy including the Naval Air Warfare Center, or any other Military Department thereof.

## REFERENCES

1. Widnall, Sheila E., Barrows, Timothy M., "An analytical Solution for Two and Three-Dimensional Wings in Ground Effect", Massachusetts Institute of Technology, Journal Of Fluid Mechanics, Cambridge, Great Britain, Vol. 41, Part 4, Page 769 - 792, 1970.
2. Borst, Henry V., "Analysis of Vehicles with Wings Operating in Ground Effect", AIAA Paper 79-2034, AIAA/SNAME Advanced Marine Vehicles Conference, October 2 - 4, 1979, Baltimore, Maryland.
3. Carter, Arthur W., "Effect of Ground Proximity on the Aerodynamic Characteristics of Aspect Ratio 1 Airfoils with and without End Plates", NASA TN D-970, October 1961.
4. Hooker, Stephan F.,"Review of Current Technical Knowledge Necessary to Develop Large Scale Wing-in-Surface Craft", AIAA Paper 89-1497-CP, Intersociety Advanced Marine Vehicles Conference, Arlington, Virginia, 5-7 June 1989.
5. General Dynamics, Fort Worth Division, Post Office Box 748, Fort Worth, Texas 76101, Video, "B-58 - Low Altitude Bombing".
6. Scott, William B., "B-1B Excels in Conventional Role", Aviation Week and Space Technology, 27 July 1992.
7. Beech, Eric, "Sea Change for Buccaneers", Flight International, 18-24 September 1991.
8. Raymer, Daniel P., "Aircraft Design: A Conceptual Approach", AIAA Education Series, 1989.
9. Lievens, C., & Poisson-Quinton, P.,"Analyses Critiques et Recherches en Laboratoire au Stade de L'Avant-Projet D'un Avion", Aircraft Design and Optimization, Conference Proceedings No 147, AGARD-CP-147-Vol. 1, June 1974.
10. Voytkunskiy, Ya, I.; and Faddeyev, Yu, I.; and Poleshchuk, M. A. "Influence of Viscosity on Profile Lift and Drag Near a Screen", Leningrad Shipbuilding Institute, Transaction #65, 1967.
11. Ermolenko, S. D., & Khrapovitskii, V. G., " Influence of Air Compressibility on the Aerodynamic characteristics of a Wing Moving at Subsonic Speed Near the Earth's Surface", Izvestiya VUZ. Aviatsionmaya Tekhnika, Vol 12, No. 4, 1969.
12. Ermolenko, S. D., & Khrapovitskii, V. G., "Aerodynamic Characteristics of a Wing Systems Moving at Subsonic Speeds Near the Earth or Smooth Water Surface", Samoietostroyenie i Tekhnika Nozdush'nogo Flota, Kharkov, 1973.
13. Rinoie, K., "Experiments on a 60 Degree Delta Wing with Vortex Flaps and Vortex Plates", The Aeronautical Journal, Pages 33 - 38, Volume 97, Number 961, January 1993.
14. Er-EL, J.; Weihs,D.; "Ground Effect on Slender Wings at Moderate and High angles of Attack", Journal of Aircraft, Pages 357 - 358, Volume 23, No. 5, May 1986.
15. Bagley, J. A.;"The Pressure Distribution on Two-Dimensional Wings Near the Ground", Aeronautical Research Council, R&M 3238, 1961.
16. McDonnell Douglas Generated Performance Comparison for Cathay Pacific, Aviation Week and Space Technology, page 32, November 25, 1991.
17. Edwards, OM, FRS, Sir George, "The Technical Aspects of Supersonic Civil Transport Aircraft", The Royal Society, 6 Carlton House Terrace, London SW1Y 5AG, March 29, 1973.
18. Aviation Week and Space Technology, "Sukhoi Selects Delta Wing for Next Multirole Fighter", page 29, November 11, 1991.

# L'AVENIR D'AVIONS CARGOS MULTI-ROLES A LARGE CAPACITE ET GRAND RAYON D'ACTION

## (THE FUTURE OF LARGE CAPACITY/LONG RANGE MULTIPURPOSE AIR CARGO FLEETS)

par

**Philippe Poisson-Quinton**
ONERA
B.P. 72
92322 Chatillon Cedex
France

## SUMMARY

Both commercial and military aspects of Cargo Transport Aviation were discussed at the International Symposium organized by the French Aerospace Academy (ANAE), held in March 1993 in Strasbourg [Ref. 1].

In the framework of this AGARD Flight Mechanics Panel Symposium on "Long Range and Long Endurance Operation of Aircraft", this paper summarizes some of the contributions and discussions dealing with the future role of the Air Cargo Transportation in relation to a global international policy of military and humanitarian intervention, including their technical and operational aspects.

In a first part, the status of the World's Air Cargo activity is reviewed in terms of the main operational cargo airplanes, their capacity and their range, used both for commercial (Fig. 1) and military (Fig. 3) purposes; it includes the family of large cargos (Fig. 2) developed by Antonov in Ukraine and preliminary designs of huge cargo projects by the Russian laboratory TsAGI for 250 to 500 tons payload, and by NASA with spanloader or conventional schemes for intermodal containers transport (Fig. 6).

In a second part, the present U.S. Military Airlift forces are analysed (Fig. 4), with some comments on their recent global airlift deployment during the Gulf War (Fig. 5).

It is concluded that, as regards long term global policy, such existing task forces are totally inadequate to either stop immediately some local conflicts around the world, or to save population, in case of major natural or man-made (nuclear hazard?) disasters.

That is why a much larger airlift system should be developed on an intergovernmental basis, the main objective would be its "strategic efficiency" instead of a "profit earning capacity", as used in commercial aviation.

For that purpose, a "supercargo" can be defined, developed and produced in the framework of an international consensus between the major aeronautical powers.

Its size, configuration, operational characteristics and performance must be discussed, and a compromize agreed to cope with the main military and humaritarian missions; but such "supercargo" airplane would be certainly much larger than the present ones, with two to four times their payload, and a transcontinental range capability; for their development, advantage would be taken of the best technologies that would become available in the next decade, and of the availability of design capability in the world's aircraft industry resulting from the present crisis. A flying wing configuration is suggested as a basis for a preliminary project (Fig. 7, 8 and 9).

Finally, there is certainly a commercial spin-off of such massive supercargo production, if used to compete successfully with the surface transportation systems (sea, road, rail) of large intermodal containers already used on major international markets.

-.-.-.-.-

L'AVENIR D'AVIONS CARGOS MULTI-ROLES A LARGE CAPACITE ET GRAND RAYON D'ACTION

## I) INTRODUCTION

Au cours d'un Symposium International organisé en mars 1993 à Strasbourg par l'Académie Nationale de l'Air et de l'Espace (ANAE), le double aspect commercial et militaire a été analysé [1]. Son intérêt était :

- de réunir tous les acteurs de cette activité aéronautique en croissance, avec ses aspects économiques, réglementaires et de gestion aéroportuaire,

- d'entendre les points de vue des utilisateurs, des chargeurs et des compagnies aériennes,

- et enfin de prendre connaissance des propositions de constructeurs.

*Presented at an AGARD Meeting on 'Recent Advances in Long Range and Long Endurance Operation of Aircraft', May 1993.*

L'ensemble des 35 communications, des interventions et des conclusions de la table ronde, en cours d'édition dans des Actes de l'ANAE, constitueront un document de grande valeur. Dans le cadre du présent Symposium AGARD/FMP sur les aspects opérationnels des avions à grand rayon d'action et longue endurance, il a semblé intéressant d'en présenter une courte synthèse et d'en tirer quelques conclusions personnelles relatives à l'avenir de gros avions cargo multi-missions militaires/civiles dans un contexte d'opérations internationales.

## II) ETAT ACTUEL DU TRAFIC DE FRET AERIEN COMMERCIAL DANS LE MONDE

La figure 1 résume les données essentielles de l'activité fret aérien commercial actuel. Il est manifestement lié à l'état de l'économie mondiale, (tout comme le trafic passagers) et l'on prévoit pour les 10 prochaines années une croissance de l'ordre de 7 % par an [2, 3, 4].

Cependant, l'activité aérienne subit actuellement de plein fouet les conséquences de la récession mondiale, et dans ces conditions, les utilisateurs aussi bien que les compagnies aériennes estiment qu'à court terme, l'objectif primordial est d'augmenter la rentabilité de l'activité de fret en utilisant au mieux le matériel existant ou en commande dans les années 80/90 [2, 3, 4], c'est-à-dire :

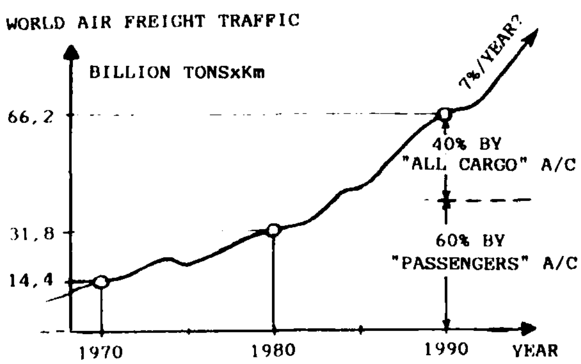
- les soutes des avions de transport régulier pour passagers ;
- des avions "tout-cargo" directement conçus pour cet usage, ou adaptés ultérieurement à partir de versions "passagers", et qui représentent un millier d'avions dans le monde occidental.

Ces deux flottes distinctes se partagent respectivement 60 % et 40 %, du trafic total du fret aérien mondial qui, en 1990, représentait 25 millions de tonnes, soit 66 milliards de tonnes × kilomètres transportés. Cela représente 1 % seulement du trafic en tonnage, mais 10 % en valeur du fret total mondial - mer, fer, route et air confondus -. Enfin, le fret représente seulement 12 % des recettes mondiales du transport aérien.

Par ailleurs, il est reconnu que tout progrès réalisé dans l'activité du fret aérien passe par une amélioration obligatoire du traitement du fret au sol, sur l'aéroport puis vers le destinataire final. Enfin, une plus grande autonomie est souhaitée entre le trafic passagers et l'activité "tout-cargo fret-express".

En ce qui concerne les véhicules, la figure 2 résume les caractéristiques charge utile/masse au décollage de l'ensemble des avions cargo opérationnels dans le monde ainsi qu'une projection de futurs projets de "super-cargos" sur lesquels nous reviendrons plus loin.

*Fig. 1* COMMERCIAL WORLD AIR CARGO IN PERSPECTIVE




SINCE 1970, THE AIR FREIGHT TRAFFIC HAS DOUBLED EVERY DECADE.
A 7% FREIGHT TRAFFIC GROW IS EXPECTED FOR THE NEXT DECADE (to be compared with a 5-6% grow for the passenger's traffic)

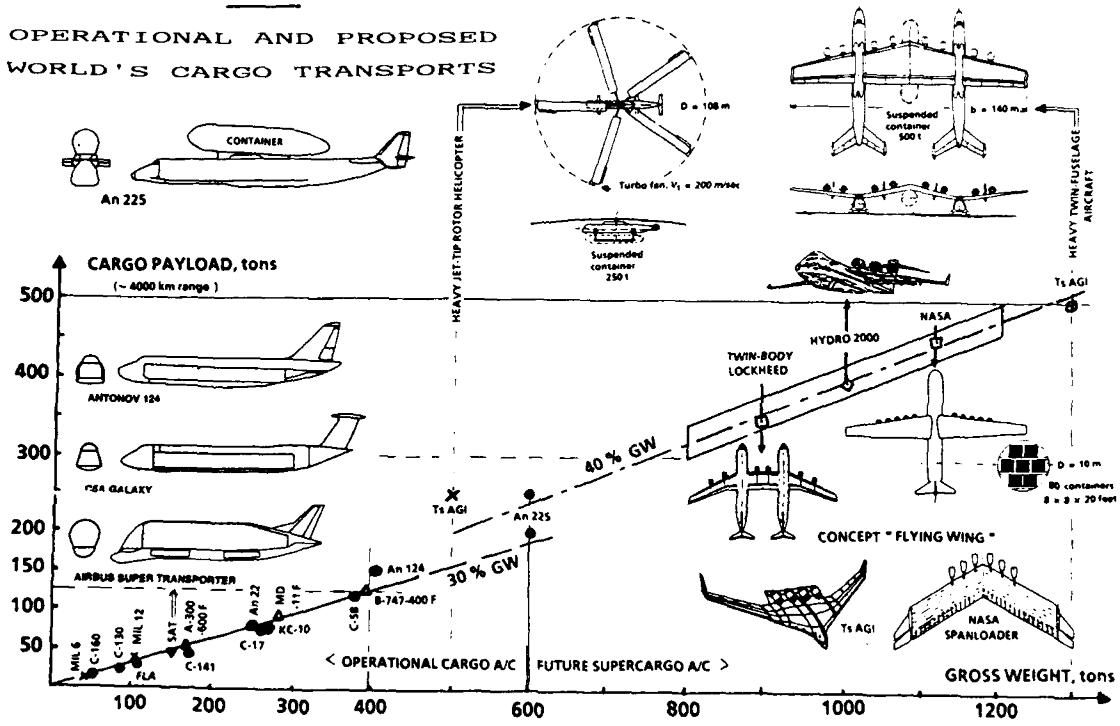
- THE WESTERN CARGO JET FLEET INCLUDED 982 AIRPLANES (END 1992); 60% OF THEM WERE CONVERTED FROM FORMER PASSENGER'S A/C; 107 NEW CARGO A/C WERE ORDERED.

AIR FREIGHT TRAFFIC IN 1990 :

- 25 MILLION TONS (i.e. 1.1% MARITIME "DRY FREIGHT")
- 66 BILLION TONSxKILOMETERS FLOWN (36 Billion tons x nautical Miles)
- THIS FREIGHT TRAFFIC ACCOUNTS FOR ABOUT 28% OT THE TOTAL AIR TRAFFIC; 72% IS DEVOTED TO PASSENGER'S TRANSPORT, WITH 171 BILLION TONSxKM (1 PAX - 90 Kg)
- THE AIR FREIGHT MARKET REPRESENTS ONLY 12% OF THE WORLD AIR TRAFFIC TURNOVER (INCLUDING 1% FOR THE AIR MAIL)
- 90% OF THE FREIGHT TRAFFIC IS FLOWN BY COMPANIES FROM EUROPE (34%), USA (28%) AND ASIA/PACIFIC (28%).
- THE INTERNATIONAL TRAFFIC REPRESENTS MORE THAN 70% OF THE TOTAL, WITH 5000Km MEAN RANGE

*Fig. 2*

OPERATIONAL AND PROPOSED WORLD'S CARGO TRANSPORTS




N.B.)Commercial Cargos -Δ-, Rotorcraft, -x-

## III) LE FRET AERIEN MILITAIRE

Sur le plan militaire, l'activité cargo s'est considérablement développée au cours des deux dernières décennies [5, 6, 11] en raison du développement des conflits locaux autour du monde et des interventions humanitaires qui en sont quelquefois la conséquence récente (Yougoslavie, Somalie, etc.).

Les principaux avions spécialisés pour ces missions militaires sont mentionnés sur les figures 3, avec leurs caractéristiques de charge utile en fonction de leur rayon d'action (y compris la mission de convoyage à vide), respectivement pour les cargos lourds [5, 19], (Fig. 3 a) et pour les cargos moyens [7, 8], (Fig. 3 b).

Une mention spéciale doit être faite au nouveau cargo de l'US Air Force, en cours de vols d'essais par McDonnell-Douglas [7], le C-17A, qui a environ la taille du C-141, mais dont la capacité interne de chargement est voisine de celle du C-5A, tandis que ses performances STOL (volets soufflés par les 4 turbo-fans en pods lui permettent d'utiliser des pistes courtes comme un C-130 (Fig. 3c).

Deux pays, les USA et l'ex-URSS, possèdent des systèmes de transports de fret militaire très développés ; il est intéressant de rappeler à ce sujet l'état actuel des forces opérationnelles américaines [5] dans le cadre de "US Air Mobility command" (Fig. 4), ainsi que son déploiement récent à l'occasion de la guerre du Golfe (opérations "U.S. Desert Shield/Desert Storm" (Fig. 5) :

*Fig. 3 a* - PAYLOAD / RANGE OF HEAVY CARGOS

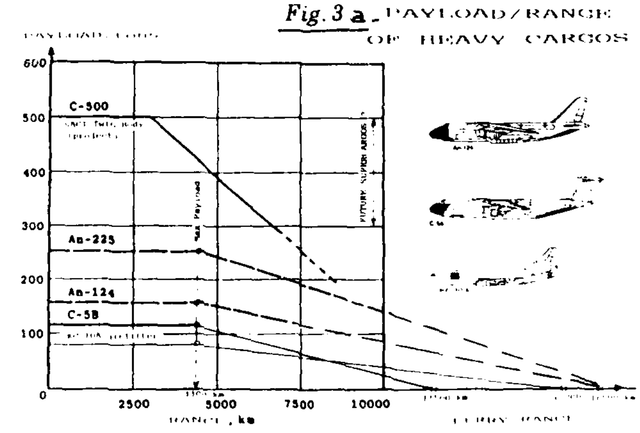



*Fig. 3 b* - MEDIUM MILITARY CARGOS

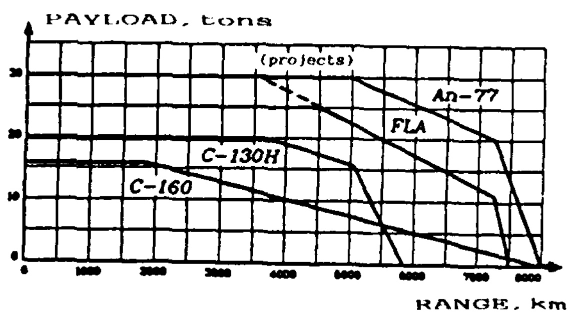
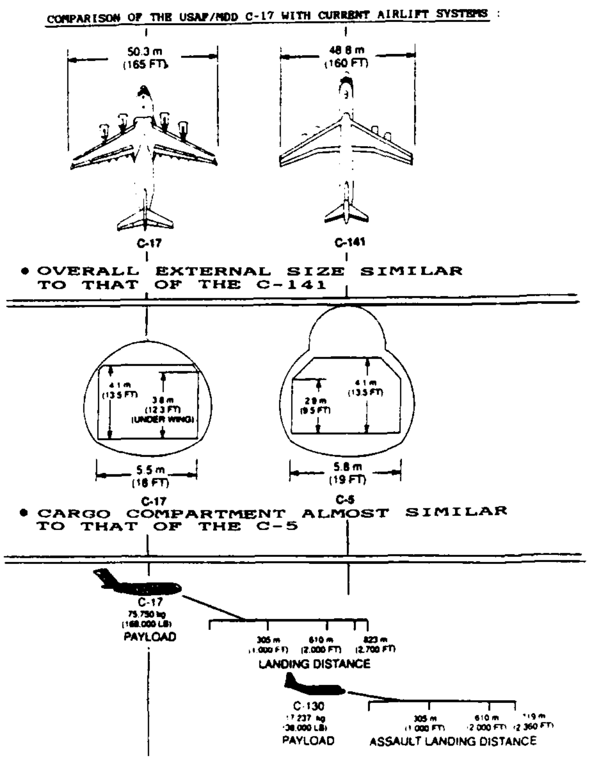


*Fig. 3 C*

U.S. APPROACH TO MILITARY AIRLIFT: C-17




15 800 missions ont été accomplies par l'ensemble des flottes actives et de réserve de l'US Air Force, complétée par la flotte Civile de Réserve (CRAF) : 544 000 tonnes de cargo et 501 000 passagers/troupes transportés, avec une moyenne de 125 missions par jour, sur rayon d'action moyen de 7 500 miles nautiques, s'étendant sur plusieurs mois.

Cependant, les flottes d'avions cargos spécialisés disponibles ou en projet à court terme dans les grands pays seront certainement insuffisantes pour assurer à long terme une force d'intervention globale et rapide, placée sous une responsabilité intergouvernementale et capable, soit d'étouffer dans l'œuf un germe de conflit avant qu'il ne dégénère, soit de porter rapidement secours à un pays subissant une catastrophe majeure, ou encore de répondre aux demandes humanitaires. Il y a tout lieu de penser que ces actions politiques internationales seront de plus en plus essentielles pour le maintien de la paix mondiale.

Dans ce domaine, on ne peut plus raisonner en termes de rentabilité commerciale mais plutôt en termes d'efficacité stratégique, une notion vitale pour la communauté internationale dans les prochaines décennies. Les objectifs étant différents, il faut alors reprendre la conception technique et l'utilisation opérationnelle d'une flotte adaptée, l'étudier, la développer puis la gérer à un niveau intergouvernemental.

*Fig. 4*

**PRESENT U.S. MILITARY AIRLIFT FORCES**

| Type of aircraft | Number | Millions TON-N.MILES per DAY: Unit capacity | Millions TON-N.MILES per DAY: Total | |
|---|---|---|---|---|
| • LOCKHEED C-5B (Gross weight 385 t., payload 108 t) (cruise speed = 450 Kts) | 109 | 0.151 | 16.5 | LONG RANGE INTER THEATER CARGO AIRCRAFT — ~ 8000 Tons per DAY ON A 4000 NM ROUTE (Transatlantic crossing) |
| • LOCKHEED C-141 B (GW = 172 t, P = 36 t, $V_C$ = 425 Kts) | 234 | 0.066 | 15.4 | |
| • DOUGLAS KC-10 Cargo (GW = 290 t, P = 88 t, $V_C$ = 480 Kts) | 10 | 0.111 | 1.1 | |
| • LOCKHEED C-130 H (GW = 87 t, P = 18 t, $V_C$ = 300 Kts) | 133 | 0.006 | 2.4 | INTRATHEATER CARGO AIRCRAFT |
| • future MD-DOUGLAS C-17A (GW = 264 t, P = 78 t, $V_C$ = 450 Kts) | ? | 0.152 | | |
| • Civil Reserve Air Fleet CRAF (Stages I + II : cargos + convertibles) | 148 | OPERATIONAL CAPACITY* | 17.5 | |
| TOTAL CARGO | 934 A/C | | 52.9 MILLIONS of TON-N MILES per DAY | |
| • CRAFT (Stage III passengers) | 262 | → | LONG RANGE INTERTHEATER PAX A/C 140 MILLIONS OF PAX-N MILES per day | |

Note * OPERATIONAL CAPACITY = PAYLOAD • BLOCK SPEED • UTILIZATION RATE (50 %) (94 %)/$10^6$
Example for the C-17A: 48 tons 436 Kts 15.2 h 0.50 0.94/$10^6$
= 0.152 MTM/D

*Fig. 5*

A SPECICIC CASE : U.S. AIR MOBILITY OPERATIONS DURING THE GULF WAR

(THE LARGEST IN HISTORY)

"DESERT SHIELD/DESERT STORM" (Aug.1991-March 1992):

.15800 MISSIONS FLOWN TO AND FROM THE MIDDLE EAST (MAX. RANGE 7500 nm.) including :

- 544000 tons of FREIGHT
  (i.e. 15% of the " dry cargo", with 85% by SEA CARRIERS)
- 501000 PASSENGERS/TROOPS

. Includes the CIVIL RESERVE AIR FLEET (CRAF) participation (Stages I and II) | -27% CARGO (60 A/C) -64% PERSONNEL (94 A/C)

. 200 Millions nm. flown during 50000 sorties;

. only one loss (a C-5 in Germany)

## IV) LE BESOIN DE CARGOS GEANTS

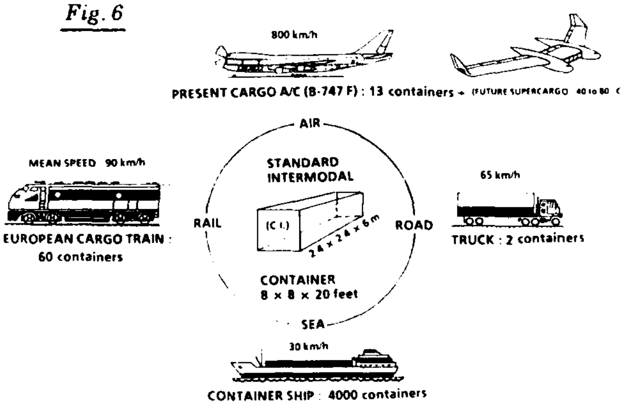
Un autre aspect à prendre en considération est l'utilisation obligatoire du transport aérien pour les chargements exceptionnellement volumineux, donc impossibles à transporter par voie terrestre. C'est grâce au *Super Guppy*, avion quadri-propulseur reconstruit autour d'un volumineux fuselage, qu'Airbus Industrie a pu transporter depuis 1971 les éléments des Airbus successifs fabriqués en Angleterre et en Allemagne vers Toulouse pour leur montage final et leur réception en vol [9] ; de même, les navettes spatiales américaines et russes sont transportées respectivement sur le dos d'un Boeing 747 et d'un Antonov 225, tandis que le *Super Guppy* a d'abord servi à transporter les étages des grands lanceurs spatiaux américains. A court terme (1995), Airbus Industrie prépare un successeur, le biréacteur S.A.T. (Super Airbus Transporter), construit à partir d'un biréacteur A300-600 [9] beaucoup plus performant, répondant déjà à un besoin de transport de charges volumineuses à plus grande vitesse. L'étape suivante, étudiée par le laboratoire TsAGI en Russie [10] est beaucoup plus ambitieuse et prévoit le transport de conteneurs détachables suspendus (Fig. 2) :

- soit sous un hélicoptère géant de 500 tonnes muni d'un rotor de 100 mètres de diamètre, propulsé par 5 turbo-fans en bout de pales, capable du transport ponctuel de charges de l'ordre de 250 tonnes ;
- soit sous un avion bifuselage de 1 300 tonnes - voilure d'envergure 140 m, 8 turbo-fans - capable de transporter une charge de 500 tonnes sur 3 000 km.

Bien que ces projets demandent des investissements considérables en recherche et en développement, ils peuvent répondre à une demande future de quelques unités dans chaque pays. A l'échelle mondiale, cela justifierait une production importante mais il va de soi qu'une telle activité devrait être conduite dans le cadre d'une coopération internationale.

Un dernier aspect du transport massif de fret autour du monde est son caractère actuellement de plus en plus "intermodal", car il utilise des "conteneurs de 20 pieds" standardisés (cube de 2,4 × 2,4 × 6 m³) dont la manutention est automatisée entre navire, camion et train (Fig. 6). Pour que l'avion puisse entrer efficacement dans cette boucle du commerce mondial, il faut augmenter considérablement sa capacité d'emport, et aussi concevoir des systèmes de chargement et de déchargement rapides.

*Fig. 6*




De tels avions géants "porte-conteneurs" devraient connaître un marché important dans le futur, car ils présentent des avantages indiscutables par rapport au transport maritime (gain de temps, acheminement s'exprimant en heures et non plus en jours, livraison au voisinage du destinataire en n'importe quel point du monde), et aussi par rapport aux transports terrestres qui souvent sont insuffisants ou déjà saturés, ce qui est le cas des autoroutes entre mégapoles [11].

Pour apprécier la charge utile souhaitable pour de futurs "supercargos", il faut examiner celle déjà possible avec les plus gros avions existants, et celle visée dans plusieurs avants-projets. La figure 2 résume ces deux aspects en présentant la charge utile en fonction de la masse au décollage pour des avions cargos militaires et civils opérationnels ou en développement [11] : ils se placent approximativement sur une droite correspondant à une charge utile représentant 30 % de la masse au décollage, soit 120 tonnes de charge utile pour une masse au décollage de 400 tonnes environ dans le cas des plus gros cargos américains (civil : B-747 F et militaires : C-5B). Les cargos Antonov (Ukraine) An-124 et An-225 [19] se situent plus haut, au voisinage de la droite correspondant à CU = 0,4 MD. Notons que l'hexaturbofan Antonov 225, construit en 2 exemplaires, reste le plus gros avion du monde (MD : 600 tonnes), capable soit de transporter 250 tonnes sur courte distance, soit de parcourir 15 400 km.

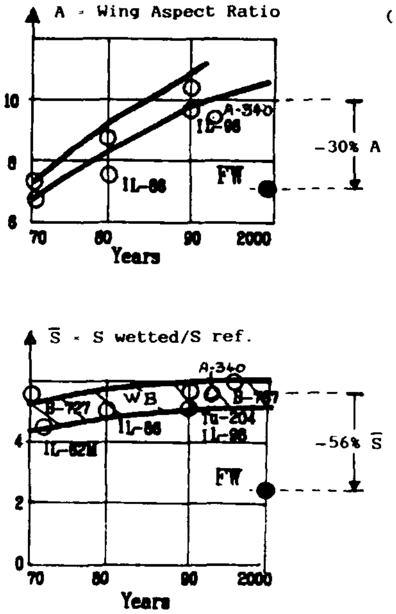
En extrapolant cette droite, on découvre les différents avant-projets présentés au Symposium de Strasbourg : au centre de ces supercargos se trouve un projet d'hydravion géant, Hydro-2000, présenté par l'amiral Goupil [13] : ce concept intéressant permet de s'affranchir des limitations de pistes et de bénéficier d'un très grand nombre de plans d'eau autour du monde, ainsi que des installations portuaires pour la manutention de ses conteneurs (CU = 400 tonnes sur 6 500 km, masse au décollage MD = 1 000 tonnes) ; sa propulsion ferait appel à 6 turbo-fans de la classe 90 000 livres (6 × 41 tonnes) déjà en cours de développement (par exemple le GE-90 de General Electric / SNECMA).

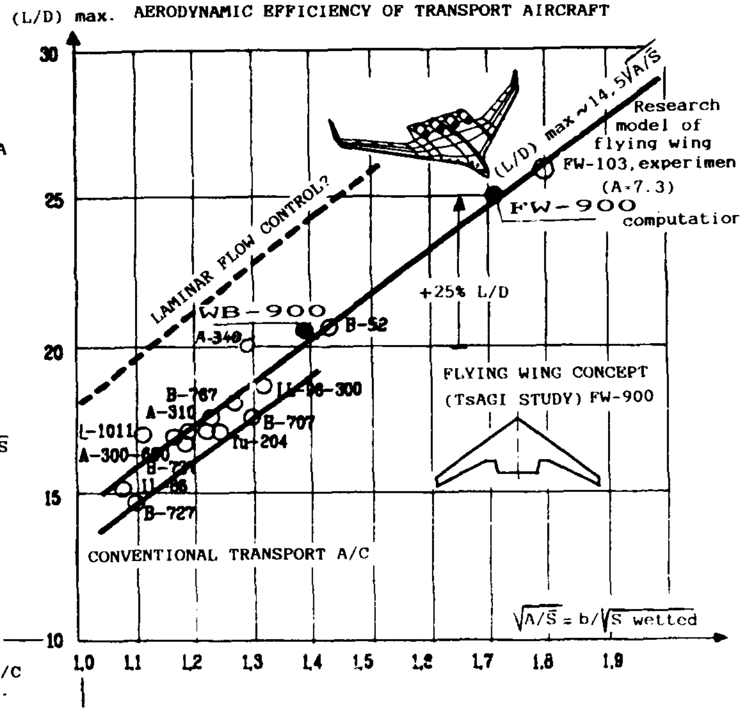
Le concept bifuselage étudié par Lockheed [14] (CU = 300 tonnes, MD = 900 tonnes) est intéressant non seulement en raison de sa large surface d'atterrisseurs mais aussi en raison du rendement structural de sa voilure (Fig. 8), qui permet un grand allongement et donc un bon rendement aérodynamique.

Enfin, une étude récente de NASA-Langley [15] décrit un projet de porte-conteneur géant – capacité 84 conteneurs, par rangées de 7 dans un fuselage circulaire de 10 m de diamètre ; c'est une configuration classique à 10 turbopropulseurs à hélices rapides permettant une faible consommation (consommation spécifique = 0,43, mais conduisant à une vitesse de croisière modeste (Mach 0,65, d'où l'utilisation possible d'une simple voilure sans flèche, de grand allongement, mais dotée d'un contrôle de laminarité pour réduire sa traînée (finesse de 25 à comparer à 18 environ pour les avions actuels). Avec une masse au décollage de 1 113 tonnes, il pourrait transporter 450 tonnes en conteneurs sur 9 000 km.

On a également porté sur la figure 2 un projet d'aile volante géante pour 1 000 passagers proposé par le TsAGI [16], qui pourrait préfigurer un cargo géant dont la charge utile serait répartie dans la partie centrale très épaisse de l'aile ; cette aile volante (FW-900) est créditée d'une finesse aérodynamique remarquable de 26 à un Mach de croisière de 0,8 d'après les résultats de soufflerie extrapolés au vol ; la figure 7 montre que cette finesse est de 25 % supérieure à celle d'un avion classique de même capacité et mêmes performances (WB-900), due à une surface mouillée, donc à une traînée de frottement, inférieure de 56 % à celle des gros porteurs classiques actuels, malgré leur allongement supérieur de 30 %. De telles performances avaient déjà été estimées par la NASA qui avait lancé, dans les années 70, des études d'avant-projets avec les constructeurs américaines [14, 15, 17, 18] afin de rechercher les configurations les mieux adaptées au transport massif de fret ; l'une d'elles était une aile volante géante dont le fret, constitué de conteneurs intermodaux, était réparti le long de l'envergure de l'aile suivant le concept "spanloader". La figure 8 [18] montre que ce concept permet de réduire la masse structurale de 20 % par rapport à celle d'une configuration classique ; on note aussi que la solution "bifuselage" est intéressante.

Malheureusement la NASA avait raison trop tôt et ces projets furent abandonnés faute de marché, ce qui n'est probablement plus le cas aujourd'hui.




N.B.) WB-900 : conventional wing/body A/C with the same capacity than FW-900.

ULTRA HIGH CAPACITY TRANSPORT "FLYING WING" CONCEPT BY TsAGI

CRUISE Mach Nr.-0.8; RANGE: 10000 Km

*Fig. 7*

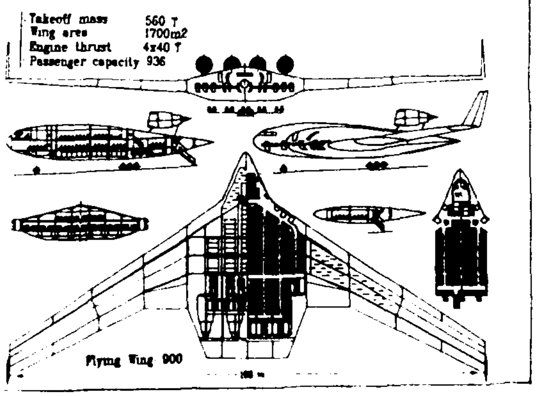
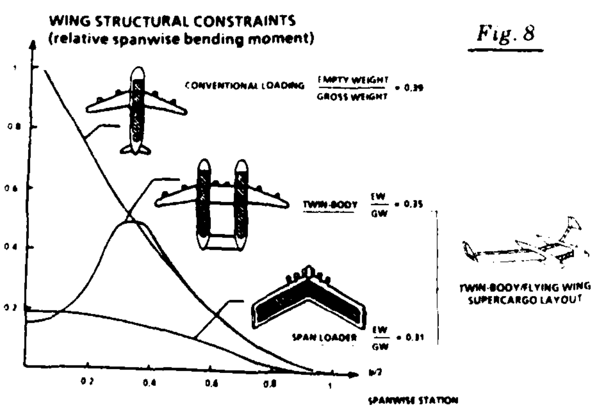



*Fig. 8*



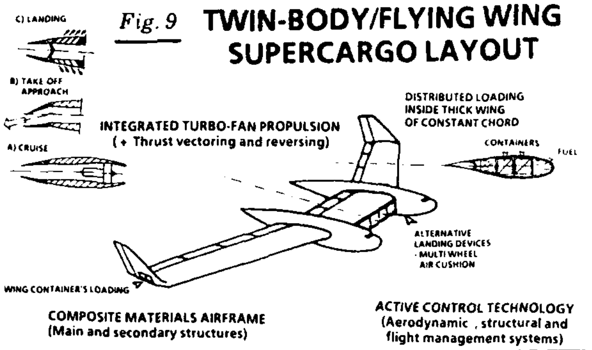

## V) ESQUISSE D'UN PROJET DE CARGO STRATEGIQUE GLOBAL

A partir de ces projections de différents concepts de supercargos, on peut donc essayer d'esquisser ce que pourrait être un projet de cargo "stratégique global" susceptible d'intéresser non seulement les gouvernements (les frais initiaux de recherche pourraient être financés au niveau international), mais aussi des utilisateurs commerciaux potentiels d'une flotte d'avions "porte-conteneurs". Cette flotte serait d'ailleurs complémentaire et non pas rivale de celle des avions cargos actuels, car son marché serait à conquérir sur les transports de surface, en particulier sur les axes commerciaux futurs: Transpacifique, Transatlantique et Transibérien. Un accroissement du marche total mondial du fret de 1 % nécessiterait une bonne centaine d'avions porte-conteneurs à l'orée du XXIe siècle et cette demande nouvelle viendrait s'ajouter au besoin de transport massif "d'intervention intergouvernementale".

C'est probablement la meilleure chance, pour les bureaux d'études et les centres de recherche de par le monde, d'entrer dès maintenant en compétition pour faire valoir leurs meilleures idées et réaliser un "saut technologique" qui sera profitable à tous. Très égoïstement, je pense au rôle éminent que l'Europe pourrait jouer dans une telle compétition...

Sur la figure 9, j'ai caricaturé un tel projet dans l'unique intention de souligner les avances technologiques souhaitables, qui intéressent à la fois l'aérodynamique, le système propulsif, la conception structurale nouvelle - utilisant en priorité des matériaux composites -, ainsi que les systèmes automatiques de contrôle et de gestion du vol.

*Fig. 9* **TWIN-BODY/FLYING WING SUPERCARGO LAYOUT**




Le concept figuré ici est fondé sur une configuration d'«aile volante», combinant les avantages structuraux du double fuselage et ceux d'une voilure en flèche épaisse et de corde constante, pouvant contenir une par ie de la charge utile répartie en envergure (Fig. 8). Le système propulsif, intégré à l'aile centrale, comporte un certain nombre de turbo-fans à grand taux de dilution, de faible consommation et de bruit modéré, utilisés aux basses vitesses pour participer à l'hypersustentation – effet *jet flap* – et au freinage aérodynanique lors de l'atterrissage. Les systèmes de contrôle automatique permettent en particulier de voler "instable en longitudinal et en route", d'où réduction des surfaces d'empennages, et donc de la trainée. La viabilité d'un tel contrôle sur une aile volante est déjà démontrée avec le bombardier américain Northrop B-2 ; notons que des plans "canard" pourraient s'avérer nécessaires pour équilibrer une forte hypersustentation. Enfin, la base des 2 fuselages est occupée, soit par des atterrisseurs multiroues, soit par des coussins d'air éclipsables assurant une bonne répartition de la charge au sol et permettant d'utiliser des terrains sommairement préparés. En effet, pour une pleine efficacité opérationnelle de supercargo "d'intervention globale" [12] évoqué plus haut, on ne pourra certainement pas se contenter de missions entre grands aéroports ou bases militaires, il faudra donc pouvoir utiliser aussi des terrains sommairement préparés, ce qui implique un concept STOL/décollage-atterrissage court.

Par ailleurs, un tel avion doit pouvoir intervenir en n'importe quel point du globe en partant de quelques bases principales, ce qui implique un rayon d'action à pleine charge de l'ordre de 6 000 km, et environ le double en mission "convoyage", pour laquelle on pourrait remplacer la charge utile par du carburant supplémentaire rapidement stocké à bord de conteneurs spéciaux ; à la limite, une fonction de ravitaillement en vol pourrait même être envisagée.

L'application de toutes ces technologies, nouvelles mais déjà "validées" pour la plupart, devraient conduire à une configuration nettement plus performante que celle des avions classiques actuels, tant en ce qui concerne le rendement structural – le rapport entre la masse à vide opérationnelle et la masse au décollage – serait dimide plus de 20 % grâce à l'emploi généralisé de matériaux composites ; le rendement aérodynamique – la finesse – serait augmenté de 18 à 24 environ, soit un gain de plus de 30 %, et la charge utile transportable passerait de 30 % à 40 % de la masse au décollage (Fig. 2). Cette masse au décollage pourrait se situer entre 800 et 1 200 tonnes suivant les besoins exprimés par les futurs utilisateurs militaires (missions stratégiques globales) et civils (porte-conteneurs intermodaux). Les spécifications pourraient faire l'objet d'un consensus quant à la capacité d'emport de conteneurs et quant aux performances de basse vitesse minimale afin de pouvoir utiliser dans les deux cas des pistes médiocres. Bien entendu, ces supercargos seraient complémentaires des flottes militaires et commerciales "classiques" dont les rôles, et donc les spécifications, resteront fort différents.

En ce qui concerne la vitesse de croisière optimale, on n'est pas astreint, comme pour un avion de transport de passagers, à minimiser le temps du voyage, en particulier dans le cas des longues étapes, et l'économie opérationnelle conduira probablement à des nombres de Mach de l'ordre de 0,70 à 0,75 en croisière, qui sont bien adaptés aux gros turbo-fans à grand taux de dilution. Ces derniers sont plus fiables que de gros turbo-propulseurs à hélices rapides, et surtout ils offrent la possibilité d'envisager une intégration intelligente de la propulsion à la cellule, grâce à laquelle on pourra développer un flux hypersustentateur, particulièrement souhaitable pour ce type d'avion "multi-missions".

Tous ces facteurs peuvent coucourir à une forte diminution du coût de la tonne-kilométrique, qui toutefois restera toujours supérieur à celui des transports de surface [15]. Mais la réduction des temps de transport aérien est inestimable et il est clair que nous en avons définitivement besoin.

En conclusion, il faut peut-être rappeler que nous savons voler depuis 90 ans, que nous nous sommes servis de la troisième dimension pour le meilleur et pour le pire, et je souhaite dire que le moment est venu de se fixer des objectifs à long terme pour utiliser au mieux nos capacités créatrices au bénéfice de tous, en ces temps d'après-guerre froide et de paix chaude. Le lancement d'un projet de supercargo ne pourrait-il pas être un bon thème de consensus international ?

## REFERENCES


[1] *Actes du Symposium International sur l'avenir de l'aviation de transport de fret, Strasbourg, 25-27 mars 1993*, ANAE, 1, Av. Camille-Flammarion, 31500 Toulouse (à paraître en septembre 1993).

[2] Bernard Pellissier (DGAC), La conjoncture économique du transport aérien de marchandises, *Nouvelle Revue d'Aéronautique et d'Astronautique*, n° 1, 1993.

[3] Serge Germon (DGAC), Le fret aerien et l'économie mondiale, *Actes du Symposium*, ANAE, voir [1].

[4] J.-F. Vivier (Aérospatiale), Le marché du fret aérien, [*id.* 1].

[5] Milton J. Minneman (Pentagone), The United States Dpt. of Defense Air Mobility fleet, an active and reserve military and civil partnership, [*id.* 1].

[6] Colonel Champagne (COTAM), Le Transport aérien militaire français et son action dans le domaine de l'aide humanitaire, [*id.* 1].

[7] R.K. Sable et G.G. Field (McDonnell-Douglas, Etats-Unis), C-17 program and status, [*id.* 1].

[8] D.K. Empson (Euroflag, UK), Status of the FLA, a European military transport project, [*id.* 1].

[9] D. Knospe (Airbus Industrie), Air transport of outsized cargo, [*id.* 1].

[10] V.B. Denisov et a! (TsAGI, Russie), Air transportation system for shipping outsized cargoes, [*id.* 1].

[11] J.P. Roeder (Airbus Industrie), Civil freighters and military transports, their origins and developments,

[12] Ph. Poisson-Quinton (ONERA, ANAE), Vers une force d'intervention aérienne internationale à base de cargos stratégiques, [*id.* 1].

[13] Amiral (CR) Yves Goupil, Vers l'hydravion lourd, une des solutions pour le développement du fret, [*id.* 1].

[14] Roy H. Lange (Lockheed-Georgia), A review of unconventional Aircraft design concepts. *ICAS 86-2.2.1.* 1986.

[15] S.J. Morris et W.C. Sawyer (NASA/Langley), Advanced Cargo Aircraft may offer a potential renaissance in freight transportance, [*id.* 1].

[16] V.E. Denisov et al. (TsAGI, Russie), Conceptual design of very large capacity airplane in flying wing layout, [*id.* 1].

[17] NASA/Langley, An outlook for cargo aircraft of the future, *TMX-72.796* (novembre 1975).

[18] G.G. Kayten (NASA/Hq), An overview of large cargo aircraft technology studies, [*id.* 1].

[19] O. Bogdanov (Antonov, Ukraine), Future Cargo Aircraft, [*id.* 1].

# OPTIMISATION OF COMPOSITE AIRCRAFT STRUCTURES BY DIRECT MANUFACTURING APPROACHES

G.Berchtold
J. Klenner
Deutsche Aerospace AG
Military Aircraft
P.O. Box 801160, 8000 München 80
Germany

## SUMMARY

The present high performance aircraft designs are increasingly using high strength composite structures, mainly made of unidirectional carbonfiber tapes.
But the composite technology is still afflicted with several weak points, e.g. the lack of adequate mechanized tape application techniques for complex compound structures, unsatisfying designs and design methods and missing continuous CAD/CAM-linkage.
*In the following paper we will describe an "Integrated Tape* Laying System" (ITLS) which uses a new tape steering technology for automated manufacturing of complex parts. This system integrates the steering technology's potentials and restrictions completely in the design process to avoid time consuming iteration loops and to optimise the structure.
To be able to understand the detailed process a short overview about two different geometry models demonstrated on a typical example will be given. From this the optimal detailed process will be derived, with an important influence from the specific manufacturing technology.
Finally some remarks on economic potentials are outlined with there impact on typical composite aircraft parts related to different automated manufacturing techniques.

## 1. INTRODUCTION

One major basic target for long range and long endurance operation of aircraft is minimum structural weight.
For reaching this target the use of composite structures will have the biggest potential. The unidirectional properties of carbonfiber e.g. are about 6 times higher in the specific tensile strength and about 3 times higher in the specific stiffness compared to aluminium alloy. However, these values are related to one single material orientation which is not applicable in most practical designs. But half of the above values should be achieved in future.
Although meanwhile well established and used in aircraft industry, the composite technology still suffers several weak points. First, most realized aircraft parts are no real composite designs; due to their history, material replacement philosophy plays a major role. As a result, the weight reduction achievements did not fullfill the expectations.
Second, the lack of mechanized and automated techniques for complex structures, the missing predictability of the fiber path in the case of compound contours and the still dominating serial design, stressing and manufacturing of the parts are some of these weaknesses. They result in long product lead times, high costs and unsatisfying weight reduction.
This paper describes a new approach for the integrated design and manufacturing of complex composite aircraft structures that may help to overcome existing obstacles. The driving element is a newly developed manufacturing technique based on a controlled deviation from the geodesic course or "natural path" of unidirectional tape during tapelaying.
This principle, meanwhile successfully proven with an advanced tapelaying machine, not just enables the manufacturer in future to produce non-developable composite structures at the same quality level as single curvature components but also gives engineering the ability to predict and take into account the resulting fiber orientation throughout the part while designing and stressing.
As a result, three dimensionally contoured parts that make up a high percentage of aircraft components can be realized in a lightweight composite design, and even developable parts can be made lighter by applying tape steering technology.
In order to gain maximum benefits it is inevitable to establish this new approach as an integrated process right from the beginning. It is neither helpful to use advanced design techniques without taking the manufacturability into account, nor does it make any sense to generate NC-programs for a sophisticated tape application apparatus on the basis of a conventional part design.
Thus Engineering and Manufacturing at Deutsche Aerospace Military Aircraft strived for a fully integrated process that takes advantage of the potential of tape steering during 3D-design, links the stress analysis and optimisation and generates at the design level a part program that can directly be post-processed into NC-data for the tape application machine.

## 2. TAPE STEERING TECHNOLOGY

Composite parts feature an increased benefit from the inherent superior performance of unidirectional (UD) tape over non-UD material forms. The more the fibers are continuous, straight and follow the load path the larger the benefit. In the case of flat or single

*Presented at an AGARD Meeting on 'Recent Advances in Long Range and Long Endurance Operation of Aircraft', May 1993.*

curvature, i.e. developable components, this can be achieved by manual tapelaying as well as with various mechanized tape application devices. The introduction of a second curvature results in a non-developability and causes a problem because so far no method that can reproduce the same quality level as known from single curvature parts is available.
The double curvature concerned may result from a global non-developability (e.g. due to aerodynamic or radar signature requirements) or from local spherical areas (e.g. offset-zones or local ply build-ups). Non-developable parts become a major concern the more composites are used throughout the aircraft structure, large integrated part designs are preferred for weight and cost saving purposes and contour compromises are minimized for the sake of aerodynamic and radar signature performance.
The single piece center fuselage CFRP skin as shown in Fig.1 is a typical example for this situation.

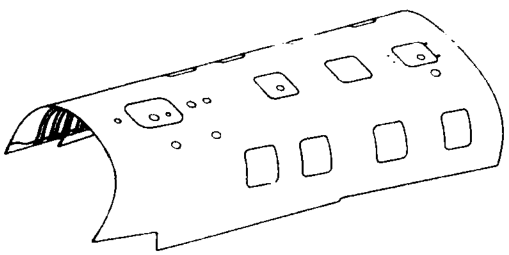


**Fig. 1 Single piece CFRP center fuselage skin (5m length)**

## 2.1 BASIC PROBLEM AND PRINCIPLE SOLUTIONS

When laying UD-tape of a given constant width onto a non-developable surface without forcing the tape to deviate from its natural path, converging or diverging of adjacent tape courses depending on the concave or convex surface geometry will occur, resulting in unacceptable overlaps and gaps. Adjusting the tape width by contouring is a way to avoid overlaps and gaps. But this method, that is used in existing tapelaying machines, results in the cutting of load-carrying fibers and thus weakens the composite part.

The controlled deviation from the natural tape path as indicated in Fig. 2 is a better solution because it maintains continuous fibers whilst also avoiding gaps, overlaps and cuttings.
This "tape steering" technology is difficult to realize, because the simple "curving" of the tape results in fiber disorientations and wrinkles on the compression side of the tape due to the fact, that the fiber lengths do not coincide with the lengths of the lay-up track of the individual fibers across the tape width (see Fig. 3) The reduction of the tape width down to the size of a tow like proposed and successfully demonstrated for single and multiple tow placement (see Ref.1 and 2) minimizes this effect but does not prevent it completely. The remaining micro-wrinkels could be acceptable from a stress point of view and - after maturing - the related technique could become a viable method for the production of several composite parts.

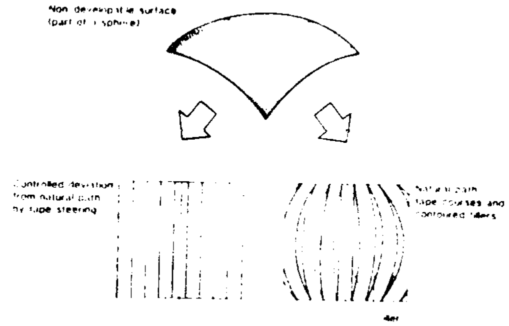


**Fig. 2 Different methods of covering non-developable surfaces**

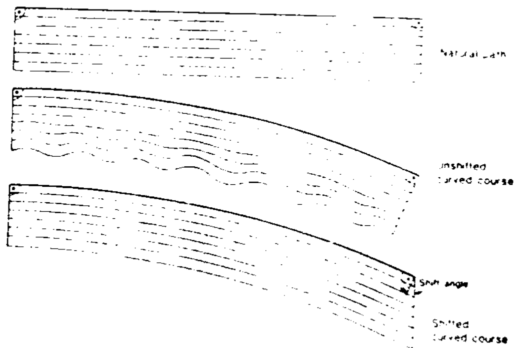


**Fig. 3 Tape steering with and without fiber shifting**

At DASA/MBB Military Aircraft Division a different technique has been developed and patented in the recent years (see Ref. 4). This method allows a controlled tape steering by using a proprietary fiber shifting process that results in a curved tape course without fiber disorientations and/or wrinkles. As sketched in Fig. 3 the key feature of this technique is the relative movement of adjacent fibers within a tape, that is made possible due to the visco-plastic behaviour of the uncured thermoset resin system and results in coinciding lengths of individual fibers and their related lay-up tracks.

## 2.2 TECHNICAL REALIZATION AND POSSIBLE APPLICATIONS

The developed and successfully demonstrated DASA/MBB tape steering/fiber shifting technology (Fig. 4 shows 75 mm UD-tapes laid with an experimental tapelaying head along a 8m radius) is based on the principle, that the excessive length of the fibers is compensated by a corresponding difference in course length between the supply reel and the compaction roller of a tapelaying head. This can be achieved by various linear or rotational movements of the supply reel relative to the compaction roller.

A more efficient concept for the introduction of the required fiber shifting is shown in Fig. 5. A shifting device between sup

Fig. 4 Steering of 75 mm wide UD-tapes along a 5 m radius

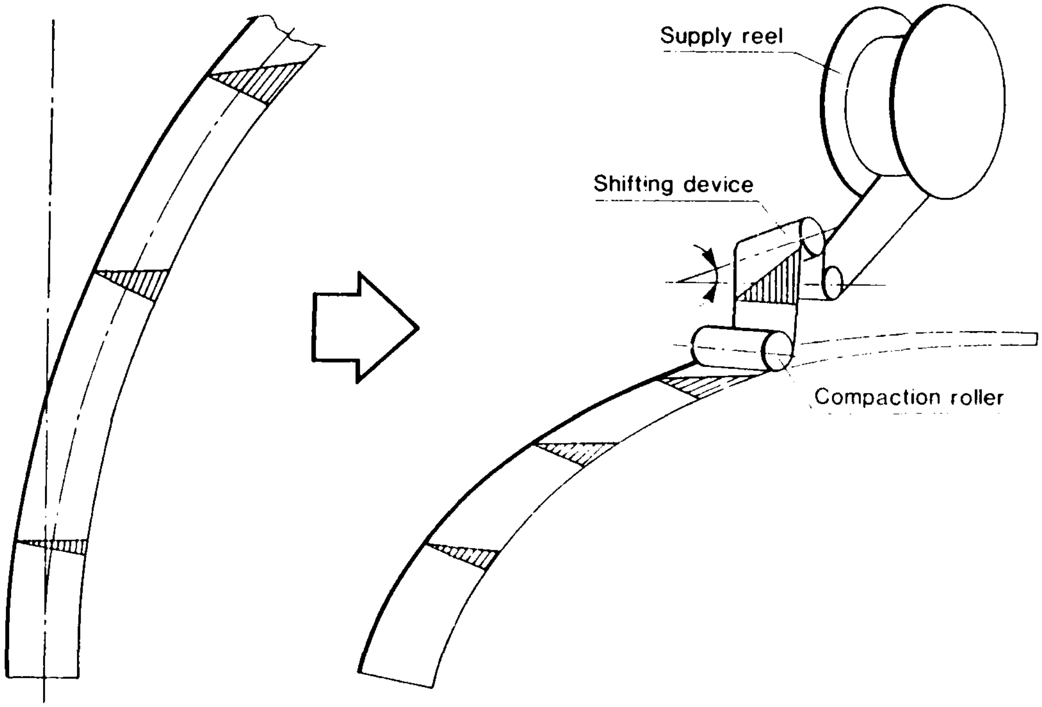



Fig.5 Fiber shifting device for tape steering

ply reel and compaction roller takes care of the excessive fiber length and generates the required shifting angle that is a function of the radius and the length of the tape course to be laid. The linear shifting can be extended to non-linear fiber shifting by using a more complex shifting device in order to cover also double courved surfaces within the tape width, e.g. in the case of ramp areas. It is important that the velocity vectors of the shifting device are parallel to the related vectors of the dispensed fibers and that the speed can vary across the tape width. Otherwise fiber distortion and lateral movement of the tape will occur (see rel. patent Ref. 4 and Fig. 6).

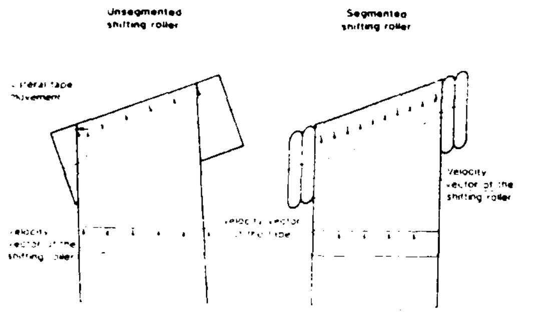



**Fig. 6 Effects of different shifting device designs**

On the basis of the above mentioned tape steering/fiber shifting concept a tapelaying head has been built and tested by the Ingersoll Milling Machine Company, USA, which is able to steer tape and perform all other functions including complex cutting and scrap removal. The head allows the application of up to 150 mm wide UD-tape onto compound non-developable surfaces, thus enabling the mechanized/automated manufac-ture of composite parts like the fuselage skin displayed in Fig. 1. But also in the case of a developable component tape steering can be applied for higher structural efficiency (see chapter 4).

As the fiber shifting task adds even more axis and thus more complexity to the anyhow complex multi-axis control of an advanced tapelaying head, the generation of the required NC-data can only be performed upstream by a powerful software. Consequently component design, stress analysis and the generation of manufacturable geometry data must be integrated into a combined software package.

## 3. THE INTEGRATED TAPE LAYING SYSTEM PROCESS

This chapter will be used to explain the influence of the specific manufacturing technology, such as the prior described tape steering method, on the upstream part of the aircraft design process.

In 1989 a project was started by the MBB aircraft engineering department to evaluate the general process from design to manufacturing based on the geometry of the aircraft. This base was chosen because the geometry is the major information which has an origin already in the conceptual design and which ends with the manufacturing of the aircraft itself.

More details about this global process are explained in Ref. 5 and Ref. 6. However the 3D-geometry of sheet metal parts or milled parts is relatively easy to handle because only the outside geometry information is needed for manufacturing in a CIM-process. The amount of data is controllable and there is still the the possibility to do some minor changes on the shop floor level if the manufacturability constraints of the NC-machine are not properly matched.

This is different for composite parts made out of the raw material tape.

The geometry data for each individual tape path and its cuttings have to be generated for the manufacturing. For instance, the skin structure of the centre fuselage in Fig. 1 is made out of about 9000 single tapes with start- and endcuts and some of them with complex side cuts. Within the ITLS-system this is done using splines to minimize the data to be transferred.

One can easily recognize that with this complex and large amount of data it is not possible to change, adapt or correct interactively any data after completion of the design phase like it is done with milled parts NC data where only the "outside" geometry of the part is needed for manufacturing.

To fulfil all the manufacturing constraints (e.g. steering radii, cut angles, minimum tape width for side cuts...) the only possible method is to simulate the manufacturing process within the design process.

This is done by starting with the major periphery definition for each ply family. The corresponding implicit peripheries are automatically generated by the software (see Fig. 7).

The next activity is to set up the so-called laminate matrix. This matrix defines the logical buildup of the laminate, that means how to position the individual plies of the different ply families within the thickness of the laminate.

To accelerate this interactive process a ruled based software module is planned in future.

After preparations the automatic simulation process is started ply by ply (Fig. 7). If an error occurs due to a manufacturing constraint the designer instantly has to solve the probelm by shifting the tapes or changing the starting point.

After completing this design the whole geometry is sent by a push of a button to the front end computer of the tape laying machine ready to start the manufacturing process.

Additional information is described in Ref. 7. It has to be mentioned that the designer has to decide what type of tape laying head he wants to use before he starts the part design. This methodology, though, returns the knowledge of manufacturing technology to the designer, which is not easy to accomplish in large companies due to separation of process phases by organisational fences.

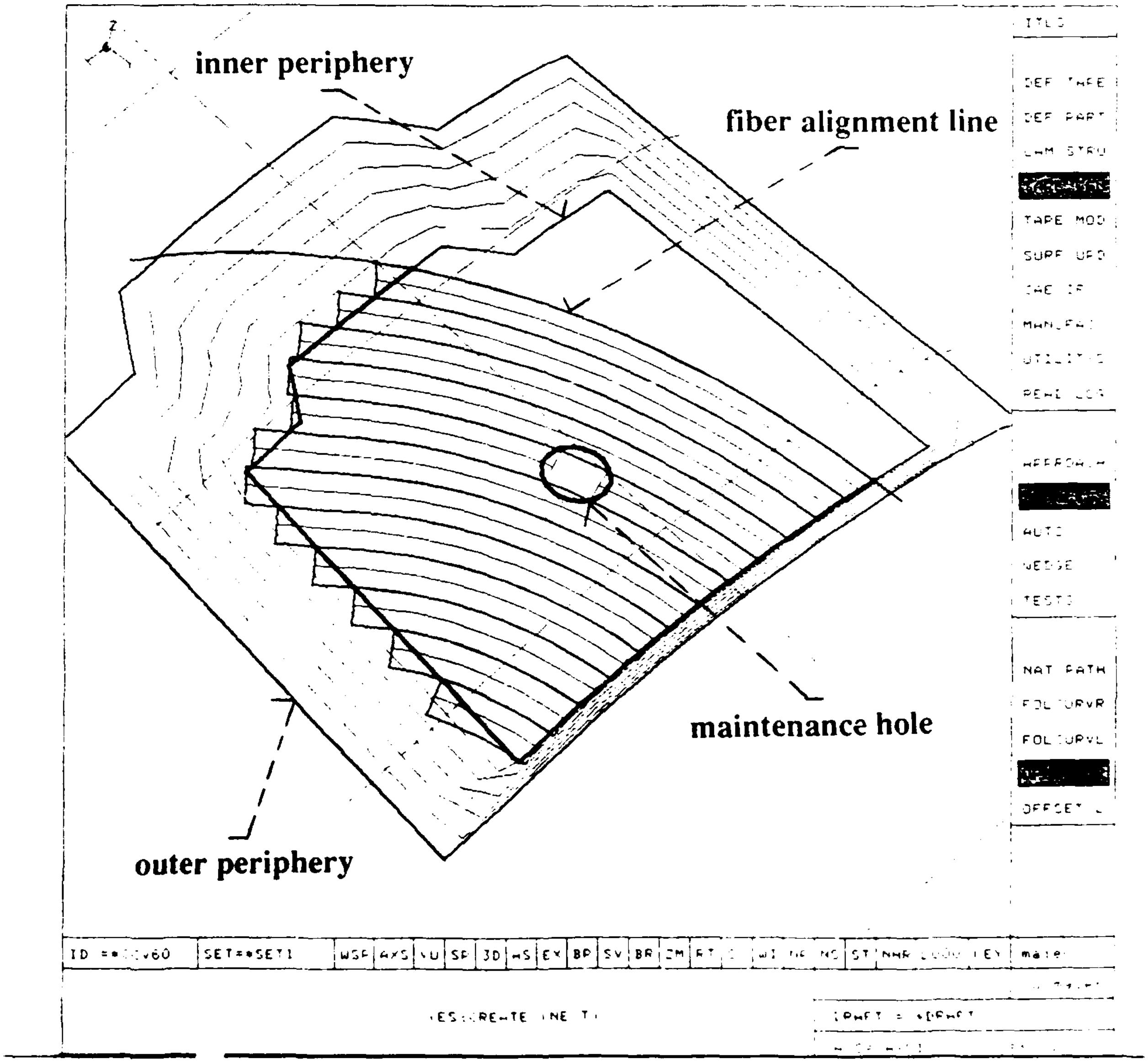



Fig. 7 ITLS path and periphery generation example

# 4. THE UTILIZATION OF TAPE STEERING FOR STRUCTURAL OPTIMISATION

## 4.1 ADAPTION OF STRUCTURAL OPTIMISATION FOR TAPE STEERING BASED ON FINITE ELEMENT GEOMETRY

In respect to composite structure optimisation it is already standard to optimise the thickness distribution of each individual layer with its given constant fibre orientation across the structure.

For a couple of years one knows that there exists a high potential in weight reduction if the fiber orientation is changed along its path (Ref. 8). But at that time no manufacturing method to be able to achieve this in production was known.

The tape steering method was originally developed to be able to manufacture non-developable structure. As soon as this method was proven in the manufacturing department the optimisation software MBB-Lagrange was adapted to be able to handle as additional design variables the individual fiber orientation within every finite element. To validate the functionality of the modified Lagrange test examples have been carried out.

One of these is illustrated in Fig. 8.

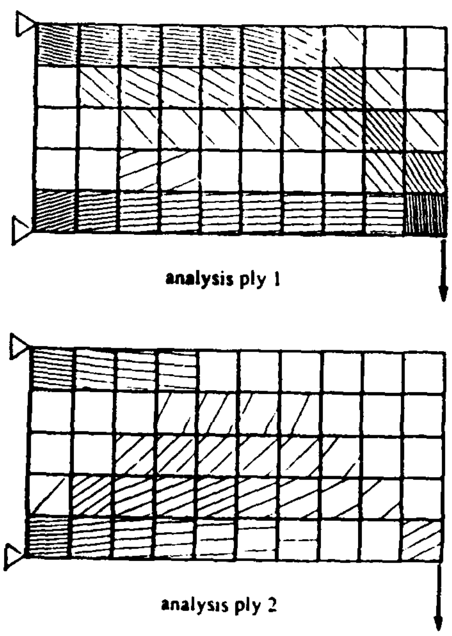



**Fig. 8 Test example cantilever beam**

In this example a cantilever beam which is supported on the lower and upper left end, is loaded with a vertical force on the right end. A failure criteria for each composite element and a displacement restriction at the force loaded node are the optimisation constraints.

Design variables are the thicknesses of each element represented by the density of the lines and the fiber orientation also within each element represented by the orientation of the lines.

The optimiser had two different analysis plies to handle in this case for minimizing the structural weight which was the objective function.

It can easily be seen that the ply no.1 was used to support the upper load path for tension and the lower load path for compression. Ply no. 2 was automatically used to support the shear stress between the two pathes. Elements out of the load paths had been set to zero thickness.

This and many other test examples proved the quality of the Lagrange code in respect to the handling of fiber orientation optimisation.

It has to be mentioned that the system at this stage does not know anything about manufacturing-constraints coming e.g. from minimum steering radii. Therefore the manufacturability still has to be proved in an separate simulation process.

One of the first real aircraft structures which was used to apply fiber orientation optimisation was an fin structure design with carbon fiber skins supported by an aluminium honeycomb core. The related finite element model is shown in Fig.9.

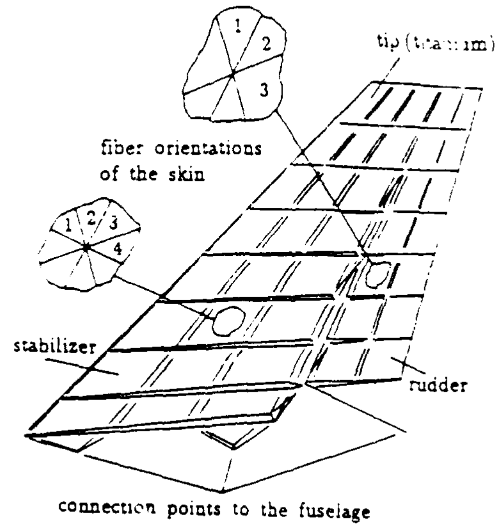



**Fig. 9 Analysis model of the fin**

The model has five static load cases, 119 stress limitations for the isotropic elements, 252 limitations for the failure criteria of the composite elements, an aeroelastic efficiency constraint for the rudder and one for the fin and finally a flutter speed constraint.

So the optimiser had to handle a total of 1862 constraints with 186 design variables.

The results of the optimised structure are shown in Fig. 10.

It is important to repeat that these are the results of the optimisation without the important manufacturing constraints like minimum steering radii.

Nevertheless, a skin weight of 25.3 kg was achieved by using tape steering as an additional engineering degree of freedom. The skin weight with constant fiber orientation across the structure for each ply is 34.6 kg as a comparison.

At the time when this paper was prepared the iteration loop with the manufacturing simulation was not finished. So the result outlines the maximum potential for this case.

A close look at the result of ply no. 2 shows an S-shape fiber orientation across the fin. By searching for those constraints

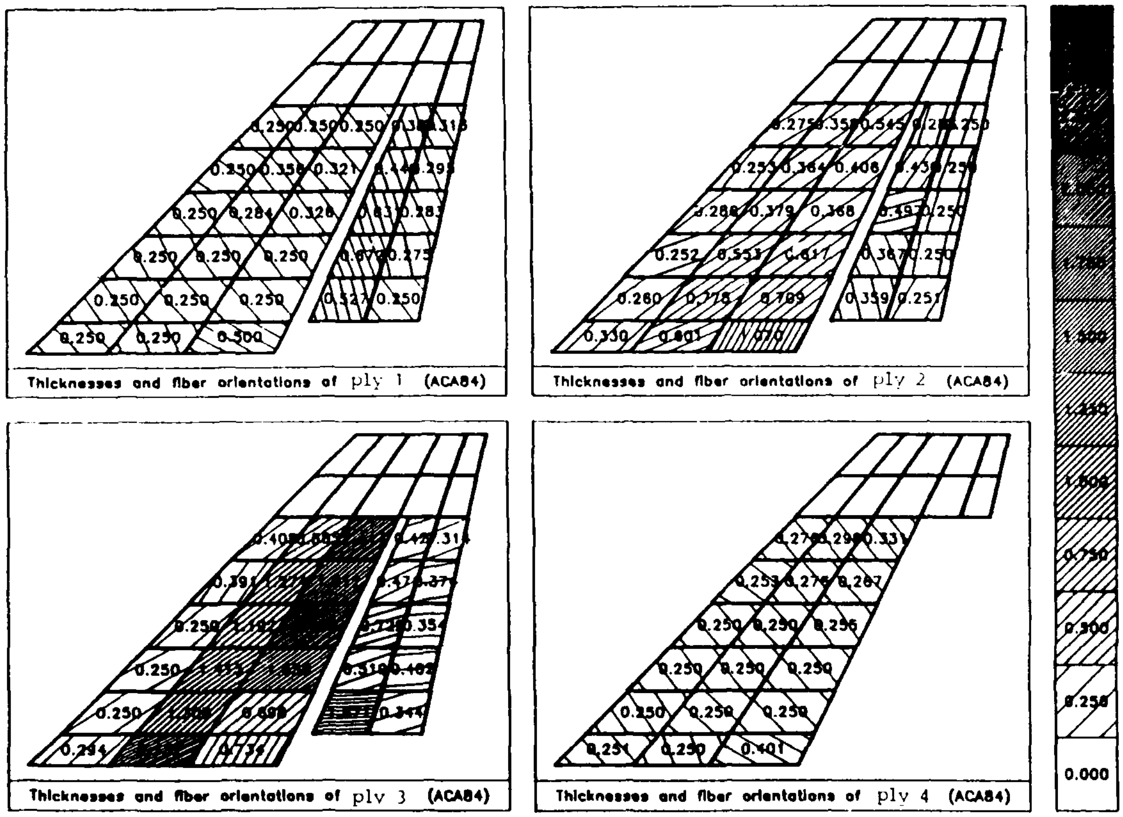



**Fig. 10 Optimisation results of the fin**

which were active for the final optimisation iteration it was recognized that the aeroelastic efficiences had been dominant.

So this S-shape can be interpreted as the optimal stiffness distribution to gain the aeroelastic efficiencies with minimum weight.

This and some other examples showed that the potential to obtain additional high weight reductions by using the fiber orientation optimisation within each plies are highest for structures with complex constraints coming from different physical effects like aerodynamically loaded structures.

A simple statically loaded structure with straight load paths will not gain much advantages by using tape steering.

More information about the theory specifically in the optimisation code was persented recently in different papers (Ref.9/10).

## 4.2 THE DETAILED ITLS PROCESS

Fig. 11 shows the present state of the ITLS process including structural optimisation.

This process begins with material studies and stress estimation for evaluation of structural principles. It is a small but important process.

The actual part design starts in most cases of aircraft structures with the definition of the structural surface out of the loft surface. This geometry and the geometry from parallel processes are directly transferred to the CAE-"side" to generate the 3-dimensional finite element mesh.

After adding the loads and completing the input including definition of design variables and constraints a structural optimisation is carried out.

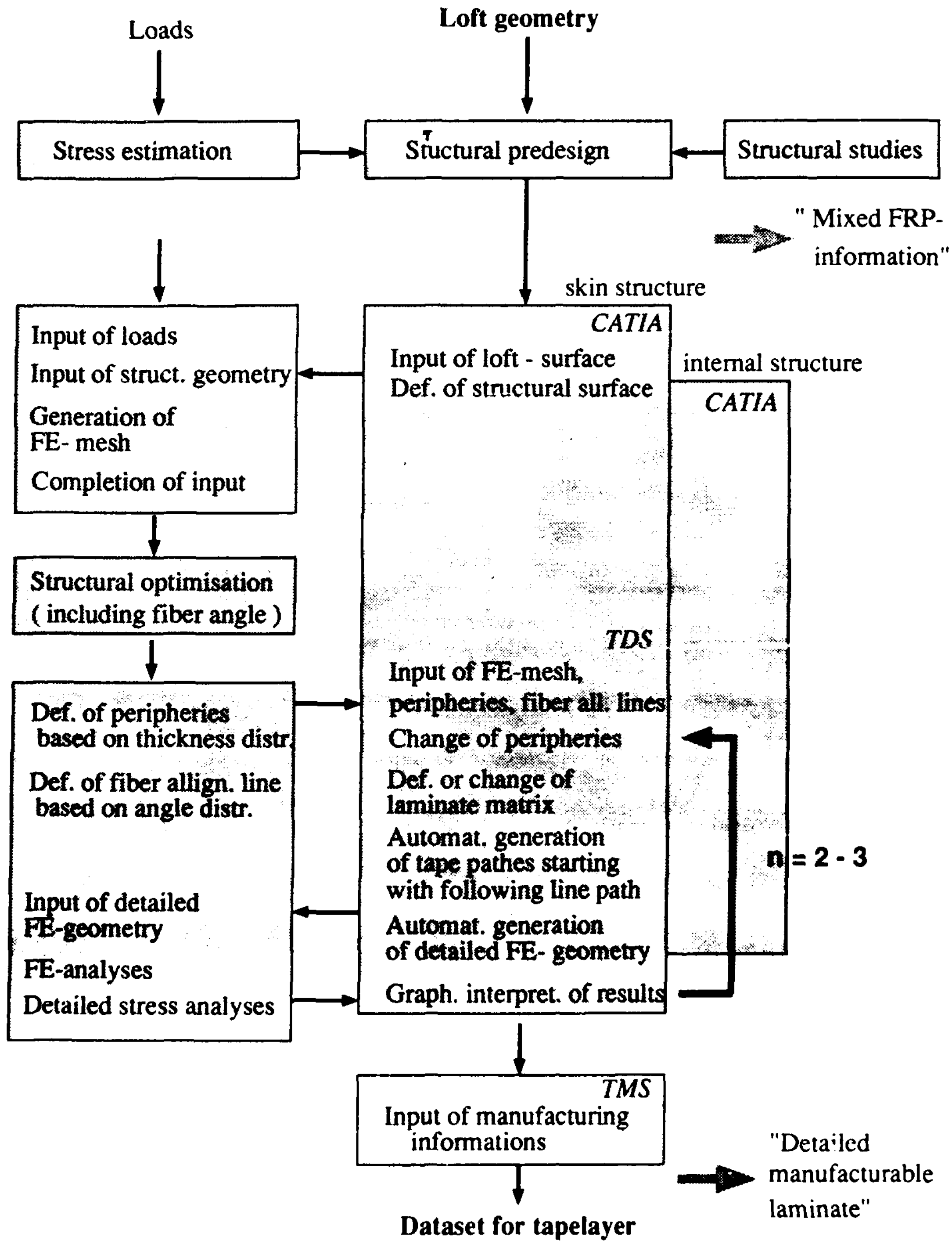



FIG. 11 Detailed ITLS design process

Results are the thickness distribution and fiber orientation distribution for each defined ply across the whole structure (Fig. 10). The area limitations from the thickness-distribution represent the major ply peripheries and are transferred by curves on surfaces data to the 3D-CAD-system. In addition, a curve which represents the average fibre orientation within each major ply periphery is also transferred.

On the CAD-"side" a composite designer has to build up a laying matrix, which represents the information of the logical stacking sequence for each individual layer within the thickness of the structure. With the incoming major ply peripheries the system automatically creates all implicit ply peripheries and with the information of the fiber orientation line it automatically simulates the tape laying process using tape steering for avoiding cutting as much as possible (Fig. 7).

This process takes into account all machine restrictions like steering radii and cutting limitations.

As the optimisation programme has not implemented these machine restrictions yet it is evident that there are still some iterations necessary to obtain the optimal manufacturable structure.

For an accurate finite element analysis the ITLS-system reads in the FE-mesh, projects it onto the structure and automatically calculates the properties for each element.

The data created by this system are directly usable for the shop floor NC-computer at the tape laying machine without any human interactions.

It must be mentioned that the effort for the first design loop is compared to the old design process, relatively high because the accurate stacking sequence of the layers is taken into account from the beginning.

The overall efficiency esults by minimizing the local iterations from design to stress and by avoiding iteration loops coming up from the manufacturing department.

This principle of avoiding process iterations by taking care of restrictions from downstream right in time is one of the basic philosophies behind the ideas of "simultaneous engineering".

Only with the performance of modern computer systems these simulations can been achieved.

Typical production examples showed a reduction of the time from design to manufacturing up to 80 percent.

## 4.3 ADAPTION OF STRUCTURAL OPTIMISATION FOR TAPE STEERING BASED ON A CONSTRUCTIVE DESIGN MODEL

After first use in production of the prior optimisation code including the ITLS it was recognized that the missing manufacturing constraints, like tape steering constraints and ply drop of angles, caused unnecessary iteration loops with the ITLS-simulation. So it was decided to switch from the finite element based geometry, which also created a large amount of design variables and constraints to the constructive design model (Ref. 10).

Constructive design models have the following advantages:

- optimisation results can be directly utilized
- no errors in the results by transforming finite element properties into a constructive layout
- manufacturing and constructive constraints can be formulated mathematically and directly considered in the optimisation
- higher acceptance of the optimisation results in practice
- multidisciplinary optimisation with different analysis models can be carried out
- analysis models can be changed in the optimisation process, e.g. mesh adaption for shape optimisation or mesh refinement in order to achieve sufficient analysis accuracy

The disadvantage of constructive models is the higher code programming effort necessary for practical realization. In shape optimisation these models are already usual.

The constructive description of the monolitic skin is made in such a way that all single plies which have the same fiber orientation are combined in one ply group. Since not all plies of this group cover the total surface a so called "ply group mountain" is obtained (Fig. 12). Herewith, the drop-off angles can be modelled and restricted to certain values to match manufacturing rules for the load transfer from one individual ply to the next ply.

The "ply group mountains" were mathematically formulated using Bezier surfaces. The control points of these Bezier surfaces are the design variables.

The equivalent optimisation results of the cantilever beam (see Fig. 8) are shown in Figure 13. The course directions of the two analysis plies are similar but smother in curvature due to the now integrated tape steering constraints. The weight reduction of course is then lower.

At present, the fin from Fig. 9 is under test with the new constructive model. First results show very similar fiber orientations but with real manufacturing constraints incorporated (Ref. 12).

In addition, there are only one to two iteration loops to the ITLS-simulation necessary to match all the other manufacturing constraints, like cutting restrictions and so on.

It has not been planned to integrate this remaining manufacturing c nstraints into the optimisation code in the future because their influcence on the global design is low and because of their high number. This increasing number of constraints would increase the optimisation iterations unnecessarily due to the far more complex "design space". The risk of getting convergence problems is therefore increasing.

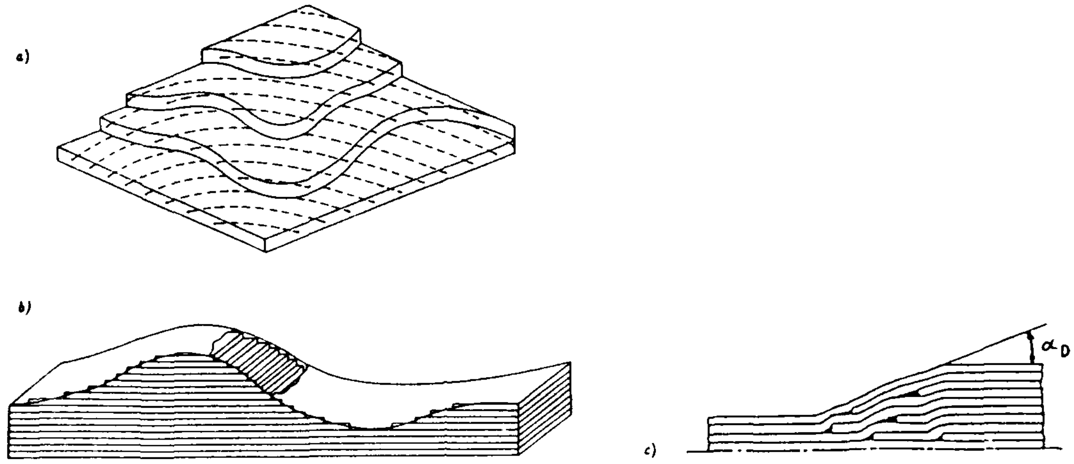



**Fig. 12:** a) "Mountain" of plies with the same fiber orientation b) Envelopping surface of the "ply group mountain"
c) Real built-up to prevent delamination

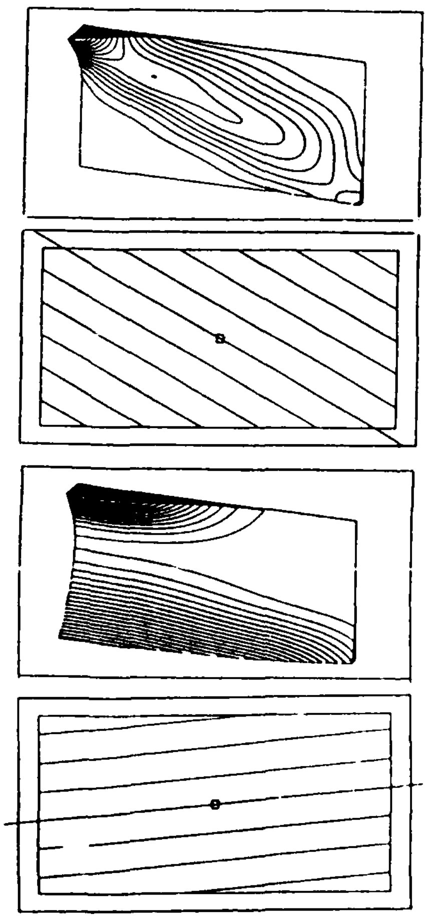


**Fig. 13a Thickness distribution for straight tape courses**

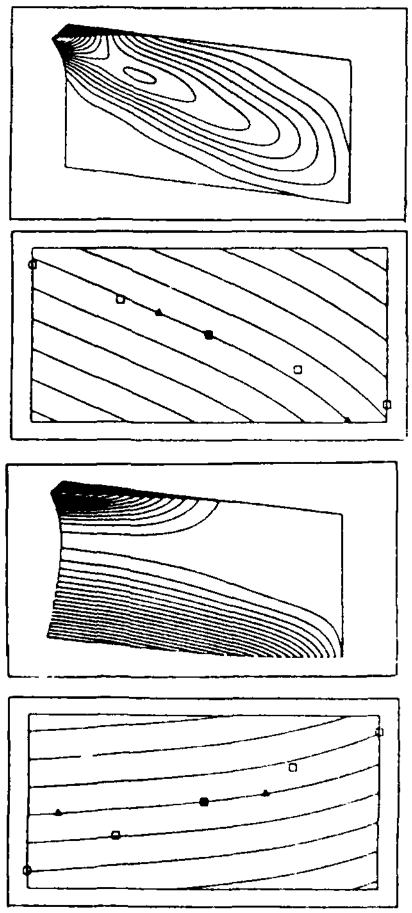


**Fig. 13b Thickness distribution for curved tape courses**

## Conclusion

With the availability of the tape steering technology it is possible to introduce the high strength to weight composite material to nearly all structural airframe elements (see Fig. 14). This was achieved with the break-through idea that it is possible to steer a tape without getting a loss of structural quality. The economic aspects are secured by using tape material instead of single tows to optain high productivity of the machine.

It was recognized that the possibility of steering a tape opened a new engineering degree of freedom with a very high potential of weight savings for aircraft structures with physically different constraints. However, this only can be attained by the use of mathematical driven optimisation codes. To overcome certain problems with the formulation of some manufacturing constraints it was important to introduce a constructive design model.

In addition, the integrated process showed up a remarkable reduction of the time from design to part production. This was obtained by using the newest tools from the field of information technology to be able to handle the complexity and size of the related data.

The highly integrated process also returns engineering tasks, which in the last years required own departments, back to the designer. The necessity of taking care of the manufacturability will positively influence the creative work of future composite designers.

Finally, it should be mentioned that the success of the manufacturing technology related process integration could only be achieved by a very strong teamwork between the engineering and manufacturing departments.

Such a teamwork is also necessary to completely introduce the new process within the organisation which has to be adapted to it to get the maximum efficiency for the company.

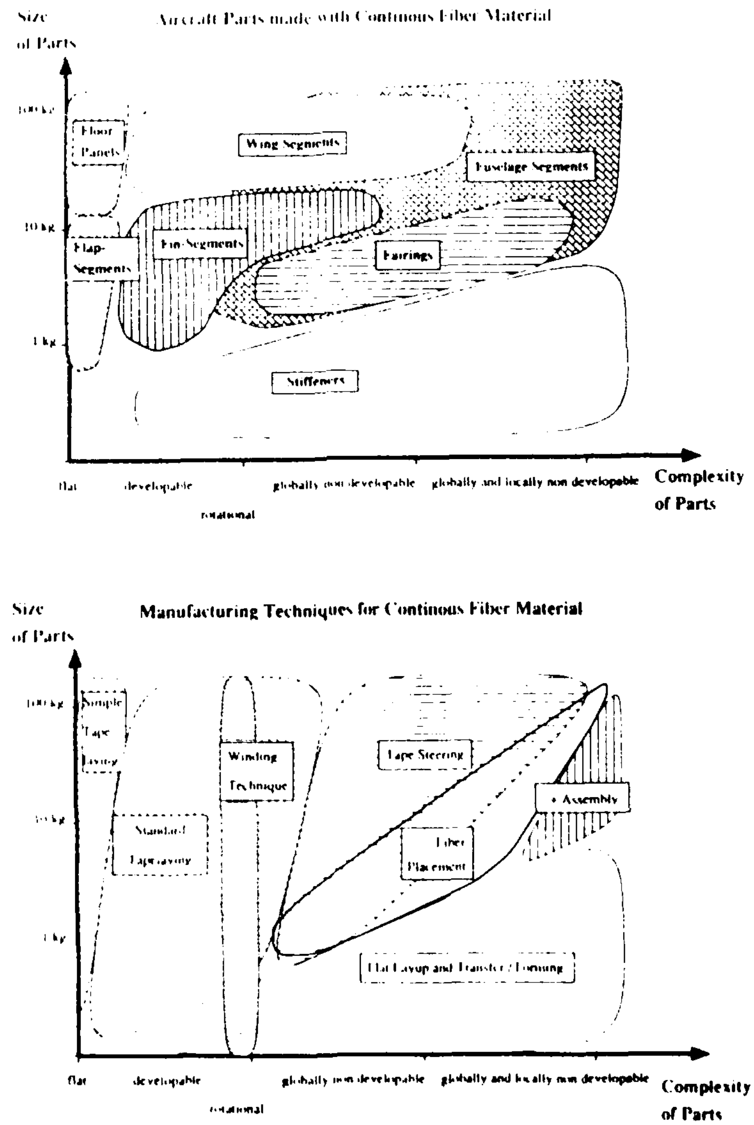



**Fig. 14** **Manufacturing techniques and aircraft parts for fiber material**

## References


[1] W.Hartmann
Anordnung zum gesteuerten Ablegen von Fasern auf eine Form.
(Device for Controlled Placement of Tows on a Mould)
German Patent No. DE3226290 C2, September 1985

[2] J.Gavin
J.Holthaus
Fiber Placement - Birth of a New Advanced Composite Technology
International Congress on Fiber Reinforced Technology-Verbundwerk 90, Wiesbaden, Germany, 21.-23.02.1990, Paper No. D 14

[3] J.Klenner
Bewertungs- und Auswahlalgorithmen kostenoptimaler Prepreg-Applikationsverfahren im Rahmen der Fertigung hochbeanspruchter Flugzeugbauteile aus faserverstärktem Kunststoff
(Evaluation and Selection Algorithms Used for Identifying Cost-effective Prepreg Application Processes in the Manufacturing of Highly Loaded Aircraft Components Made of Fiber-reinforced Plastic)
Dissertation, Technical University of Brunswick, Germany, 1989.

[4] J.Klenner
H.Brandis
Vorrichtung zum Ablegen von Faserbändern auf doppelt gekrümmten Körpern oder Flächen
(Device for the Placement of Fiber Tapes on Bodies or Surfaces With Double Curvature)
German Patent No. DE 4002087 C2, November 1991

[5] G.Berchtold; J. Klenner
The integrated design and maufacturing of composite structures for aircraft using an advanced tape laying technology. DASA/MBB Military Aircraft Division, Germany. DGLR-Jahrestagung, Bremen, Sept. 1992

[6] J.Krammer, A. Rüttinger
The Process Network in the Design and Manufacturing of Aircraft
AGARD LECTURE SERIES 76. SMP
Antalya, Turkey, April 1993

[7] K.Geißendörfer
CAP debis IAS GmbH
CATIA-GII development for an integrated design and manufacturing system in aircraft industry.
ECU European CATIA Users Association, Anual Conference 1992, Mont Pellier, Oct. 12th - 14th, 1992

[8] G. Berchtold
Zur Strukturoptimierung von Faserverbund Turbomaschinenschaufeln
(Structural Optimisation of Fiber Reinforced Blades for Jet-Engines)
Dissertation, Technical University of Munich, Germany, 1987

[9] J. Krammer
Practical Architecture of Design Optimisation Software for Aircraft Structures Taking the MBB-Lagrange Code as an Example

AGARD Lecture Series 186
"Integrated Design Analysis and Optimisation of Aircraft Structures", May 1992

[10] J. Eschenauer
Multidisciplinary modeling and optimization in design processes. Zeitschrift für angewandte Mathematik 72 (1992) 6, T438 -T466.

[11] Constructive Design Models for Multidisciplinary Optimisation of Fiber Composite Structures.

H.Eschenauer
G.Schuhmacher
Research Center for Multidisciplinary Analyses and Applied Structural Optimisation
Uni-GH Siegen, Germany
J.Krammer
DASA/MBB Military Aircraft Division, Germany

NASA/AIAA/Air Force Conference on Multidisciplinary Analyses and Optimisation, Cleveland, Ohio, Sept. 1992

[12] B.Münker
Multidisciplinare Sensitivitätsanalyse und Optimierung von Faserverbund-Flugzeugstrukturen mittels konstruktiver Entwurfsmodelle. Diplomarbeit D02/93 Institut für Mechanik u. Regelungstechnik, Univ. Siegen 1993

la finesse – serait augmenté de 18 à 24 environ, soit un gain de plus de 30 %, et la charge utile transportable passerait de 30 % à 40 % de la masse au décollage (Fig. 2). Cette masse au décollage pourrait se situer entre 800 et 1 200 tonnes suivant les besoins exprimés par les futurs utilisateurs militaires (missions stratégiques globales) et civils (porte-conteneurs intermodaux). Les spécifications pourraient faire l'objet


European military transport project, [id. 1].

[9] D. Knospe (Airbus Industrie), Air transport of outsized cargo, [id. 1].

[10] V.B. Denisov et al. (TsAGI, Russie), Air transportation system for shipping outsized cargoes, [id. 1].

[11] J.P. Roeder (Airbus Industrie), Civil freighters and military transports, their origins and developments,




# ETUDES D'ECOULEMENTS LAMINAIRES CHEZ DASSAULT AVIATION: CALCULS ET ESSAIS EN VOL


J.C. Courty
Dassault Aviation, Division des Etudes Avancées
78 quai Marcel Dassault, 92214, Saint-Cloud, France
C. Bulgubure
Dassault Aviation, DTM, Mérignac, France
D. Arnal
ONERA-CERT, DERAT, Toulouse, France



**RESUME**

Les outils de calcul utilisés à Dassault Aviation concernant les couches limites laminaires, les critères de transition et les analyses de stabilité linéaire sont passés en revue et discutés en terme de précision mais aussi d'efficacité lorsque ces outils doivent etre utilisés dans un processus d'optimisation d'une aile d'avion.

Ces outils de calcul ont été utilisés pour la conception d'une dérive laminaire testée en vol sur FALCON 50 (1985-1987), et pour la conception d'une aile à laminarité hybride testée en vol sur FALCON 50 au cours d'une seconde phase (1987-1990).


**LISTE DES SYMBOLES**

| | |
|---|---|
| M | nombre de mach |
| U | module de la vitesse |
| $\rho$ | masse volumique |
| p | pression statique |
| Cp | coefficient de pression |
| $\sigma$ | écart type d'une grandeur |
| X | abscisse mesurée normalement au bord d'attaque de voilure |
| XT | abscisse de transition |
| C | corde de la voilure normalement au bord d'attaque |
| $\bar{R}=W\eta/\nu$ | nombre de Reynolds utilisé pour la contamination de bord d'attaque |
| W | vitesse parallèle au bord d'attaque |
| $\eta$ | épaisseur caractéristique de couche limite sur un bord d'attaque $\eta=\sqrt{\nu/du/dx}$ |
| du/dx | gradient de la composante de vitesse normale au bord d'attaque |
| phi | angle de flèche |
| Tp | température pariétale |
| Tf | température athermane |
| $\beta$ | paramètre de gradient de pression de Hartree |

## 1. INTRODUCTION

**En 1984 l'Etat Francais a initié et en partie financé un programme de recherches sur la laminarité intitulé : "Developpement Technique Probatoire de Laminarité".**

Des industries aéronautiques francaises (Aérospatiale et Dassault Aviation) furent impliquées dans ce programme ainsi que des centres de recherches, spécialement l'ONERA-CERT/DERAT.

C'est dans ce cadre qu'ont eu lieu les essais en vol menés par Dassault Aviation avec le FALCON 50 comme démonstrateur. Ces études ont été conduites de 1985 à 1990 en étroite collaboration avec les centres de recherches en particulier l'ONERA-CERT et ont permis d'acquérir un grand nombre de données concernant la laminarité naturelle et la laminarité hybride, données qui étaient alors inexistantes en France.

Dans le cadre des technologies de laminarité passive ou active, de gros efforts ont donc été consentis à la fois sur le plan théorique et sur le plan expérimental (essais en soufflerie et essais en vol).

Sur le plan théorique ces efforts ont été dirigés vers la prédiction de la transition des couches limite laminaires tridimensionelles compressibles avec transfert de chaleur et aspiration pariétaux. Ceci implique le développement de méthodes de calcul de couche limite très précises puisque servant de support aux calculs de stabilité linéaire, ainsi que le meilleur choix de stratégie d'intégration des amplifications pour les calculs de stabilité. Ces méthodes de calcul ont été validées par l'ONERA-CERT par comparaison à de nombreux tests en soufflerie.

Sur le plan experimental nous abordons ici essentiellement les essais en vol dont le but était d'obtenir des données pour:
- valider et améliorer les outils numériques par comparaison aux résultats de vol
- démontrer la faisabilité du concept de laminarité en conditions de vol.

## 2. PHENOMENES DE TRANSITION

On rappelle brièvement les differents types de transition auxquels on doit faire face lorsque l'on désire optimiser la laminarité sur une voilure. On peut les classer en deux catégories selon que la transition résulte de l'amplification de perturbations

*Presented at an AGARD Meeting on 'Recent Advances in Long Range and Long Endurance Operation of Aircraft', May 1993.*

de très petite amplitude ou de l'amplification de perturbations d'amplitude finie.

Ces différents mode de transition sont illustrés sur la figure 1.

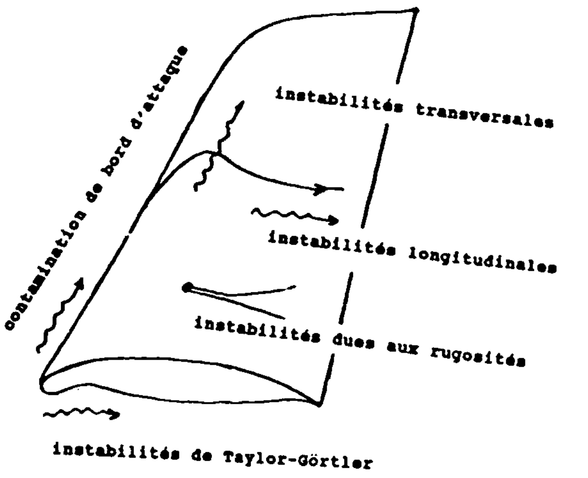



**Fig. 1 Différentes types d'instabilités rencontrées sur une aile**

**2.1 Amplification de perturbations de faible amplitude**

- Transition induite par instabilités longitudinales (ondes de Tollmien-Schlichting),essentiellement lorsque l'écoulement est à forte dominante bidimensionelle

- Transition induite par instabilités transversales,lorsque l'écoulement a une forte dominante tridimensionelle

- Transition induite par instabilités de Taylor-Gortler, lorsque l'écoulement évolue sur paroi concave

**2.2 Amplification de perturbations d'amplitude finie**

- Transition induite par rugosité isolée tridimensionelle

- Transition induite par contamination de bord d'attaque

La première classe de phénomènes (2.1) peut etre traitée avec succès à l'aide de calculs de couche limite suivis par une analyse de stabilité linéaire (ref 1).

La seconde classe de phénomènes (2.2) ne peut etre traitée par une analyse de stabilité linéaire puisque les perturbations initiales sont trop importantes pour qu'un processus de linéarisation puisse etre appliqué. L'outil numérique adéquat sera la simulation numérique directe lorsqu'elle en sera au stade de l'industrialisation. En attendant, les seuls outils industriels existants sont les critères semi empiriques comme ceux de Van Driest et Blummer (ref 2) et Pfenninger et Poll (ref 3,4).

**3. ETAT DE L'ART DES CODES DE COUCHE LIMITE ET DE STABILITE LINEAIRE CHEZ DASSAULT AVIATION**

**3.1 Codes de couche limite**

Les méthodes intégrales sont très populaires et très efficaces pour des calculs de couche limite lorsqu'on s'interesse à des quantités intégrales comme le coefficient de frottement pariétal ou les épaisseurs caractéristiques ,et sont largement utilisées dans l'industrie à cause de leur faible coût ,ce dernier point étant très intéressant lors des nombreuses boucles d'optimisation d'un avion.

En revanche, les calculs de stabilité linéaire nécessitent une connaissance très précise des profils de vitesse et de température de couche limite. Pour cette raison, il est nécessaire de résoudre les équations complètes de couche limite et pour les études de transition ,nous utilisons le code de couche limite en volumes finis de l'ONERA-CERT dont la description est faite dans la référence 5.

**3.2 Code de stabilité linéaire**

**3.2.1 Calculs "exacts" de stabilité**

Les perturbations de vitesse et de pression sont supposées de la forme:

$q'=q(y)*\exp(i(\alpha x+\beta y-wt))$ où $q(y)$ est une fonction amplitude complexe.

En théorie spatiale:
w est réel et $\alpha$ et $\beta$ sont complexes
le nombre d'onde $\vec{k}=(\alpha_r, \beta_r)$
et le vecteur amplification est
$\vec{A}(-\alpha_i, -\beta_i)$

En théorie temporelle:
w est complexe et $\alpha$ et $\beta$ sont réels
le nombre d'onde $\vec{k}=(\alpha, \beta)$
et le taux d'amplification temporelle est
wi

Ces codes de stabilité calculant les ondes les plus instables, on peut définir pour chacunes d'elles le taux d'amplification global $A/A^\circ$:

$A/A^\circ = \exp \int_{x_0}^{x} -\alpha_i \, dx$ en théorie spatiale
$-\alpha_i$ est remplacé par wi/Vg en théorie temporelle où $Vg=\partial w_r/\partial\alpha$ est la vitesse de groupe (ref 6)

En suivant l'idée de Van Ingen( ref 7) établie pour les écoulements bidimensionnels, on suppose que la transition se produit lorsque le rapport $A/A^\circ$ de l'onde la plus instable atteint une valeur limite $e^N$, avec N généralement compris entre 7 et 10.
L'extension de la méthode du $e^N$ aux

écoulements tridimensionnels n'est pas si aisée et un des problèmes est d'adopter une stratégie cohérente de maximisation des taux d'amplification ( Arnal et al ref 1, Laburthe ref 8).

Ces types de calculs consomment du temps humain et du temps calcul. Par exemple,un calcul de stabilité linéaire (pour une analyse de 10 fréquences) pour 30 profils de couche limite le long d'une ligne de courant sur une voilure, consomme 3 heures CPU sur un CRAY XMP.

De plus, les procédures d'initialisation ne sont pas complètement automatiques et demandent une habitude et un savoir faire de la part de l'utilisateur.

**3.2.2 Base de données de stabilité**

Une voie prometteuse pour l'utilisation de calculs de stabilité à moindre coût est l'élaboration de base de données permettant un gain de temps d'un facteur 1000.Cette base de données repose sur la méthode des paraboles, à l'origine développée par D. Arnal pour des conditions de paroi adiabatique et étendue aux cas non adiabatiques par l'ONERA-CERT et Dassault Aviation durant le projet européen ELFIN (European Laminar Flow INvestigation) dans le cadre BRITE/EURAM.
Cet outil permet alors de calculer très rapidement la stabilité de couches limites bidimensionelles compressibles ( $0<M<1.3$ ) avec transfert de chaleur ( $.8<Tp/Tf<1.1$ ) pour des gradients de pression $\beta$ longitudinaux quelconques.

L'idée de la méthode est que la courbe du taux d'amplification d'une onde de fréquence donnée en fonction du nombre de Reynolds , peut être approximée par deux demi-paraboles ( figure 2 ).
Sur la figure 3 on peut voir que pour des écoulements décélérés ($\beta$=-0.121) et de basses fréquences la forme de la courbe n'est plus une demi-parabole à cause de l'apparition d'un mode inflexionnel. La méthode a donc été améliorée afin de modéliser ces modes inflexionnels.

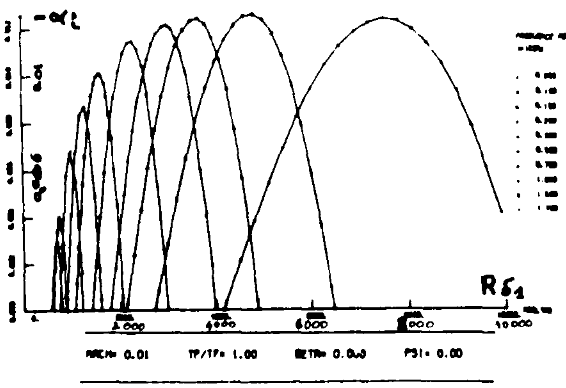



**Fig. 2 Amplification locale fonction du Reynolds pour plusieurs fréquences réduites**

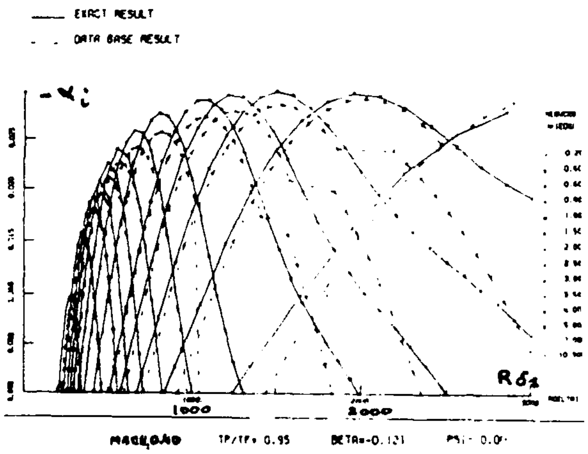



**Fig. 3 Amplification locale fonction du Reynolds . Comparaison calcul stabilité linéaire exact et interpolation dans la base de données.**

Les cas de calculs constituant la base de données sont les suivants:

Mach : 0.0 0.6 0.9 1.1 1.3
Tp/Tf: 0.8 0.9 1.0 1.1
$\beta$ : 0.2 0.1 0.05 0. -0.05 -0.1 -0.15 -0.185

Pour ces 160 calculs de stabilité linéaire "exacts" nous avons stocké tous les paramètres nécessaires à la description des courbes d'amplification.

Pour une couche limite quelconque soumise à un Mach extérieur donné, à un transfert de chaleur donné Tp/Tf et à un gradient longitudinal, on interpolle dans la base et on accède au diagramme de stabilité très rapidement.

Sur les figures 3 et 4 ( respectivement amplification locale et amplification totale fonctions du nombre de Reynolds basé sur l'épaisseur de déplacement) on présente les courbes de stabilité calculées pour Mach=0.4 Tp/Tf=0.95 $\beta$ =-0.121 , par la méthode base de données interpollée et par le calcul exact.
L'accord est satisfaisant et les courbes enveloppes (figure 4) utilisées pour prédire la transition par la méthode du $e^N$ donnent des résultats très semblables.

Signalons enfin que dans le cadre de la seconde phase du projet européen ELFIN, Dassault Aviation va collaborer à l'établissement d'une base de données semblable mais étendue aux écoulements tridimensionnels.

**3.3 Prédiction de la transition**

Comme nous l'avons déjà mentionné,au cours d'une boucle d'optimisation d'une aile ,nous avons besoin d'outils efficaces et rapides pour la prédiction de la transition.

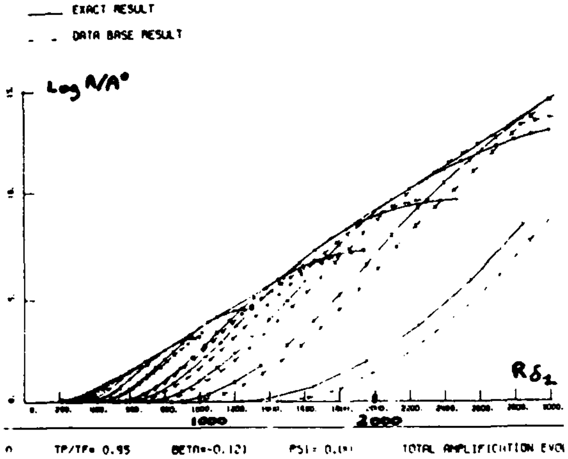



**Fig. 4 Amplification totale fonction du Reynolds et de la fréquence. Comparaison calcul de stabilité linéaire exact et interpolation dans la base de données.**

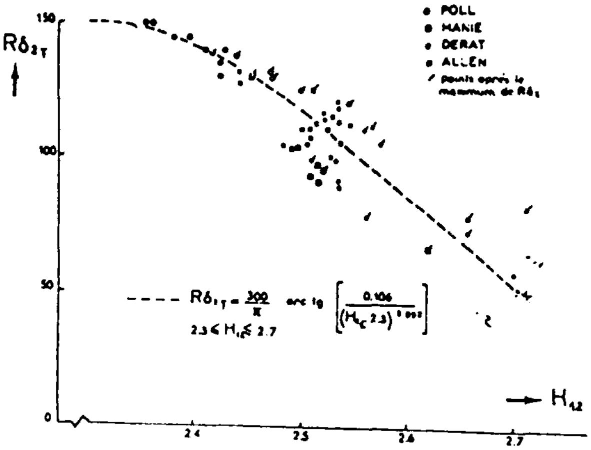



**Fig. 5 Critère transversal C1**

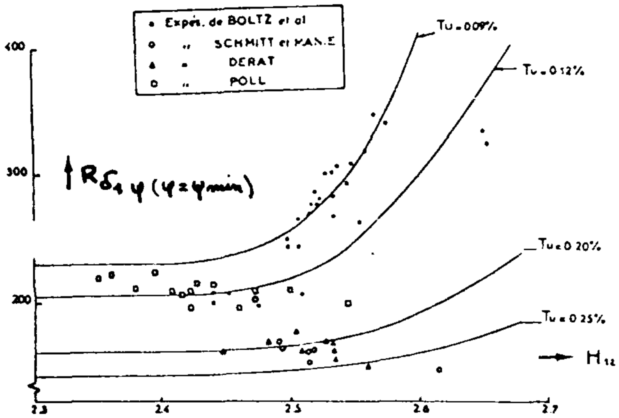



**Fig. 6 Critère transversal C2**

Comme nous l'avons dit au paragraphe précédant, l'extension de la méthode du $e^N$ aux écoulements tridimensionnels conduit à des problèmes fondamentaux toujours à l'étude.
C'est pour ces raisons que dans un contexte industriel nous continuons d'utiliser des critères de transition analytiques.

Pour la transition induite par instabilités longitudinales nous utilisons le critère classique de Granville ou la méthode des paraboles.

Pour la transition induite par instabilités transversales nous utilisons deux critères C1 et C2 développés par l'ONERA-CERT (ref 9).

-critère C1 : c'est une corrélation entre $R\delta 2$ (nombre de Reynolds basé sur l'épaisseur de déplacement transverse) et le paramètre de forme longitudinal H12 (figure 5). L'hypothèse sous-jacente est que la direction d'instabilité maximale est la direction transverse (psi=90°)

-critère C2 : ce critère es fondé sur le fait que la direction psi de plus grande instabilité n'est pas 90° mais psimin (autour de 85°). C'est une corrélation entre $R\delta 1$psimin (pour psi=0 $\delta 1$psi= $\delta 1$, pour psi=90° $\delta 1$psi=$\delta 2$), H12 et le taux de turbulence à l'infini amont Tu (figure 6). Cette corrélation est basée sur des calculs de stabilité linéaire menés pour un grand nombre de profils de couche limite projetés selon plusieurs directions psi selon l'hypothèse de Stuart (ref 8,10).
Ce critère est plus réaliste que le critère C1 puisqu'il prend en compte le taux de turbulence extérieure et surtout la direction d'amplification maximum des ondes les plus instables.

Pour la contamination de bord d'attaque nous utilisons le critère de Poll (ref 4) basé sur une valeur limite d'un nombre de Reynolds $\overline{R}$ calculé sur la ligne de glissement d'une aile en flèche à l'aide de la vitesse le long de cette ligne et du gradient de vitesse normalement au bord d'attaque. La valeur limite de $\overline{R}$ au dessus de laquelle il y a contamination est voisine de 250.

### 3.4 Validation des critères de transition en soufflerie

Sur les figures 7b et 7c on montre des positions de transition calculeées et mesurées expérimentalement sur une aile en flèche pour différents nombre de Reynolds, dans la soufflerie F2 au Fauga. Ces résultats ont été obtenus par Arnal et Juillen (ref. 1). La répartition de vitesse est montrée sur la figure 7a.

Sur la figure 7b on constate que les critères C1 ou C2 sont bien adaptés pour les plus grands nombres de Reynolds, pour lesquels les instabilités longitudinales et transversales sont bien distinctes et où il est légitime de calculer séparément

l'amplification totale des deux types d'instabilités.
Mais lorsque les deux types d'instabilités coexistent et interagissent l'application de critères distincts conduit à des désaccords avec l'expérience. Dans ce cas, les calculs de stabilité linéaire peuvent aider à comprendre les raisons de ces désaccords et des résultats obtenus par la méthode du $e^N$ en intégrant le taux d'amplification locale dans la direction de plus grande instabilité, montrent un très bon accord avec la soufflerie ( figure 7c).

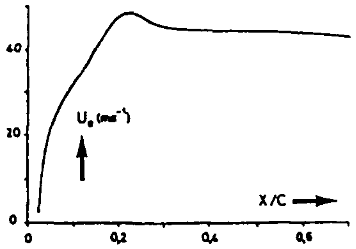



**Fig. 7a Distribution de vitesse sur le profil (cas (49,-2))**

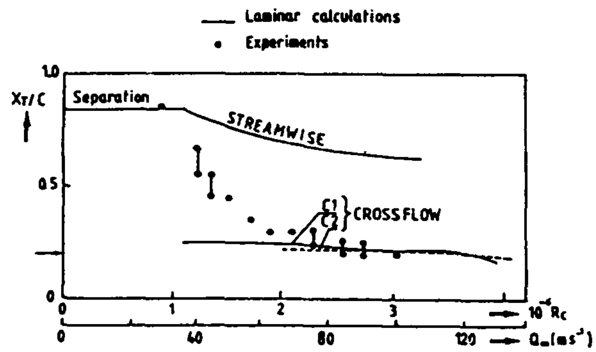



**Fig. 7b Position de la transition (critères C1 et C2)**

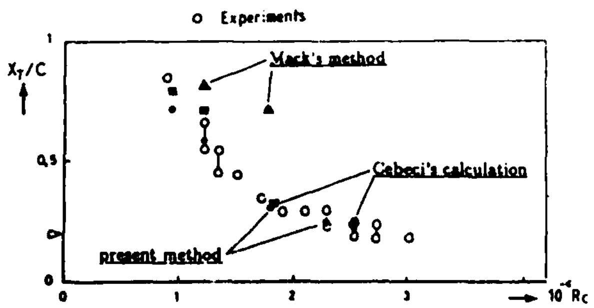



**Fig. 7c Position de la transition (méthode du $e^N$ )**

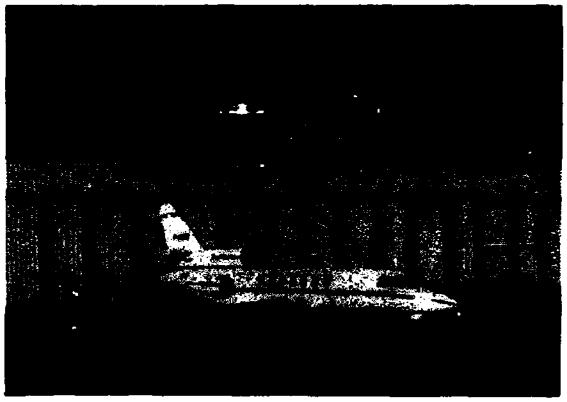


**Fig. 8 FALCON 50**

## 4. OBJECTIFS DES ESSAIS EN VOL

Les expérimentations ont été menées sur le FALCON 50 qui fut choisi comme avion de démonstration (figure 8); elles se sont déroulées en 2 phases principales d'essais en vol suivies d'une phase de validation de la soufflerie recréant les conditions de vol. Ces expérimentations ont été choisies de manière à couvrir les conditions de vol (Mach, Reynolds, angles de flèche), et à acquérir les données nécessaires à la conception d'un future aile laminaire pour avion d'affaires (figure 9).

- La phase I (1985-1987) avait comme objectifs de montrer qu'il était possible de faire fonctionner en vol une section de voilure en LAMINARITE NATURELLE , et d'acquérir des données en vue de déterminer les limites de ce concept. Les essais ont été menés sur un profil d'aile optimisé en vue de supporter une zone d'écoulement laminaire étendue , et de mettre en jeu principalement les instabilités longitudinales pour une flèche de 25 degrés et les instabilités transversales pour une flèche de 35 degrés.

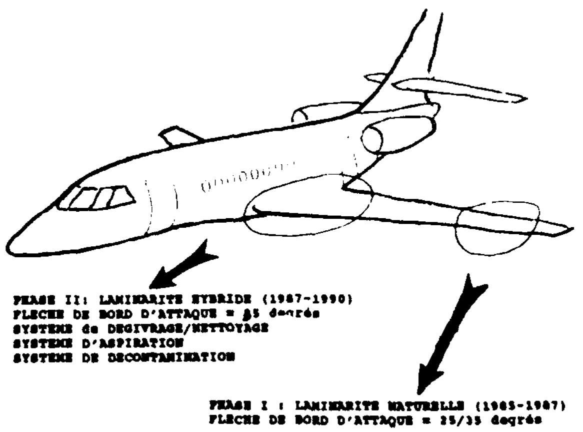



**Fig. 9 Objectifs des phases I et II**

- La phase II (1987-1990) fut beaucoup plus ambitieuse puisque ses objectifs étaient de démontrer la faisabilité du concept de LAMINARITE HYBRIDE avec un système de nettoyage et de dégivrage de bord d'attaque d'une aile dont le rayon et l'angle de flèche du bord d'attaque nécessitaient le développement d'un système anti contamination et d'un système d'aspiration.

## 5. PHASE I: DEMONSTRATION DE LA LAMINARITE NATURELLE

### 5.1 Installations et moyens d'essais

L'élément de voilure testé, de 1.80 m d'envergure, 1 m de corde d'emplanture et 0.70 m de corde d'extrêmité , a été monté sur la partie supérieure de la dérive tronquée de l'avion (figure 10), une plaque de garde horizontale séparant les deux écoulements.

L'angle de flèche nominale était de 25 degrés avec possibilité de passer à 35 degrés par adjonction d'une cale. Le modèle testé était composé d'une structure métallique recouverte d'une couche de résine de 3 mm d'épaisseur. La variation de portance de l'élément de voilure était obtenue par variation du dérapage de l'avion.

Ce montage original, bien que plus délicat à réaliser, a été préféré à la solution du manchon utilisé dans d'autres programmes, afin de minimiser les interactions avec le champ aérodynamique de l'avion mais aussi pour recréer un écoulement amont aussi proche que possible de l'écoulement à l'infini amont ( principalement en termes de fluctuations de pression et de vitesse).

Les conditions de vol ont été choisies de manière à couvrir une gamme de nombre de Mach de 0.5 à 0.85 et de nombre de Reynolds de 3.7 E+06 à 7.0 E+06 pour des coefficients de portance CL variant de -0.10 à +0.50.

**Fig. 10 Demonstrateur pour études de laminarité naturelle (Phase I)**

### 5.2 Instrumentation

L'instrumentation (figure 11) a été définie de manière à obtenir des mesures des différents paramètres de l'écoulement qui sont respectivement:

(a) la position et l'étendue de la transition mesurée en temps réel à l'aide de:

- 22 films chauds compensés en température et situés à l'extrados et à l'intrados; ces films après calibration permettent d'autrepart d'obtenir les coefficients de frottement.

- 2 cameras infra-rouge installées dans des pods à chaque extrèmité de l'empennage horizontal.

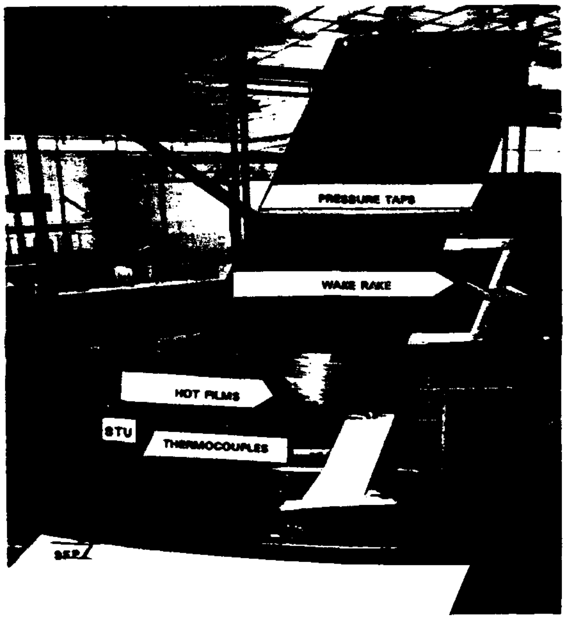



**Fig. 11 Instrumentation de la phase I**

(b) la turbulence et le bruit à l'aide de :
- un capteur (STU) mesurant le niveau de fluctuations de vitesse de l'écoulement amont
- un capteur de pression instationnaire (SFP) mesurant les fluctuations de pression

Ces capteurs sont situés de part et d'autre de la plaque de garde.

(c) la trainée du profil de voilure par mesure du sillage à l'aide d'un peigne de sillage comportant 44 prises de pression totale et une prise de pression statique.

(d) la température de paroi à l'aide de 2 thermocouples situés au dessus de la plaque de garde.

(e) la distribution de Cp et la détermination de la portance générée par le dérapage de l'avion ,à l'aide d'une rangée de 26 prises de pression statique située aux 2/3 de l'envergure.

**5.3 Essais en vol**

Les essais en vol effectués pour les 2 angles de flèche (25 et 35 degrés) et pour une transition naturelle et imposée ont permis :

(a) de vérifier le bon fonctionnement de l'instrumentation

(b) de montrer qu'il était possible d'obtenir une zone laminaire étendue.La figure 12 montre un exemple de visualisation obtenue par caméra infra-rouge mettant en évidence:

- une zone laminaire s'étendant sur environ 70% de corde

- une transition induite par l'installation des films chauds

- une transition en extrémité de voilure, due à la forte tridimensionnalité de l'écoulement

(c) et bien sur d'acquérir tous les paramètres nécessaires à l'exploitation des résultats.

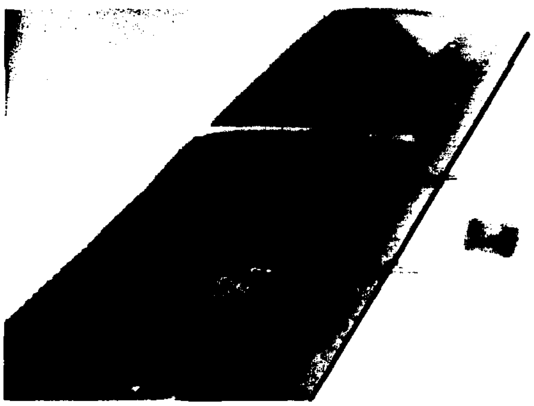


**Fig. 12 Image obtenue par caméra infra-rouge**

**5.4 Principaux résultats**

5.4.1 Mesures de bruit et de turbulence

L'analyse des signaux des sondes STU et SFP a permis d'acquérir les quantités $\overline{p'}/(0.5\overline{\rho U})$ et $\overline{(\rho U)'}/(\overline{\rho U})$ . La figure 13 relative aux vols 484 et 489 montre:

- qu'il n'y a pas d'influence significative de l'altitude ou du nombre de Mach sur les résultats

- que les niveaux de turbulence varient entre 0.01% et 0.02% alors que les niveaux de fluctuations de pression varient de 0.20% à 0.45%.

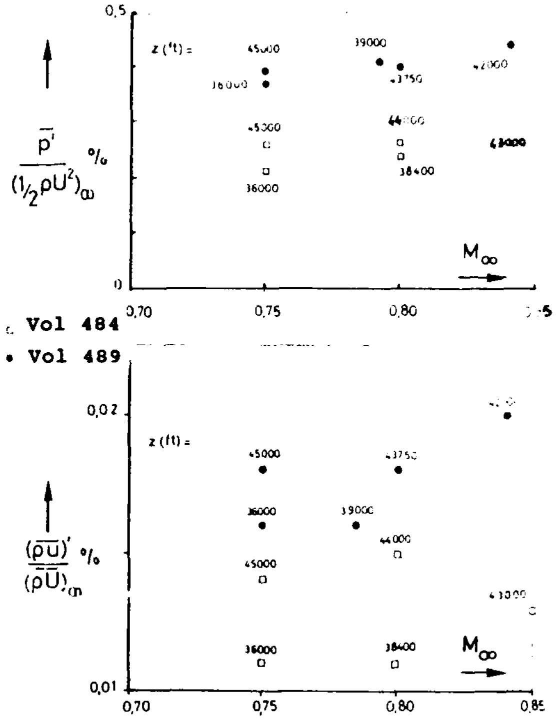



**Fig. 13 Mesures des fluctuations de pression et de vitesse**

Ces résultats sont à comparer à ceux obtenus dans des souffleries de très bonne qualité montrant des niveaux de turbulence de 0.1% et des niveaux de fluctuations de pression de 0.3%. On observe que bien que les niveaux de fluctuations de vitesse de vol soient 6 à 7 fois plus faibles que ceux obtenus en soufflerie, les niveaux de fluctuations de pression sont semblables.

5.4.2 Comparaison calcul/vol de la position de la transition

Un des premiers objectifs de ces essais en vol était d'obtenir des résultats expérimentaux destinés à vérifier la validité des critères.

Etant donné que l'analyse des films chauds permet de déceler la position de la transition (plus exactement le milieu de la zone transitionnelle), il était interessant de comparer ces résultats à ceux obtenus par calcul utilisant les critères semi-empiriques C1 et C2 présentés au paragraphe 3.3.

Sur la figure 14 on compare les positions expérimentales de transition obtenues pour différents nombre de Reynolds à celles obtenues par application des critères C1 et C2 pour les différents niveaux de turbulence mesurés. On constate que:

(a) C1 est en bon accord avec le vol si l'on considère que le critère donne le début de la zone de transition et non pas son milieu comme l'indiquent les films chauds

(b) C2 ,même avec le plus fort niveau de turbulence de vol, prédit une transition trop tardive.

On a alors recherché le niveau de turbulence qu'il faudrait prendre en compte dans le critère C2 pour retrouver les positions de transition de vol. Les résultats ont alors montré qu' en vol le paramètre essentiel gouvernant l'instabilité ne serait pas les fluctuations de vitesse mais les fluctuations de pression.

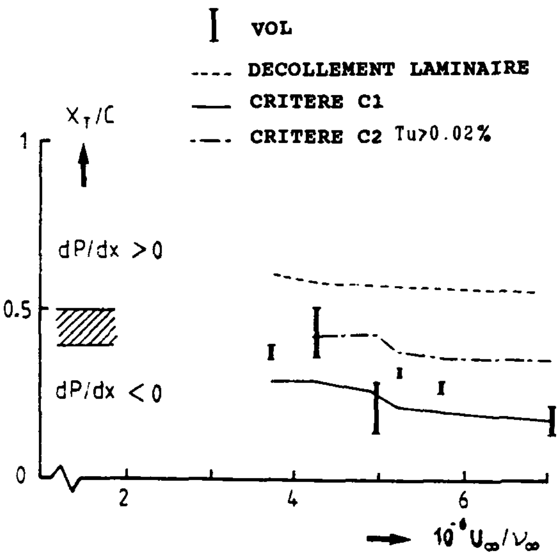



**Fig. 14 Corrélation de la position de la transition**

### 5.5 Conclusions de la phase I

Ces essais en vol ont permis d'acquérir une certaine quantité de données non disponibles en France à l'époque, concernant le phénomène de transition en vol et les differents paramètres qui la gouvernent, plus particulièrement les niveaux de turbulence amont et de fluctuations de pression.

Ils ont aussi permis de valider le critère C1 concernant la position de la transition.

L'utilisation du critère C2 et le niveau de turbulence à appliquer pour corréler la position de la transition ont mis en lumière l'importance croissante du niveau de fluctuation de pression lorsque le niveau de turbulence décroit.

## 6. PHASE II: DEMONSTRATION DE LA LAMINARITE HYBRIDE

### 6.1 Installation et moyens d'essais

En 1987 , les résultats de la phase I ont montré qu'il était possible de calculer et de faire voler une section de voilure en écoulement laminaire naturellement, puisque les critères de transition ont été bien corrélés et que les essais ont permis d'acquérir la connaissance nécessaire à leur amélioration.

Le but de la phase II était de démontrer la possibilité d'obtenir un écoulement laminaire sur une aile de forte flèche (35° de flèche de bord d'attaque) pour des Reynolds de vol allant de 12 E+06 à 20 E+06 , en controlant l'instabilité transverse par aspiration de couche limite à travers une paroi poreuse sur 10% de corde à l'extrados. Le but était de maintenir l'écoulement laminaire sur environ 30% de corde. Cette étude a été réalisée sur la partie interne de l'aile du FALCON 50 (figure 15).

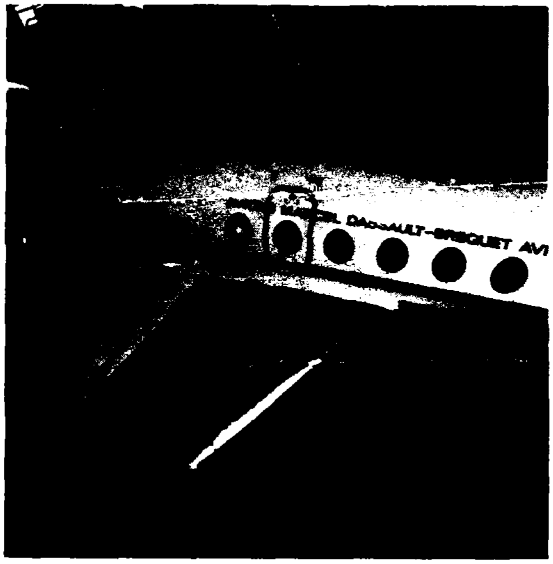



**Fig. 15 Installation pour la démonstration de laminarité hybride**

C'est une zone où les forts effets tridimensionnels à l'emplanture , la flèche, et les Reynolds de vol ont demandé successivement:

- l'optimisation d'une nouvelle voilure d'emplanture en modifiant les profils jusqu'à environ 65% de corde,
- le développement d'un système d'aspiration incorporant le système de dégivrage et de nettoyage de bord d'attaque,
- le développement d'un système capable d'éviter la contamination de bord d'attaque.

### 6.1.1 Conception du bord d'attaque et du système d'aspiration

Le bord d'attaque laminaire ( figure 16) optimisé a été rajouté sur le profil initial, le raccord se faisant à l'aide de résine. L'extrados du bord d'attaque consistait en une plaque TKS perforée au laser. L'aspiration se faisait à travers 6 canaux reliés à une trompe d'aspiration. Deux panneaux TKS de dégivrage situés sur la ligne de glissement permettaient d'appliquer un liquide MPG (Monopropylène Glycol) sur le bord d'attaque.

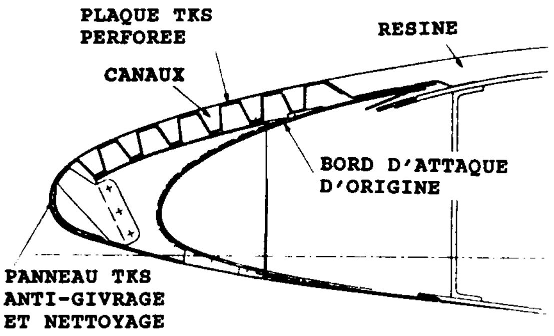



**Fig. 16 Conception du bord d'attaque**

### 6.1.2 Définition et optimisation du "bump" de bord d'attaque. Essais en soufflerie

Avant de réaliser un écoulement laminaire hybride capable de minimiser l'instabilité transversale sur une aile en flèche, il est impératif de vérifier que la turbulence générée par les couches limites de fuselage et convectée le long de la ligne de glissement, est suffisamment amortie pour éviter la contamination de tout le bord d'attaque. Pour un écoulement incompressible la prédiction de la contamination est basée sur la valeur du nombre de Reynolds $\overline{R}$ décrit au paragraphe 3.3.

Les calculs menés sur le nouveau profil d'aile optimisé avaient montré que la contamination se produirait sur toute la partie interne de l'aile pour des Reynolds unitaires supérieurs à 4 E+06 ,c'est à dire pour tous les points de vol envisagés.

**Afin de combattre ce phénomène , l'optimisation théorique d'un système appelé "bump" a été réalisée par des calculs tridimensionnels. Des essais sur une maquette simplifiée ont été menés dans la soufflerie T2 de l'ONERA-CERT pour plusieurs configurations de manière à valider les performances prédites.**

**La figure 17a montre la maquette soufflerie equippée de 4 films chauds sur le bord d'attaque afin de qualifier la nature de l'écoulement sur la ligne de glissement.**

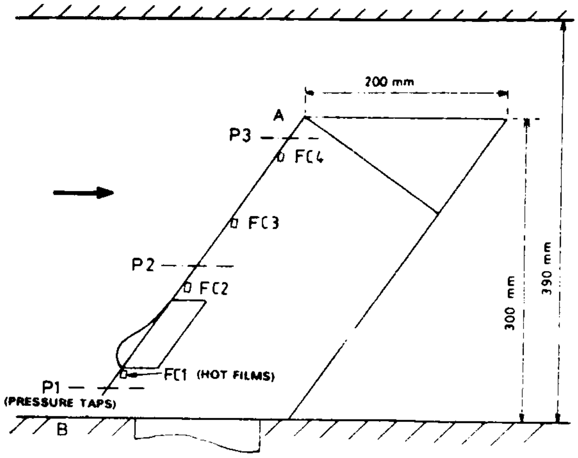



**Fig. 17a Maquette pour les essais en soufflerie à T2**

La figure 17b montre les résultats obtenus,représentant le niveau de turbulence derrière le bump (film chaud FC2) en fonction du Reynolds $\overline{R}$ . On peut constater que:

- sans bump, on retrouve la valeur critique classique de $\overline{R}$=250,
- les bumps numéro 1 et 2 apportent un gain substantiel en repoussant la limite vers $\overline{R}$=300

La configuration numéro 3 ( bump numéro 1 un peu plus éloigné de la paroi) améliore encore les résultats puisque son fonctionnement reste correct jusqu'au Reynolds $\overline{R}$ maxi testé, c'est à dire $\overline{R}$=320.

Le bump numéro 1 fut donc fabriqué et installé sur l'avion ( figure 18).

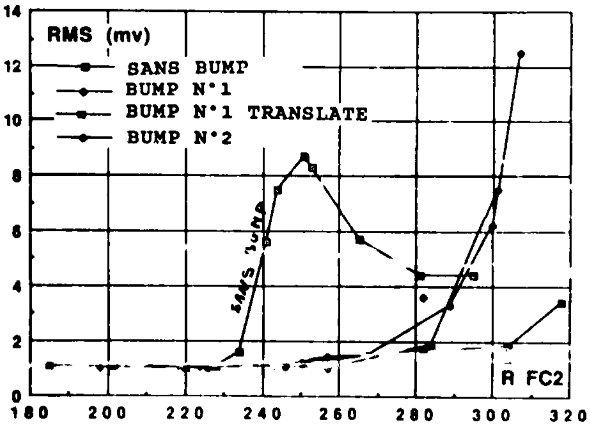



**Fig. 17b Résultats d'essais de soufflerie du bump**

**Fig. 18 Bump installé sur avion**

**6.2 Instrumentation**

L'instrumentation utilisée ( figure 19) durant cette phase II consistait en:

- 3 rangées de capteurs de pression statique pour mesurer la distribution de Cp près du bord d'attaque

- 3 rangées de 12 films chauds pour détecter la position de la transition et installés derrière la zone aspirée dans la partie en résine

- une série de 14 films chauds à l'extrados et de 14 autres films chauds à l'intrados de part et d'autre de la ligne de glissement, installés sur des feuilles de "Kapton" collées sur le bord d'attaque. Cette instrumentation qui cachait en partie la zone d'aspiration n'était montée que pour les essais de contamination de bord d'attaque et était enlevée pour les essais en vol avec controle de couche limite par aspiration.

- un pod pouvant abriter soit une caméra infra-rouge pour visualiser les transitions, soit une caméra vidéo pour controler l'efficacité des systèmes de dégivrage et de nettoyage de bord d'attaque

- 2 capteurs de mesure de turbulence amont installés sur le pod en position haute et basse, et 1 capteur de mesure de fluctuation de pression amont

- 5 vélocimètres "Testovent" pour mesurer le taux d'aspiration dans chaque canal, ainsi que des capteurs de pression statique tout le long du système d'aspiration

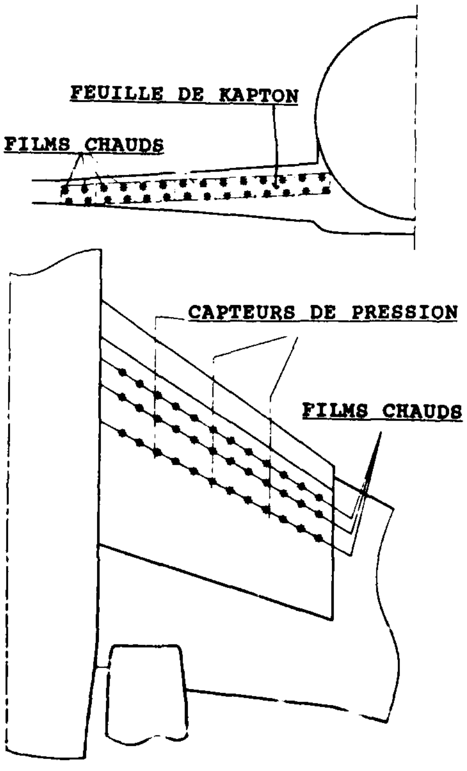



**Fig. 19 Instrumentation de la phase II**

**6.3 Essais en vol**

Les essais en vol de cette phase se sont déroulés en 2 étapes bien distinctes:

**(a) sans bump**

Une première série de vols a été effectuée de façon à:

- valider le système TKS de nettoyage et de dégivrage de bord d'attaque. De plus ces tests ont permis de confirmer la position de la ligne de glissement selon l'incidence afin de positionner correctement les films chauds pour les tests de contamination

- mettre en évidence la contamination de bord d'attaque pour différentes conditions de vol

- mettre en évidence les effets du taux d'aspiration dans ces conditions

**(b) avec bump**

**Ces vols ont été effectués afin de déterminer les différents paramètres influençant l'étendue de la zone laminaire:**

- **effet du bump sur la décontamination**

- **effet de l'angle de flèche du bord d'attaque ( par variation de l'angle de dérapage de l'avion)**

- **effet du taux d'aspiration et de sa distribution dans les canaux 1 à 6**

### 6.4 Principaux résultats de la phase II

(a) Nettoyage du bord d'attaque

Les vols effectués à basse altitude ont démontré l'efficacité du système TKS et du liquide utilisé, puisque qu'après vol on comptait 600 insectes/m2 sur le bord d'attaque gauche non traité alors qu'on ne notait aucun problême de pollution sur le bord d'attaque droit.

(b) Contamination de bord d'attaque: effet du bump

Après analyse des enregistrements des films chauds de bord d'attaque et d'extrados, les vols effectués sans bump ont montré que toute l'aile était contaminée. Les vols effectués pour différents angle de flèche (différents dérapages) et différents nombre de Reynolds ont permis de quantifier l'étendue et la variation de la zone contaminée et de corréler les calculs. Dans le cas le plus favorable , une petite zone intermittente fut observée en extrêmité de manchon (figure 20a ).

Ces essais furent alors répétés avec le même taux d'aspiration, mais avec un bump situé à 150 mm puis 300 mm de l'emplanture (figures 20b et 20c). Un net progrès fut constaté par rapport aux essais précédants, puisque tous les films chauds délivraient un signal intermittent jusqu'à 25% de corde avec le bump à 150 mm. La configuration avec bump à 300 mm permit de faire apparaitre une zone laminaire.

(c) Effet du taux d'aspiration et de l'angle de flèche

Les effets du taux d'aspiration( c'est à dire de sa distribution et de son intensité), et les effets de l'angle de flèche ( 5° de dérapage pour passer de 35° de flèche à 30°) furent étudiés en détail pour différents Reynolds de vol.

- sans aspiration, avec ou sans dérapage, tous les films chauds délivrèrent un signal turbulent ( figure 21a )

- pour un taux d'aspiration raisonnable (c'est à dire insignifiant dans le bilan énergétique) et sans dérapage ,la zone laminaire s'étendait jusqu'à 25% de corde (figure 21b ) . Elle s'étendait jusqu'à presque 30% de corde (figure 21c ) lorsque la flèche de bord d'attaque fut réduite à 30°.

### 6.5 Conclusions de la phase II

Ces séries d'essais en vol ont permis:

- de développer un certain nombre de technologies, spécialement le système d'aspiration qui peut être directement installé sur avion, et le procédé conçu pour éviter la contamination turbulente sur le bord d'attaque d'ailes en flèche. Ils ont aussi permis de déterminer les différents paramètres pouvant affecter les performances de ces systèmes.

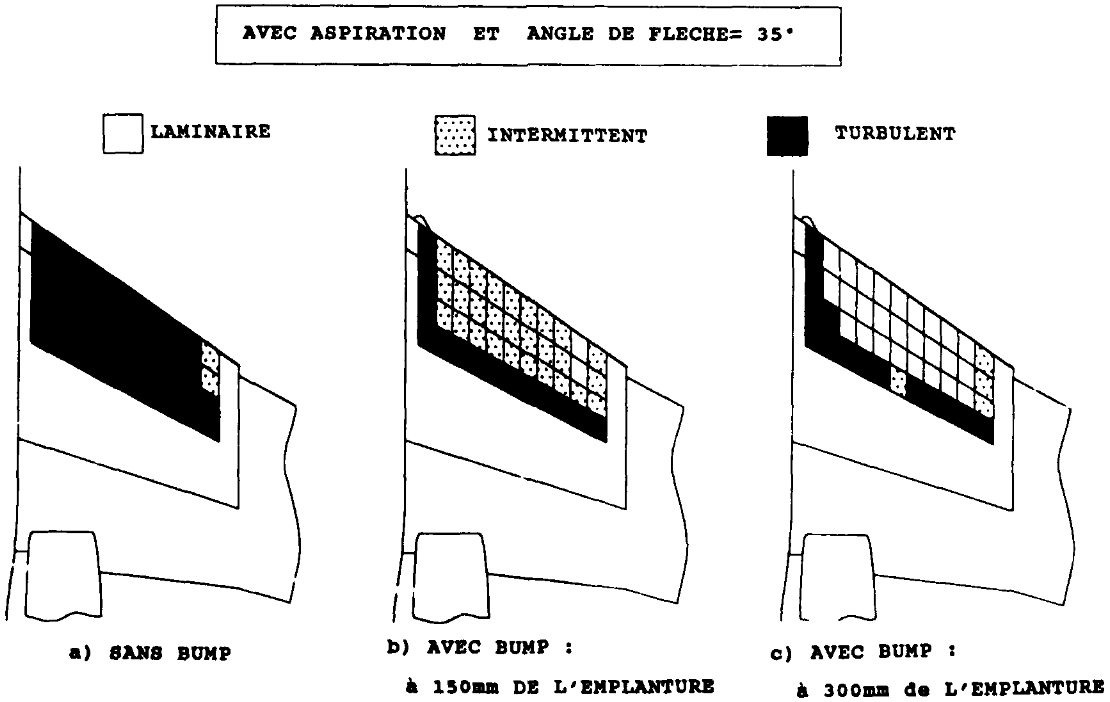
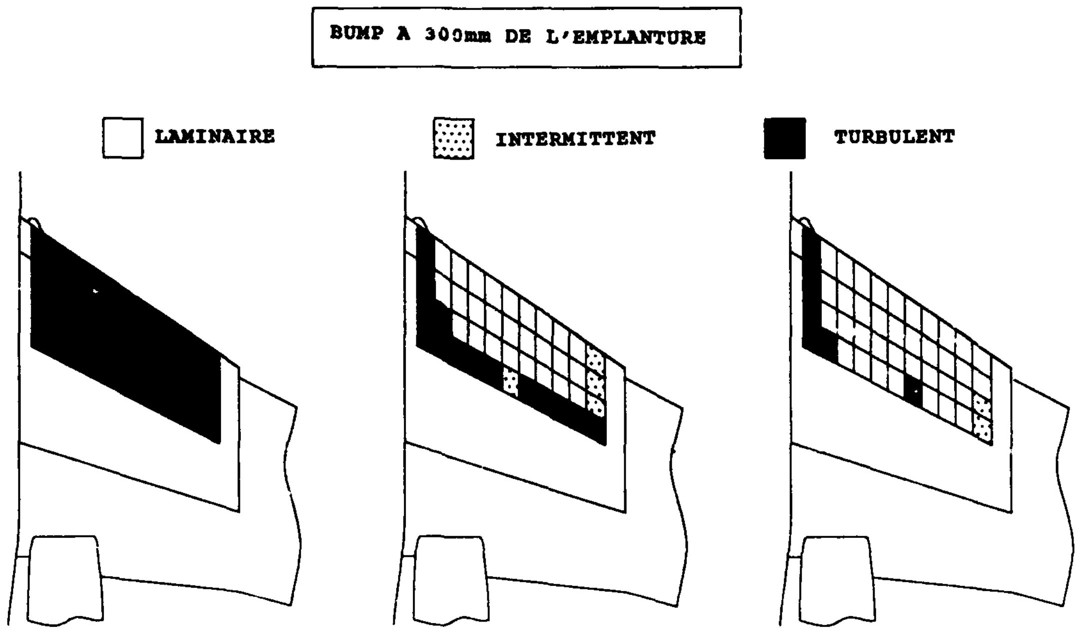



**Fig. 20 Effet du bump sur l'étendue de la zone laminaire**




**a) SANS ASPIRATION ANGLE DE FLECHE= 35°**

**b) AVEC ASPIRATION ANGLE DE FLECHE= 35°**

**c) AVEC ASPIRATION ANGLE DE FLECHE= 30°**

**Fig. 21 Effet de l'aspiration et de l'angle de flèche**

- de montrer que le débit d'aspiration nécessaire à une laminarité hybride sur une portion d'aile de FALCON 50 était relativement faible et de poids négligeable dans le bilan énergétique.

## 7. PERSPECTIVES

### 7.1 Concernant la prédiction de la transition

Grâce au processus de croissance linéaire qui généralement domine sur une distance relativement importante avant le début de transition, l'application de la méthode du $e^N$ en conjonction avec des calculs de couches limites tridimensionnelles donne des estimations de transition qui sont d'une grande importance pour des applications pratiques.

Mais lorsque lorsque le processus d'instabilité n'est plus lent et est essentiellement non linéaire, il faut continuer de rechercher expérimentalement et théoriquement les chemins vers la turbulence .

**Comme le soulignent Morkovin et Reshotko (ref. 16), à cause de la complexité des phénomènes de transition et du nombre de paramètres variés agissant sur eux, les tests de validation devront avoir des domaines de recouvrement au niveau des paramètres aussi bien qu'une redondance au niveau des mesures de transition.**

En outre les simulations numériques directes ( ref. 11, 12, 13, 14, 15) ont fait de tels progrès au cours des dix dernières années qu'on peut les utiliser pour comprendre les traits saillants du processus non linéaire et pour identifier les paramètres qui gouvernent son occurence. Ils sont devenus de très précieux outils de compréhension du phénomène de transition.

### 7.2 Concernant les essais en vol

A la fin 1990, les résultats obtenus pendant les phases I et II de ce programme ont permis de montrer que le concept de laminarité était viable pour les avions d'affaires, puisqu'un certain nombre de technologies requises étaient maitrisées,l'énergie nécessaire étant négligeable devant les gains attendus.

C'est la raison pour laquelle Dassault Aviation s'est engagée dans cette voie et a initié dès cette année un nouveau programme qui lui permettra d'approfondir ses connaissances pour préparer l'implantation de la laminarité hybride à un niveau industriel:

- en étendant les actions de phase II aux deux ailes internes du FALCON 900 afin de tester la robustesse des systèmes requis à un niveau opérationnel

- en préparant une action de plus grande envergure destinée à optimiser une aile entièrement laminaire , ouvrant la voie aux études du future FALCON.

**REFERENCES**


1. Arnal D., Casalis G., Juillen J.C. "Experimental and theoretical analysis of natural transition on infinite swept wing", IUTAM Toulouse, 1989

2. Van Driest, Blummer, "Boundary layer transition at supersonic speed: roughness effect with heat transfer", AIAA Journal vol.6 n° 4,April 1968, pp 603-607

3. Pfenninger W., "Flow phenomena at the leading edge of swept wings. Recent developments in boundary layer research",Part IV,AGARDograph 97,May 1965

4. Poll D.I.A, "Transition in attachment line flows", IUTAM Toulouse 1989

5. Arnal D., "Three dimensional boundary layers: laminar turbulent transition",AGARD report n° 741,1986

6. Gaster M., "A note on the relation between temporally increasing and spatially increasing disturbances in hydrodynamic stability", J.Fluid Mechanic, Vol 14,pp 222-224, 1962

7. Van Ingen J.L., "A suggested semi empirical method for the calculation of the boundary layer transition region",Univ. of Technology,dept of Aero. Eng. Dept. UTH-74 Delft,1956

8. Laburthe F., "Problème de stabilité linéaire et prévision de la transition dans des configurations tridimensionnelles,incompressibles et compressibles", Thèse ENSAE, 1992

9. Arnal D.,Habiballah M.,Coustols E., "Laminar instability theory and transition criteria in two and three dimensional flows", La recherche aérospatiale n° 1984-2,1984

10. Gregory N., Stuart J.T., Walker W.S., "On the stability of three dimensional boundary layer with application to the flow due to a rotating disc",Phil. Transactions of the Royal Society of London, Series A,Vol. 248,1955

11. Kleiser L., Meyer F., "Numerical simulation of transition due to crossflow instability",IUTAM Toulouse,1989

12. Lesieur M., Normand X., Comte P., "Large eddy simulation of mixing layers",IUTAM Toulouse, 1989

13. Fasel H., "Numerical simulation of instability and transition in boundary layer flows",IUTAM Toulouse, 1989

14. Spalart P.R., "Direct numerical study of crossflow instability",IUTAM Toulouse, 1989

15. Hussaini M.Y., Erlebacher G., "Second mode interactions in supersonic boundary layers",IUTAM Toulouse, 1989

16. Morkovin M.V., Reshotko E., "Dialogue on progress and issues in stability and transition research",IUTAM Toulouse, 1989

# IMPROVEMENT OF ENDURANCE PERFORMANCE BY PERIODIC OPTIMAL CONTROL OF VARIABLE CAMBER

by

**G. Sachs*** and **R. Mehlhorn****
Technische Universität München
Arcisstrasse 21
80290
Munich
Germany

## ABSTRACT

Other than in classical theory, endurance cruise is considered as an optimal periodic control problem where the state and control variables change in a periodic manner. Variable camber is introduced as a further control in addition to angle of attack and thrust setting. By periodically varying camber in a coordinated process with the two other controls, it is possible to fully exploit its potential of improving the lift/drag ratio for increasing the endurance of aircraft.

It is quantitatively shown which gain in endurance performance can be achieved. Results are presented for an idealized engine model showing no control rate limitations as well as for a realistic model with constraints on control rates imposed. The numerical values for the constraints are chosen such that only slow thrust changes are admitted.

## 1 NOMENCLATURE

| | |
|---|---|
| $C_D$ | drag coefficient |
| $C_L$ | lift coefficient |
| $D$ | drag |
| $g$ | acceleration due to gravity |
| $H$ | Hamiltonian |
| $h$ | altitude |
| $J$ | performance criterion |
| $L$ | lift |
| $M$ | Mach number |
| $m$ | mass |
| $S$ | reference area |
| $\overline{S}$ | switching function |
| $T$ | thrust |
| $t$ | time |
| $V$ | speed |
| $\alpha$ | angle of attack |
| $\gamma$ | flight path angle |
| $\delta_T$ | throttle setting |
| $\delta_{VCi}$ | variable camber setting, $i = 1, ...j$ |
| $\lambda$ | Lagrange multiplier |
| $\varrho$ | athmospheric density |
| $\sigma$ | fuel consumption factor |

* Prof. Dr.-Ing. Gottfried Sachs, Director, Institute of Flight Mechanics and Flight Control.

** Dipl.-Ing. Rainer Mehlhorn, Research Assistant.

## 2 INTRODUCTION

Optimizing endurance cruise is a basic problem of aircraft performance where the time which can be spent in the air for a given amount of fuel is maximized while the distance covered is not of interest. According to classical theory, endurance cruise is a steady-state flight at constant speed or altitude or both. Maximizing endurance is achieved by an appropriate altitude/speed combination such that fuel flow rate is minimized. The controls (throttle and elevator) are constant or show small gradual variations because mass will be changing rather slowly as fuel is consumed. Techniques for optimization classical endurance cruise are well known (e.g., Refs. 1-4).

Recent research in aircraft performance has shown that there may be a non-steady type of cruise which yields a superior endurance performance (Refs. 5-7). This type of cruise is characterized by a periodic trajectory. Each period of the trajectory consists of two phases one of which is a high-thrust climbing flight while the other is a descent at low thrust.

With the use of wings which can adjust their profile, the performance requirements of different types of maneuvers can be better met. This technique is based on an aerodynamic concept termed "Variable Camber" which provides an efficient means for improving the lift/drag characteristics of aircraft (Refs. 8-11).

The performance potential of periodic optimal control of endurance cruise can be further enhanced when the improved aerodynamic capability of variable camber can be additionally utilized (Refs. 4, 12). This is because periodic optimal control can provide a particular advantage of variable camber by continually adjusting the wing profile during the unsteady phases of a period.

It is the purpose of this paper to provide a further insight into the endurance performance improvement possible by periodic aircraft cruise in combination with control of variable camber. It will be shown which endurance increase can be achieved by optimal periodic control when compared with the best steady-state cruise. A further topic on which emphasis is put is of a more practical nature. It concerns a limitation of throttle control rate in order to avoid abrupt thrust changes.

*Presented at an AGARD Meeting on 'Recent Advances in Long Range and Long Endurance Operation of Aircraft', May 1993.*

## 3 STEADY-STATE CRUISE AND VARIABLE CAMBER CONSIDERATIONS

For reference purposes, some basic properties of steady-state cruise and variable camber aerodynamics are considered first.

Maximizing endurance in steady-state cruise requires to minimize fuel flow. This means to determine the minimum of the expression

$$\dot{m}_f = \sigma T \tag{1}$$

With the use of $T = D = C_D(\varrho/2)V^2S$ and $mg = L = C_L(\varrho/2)V^2S$, Eq. (1) may be rewritten as

$$\dot{m}_f = \sigma \frac{C_D}{C_L} mg \tag{2}$$

When treating thrust specific fuel consumption $\sigma$ as a constant which is a reasonable assumption for jet propelled aircraft considered here, maximum endurance is achieved by a flight condition at minimum drag/lift ratio $(C_D/C_L)_{min}$. In case of a parabolic drag polar $C_D = C_{D_0} + KC_L^2$, the following relation for the optimal lift coefficient in regard to $(C_D/C_L)_{min}$ holds

$$C_L = \sqrt{C_{D_0}/K} \tag{3}$$

This relation may be considered as a reference. For a more realistic modelling, the dependency of specific fuel consumption on Mach number, altitude and throttle setting and the effect of Mach number on drag as well as non-parabolic characteristics of the drag polar must be accounted for. An explicit solution may not be possible and numerical or graphical methods are required to determine the minimum of $\dot{m}_f$ as described by Eq. (1), Refs. 1-4.

Steady-state endurance performance can be improved with a variable camber wing. From Eq. (2) it follows that it is necessary to find the best drag/lift ratio for the lift coefficient at which endurance cruise is conducted. This is illustrated in Fig. 1. This Figure shows individual drag polars as generated by appropriate camber settings for some flight conditions like cruise, maneuver, loiter etc. The difference between the best drag/lift ratios of the individual polars show that a significant aerodynamics advantage may be possible by appropriately controlling camber. The envelope of all drag polars possible is a measure for the aerodynamics performance of a variable camber wing.

As may also be seen in Fig. 1, loitering corresponds to a flight at a larger lift coefficient than range cruise. It may also be of interest to note that loitering is conducted at a relatively small Mach number avoiding drag increase due to compressibility.

The maneuvers indicated in Fig. 1 basically represent steady-state flight conditions. Accordingly, variable camber is usually considered as a steady-state control which is held constant during a maneuver. In this paper, variable camber is introduced as a non-steady control which is continually changed. Thus, it is possible to exploit the potential of variable camber for further improving aircraft performance.

## 4 PROBLEM FORMULATION FOR PERIODIC OPTIMAL CRUISE

The unsteady phases of a periodic trajectory require to adequately model the dynamics of the aircraft as well as aerodynamics and powerplant characteristics. The equations of motion may be written as

$$\begin{aligned} \frac{dV}{dt} &= \frac{T}{m} - \frac{D}{m} - g\sin\gamma \\ \frac{d\gamma}{dt} &= \frac{L}{mV} - \frac{g}{V}\cos\gamma \\ \frac{dh}{dt} &= V\sin\gamma \\ \frac{dm_f}{dt} &= f(V, h, \delta_T) \end{aligned} \tag{4}$$

The characteristics of lift and drag may be modelled as $L = C_L(\varrho/2)V^2S$ and $D = C_D(\varrho/2)V^2S$ where

$$\begin{aligned} C_L &= C_L(\alpha, \delta_{VCi}, M), \quad i = 1, \dots j \\ C_D &= C_D(\alpha, \delta_{VCi}, M), \quad i = 1, \dots j \end{aligned} \tag{5}$$

For changing variable camber setting, a multiple set of individual control devices $\delta_{CVi}$ may be applied. The actual number denoted by $j$ is due to the specifics of a technical design such as leading and trailing edge flaps or a segmentation of a wing (Ref. 9). In this paper, a combination of leading and trailing edge flaps is considered (implying that $j = 2$), Fig. 2. From the results presented it follows that the lift/drag ratio can be effectively improved by appropriate setting of variable camber as indicated by the envelope. As may be seen, a rather complex functional relationship exists between drag coefficient and the other quantities involved.

The thrust model accounts for the effect of speed, altitude and thrust setting. It may be expressed as

$$T(V, h, \delta_T) = \delta_T T_{max}(V, h) \tag{6}$$

Fuel consumption characteristics are described by the following relation

$$\dot{m}_f = \dot{m}_{f_0}(h) + \delta_T \sigma(V) T_{max}(V, h) \tag{7}$$

During a period $t_{cyc}$ of a trajectory, a certain amount of fuel is consumed. This amount can be considered small when compared with the total mass of the aircraft

$$m_f(t_{cyc}) - m_f(0) \ll m \tag{8}$$

As a consequence, the mass of the aircraft can be considered constant for the duration of one period.

Periodicity of the flight path implies the following boundary conditions

$$V(t_{cyc}) = V(0)$$
$$\gamma(t_{cyc}) = \gamma(0) \qquad (9a)$$
$$h(t_{cyc}) = h(0)$$

The initial condition for the fuel mass can be written as

$$m_f(0) = 0 \qquad (9b)$$

Control variables are angle of attack $\alpha$, variable camber setting $\delta_{VCi}$ and throttle setting $\delta_T$ which are subject to the following inequality constraints

$$\alpha_{min} \leq \alpha \leq \alpha_{max}$$
$$(\delta_{VCi})_{min} \leq \delta_{VCi} \leq (\delta_{VCi})_{max}, \quad i = 1, ...j \qquad (10)$$
$$0 \leq \delta_T \leq 1$$

The atmospheric model which is used for describing air density, speed of sound and thrust dependencies on altitude agrees with the ICAO Standard Atmosphere (Ref. 13).

The optimization problem is to determine a periodic trajectory which yields the maximum of flight time per fuel consumed. For this purpose, the performance criterion

$$J = \frac{t_{cyc}}{m_f(t_{cyc})} \qquad (11)$$

is introduced.

The optimization problem may now be formulated as to find the control histories $\alpha$, $\delta_{VCi}$ and $\delta_T$, the initial states $(V(0), \gamma(0), h(0))$ and the optimal cycle length $t_{cyc}$ which maximize the perfomance criterion subject to the dynamic system described by Eq. (4), the boundary conditions given by Eqs. (9a,b) and the inequality constraints for the control variables, Eq. (10).

For solving this problem, an optimization procedure based on the minimum principle and the method of multiple shooting was applied. Details are described in the Appendix.

## 5 BASIC PROPERTIES OF PERIODIC OPTIMAL CRUISE

The results presented in this section are intended to show basic properties of periodic optimal endurance cruise. They may be considered as a reference in as much as there are no restrictions of control rates which may be limited from a practical point of view. All other characteristics of the aircraft are realistically modelled. This particularly concerns aerodynamics, the main characteristic of which is the drag/lift relationship and its dependency on variable camber setting and Mach number. This rather complex dependency is modelled according to the example shown in Fig. 2 for three Mach numbers. The aircraft considered may be regarded as representative for vehicles capable of supersonic speed.

An optimal period of maximum endurance cruise is presented in Figs. 3-5. There is a significant increase in endurance of 25.4 % when compared with the best steady-state cruise.

This increase is achieved by an unsteady maneuver which combines a high-thrust climb phase followed by a descent phase at idling (Fig. 3). As may be seen in Fig. 4, a considerable use is made of variable camber which is changed in a wide range. In the high-thrust climb phase (Fig. 5), camber is set at low values indicating a decambering of the wing. A large camber setting is applied for the descent phase at idling.

Fig. 6 shows further details of optimal control of variable camber. For the range of high lift coefficients, a large camber setting is applied and the Mach numbers attained are rather small. The opposite holds for the range of small lift coefficients. The correlation existing between these quantities indicates a favorable usage of the variable camber potential for application to periodic control of endurance. This is because the effectiveness of variable camber in improving the lift/drag ratio is rather high at small Mach numbers (Fig. 2). This particularly holds for the upper range of lift coefficients. By contrast, the effectiveness is considerably reduced at high subsonic Mach numbers (Fig. 2).

## 6 THRUST MODEL WITH CONSTRAINED CONTROL RATE

The control of thrust in the previously considered reference case shows a bang-bang type behavior which means a switching between its maximum and minimum values at an infinite control rate. Such a behavior is not realistic because of limitations existing for the control rate of thrust. Furthermore, even a high control rate may be not feasible because there are detrimental effects on engine life time when thrust is very rapidly changed from idling to maximum and vice versa. In order to reduce such effects and to realistically simulate thrust control characteristics, an expanded model is introduced. This model shows a limitation in thrust control rate where a time of 10 sec was chosen for changing thrust from idle to maximum (dry) and vice versa.

The effect of constraining thrust control rate on periodic optimal endurance cruise is shown in Figs. 7-9. There is only a small effect on the endurance improvement achievable with periodic optimal control due to delayed thrust buildup caused by the rate constraint. The optimal trajectory is quite similar to the previously considered reference case.

It may be of interest to note how fuel is consumed during maximum thrust and idling phases. This is illustrated in Fig. 10. As may be seen, a significant portion of fuel is consumed during the idling phase. Despite the fact that this portion is wasted, periodic optimal control provides an improvement in the overall performance.

Though the optimal period length is more than 10 min, a further increase may contribute to an ease in control and also to a further reduction of problems as regards engine life time considerations. This is because an increased period length would mean a reduction of the number of engine cycles necessary for a given total endurance time. Figs. 11-13 show characteristics of a trajectory when the period length is doubled as compared with the optimal value. As may be seen, endurance performance is slightly reduced. The trajectory shows some changes when compared with the optimal case. Basically, the altitude range is extended for enabling a longer period so that the maximum thrust as well as the idling phases are increased. Control of variable camber is quite similar to the optimal period case.

Another consideration of practical interest concerns the loads occuring during periodic cruise. This is illustrated in Fig. 14 which shows the history of the load factor for periodic optimal cruise (as depicted in Figs. 7-9). From the results presented in Fig. 14 it follows that there are some load factor variations during pull up and push down phases when the trajectory is changed from a climb to a descent and a vice versa. However, the main portion of the trajectory shows a practically constant load factor equivalent to a steady-state flight condition.

## 7 CONCLUSIONS

For periodic optimal endurance cruise, variable camber is considered as a control in addition to thrust and angle of attack which are the controls usually applied. It is shown that a significant increase of endurance performance can be achieved when compared with the best steady-state cruise. By periodically varying camber in a coordinated process with the two other controls, it is possible to fully exploit its potential of improving the lift/drag ratio for increasing the endurance of aircraft.

The results presented include a realistic modelling of engine characteristics which account for a control rate limitation. The constraints chosen for control rates are such that thrust is changed rather slowly in order to reduce problems concerning engine life time. Such problems may result because the engine is operated alternately at a high and a low thrust setting. A further means for reducing engine life time problems is to increase the period length so that a smaller number of thrust control cycles is required for a given total endurance time. It is shown that endurance performance improvement stays at a significant level even if the period length is doubled when compared with the optimal value.

A further consideration of practical interest concerns the load factor attained during period optimal endurance cruise. It is shown which changes exist. They mainly concern the pull up and push down phases of the trajectory.

## 8 APPENDIX (OPTIMALITY CONDITIONS)

For solving the periodic control problem described, optimization methods are required with the use of which a solution can be constructed. The technique applied in this paper is an indirect method which makes use of establishing optimality conditions including additional differential equations. Furthermore, an efficient numerical method is required which is capable of solving the problem at hand. The technique applied in this paper is based on the method of multiple shooting (Ref. 14).

Necessary conditions for optimality can be determined by applying the minimum principle. For this purpose, the Hamiltonian is defined as

$$H = \lambda_V \left(\frac{T}{m} - \frac{D}{m} - g \sin\gamma\right) + \lambda_\gamma \left(\frac{L}{mV} - \frac{g}{V}\cos\gamma\right) + \\ + \lambda_h V \sin\gamma + \lambda_f(\dot{m}_{f0} + \sigma T) \tag{A1}$$

where the Lagrange multipliers $\lambda = (\lambda_V, \lambda_\gamma, \lambda_h, \lambda_f)^T$ have been adjoined to the system of Eq. (4). The Lagrange multipliers are determined by *

$$\begin{aligned} \frac{d\lambda_V}{dt} &= \lambda_V \frac{D_V - T_V}{m} + \lambda_\gamma \frac{L - V L_V - mg\cos\gamma}{mV^2} - \\ &\quad - \lambda_h \sin\gamma - \lambda_f(\sigma_V T + \sigma T_V) \\ \frac{d\lambda_\gamma}{dt} &= \lambda_V g\cos\gamma - \lambda_\gamma \frac{g}{V}\sin\gamma - \lambda_h V\cos\gamma \\ \frac{d\lambda_h}{dt} &= \lambda_V \frac{D_h - T_h}{m} - \lambda_\gamma \frac{L_h}{mV} - \lambda_f\left(\sigma T_h + \frac{\partial \dot{m}_{f0}}{\partial h}\right) \\ \frac{d\lambda_f}{dt} &= 0 \end{aligned} \tag{A2}$$

with the following boundary conditions

$$\begin{aligned} \lambda_V(0) &= \lambda_V(t_{cyc}) \\ \lambda_h(0) &= \lambda_h(t_{cyc}) \\ \lambda_\gamma(0) &= \lambda_\gamma(t_{cyc}) \\ \lambda_f(t_{cyc}) &= -t_{cyc}/m_f^2(t_{cyc}) \end{aligned} \tag{A3}$$

The optimal cycle time $\bar{t}_{cyc}$ can be obtained with the use of two further differential equations

$$\begin{aligned} \frac{dt_{cyc}}{dt} &= 0 \\ \frac{d\lambda_T}{dt} &= -\frac{H}{t_{cyc}} \end{aligned} \tag{A4}$$

subject to the boundary conditions

$$\begin{aligned} \lambda_t(0) &= 0 \\ \lambda_t(\bar{t}_{cyc}) &= \frac{1}{m_f(\bar{t}_{cyc})} \end{aligned} \tag{A5}$$

The optimal controls $\alpha$, $\delta_{VCi}$ and $\delta_T$ are such that $H$ is minimized. For this reason, $\alpha$ is determined either

* Partial derivatives of $D$, $L$, $T$ are denoted by subscripts, e.g., $D_V = \partial D/\partial V$.

by (from $\partial H/\partial\alpha = 0$)

$$\lambda_\gamma \frac{\partial C_L}{\partial \alpha} - \lambda_V V \frac{\partial C_D}{\partial \alpha} = 0 \qquad (A6)$$

or by the constraining bounds of Eq. (10).

The optimality conditions for variable camber setting are

$$\lambda_\gamma \frac{\partial C_L}{\partial \delta_{VCi}} - \lambda_V V \frac{\partial C_D}{\partial \delta_{VCi}} = 0, \quad i = 1, ...j \qquad (A7)$$

Otherwise, the constraining bounds of Eq. (10) become active.

With regard to throttle setting $\delta_T$, the Hamiltonian shows a linear dependence. Accordingly, a bang-bang type control or singular arcs can exist. The bang-bang type control means that the throttle takes on its boundary values according to

$$\begin{aligned} \delta_T &= 0 \quad \text{if} \quad \overline{S}(y, \lambda, C_L) > 0 \\ \delta_T &= 1 \quad \text{if} \quad \overline{S}(y, \lambda, C_L) < 0 \end{aligned} \qquad (A8)$$

where

$$\overline{S}(y, \lambda, C_L) = \frac{\partial}{\partial \delta_T} H(y, \lambda, C_L, \delta_T) \qquad (A9)$$

is the switching function and $y = (V, \gamma, h, m_f)^T$. Switching occurs when

$$\overline{S}(y, \lambda, C_L) = 0.$$

A singular arc means that the throttle is not on its boundary but takes on values interior to its admissible control set. This occurs when $\overline{S}(y, \lambda, C_L) = 0$ for a finite interval of $t$. However, such a behaviour was not observed in the numerical investigation.

Thrust control characteristics as described by Eq. (A8) are used as a reference for describing basic properties of period optimal endurance cruise. For a more realistic modelling accounting for control rate constraints, further conditions for optimality not described here have been applied.

The system described by Eq. (4) is autonomous, so that the Hamiltonian is constant. Since the final time $t_{cyc}$ is considered as free, the Hamiltonian takes on the value

$$H = \frac{1}{m_f(t_{cyc})} \qquad (A10)$$

The numerical difficulties existing in periodic optimal cruise problems require sophisticated optimization procedures and efficient computational algorithms. Such problems include the precise treatment of switching conditions, internal point and jump conditions etc. The computer code applied is based on the method of multiple shooting and provides results with high accuracy (Refs. 14, 15).

## 9 REFERENCES


1. McCormick, B.W.: Aerodynamics, Aeronautics, and Flight Mechanics. John Wiley & Sons, New York – Chichester – Brisbane – Toronto – Singapure, 1979.
2. Vinh, N.X.: Optimal Trajectories in Atmospheric Flight. Elsevier Scientific Publishing Company, Amsterdam – Oxford – New York, 1981.
3. Brüning, G., Hafer, X., Sachs, G.: Flugleistungen. 3rd Edition, Springer-Verlag, Berlin – Heidelberg – New York – London – Paris – Tokyo, 1993.
4. Sachs, G.: Optimization of Endurance Performance. Progress in Aerospace Sciences, Vol. 29, pp. 165-191, 1992.
5. Lyons, D.T. Improved Aircraft Cruise by Periodic Control. Ph.D. Dissertation, The University of Michigan, 1980.
6. Sachs, G.: Flugzeitsteigerung durch zyklisch gesteuerten dynamischen Dauerflug. Zeitschrift für Flugwissenschaften und Weltraumforschung 9, pp. 42-52, 1985.
7. Sachs, G., Christodoulou, T.: Endurance Increase by Cyclic Control. Journal of Guidance, Control, and Dynamics 9, pp. 58-63, 1986.
8. Siewert, R.F., Whitehead, R.E.: Analysis of Advanced Variable Camber Concepts. AGARD-CP-241, pp. 14-1 - 14-21, 1978.
9. AFTI/F-111 Mission Adaptive Wing Briefing to Industry. AFWAL-TR-88-3082, Flight Dynamics Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio, 1988.
10. Szodruch, J., Hilbig, R.: Variable Wing Camber for Transport Aircraft. Progress in Aerospace Sciences 25, pp. 297-328, 1988.
11. Smith, S.B., Nelson, D.W.: Determination of the Aerodynamic Characteristics of the Mission Adaptive Wing. Journal of Aircraft 27, pp. 950-958, 1990.
12. Sachs, G.: Eine neue Methode zur Steigerung der Maximal-Flugdauer. Zeitschrift für Flugwissenschaften und Weltraumforschung 15, pp. 393-400, 1991.
13. ICAO Standard Atmosphere, International Civil Aviation Organization, Montreal, 1964.
14. Bulirsch, R.: Die Mehrzielmethode zur numerischen Lösung von nichtlinearen Randwertproblemen und Aufgaben der optimalen Steuerung. Report of the Carl-Cranz-Gesellschaft, Oberpfaffenhofen, Germany, 1971.
15. Oberle, H.J.: Numerische Berechnung optimaler Steuerungen von Heizung und Kühlung für ein realistisches Sonnenhausmodell. TUM-M8310, Institut für Mathematik der Technischen Universität München, 1983.

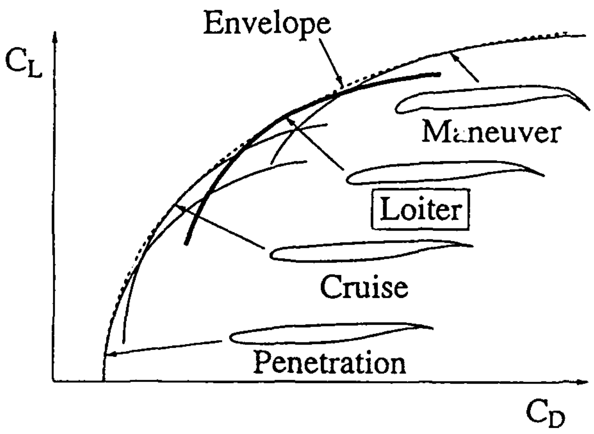



Fig. 1 Application of variable camber to different flight conditions

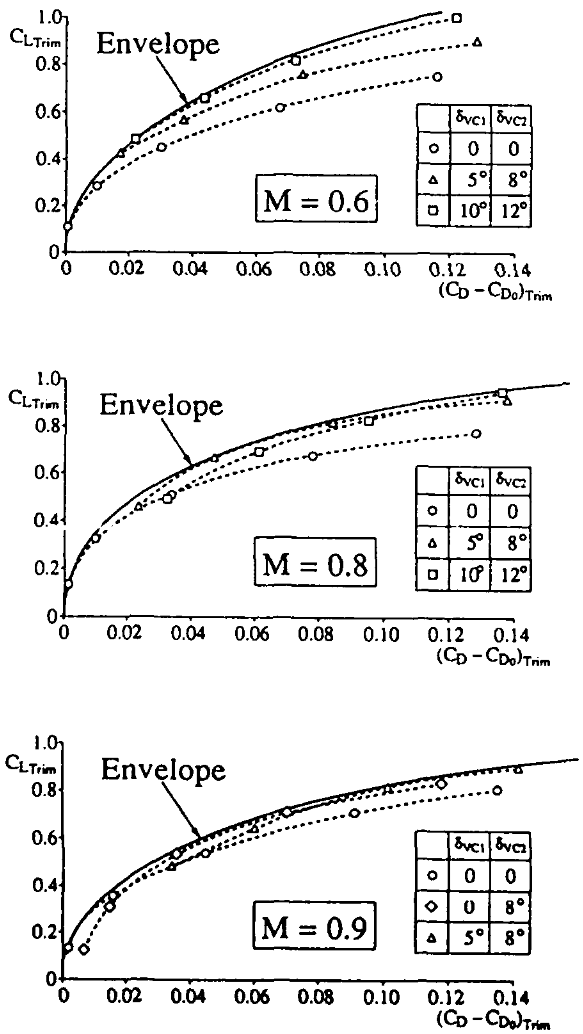



**Fig. 2 Effect of variable camber on drag characteristics (high performance aircraft), from Ref. 8**

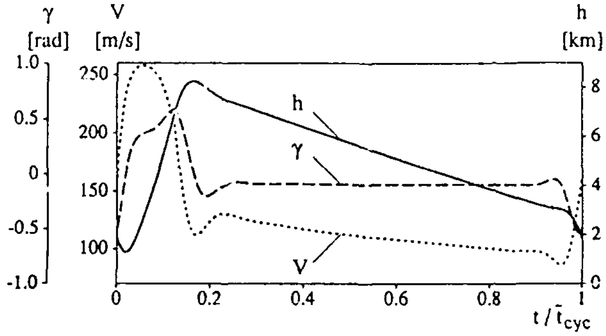



Fig. 3 Periodic optimal endurance cruise (reference case), speed, altitude and flight path angle 25.4% endurance increase, $\bar{t}_{cyc} = 597.8$ sec

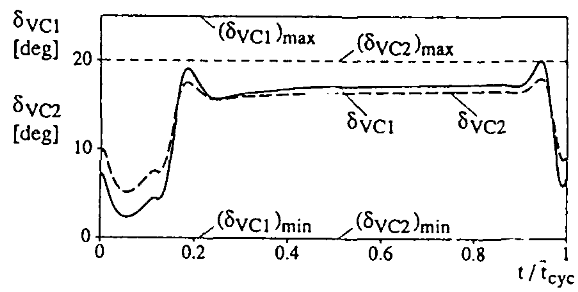



Fig. 4 Periodic optimal endurance cruise (reference case), variable camber setting 25.4% endurance increase, $\bar{t}_{cyc} = 597.8$ sec

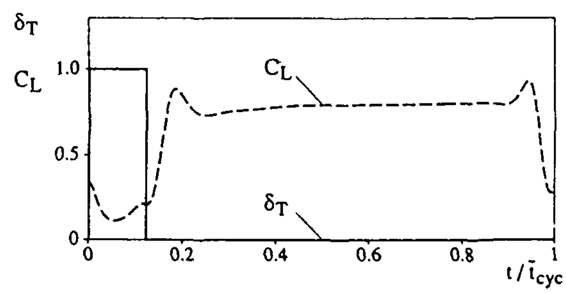



Fig. 5 Periodic optimal endurance cruise (reference case), lift coefficient and thrust setting 25.4% endurance increase, $\bar{t}_{cyc} = 597.8$ sec

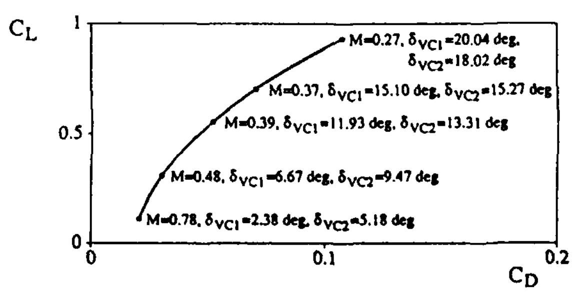



**Fig. 6 Correlation of lift/drag coefficients, Mach number and variable camber control**

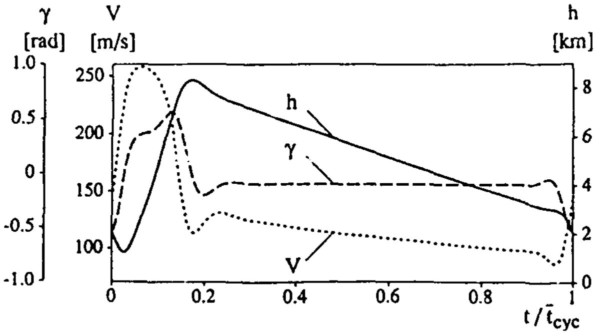



Fig. 7 Periodic optimal endurance cruise with constrained thrust control rate, speed, altitude and flight path angle
25.1% endurance increase, $\bar{t}_{cyc} = 613.2$ sec

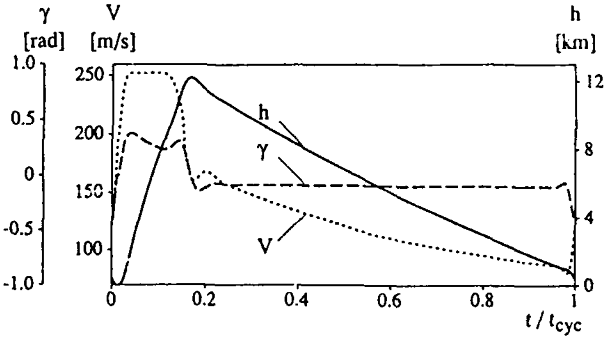



Fig. 11 Periodic endurance cruise at double of optimal period length, speed, altitude and flight path angle
21.7% endurance increase, $t_{cyc} = 1226.5$ sec

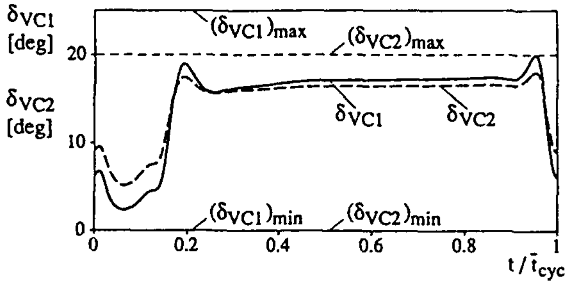



Fig. 8 Periodic optimal endurance cruise with constrained thrust control rate, variable camber setting
25.1% endurance increase, $\bar{t}_{cyc} = 613.2$ sec

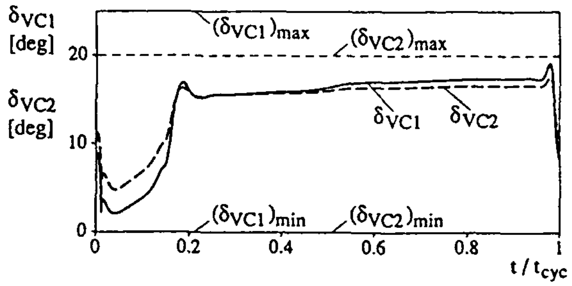



Fig. 12 Periodic endurance cruise at double of optimal period length, variable camber setting
21.7% endurance increase, $t_{cyc} = 1226.5$ sec

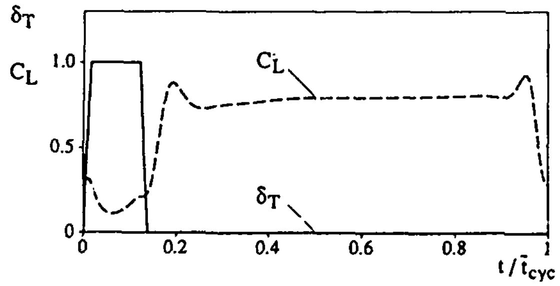



Fig. 9 Periodic optimal endurance cruise with constrained thrust control rate, lift coefficient and thrust setting
25.1% endurance increase, $\bar{t}_{cyc} = 613.2$ sec

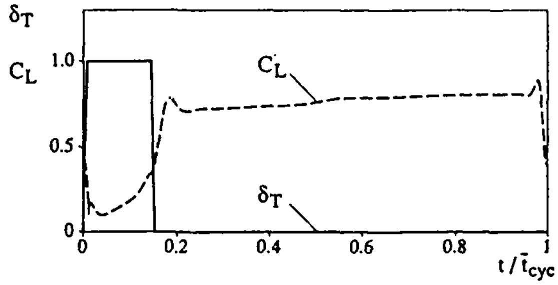



Fig. 13 Periodic endurance cruise at double of optimal period length, lift coefficient and thrust setting
21.7% endurance increase, $t_{cyc} = 1226.5$ sec

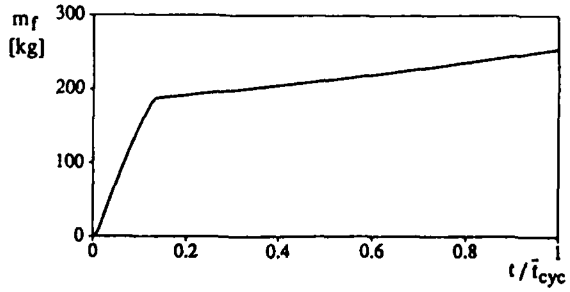



Fig. 10 Fuel consumption during periodic optimal endurance with constrained thrust control rate
25.1% endurance increase, $\bar{t}_{cyc} = 613.2$ sec

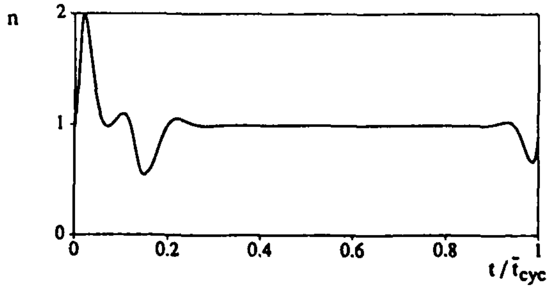



Fig. 14 Load factor during periodic optimal endurance with constrained thrust control rate
24.5% endurance increase, $\bar{t}_{cyc} = 654.6$ sec

# EH101 - A New Helicopter Capable of Long Range Missions

C J Battisson and H.E.Tatton-Brown CEng MIMechE

Westland Helicopters Ltd, U.K.
Yeovil
Somerset BA20 2YB
England

## 1 INTRODUCTION

The EH101 is a new medium helicopter being produced by EH Industries, a company jointly owned by Agusta of Italy and Westland of the UK.

The aim of this presentation is to explore the roles in which the EH101 will be called upon to cover long ranges and examine its suitability for these roles.

The roles which will be examined fall into the following categories;-

- Search and Rescue
- Self-Ferry
- Special Operations

The successful completion of such missions will demand particular capabilities of the crew and the machine. The following aspects of aircraft design will be looked at with respect to the EH101:-

- In-Flight Refuelling
- All-Weather Capability
- Maintenance Requirements
- Crew Environment

Because of the wide ranging nature of the subject and the limited time available for this presentation I intend to examine only the key points required for these roles and capabilities.

## 2 AIRCRAFT ROLES

### 2.1 Search and Rescue

The SAR mission over long ranges is one which EHI have spent some considerable time investigating with particular regard to the use of the aircraft in Canada.

We are producing an aircraft, the New Search and Rescue Helicopter (NSH), Figure 1, for the Canadian Forces who need to cover very large areas with a relatively small number of aircraft. This clearly demands both long range and high speed.

Figure 2 shows coverage of the Canadian land mass from just 4 bases. It can be seen that 80% of the country can be reached by EH101 aircraft in 12 hours operating from those 4 bases.

Figure 3 shows the increased coverage achieved using Air-to-Air refuelling.

The key assumptions used are that the self deployment reduces the SAR equipment slightly to allow take-off with full internal fuel, while the Air-to-Air refuelling case has full SAR kit and slightly reduced Fuel load.

Figure 4 shows an actual emergency which occurred in a very remote location in the North. Rescue helicopters needed to be air-freighted to Thule in Greenland, unloaded, reassembled and flown to the emergency.

The EH101 could have reached the location in less than 17 hours using in-flight refuelling. On internal fuel it would have taken less than 21 hours, Figure5.

### 2.2 Self Ferry

Most military aircraft these days need to be able to deploy to almost any part of the world in a short space of time.

This is becoming more important as the NATO countries are focussing more on the requirement for a rapid reaction capability over a wider area of operation after the end of the Cold War. The options available are limited to either transporting the helicopters in fixed wing aircraft, flying the aircraft themselves or transporting them by sea to the area.

The former may be very effective as long as the aircraft is small enough to fit into a transport plane and assuming that sufficient transport aircraft exist.

The self ferry case is likely for most situations but over long distances the deployment time may be particularly lengthy for helicopters with the added problem of obtaining clearance to fly over possible uncooperative countries.

*Presented at an AGARD Meeting on 'Recent Advances in Long Range and Long Endurance Operation of Aircraft', May 1993.*

Where a truly rapid response is required the helicopter needs to either have special ferry fuel tank provisions and/or the capability to refuel in flight.

The option of transportation by sea is slower than self ferry but has none of the diplomatic problems and can allow predisposition during a time of "build up of tension".

The EH101 has the advantage that it is designed to operate at sea and can have power blade and tail folding, Figure 6, to enable more efficient stowage in limited space. It is also "ruggedised" for conditions at sea, the extra landing loads operating from a moving deck and can withstand the corrosive conditions.

**2.3 Special Operations**
The need to carry out covert missions into hostile territory has been a reality since the earliest days of military aviation.

The prime requirement is to be able to cover long distances in order that the launch site can remain secret. It is essential to also ensure that the mission launch itself is secret.

A suitably large aircraft is required in order to accommodate the fuel and the troops. A typical scenario may be the carriage of 6 commando troops to a drop off point 300nm away from launch with the aircraft returning empty.

The last portion of the outward leg is likely to be flown nap-of-the-earth in the case of helicopter missions to avoid detection.

A representative sortie, with the limitations indicated, is shown in Figure 7 produced from our simulation using data that has been verified during the 2000 hours of development flying that has been accumulated.

The use of in-flight refuelling considerably increases the range and payload possibilities but clearly makes the logistics that much more complicated.

Other characteristics which boost effectiveness in this role are low external noise signature, high speed and all-weather capability, more about this later.

## 3 AIRCRAFT DESIGN ASPECTS

**3.1 In Flight Refuelling (IFR)**
As can be seen from helicopter roles described above, the ability to refuel in flight enhances the effectiveness of helicopters in Self-Ferry, SAR and Special Force Operations.

The EH101 is being offered with the ability to carry out IFR from a tanker aircraft or in the hover.

A design of removable IFR boom is being proposed which extends approximately 2.5 m ahead of the aircraft nose.

In the case of ship-borne aircraft this would be a retractable, telescopic probe or an easily removable extension.

The air-to-air probe will normally be of the 'Flight Refuelling' type which mates with a drogue deployed from the tanker which would typically be a C130.

The system will be capable of accepting 150 igpm at 50 psig hose end pressure.

We do not see the ability to perform refuelling from a C130 tanker to be a difficult task as long as the helicopter is stationed behind the tankers wing.

There could be some turbulence experienced from behind the fuselage due to the shedding of propeller tip vortices.

**3.2 All-Weather Capability**
Whilst the theoretical ability to cover long distances is obviously required, it will be of limited practical use if the weather is such that the aircraft can not operate.

Whatever the mission, the ability to cover a distance quickly is heavily dependent upon the helicopter being capable of being flown through a mixture of weather.

The EH101 has been designed for single pilot IFR capability in the military environment. This capability can be further enhanced by the addition of a full ice protection system which will permit operation in severe icing conditions by the use of heater mats on the main and tail rotor blades.

### 3.3 Navigation System
The Navigation system is fully integrated with a variety of sensors.

In the purely civilian role, Figure 8, the emphasis is on ground based navigation aids such as VOR, DME and a selection of Decca, Loran or Omega with GPS as an option when accepted by the Authorities.

The military system, Figure 9, is fully autonomous using a ring laser gyro inertial system with doppler and GPS aiding for over water operation (it can also be fitted with VOR/DME).

### 3.4 Radar
The Military aircraft is fitted with a Sea search radar which has the capability of locating survivors in the water. The civil version of the aircraft is fitted with a Bendix RDR 1400 Weather Radar which enhances the all-weather abilities as well as aiding the search role

### 3.5 Maintenance Requirements
The long range use of helicopters may also be restricted by the need to carry out maintenance tasks after a certain number of flying hours.

The EH101 is capable of operating for up to 12 hours without inspections. This limit will be one of the factors constraining long endurance missions involving in-flight refuelling.

This endurance has been achieved by careful design and emphasis on reliability.

There is no magic in achieving this just careful attention to details and rigorous testing of components and equipments.

The limiting maintenance requirement is the replenishment of fluids such as hydraulics, gearbox lubricants and engine oils.

There is an on board Health and Usage Monitoring (HUM) system to aid the maintenance assessment of the aircraft and to increase the ability to make use of 'on condition' replacement and overhaul. This is also a limit on the continuous flying as the accumulated data has to be down loaded for later analysis.

The HUM records allow a more accurate assessment of the aircraft condition and allows the aircraft to be cleared for extended operations away from a maintenance base.

## 4 CREW ENVIRONMENT

Having discussed the theoretical possibilities of long ranges and the type of technology applications necessary to achieve these it would be a mistake to forget the role of the pilots. Of course the fatigue of the crew is a very serious matter.

To fly for periods of around 12 hours non stop and then possibly turn-round the aircraft quickly for a further long range leg is potentially dangerous due to excessive fatigue.

It is most important that the major factors which improve the crew environment and working conditions i.e.

- Autopilot
- Automated Cockpit
- Ergonomic Controls
- Low vibration

are part of the design. Each of these factors are dealt with effectively in the EH101 cockpit.

### 4.1 Autopilot
The aircraft is fitted full auto-pilot facility which requires no Pilot intervention as a result of the first failure although a caution is given.

It has two Flight Control Computers (FCC) with two channels in each with different processors in each channel.

A full range of Autopilot functions are available including steering commands, height (Radalt & Baralt), heading and speed hold and in the Military version automatic transitions to and from the Hover with a Hover point approach.

The Autopilot includes an autostabilisation function (ASE) but the aircraft can be handled over the full flight envelope with ASE disengaged.

### 4.2 Automated Cockpit
The instruments are fully electronic and use cathode ray tube displays to display all flight and system data to the pilots as they require it, Figure 10.

The system is based on a "need-to-know" basis. The result is a crew whose workload is significantly reduced. All cautionary and warning data is available immediately to the crew as and when they need it.

Fig. 19 Instrumentation de la phase II

dérapage de l'avion)

- effet du taux d'aspiration et de sa distribution dans les canaux 1 à 6



However, it may be a point for limitless discussion as to whether on long range missions it is preferable for the pilots to have a reasonably heavy workload in order to remain safely attentive!

**4.3 Ergonomic Cockpit**
It goes almost without saying that the aircraft is capable of accommodating 5th to 95th percentile pilots and that great care has been taken in laying out the controls such that crew fatigue is minimised.

Experience shows in Civil helicopter operation that crew comfort can be very poor unless considerable attention is paid to it in the basic aircraft design.

In the military environment crew comfort can be further jeopardised by such factors as seat crashworthiness or the need to wear NBC protection.

It would be misleading of me to say that the EH101 is much better than other contemporary aircraft when it comes to military seat comfort.

Suffice it to say that a full range of crew sizes can be accommodated such that the crew members can reach controls easily whilst being seated in a good ergonomic position.

**4.4 Low Vibration**
The aircraft is equipped with Active Control of Structural Response (ACSR), a Westland designed and developed system, which is the most effective way yet found to control the ever present problem of helicopter vibration.

The system uses active control technology to minimise vibration around the airframe measuring the vibrations using 12 accelerometers on the structure and feeding the information into the ACSR controller.

This then drives hydraulic actuators in the main gearbox supports, Figure 11, that produces anti-phase movements to reduce the vibration generated by the dynamic components.

The system has had a considerable affect on the vibration levels, Figure 12, but the aircraft is still cleared to the full flight envelope with the ACSR switched off.

**5 CONCLUSION**

The EH101 has been designed as a multi-role helicopter and has the capability to perform Long Range tasks in the Military field which can be improved by the use of in-flight refuelling.

These capabilities can also be used in the SAR role to enable rescues to be achieved quicker and at longer range.

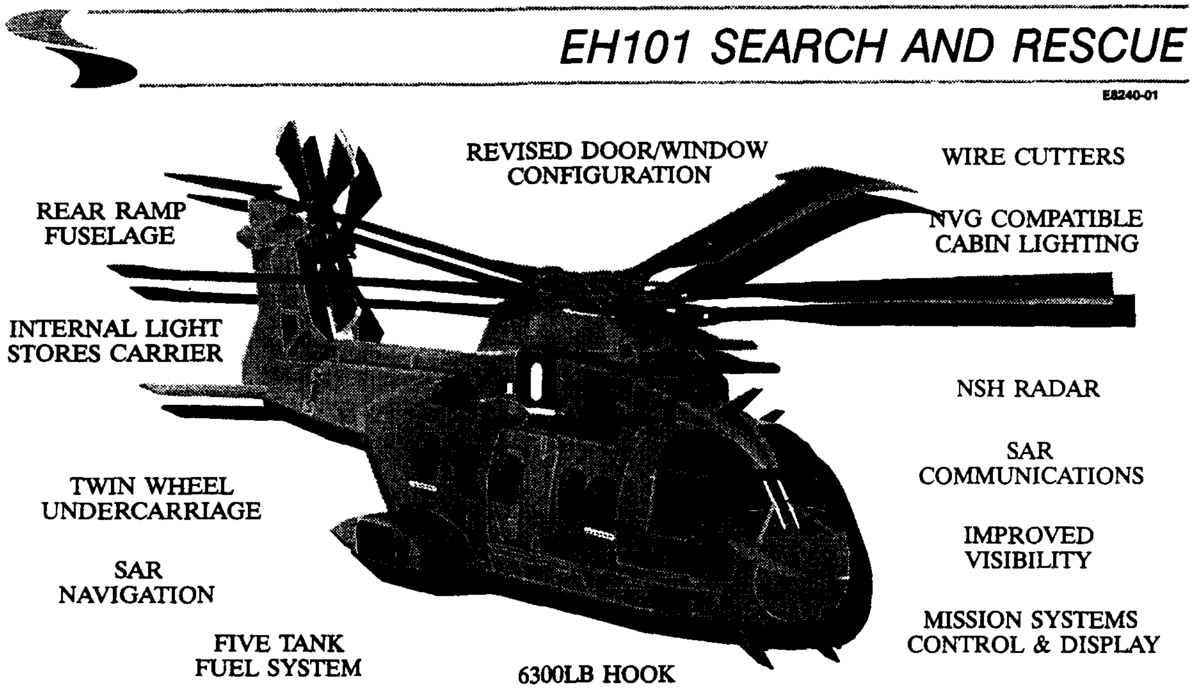



FIGURE 1

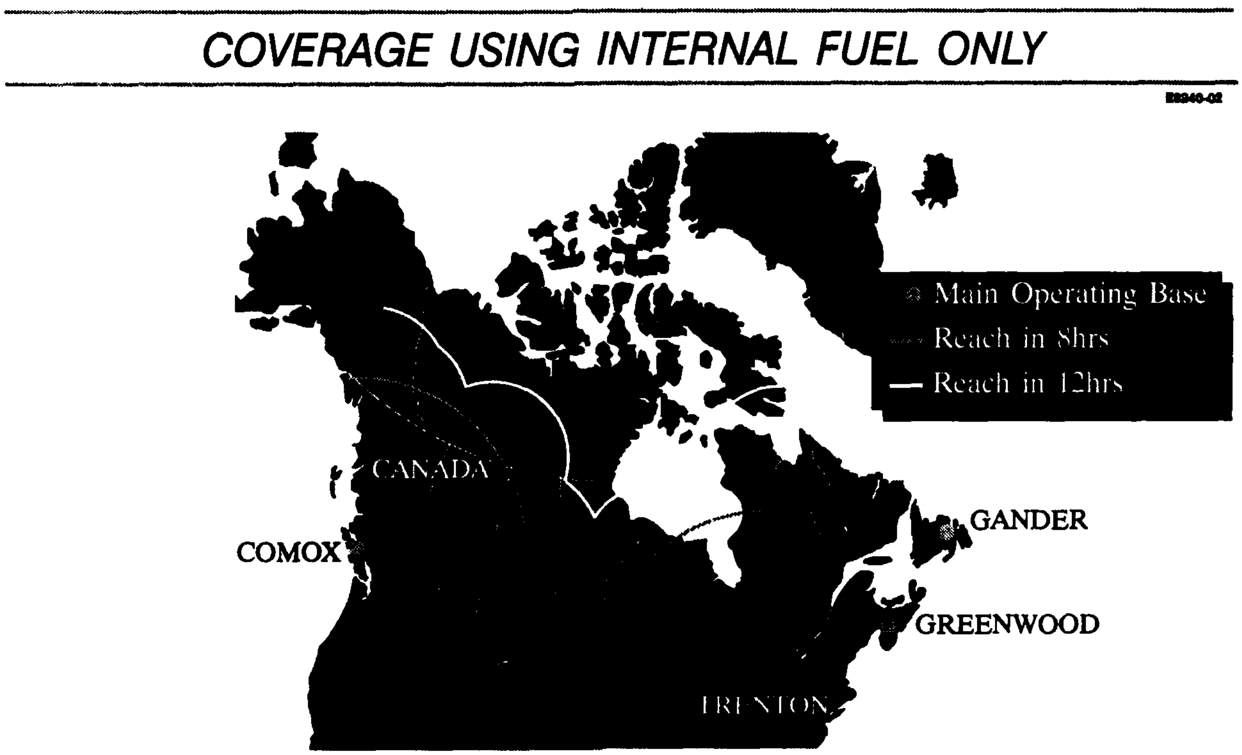



FIGURE 2

## COVERAGE USING AIR-TO-AIR REFUELING


FIGURE 3

## DEPLOYMENT TO ALERT USING AIR-TO-AIR REFUELING

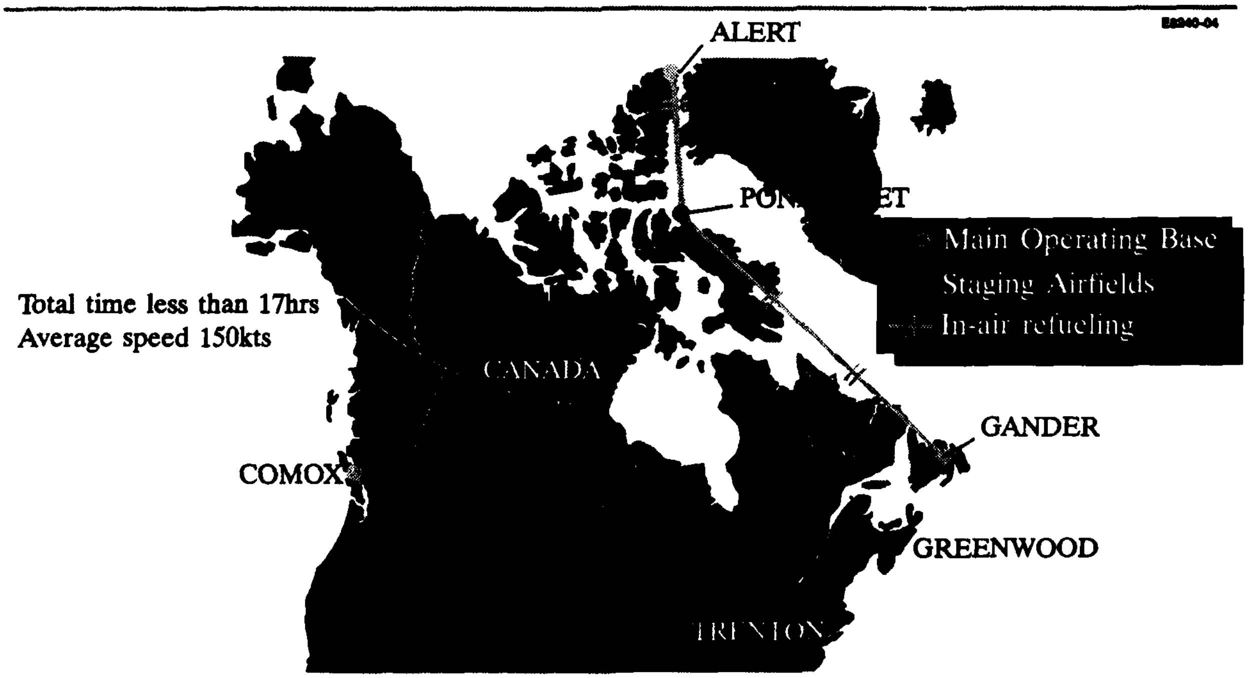



FIGURE 4

## DEPLOYMENT TO ALERT USING INTERNAL FUEL ONLY

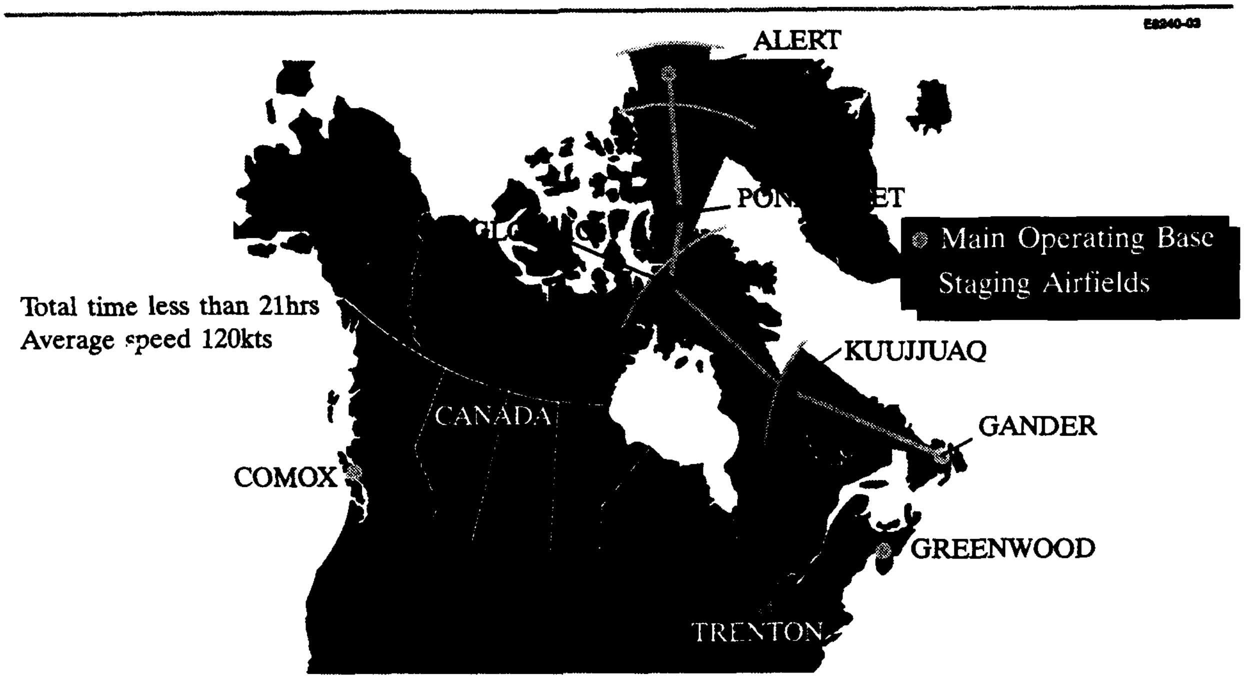



FIGURE 5

## EH101 - MAIN and TAIL FOLDED

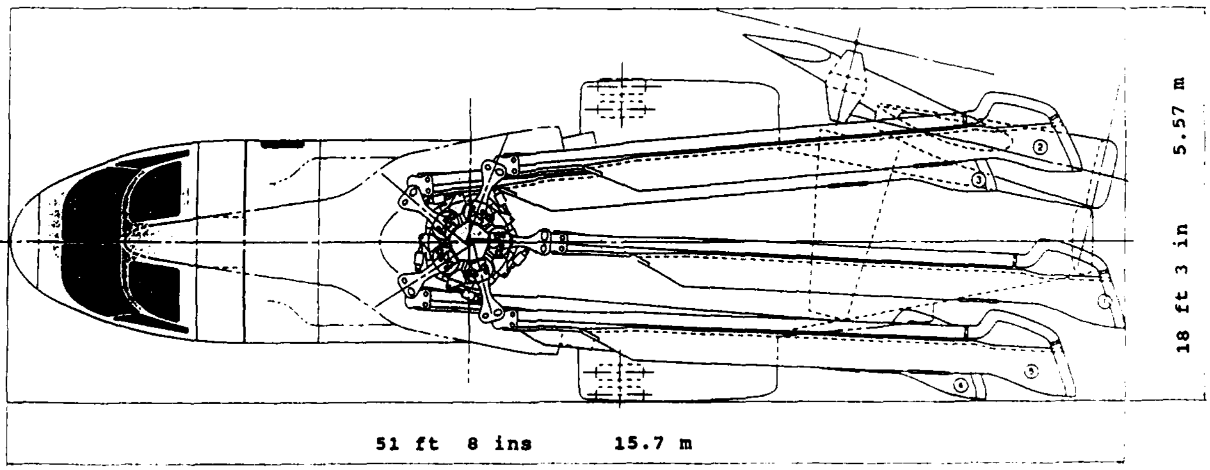



FIGURE 6

E8240-12

## EH101 2 v 3 ENGINE RADIUS OF ACTION

ISA + 0°C AMBIENT CONDITIONS

ALLOWANCES: 1 MIN HOVER FOR EACH TAKE-OFF & LANDING
4085KG MAX USEABLE FUEL

RESERVES: 15 MIN LOITER RESERVES

OPERATING WEIGHT: 9,946KG

ZERO HEADWIND

ZERO FUEL FLOW PENALTY

SORTIE: TAKE-OFF FROM SEA-LEVEL
CLIMB TO 5000FT
CRUISE OUT AT BEST RANGE SPEED
CRUISE BACK AT BEST RANGE SPEED
DESCEND TO SEA LEVEL
LAND

3-ENGINE BEST RANGE SPEED OUT/RETURN 130/135KT

2-ENGINE BEST RANGE SPEED OUT/RETURN 120/125KT

14,290KG MAX TAKE-OFF WEIGHT

WEIGHT: NSH BASIC VEHICLE WEIGHT
NO ECS PACK
4 CREW
30 SEATS IN CABIN
5-TANK FUEL SYSTEM
NO FLOTATION EQUIPMENT
NO RADOME
NO FLIR
STOWED HOIST
NO WIRECUTTERS
NO BUBBLE WINDOWS

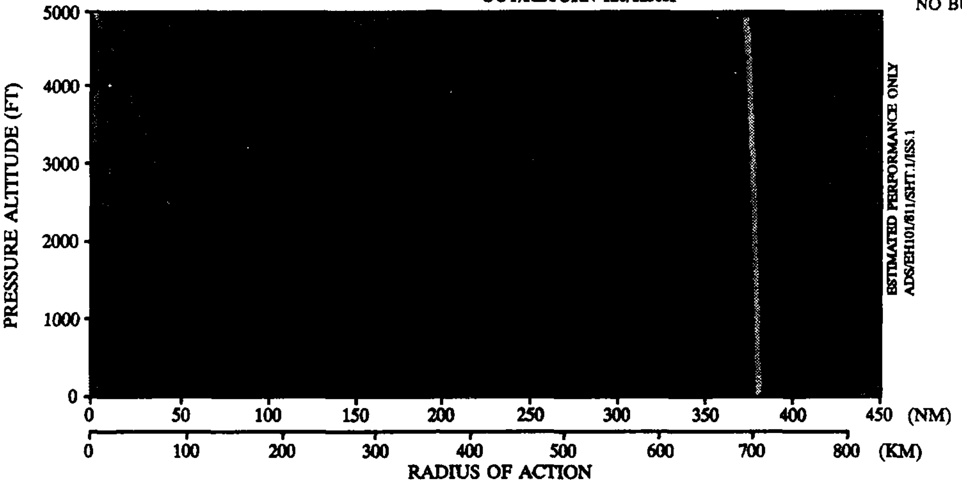



FIGURE 7

## CIVIL SYSTEM ARCHITECTURE

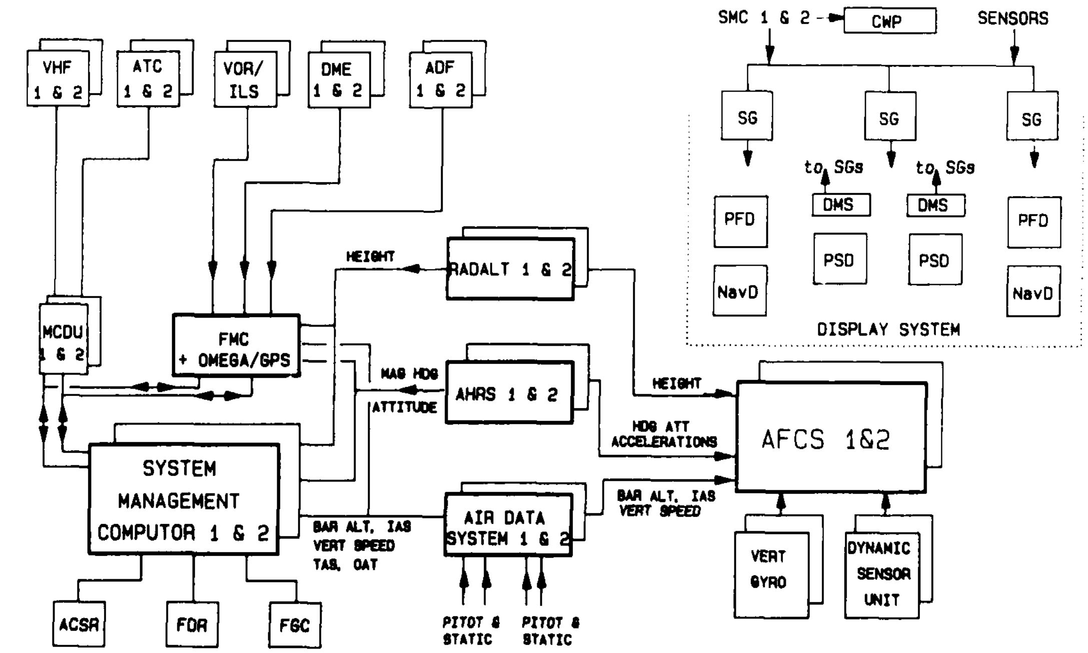



FIGURE 8

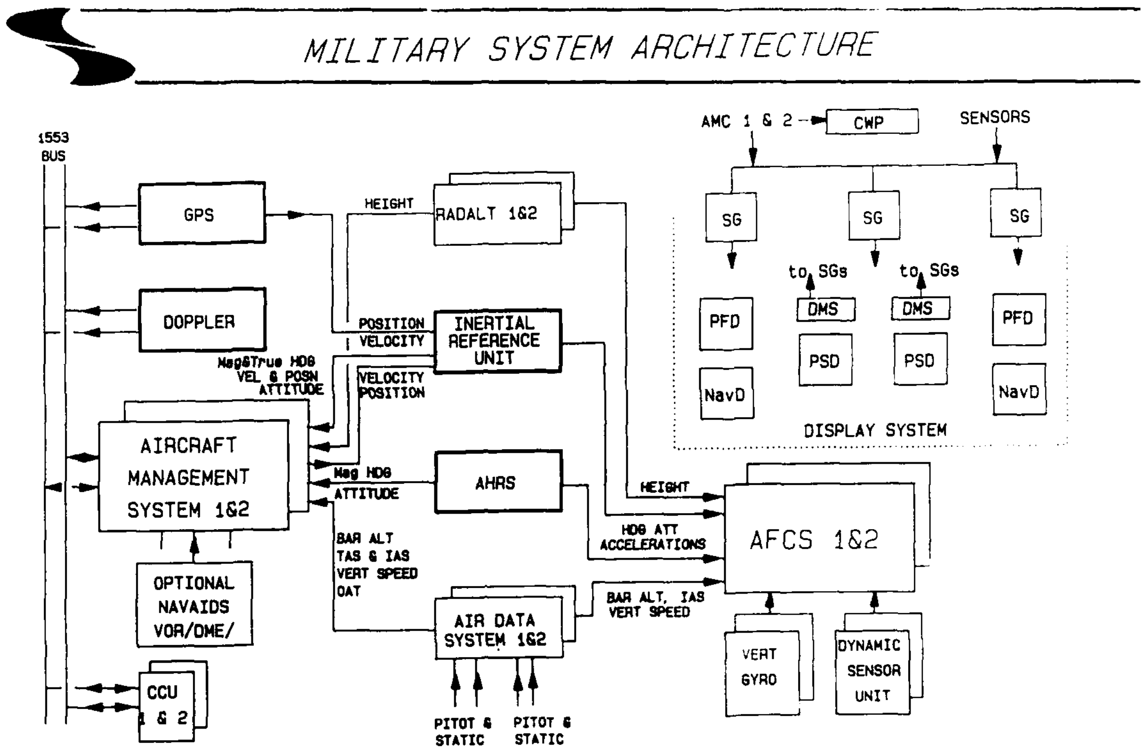



FIGURE 9

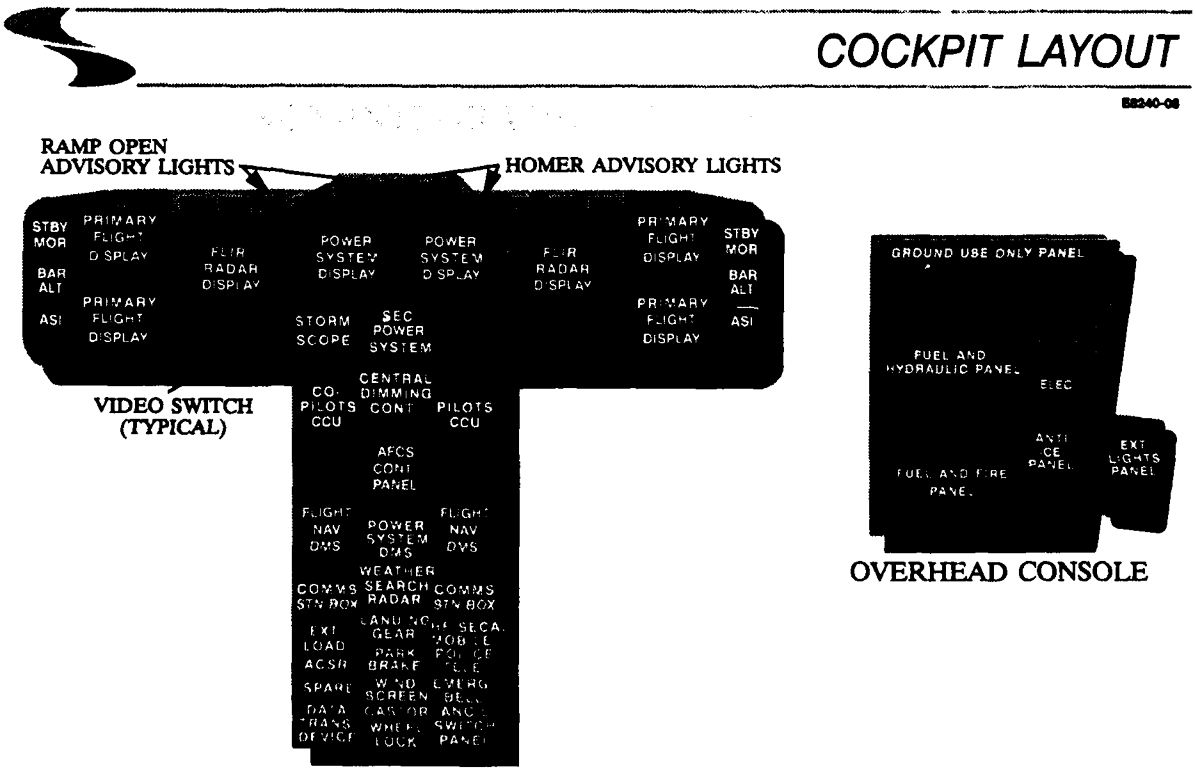



FIGURE 10

## ACSR ACTUATOR INSTALLATION - PI

E8240-09

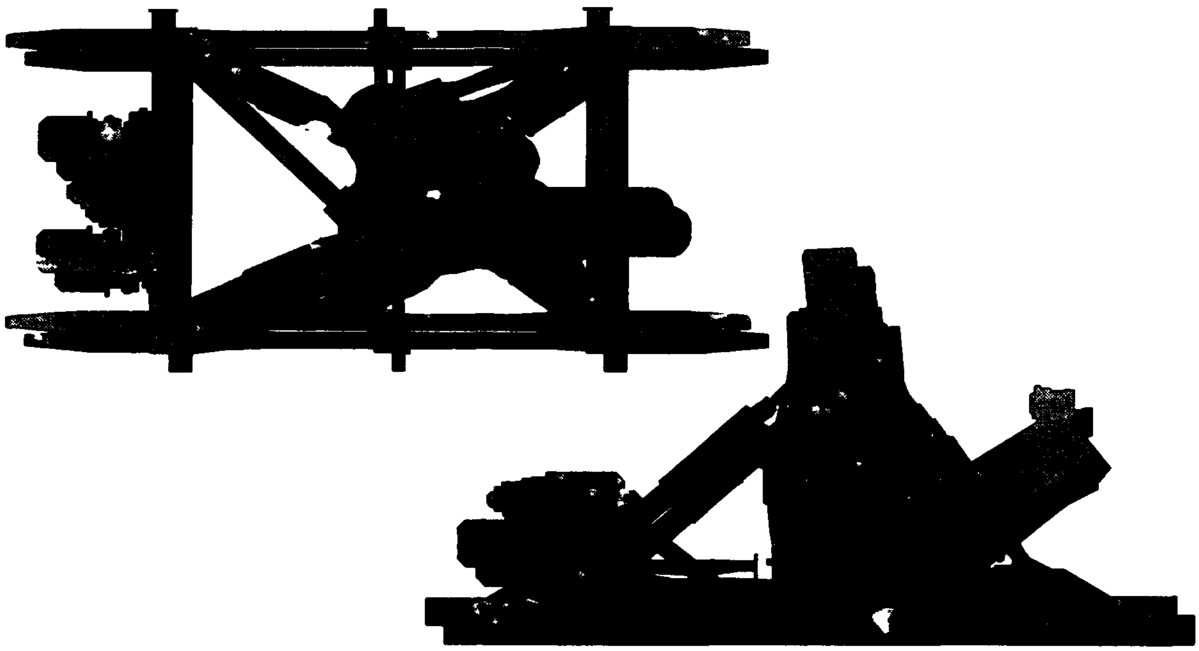


FIGURE 11

## VIBRATION

E8240-07

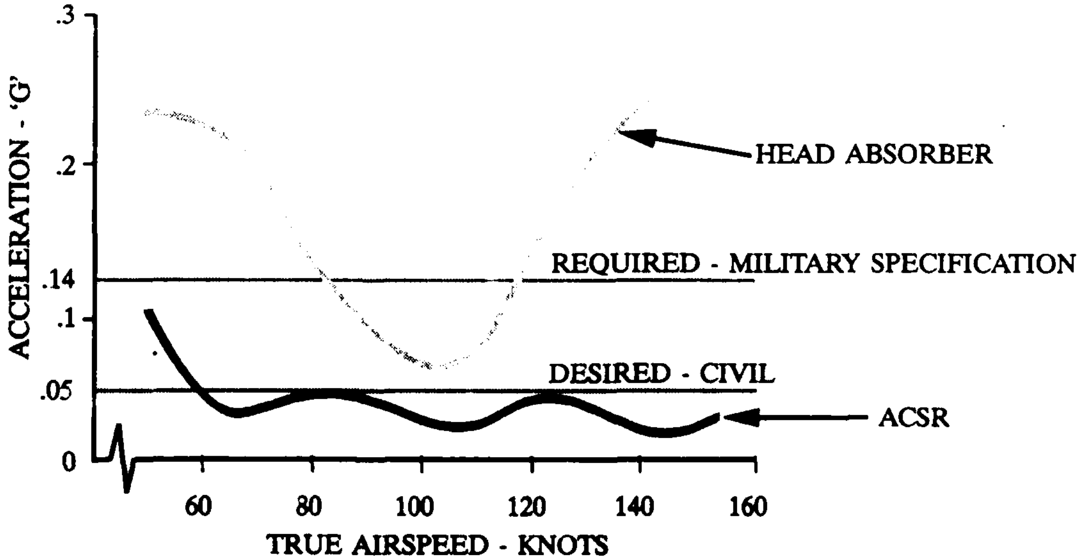



FIGURE 12

# LE CONVERTIBLE TYPE EUROFAR: VUE D'ENSEMBLE DES AVANCEMENTS TECHNIQUES ET MISSIONS FUTURES

par

**Général (CR) A. Martini**
**J. Renaud**
Eurocopter France
Etablissement de Marignane
13725 Marignane
France

Si jusqu'à ces dernières années le convertible n'a pas dépassé le stade des essais probatoires c'est que d'une part la technologie disponible ne permettait pas d'en résoudre correctement l'équation coût/efficacité, et que d'autre part le besoin n'en était pas véritablement exprimé. Les choses ont aujourd'hui changées. Les nécessités stratégiques et les progrès techniques se conjuguent pour donner corps aux Etats Unis mais également en Europe à ce vieux rêve des ingénieurs.

## 1 LES NECESSITES STRATEGIQUES

L'évolution géostratégique requiert d'avantage de mobilité et de vitesse sur des distances moyennes et rend le convertible techniquement nécessaire.

En effet, des risques multiformes se substituent à la menace unique de la guerre froide et les forces doivent disposer de capacités de projection stratégique mais aussi tactique pour permettre des réactions adaptées dans le temps et dans l'espace.

Comme les batailles linéaires laissent la place à des poles d'affrontements séparés par de grands espaces, les besoins en mobilité s'en trouvent accrus.

Les actions humanitaires et de maintien de la paix qui se multiplient nécessitent des moyens de transport pour amener vivres et matériels de façon significative au plus près des besoins. Mais parallèlement les budgets consacrés à la défense et les effectifs en réduction rendent indispensable la recherche du meilleur coût/efficacité des moyens disponibles.

Dans ce contexte, l'aéromobilité sous toutes ses formes se trouve valorisée et tout particulièrement la fonction mouvement. Certes l'hélicoptère pur reste un moyen privilégié pour assurer de façon économiquement viable le vol vertical et le transport sur courtes distances. Il est clair également que l'avion est impossible à concurrencer lorsque les trajets dépassent le millier de kilomètres à conditions toutefois de disposer de terrains même sommairement aménagés et d'accepter des ruptures de charges. Entre ces deux moyens traditionnels il y a place et besoins d'un appareil réunissant les avantages de l'un et de l'autre, au prix bien entendu de compromis sur les performances en stationnaire et sur la vitesse. Chaque fois que le besoin apparaîtra de conjuguer la capacité d'emport, le vol vertical et la vitesse le convertible apportera désormais une réponse. Les américains l'ont clairement prévu à travers le programme OSPREY et les Européens avec le projet EUROFAR.

*Presented at an AGARD Meeting on 'Recent Advances in Long Range and Long Endurance Operation of Aircraft', May 1993.*

## 2 LE PROGRAMME EUROFAR

Le programme EUROFAR (EUROPEAN FUTURE ADVANCED ROTORCRAFT) a été lancé fin 1987 par décision du Conseil des Ministres EUROPEENS dans le cadre du programme EUREKA.

La phase 1 du Programme (1988 - 1992) était destinée à évaluer la faisabilité d'un système de transport civil basé sur l'utilisation d'un convertible à rotors basculants.

Les travaux ont comportés :

- L'avant projet d'un appareil (le "BASELINE AIRCRAFT") avant projet destiné à évaluer les problèmes techniques spécifiques au convertible, à déterminer les technologies dont l'introduction sera nécessaire pour résoudre ces problèmes et enfin à effectuer une première définition d'un appareil correspondant aux demandes escomptées du marché.

- Des études de marché civil, basées sur l'utilisation d'un modèle très sophistiqué (la "DYNAMIQUE DES SYSTEMES") permettent de décrire les marchés aéronautiques comme le résultat d'une situation économique dans une zone homogène, décrite par une modélisation macro-économique.

Ces travaux ont permis d'effectuer une segmentation géographique, par taille d'appareils et par type de missions pour le marché mondial.

Des études de sensibilité ont été effectuées qui ont montré l'influence du Direct Operating Cost (DOC) pour l'opération du prix du billet en fonction du temps gagné par le voyageur enfin des infrastructures au niveau de réseau de transport.

- Enfin, des travaux relatifs aux infrastructures au système de contrôle aérien, et à la réglementation opérationnelle ou liée à la certification de l'appareil ont permis d'évaluer les composants du système de transport dont l'établissement sera nécessaire pour utiliser le convertible (et les autres appareils à décollage vertical) de façon optimisée. Une utilisation rationnelle de ces différents appareils (y compris l'hélicoptère) sous des conditions de rentabilité d'environnement et de sécurité acceptables, nécessitera une réforme du système de contrôle aérien actuel adapté à l'utilisation IFR des avions mais pas des hélicoptères.

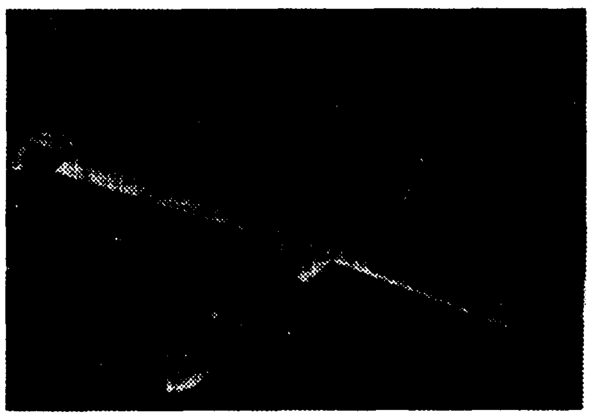
Les spécifications de mission assignées au Baseline Aircraft correspondait à :

- 30 passagers + 3 membres d'équipage
- Vitesse : 300 Kts mini
- Distance franchissable : 600 Nm
- Altitude de croisière : 7500 m
- Satisfaction des exigences de la catégorie A (Principalement panne d'un moteur au décollage).

Le convertible est capable de satisfaire à de telles spécifications du fait :

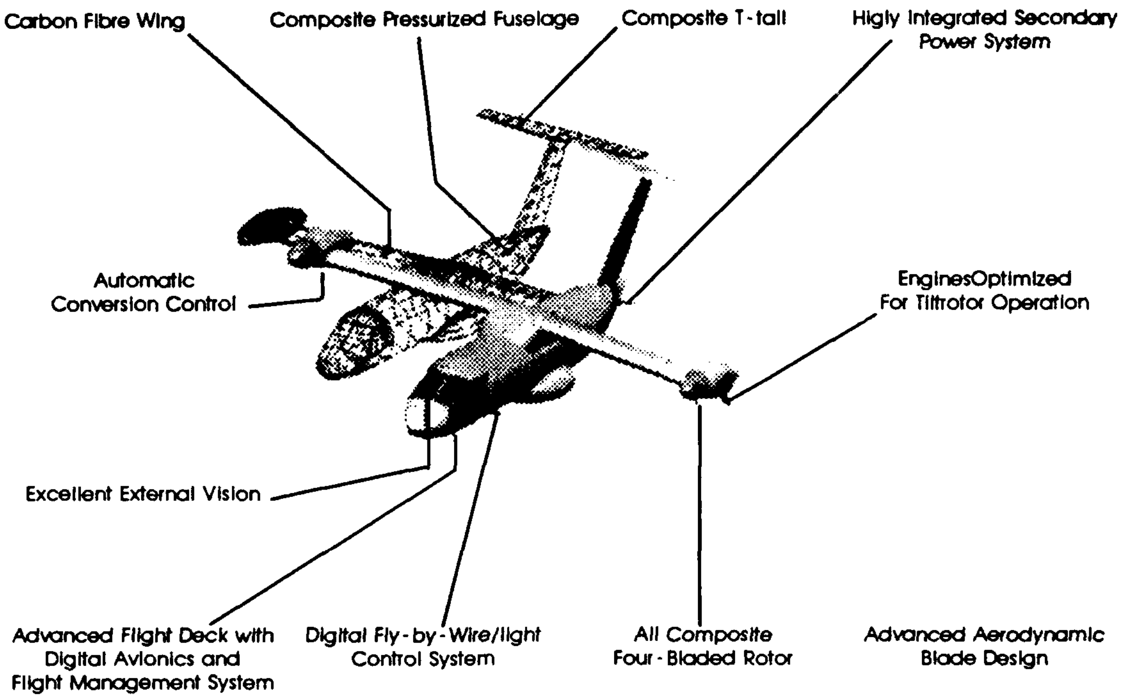
- de sa charge en disque modérée (69 kg/m2 pour EUROFAR) lui assurant des performances honorables au décollage, en stationnaire, et en mode hélicoptère (nacelles verticale).
- de son système de commande cyclique sur les rotors lui assurant des qualités de vol et de pilotabilité identiques à celle de l'hélicoptère, y compris lors de la transition.
- de sa traînée (intermédiaire entre celle de l'avion et du meilleur hélicoptère) lui procurant une haute vitesse de croisière, compte tenu de la puissance installée (335 kts pour EUROFAR à 7500 m).

L'avant projet a conduit à la définition d'un appareil de 13,6 T, 20,4 m de long, ayant des rotors de 11,2 m de diamètre. L'architecture correspond à un appareil à aile haute et dièdre avant empennage en T.



La technologie Européenne la plus avancée a été introduite sur cet appareil avec :

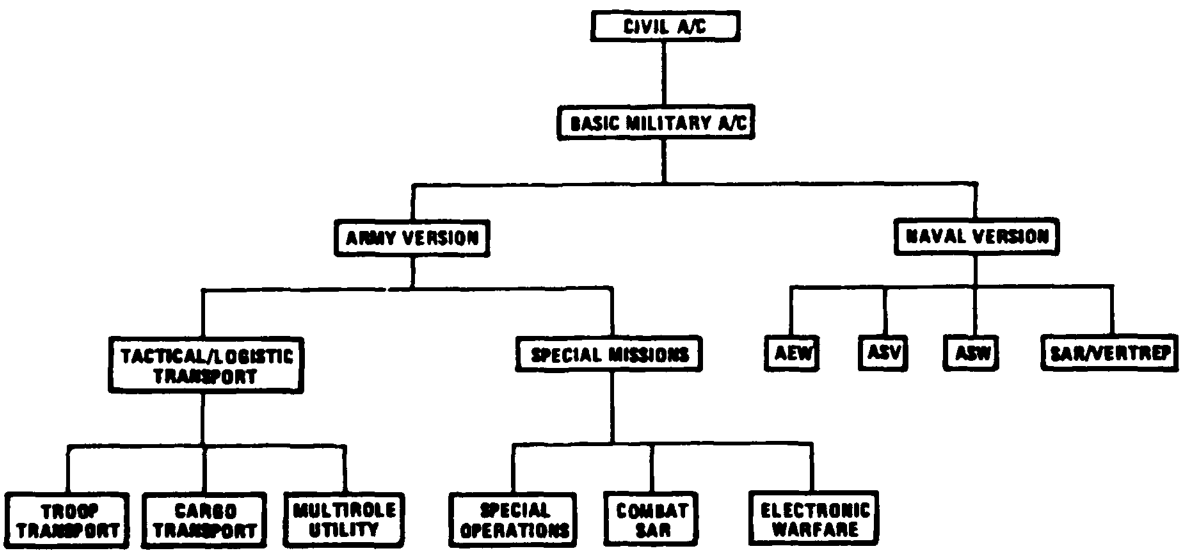
- un fuselage composite carbone-époxy pressurisé
- des commandes de vol optiques quadruplex
- un moyeu en balancier avec transmission du couple par une pièce en composite.
- des pales en composite munies de profils à haute performance.
- un cockpit avancé avec minimanches et présentation des informations par écran.




Cette définition a été confortée par d'importantes campagnes expérimentales qui ont comporté :

- des essais aérodynamiques en soufflerie sur une maquette modulaire au 1/10 (ajustée).
- l'essai aérodynamique dynamique et acoustique d'un rotor isolé (échelle 1/2.7) au banc en stationnaire (Marignane) et en conversion et croisière (soufflerie S1 Modane de l'ONERA).
- Des essais aérostatiques en soufflerie sur un ensemble aile + nacelle + rotor (WESTLAND)
- l'essai au sol d'un tronçon échelle 1 de fuselage composite (Ajustée).
- Des campagnes de simulations pilotées sur le simulateur Epopée de l'Aérospatiale Toulouse qui ont permis de conforter les lois de pilotage et d'évaluer les capacités de l'appareil (pilotes civil et militaire).

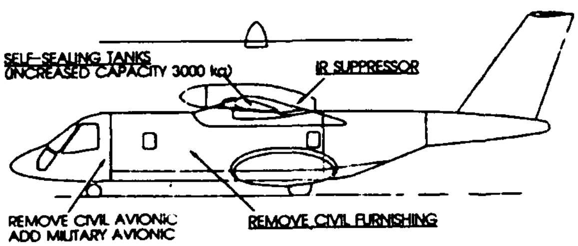
Enfin, ces études de caractère civil ont été complétées par la définition d'une famille de dérivés militaire basés sur l'appareil civil.



## 3 LES APPLICATIONS MILITAIRES D'EUROFAR

Comme cela a été souligné le projet EUROFAR est sous-tendu par une utilisation civile. Mais il est apparu très rapidement au responsable du programme que la reflexion et l'étude devaient être élargis aux besoins militaires pour des raisons évidentes touchant à l'étendue des marchés.
En l'absence d'expression des besoins de la part des armées européennes, les experts militaires ont tenté dressé le catalogue des capacité d'un convertible militaire dérivé d'EUROFAR pour le soumettre aux Etats Majors afin que ceux ci y recherchent des solutions aux problèmes que l'utilisation géostratégique leur pose. Dans l'esprit de tous, industriels et Etats Majors, il ne s'agissait pas de proposer un produit remplaçant l'hélicoptère et l'avion mais de stimuler les réflexions des utilisateurs avec un moyen disposant de capacités nouvelles.
Les principales caractéristiques de la version militaire d'EUROFAR, dérivée de la version civile sont les suivantes :

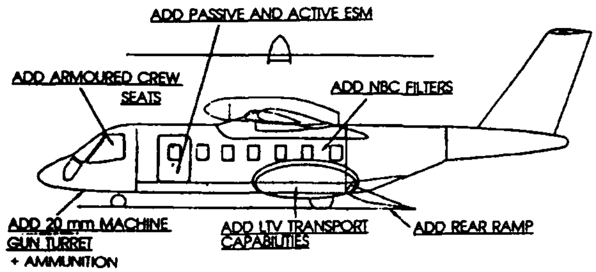
- Masse maximale : 15000 kg
- Longueur : 20 m
- Envergure : 14,7 m
- Diamètre rotor : 11,21 m
- Vitesse de croisière : 335 kts
- Charge utile maximale : 4500 kg
- Charge utile à distance maximale franchissable (30 mn de réserve) : 3300 kg pour 1360 km soit 30 militaires équipés.
- Consommation spécifique de fuel (à 300 kts et 6000 m) : 0,85 kg/km .



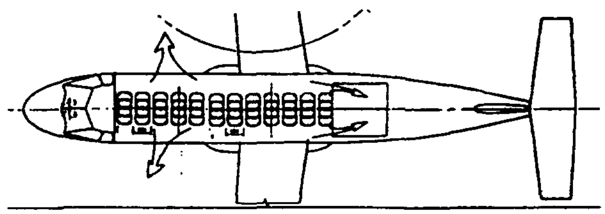

*VERSION MILITAIRE BASIQUE*

La militarisation de sa version terrestre a été prise en compte en particulier grâce à des sièges blindés pour l'équipage, des sièges troupes anti-crash des contres mesures actives et passives ainsi qu'un armement 20 mm en tourelle.

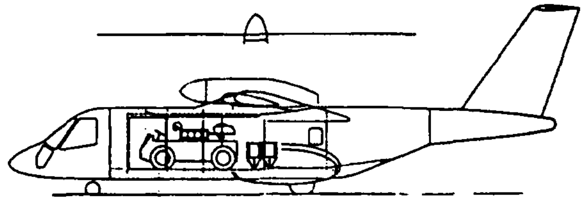
Les aménagements intérieurs permettent le transport de 30 commandos équipés ou d'un véhicule aéromobile chargé par la rampe arrière ou l'évacuation de 12 blessés couchés et médicalement assistés.



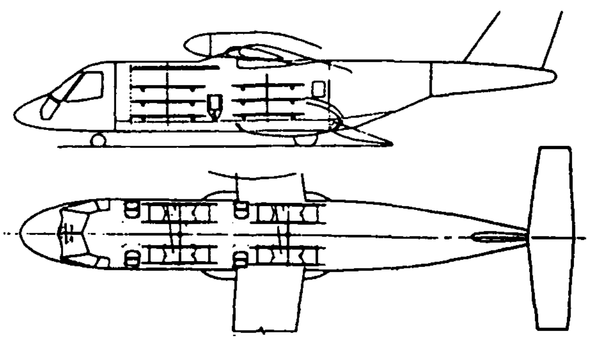

*VERSION ARMEE*



*AMENAGAMENT INTERIEUR : TRANSPORT DE TROUPE*

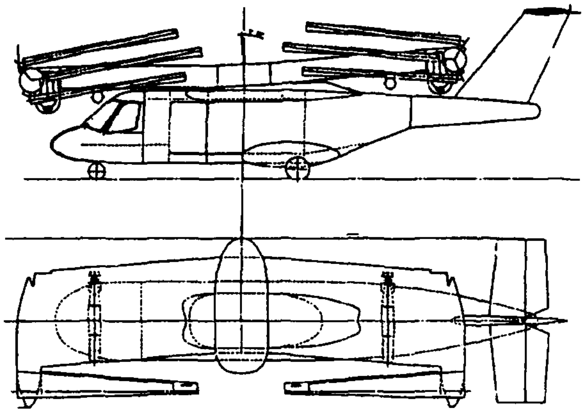


*AMENAGAMENT INTERIEUR : CARGO*



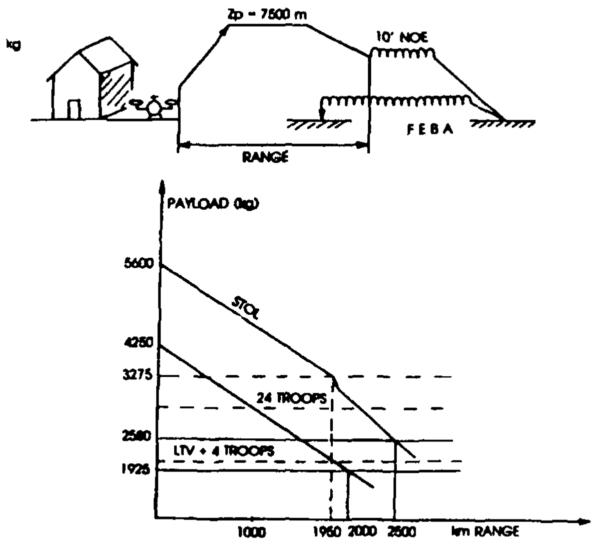
*AMENAGAMENT INTERIEUR : INSTALLATION SANITAIRE*

Une version navale pourrait être dotée d'un repliage automatique.



*VERSION MARINE : REPLIAGE AUTOMATIQUE*

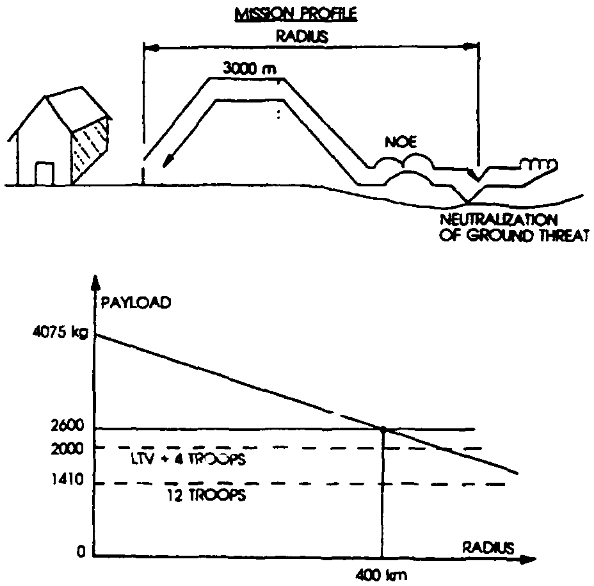
Dans ces conditions les missions types suivantes peuvent être réalisées :
- transport d'un véhicule et 4 hommes à 2000 km avec décollage vertical
- transport de 24 hommes équipés à 2000 km avec décollage roulé et 10 mm de vol statique à l'arrivée.




*MISSION TRANSPORT*

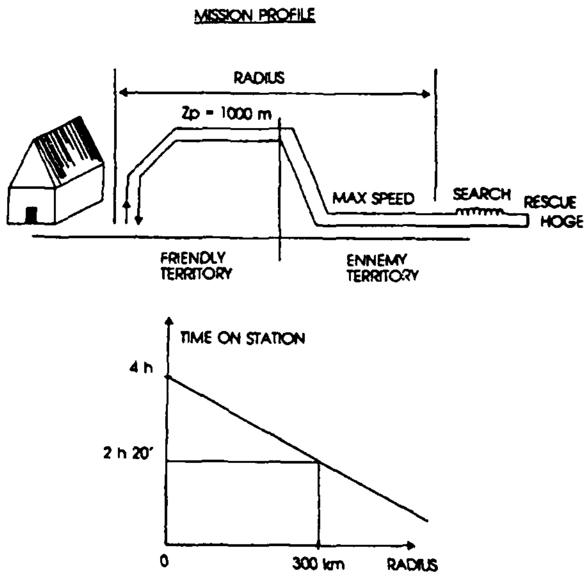
Pénétration de 12 commandos sur plus de 400 km à basse altitude et retour.

Des missions utilisant l'endurance d'EUROFAR ont également été examinées.




*OPERATIONS SPECIALES*

Par exemple la mission combat SAR permet une pénétration de plus de 310 km à basse altitude. 2h20 d'endurance sur zone et le retour après sauvetage de 5 personnes en utilisant un équipage de 3 (2 pilotes et un assistant médical).




*COMBAT SAR*

D'autres missions sont relatives à la guerre électronique et aux opérations navales.

Les Etats Majors Européens ont marqué de l'intérêt pour les capacités nouvelles apportées par le convertible même si les contraintes budgétaires ne permettent pas de les concrétiser.

## CONCLUSION

Cette présentation des capacités du convertible EUROFAR, était focalisée sur les missions militaires. Il est admis que les besoins futurs dépassent ce seul cadre. L'encombrement de l'espace aérien, l'offshore lointain imposent de nouvelles missions que le convertible pourra assurer à condition de mettre en oeuvre des procédures garantissant à la fois la sécurité des biens et des personnes et la protection de l'environnement.

A condition également d'affiner l'approche économique et de consolider la rentabilité du convertible. Une part importante de la phase 2 d'EUROFAR est dévolue à cette démonstration.

# UTILISATION DES METHODES DE CALCUL POUR OPTIMISER L'INSTALLATION MOTRICE DES AVIONS DE TRANSPORT

X.MONTHUS
Ph. COLIN
Ph. MOGILKA
A. MOLBAY-ARSAN

**AEROSPATIALE-AVIONS**
Aérodynamique de Conception - Département Aérodynamique
Bâtiment M01 - B.P. M0142/3
316 Route de Bayonne
31060 TOULOUSE Cedex 03
FRANCE

## RESUME

Dans le cadre des programmes **AIRBUS**, le service Aérodynamique de Conception d'**AEROSPATIALE-AVIONS** a pour responsabilités la définition de la forme aérodynamique du mat-réacteur, la définition de l'entrée d'air (ou l'évaluation technique de celle fournie par le motoriste) et l'optimisation aérodynamique de l'installation motrice dans son ensemble, c'est-à-dire la minimisation des effets (perte de portance ; surcroît de trainée) dus à l'interaction voilure/mat/nacelle. Cet article passe en revue les différents outils dont dispose le service pour mener à bien sa mission, à savoir le système de C.A.O. spécialement développé pour la conception aérodynamique, le mailleur et son environnement, et les principaux codes de calcul 3D pouvant traiter des configurations géométriques complexes. Trois applications récentes de ces méthodes dans le cadre du développement des avions **AIRBUS A330/A340** et de leurs dérivés sont exposées :

- Ecoulement dans la zone de l'intersection mat/voilure.
- Effet de taille du moteur par rapport à une voilure donnée et modelisation de l'effet de jet.
- Orientation du vecteur poussée du moteur par rapport à l'avion.

## NOTATIONS

| | |
|---|---|
| a | incidence |
| $a_{vp}$ | angle du vecteur poussée |
| Cp | coefficient de pression |
| M | nombre de Mach |
| Mmo | nombre de Mach maximum autorisé en opérations |
| Md | nombre de Mach maxi en piqué |
| Vc | vitesse calibré ( calibrated airspeed ; CAS ) |
| x/c | position sur une section de voilure (en % de corde c) |
| y | position d'une section de voilure en envergure |
| θ | angle de la section résultat sur le capot fan |

## INTRODUCTION

Dans le cadre des programmes AIRBUS, le service Aérodynamique de Conception d'AEROSPATIALE-AVIONS a pour responsabilités :

- la définition de la forme aérodynamique du mat-réacteur
- la définition de l'entrée d'air (ou l'évaluation technique de celle fournie par le motoriste)
- l'optimisation aérodynamique de l'installation motrice dans son ensemble, c'est-à-dire la minimisation des effets (perte de portance, surcroît de traînée) dus à l'interaction voilure/mat/nacelle (fig.1).

La conception aérodynamique comprend plusieurs étapes :

- conception des formes dans un système de C.A.O.
- maillage surfacique et volumique de ces formes
- analyse par codes CFD 3D de ces formes
- essais en soufflerie
- essais en vol

Ces étapes sont reliées par un processus itératif décrit sur la fig.2.

Dans un premier temps, nous passerons en revue les différents outils dont dispose le service pour mener à bien sa mission, à savoir le système de C.A.O. spécialement développé pour la conception aérodynamique (MICA2), le mailleur ICEM-DDN et son environnement, et les principaux codes de calcul 3D pouvant traiter des configurations géométriques complexes comme un ensemble voilure/mat/nacelle : FP3D (singularités), EFTAS (potentiel complet), SESAME (Euler) puis nous nous intéresserons à trois applications récentes de ces méthodes dans le cadre du développement des avions AIRBUS A330/A340 et de leurs dérivés :

- Ecoulement dans la zone de l'intersection mat/voilure.
- Effet de taille du moteur par rapport à une voilure donnée et modélisation de l'effet de jet.
- Orientation du vecteur poussée du moteur par rapport à l'avion.

Ces trois types d'application permettront des comparaisons des méthodes aux essais en soufflerie et parfois même aux essais en vol (pour l'A340).

## 1. METHODES DE CONCEPTION

### 1.1. Le système de géométrie MICA2

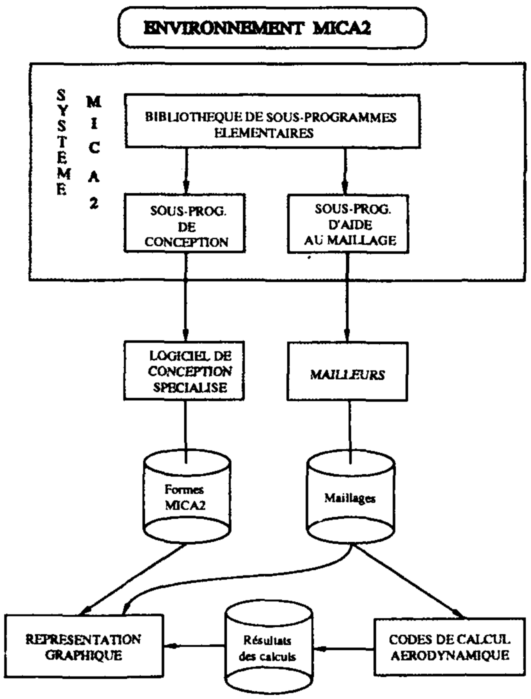
Pour assurer une parfaite cohérence entre l'environnement C.A.O. et les contraintes géométriques liées au caractère aérodynamique des formes à réaliser (continuité à l'ordre 1 et parfois 2, maîtrise des courbures, contrôle des oscillations), le groupe conception du service Aérodynamique de Conception d'Aerospatiale Toulouse a conçu son produit, le système de géométrie MICA2 (Moyens Informatiques pour la Conception Aérodynamique). Cet outil permet la génération des formes géométriques complexes, leur manipulation, l'évaluation de leurs caractéristiques et performances aérodynamiques, le traitement graphique. Ecrit en Fortran, ce système très modulaire est basé sur un mode de représentation des formes géométriques par des fonctions polynômiales biparamétrées. Ces différentes opérations sont réalisées via l'utilisation de sous-programmes que l'on peut classer en trois grands groupes : (fig. 3)

- <u>les sous-programmes de base</u> permettant d'accéder à des informations, de se positionner dans un fichier de formes géométriques, de réaliser des interpolations, des intersections entre tout type d'entités, de disposer d'utilitaires effectuant des calculs de longueurs, d'aires, de distances, de courbures etc...

- <u>les sous-programmes de conception</u> de formes, courbes 2D, 3D, surfaces, prenant en compte les contraintes de tangence et de courbure

- <u>les sous-programmes d'aide au maillage surfacique (calcul par méthode des singularités )</u>

Les formes géométriques et les maillages réalisés à l'aide de MICA2 sont stockés dans des bases de données dans lesquelles sont puisés les cas d'essai de la présente étude (cf. organigramme général du système MICA2, ci-dessous).




Organigramme général du système de géométrie MICA2

## 1.2. La génération de maillage de configurations complexes

Pour la génération des maillages volumiques requis par les solveurs avancés (potentiel complet ou Euler), Aerospatiale Avions dispose d'un environnement de maillage moderne basé sur la technique multibloc structuré, développé en coopération avec Control Data Corporation et fonctionnant en interactif sur station de travail [1].

Le maillage d'une géométrie débute par la définition d'une topologie : décomposition du domaine de calcul en blocs élémentaires connectés les uns au autres, découpage de chaque face de bloc en sous faces délimitées par un ensemble d'arètes. La décomposition en sous faces permet une plus grande souplesse dans la définition des raccords entre blocs et la particularisation de certaines parties de la géométrie (par exemple pour la définition des conditions aux limites), ce qui conduit à une réduction significative du nombre total de domaines.

Une fois la topologie du maillage définie, les arètes sont discrétisées en choisissant le type de distribution (linéaire, exponentiel...) et le nombre de points. L'architecture multidomaine structurée permet de ne fixer le nombre de nœuds que sur certaines arètes, ce nombre étant calculé automatiquement pour les autres. Les sous faces puis l'intérieur des domaines sont enfin maillés par interpolation transfinie. Le respect des formes géométriques est assuré par l'association à chaque sous face située sur la peau de la configuration, d'un ensemble de surfaces CAO sur lesquels les points de maillage de cette dernière sont projetés (fig.4).

Des métriques contrôlant la qualité des maillages sont ensuite systématiquement calculées et visualisées. Cette analyse peut alors conduire au remaillage d'un ou plusieurs blocs, ou, dans les cas les plus sévères, à une optimisation locale du maillage [2].

En phase de conception, il est courant de devoir effectuer des calculs sur un grand nombre de géométries voisines. Afin de réduire le temps de génération des maillages correspondants, on utilise la démarche suivante : toutes les opérations nécessaires à la fabrication du maillage de la première configuration sont enregistrées dans un fichier de commandes ; pour les configurations suivantes, ces opérations sont rejouées automatiquement à partir des nouvelles formes CAO. Cette technique permet d'effectuer le cycle complet maillage calcul en 2 ou 3 jours.

Afin de simplifier l'utilisation des codes de calcul, les fichiers de sortie des outils de maillage contiennent non seulement les coordonnées des points, mais aussi une description complète de la topologie utilisée, ainsi que des conditions aux limites à appliquer sur les différentes sous faces. Des interfaces permettent alors de générer automatiquement les données spécifiques aux différents solveurs.

## 1.3. Les codes de calcul 3D pour l'installation motrice

### *1.3.1. Méthode de singularités surfaciques (FP3D)*

La méthode de singularités surfaciques FP3D (écoulements tridimensionnels de fluide parfait subcritique) est intensivement utilisée dans le département Aérodynamique depuis sa mise en service en Janvier 1987.

Dans cette méthode, le fluide est supposé non visqueux, irrotationnel et faiblement compressible (écoulement subcritique). On ne s'intéresse qu'à l'état stationnaire. Les surfaces des corps sont maillées en panneaux quadrilatéraux ou triangulaires. Chacun de ces panneaux peut prendre une forme "pentafacette" non plane, donnant une plus grande précision mais coûteuse en temps de calcul, ou bien une forme "monofacette" plane plus économique.

Les configurations traitées sont très variées : du tronçon de voilure à l'avion complet avec installation motrice, hypersustentateurs, trains d'atterrissage (fig. 5).

Le temps de calcul varie de quelques minutes à plusieurs heures CPU suivant la richesse du maillage et les options de calcul. Typiquement, un calcul avion standard (maillage de 5000 panneaux sur une demi-géométrie) nécessite une demi-heure.

L'utilisation de FP3D s'étend des calculs d'analyse et de conception préliminaires (installation motrice, voilures, avant-projets, ...) à la prédiction des données aérodynamiques de l'effet de sol, en passant par certains calculs de charges, pour des géométries de complexité variée.

Couplée avec d'autres méthodes, FP3D permet également les calculs de givrage, de simulation visqueuse par couplage fort de couche limite, d'optimisation de formes par minimisation sous contraintes (en cours), et de conception en mode inverse.

En dépit de la pauvreté de la modélisation physique de l'écoulement (pas de choc transsonique en particulier), ce type de méthode conservera toujours un intérêt fondamental dans un contexte industriel. Cet intérêt réside dans la simplicité et la rapidité de mise en oeuvre des calculs sur maillages surfaciques, qui autorise les balayages et la présélection de formes complexes inhérents à toute étude de conception préliminaire.

Même les progrès récents des méthodes transsoniques plus complexes, qui exigent en particulier de générer des maillages volumiques, ne remettent pas en cause ce constat mais renforcent la nécessité pour un tel code de singularités d'être souple, adaptable à tous types de problèmes nouveaux, et surtout facile d'utilisation et fiable.

### *1.3.2. Eléments Finis Transsonique AS (EFTAS)*

Pour le calcul d'écoulements transsoniques, Aerospatiale Avions utilise depuis 1985 le solveur EFTAS, entièrement développé en interne [3], [4]. Il résout l'équation du potentiel complet par une méthode de type éléments finis, en maillages non structurés. Un couplage faible avec un code de couche limite, introduit plus récemment, permet de simuler les effets visqueux du premier ordre.

EFTAS utilise une approximation trilinéaire isoparamétrique pour le potentiel, et constante par élément pour la densité. Pour les écoulements portants, une condition de Kutta-Joukowski est appliquée afin de prévenir tout contournement de bord de fuite : un saut de potentiel est imposé sur les sillages, de façon à assurer l'égalité des pressions intrados et extrados. Pour propager plus rapidement dans l'écoulement les effets des sauts de potentiel, et ainsi assurer une convergence plus rapide de la portance, on les intègre à la solution globale en les couplant avec des solutions tourbillonnaires élémentaires.

Pour palier aux difficultés numériques liées à l'apparition d'une poche supersonique dans l'écoulement, un terme de viscosité artificielle via un décentrage du flux de masse est ajouté. Cette viscosité artificielle s'est parfois avérée insuffisante pour garantir la convergence du schéma dans le cas d'écoulements "difficiles" en maillage fin. Un terme de décentrage amont supplémentaire est alors introduit dans les zones supersoniques. Ce terme stabilisateur, issu de l'interprétation "pseudo-instationnaire" de l'algorithme de résolution itératif, disparaît à convergence.

La plus grande robustesse qu'il procure au schéma permet également de diminuer la quantité de viscosité artificielle nécessaire à la convergence du calcul, et ainsi d'obtenir des résultats de meilleure qualité.

La résolution du système non linéaire ainsi obtenu est réalisée à l'aide d'une méthode itérative de point fixe, en figeant la densité à l'étape précédente. Lorsque le terme stabilisateur supplémentaire n'est pas utilisé, la matrice à inverser à chaque itération est symétrique et on utilise l'algorithme classique du gradient conjugué, pré-conditionné par décomposition incomplète de Cholesky. Par contre, la présence du terme de décentrage introduit une dissymétrie dans le système, qui est alors résolu par la méthode GMRES.

### *1.3.3. Méthode Euler (SESAME)*

Pour compléter sa gamme d'outils de calcul d'écoulements transsoniques, Aerospatiale Avions dispose également de solveurs Euler, comme le code SESAME, développé à l'ONERA.

Basé sur la technique des volumes finis en maillages multidomaines structurés, SESAME résout les équations d'Euler instationnaires à l'aide d'un schéma explicite de type Runge Kutta à quatre pas. Il existe en version 'cell vertex' [5] et, depuis peu, en version 'cell center' [6], version actuellement utilisée par Aerospatiale Avions.

Le schéma centré est stabilisé par l'ajout d'un terme de viscosité artificielle de type Turkel-Jameson. Cette viscosité, composée de termes du second et du quatrième ordre, est appliquée sélectivement à l'aide de senseurs de discontinuité.

La convergence du schéma est accélérée par l'emploi d'un pas de temps local et l'introduction d'une phase de "lissage implicite des résidus" qui permet d'augmenter le coefficient CFL jusqu'à des valeurs de l'ordre de dix.

Des conditions aux limites variées, basées sur la méthode des caractéristiques, permettent de traiter les configurations les plus diverses, et notamment les configurations motorisées où il faut simuler un débit entrant au niveau du plan fan, et des conditions génératrices particulières dans les tuyères.

## 2. TROIS EXEMPLES D'APPLICATION

Introduction : Problèmes généraux liés à l'installation motrice sous voilure

L'installation d'un mât et d'une nacelle sous une voilure provoque différents types de perturbations de l'écoulement autour de la voilure. Certaines de ces perturbations sont d'ordre global sur l'aérodynamique de l'avion complet, d'autres sont au départ des effets locaux propres à la zone de l'installation motrice mais peuvent en se dégradant entraîner des conséquences néfastes sur les performances globales de l'avion [7].

Les effets majeurs sont les suivants :

*** *Effet global sur la portance***
L'adjonction du mât et de la nacelle à la voilure modifie radicalement la forme des profils situés dans cette zone : il en résulte une forte dégradation de la portance locale autour du mât d'où une diminution du Cz global à iso-incidence (fig. 6). Pour récupérer la valeur de Cz qui est nécessaire à l'avion, cette perte de Cz devra être compensée par une augmentation d'incidence qui aura deux conséquences majeures :

. une traînée de compressibilité en hausse du fait de l'augmentation des charges sur certaines parties de la voilure (fig. 7),
. une traînée induite dégradée du fait de la nouvelle répartition de charge en envergure qui s'éloigne de la répartition elliptique optimale.

Il s'agit donc de concevoir un ensemble de formes (mât, nacelle, voilure) minimisant cette perte de Cz.

*** *Effet global de l'orientation de la poussée du moteur***
La poussée du moteur en vol peut se décomposer en 2 parties :

- une composante s'opposant à la traînée
- une composante s'ajoutant à la portance (fig. 8)

S'y ajoutent les effets aérodynamiques induits par la présence du jet qui peuvent eux-mêmes varier avec la direction de celui-ci.
On comprend alors pourquoi il est primordial de bien évaluer l'angle de ce vecteur poussée si on désire obtenir une bonne estimation des performances aérodynamiques de l'avion.

*** *Effet local du jet moteur sous la voilure***
La taille des moteurs augmentant sans cesse par rapport aux dimensions de la voilure sans pour autant que la garde au sol de l'avion complet ne puisse être sacrifiée, il en résulte que la nacelle (et de ce fait le jet d'air chaud sortant de la tuyère) est de plus en plus proche de l'intrados voilure (fig.9) : les répartitions de pression sur le tronçon de voilure autour du mat sont altérées.

*** *Effet local du contournement de l'intersection mat/voilure***
Le contournement par l'écoulement du côté interne du mât externe à l'intrados d'un avion quadrimoteur est un problème difficile car fortement tridimensionnel (fig. 10) du fait de plusieurs facteurs :

a) courbure élevée du bord d'attaque intrados du profil voilure situé contre le mât.
b) courbure élevée du bord d'attaque du mât
c) effet de coin du mât avec le dièdre de la voilure
d) situation au milieu de l'aile externe d'où :
  - profil voilure transsonique de faible épaisseur
  - fonctionnement à Cz local élevé

Il peut résulter de ce qui précède des survitesses très importantes à la jonction du mât et de l'intrados voilure en croisière et à fortiori à grand Mach et à faible Cz.

Nous allons maintenant examiner trois exemples où l'utilisation des méthodes de calcul décrites précédemment a permis une bonne estimation du comportement de l'installation motrice dans la réalité. Tout d'abord, nous verrons comment les calculs FP3D et EFTAS sur avion complet A340 ont permis de prédire et de corriger les problèmes de contournement de mât externe par des modifications locales de l'intrados voilure appelées plastrons. Puis, nous étudierons l'influence de la taille d'un moteur à grand taux de dilution et son effet de jet sur la voilure A340 à travers les calculs SESAME simulant le jet en sortie de tuyère. Enfin, nous nous intéresserons au calcul de l'orientation du vecteur poussée d'un moteur à grand taux de dilution par le code SESAME comparé aux essais du motoriste.

## 2.1. Ecoulement dans la zone de l'intersection mat/voilure

Dans le cadre de la mise au point de l'avion A340, un décollement à fort Mach et à faible Cz, localisé à l'intrados voilure, côté interne du mât externe, a provoqué sur l'avion des vibrations d'origine aéroélastique.

Nous présentons ici la synthèse des études menées à Aérospatiale pour remédier à ce problème. Ces études ont abouti à la conception de formes tridimensionnelles modifiant l'intrados voilure et se raccordant sur la paroi interne du mât externe. De part leurs caractéristiques, ces formes ont été appelées "plastrons de voilure".

### *2.1.1. Mise en évidence du phénomène aérodynamique*

Des essais en soufflerie et des calculs de simulation de l'écoulement ont montré des survitesses importantes à l'intersection entre le côté interne du mât externe et l'intrados voilure (fig. 11) à grand Mach et à faible Cz en frontière de domaine de vol.

Les principales causes de ce phénomène sont liées à la présence de l'installation motrice sur l' aile externe optimisée en aile lisse qui a la particularité d'avoir un profil cambré de faible rayon de bord d'attaque intrados favorisant la survitesse à faible Cz.

#### *2.1.1-a Essais en soufflerie*

Divers essais sur la configuration de base (avion n°1) se sont déroulés ces dernières années dans la soufflerie S1 de l'ONERA à Modane avec une demi-maquette A340 d'Aerospatiale et une maquette complète A340 de Deutsche Airbus Aerospace, ainsi que dans la soufflerie transsonique TWT (9 ft x 8 ft) de l'A.R.A. à Bedford avec une demi-maquette A340 de British Aerospace.

L'examen des répartitions de pression Cp=f(x/c) dans la section d'essai la plus proche du côté interne du mât pour une des maquettes confirme que l'installation motrice externe induit une forte survitesse à l'intrados à faible Cz (fig. 12 ).

Lorsque le Cz diminue encore, on constate que la survitesse augmente puis s'effondre, ce qui traduit l'apparition du décollement.

On met en évidence sur la configuration de base ces décollements avec des visualisations à l'huile :

- Mach=$M_{mo}$ et faible Cz : décollement naissant à l'intrados voilure, côté interne du mât externe ( x/c=5% ) se propageant sur l'intrados voilure (fig. 13)
- Cz de croisière : l'écoulement reste attaché (fig. 14 )

Lorsque l'on augmente le Cz de la maquette en dynamique par variation continue de l'incidence, on constate la brutalité avec laquelle l'écoulement recolle au passage d'un Cz critique.

Les essais montrent également qu'à Mach=$M_d$ et faible Cz le décollement est généralisé sur l'intrados entre le mat et le Flap Track Fairing.

#### *2.1.1-b Essais en vol*

Des visualisations par fil de laine lors des essais en vol de l'avion n°1 mettent en évidence la poche de décollement à l'intrados de la voilure. Des mesures de pression réalisées lors du même vol montrent :

a) des survitesses élevées à l'intrados voilure coté interne du mat externe (fig. 15 ),
b) le pic de survitesse présent à M=$M_{mo}$ au Cz de croisière s'effondre à faible Cz. Cette chute des pressions traduit l'apparition du décollement dans la section voisine du mât (fig. 16 ).

#### *2.1.1-c Calculs*

Ces survitesses au point de croisière sont mises en évidence par un calcul avec la méthode Eléments Finis Transsoniques Aérospatiale (EFTAS) tenant compte de l'effet de viscosité (hors décollement). La fig. 11 montre que les survitesses max à l'intrados se situent côté interne du mât externe. L'examen de tracés Cp=f(X/C) de 3 coupes dans la voilure voisines du mât (y= 16. ; 16.15 ; 16.32 m) révèle (fig. 17) :

a) une survitesse importante dans la section contre le mât (y=16.32m),
b) une atténuation très rapide en envergure de cette survitesse : elle disparait en 30 cm à l'échelle avion.

Le phénomène s'accentue à plus faible Cz : un calcul EFTAS au point où les problèmes apparaissent en vol montre dans la section la plus critique (y=16.32 m) une survitesse importante (pl. 18).

### *2.1.2. Conception du plastron de voilure "A1" (comparaison calculs / soufflerie / vol)*

#### *2.1.2-a Géométrie*

Pour remédier au problème précédent, l'Aérospatiale a proposé un carénage de voilure appelé "plastron". Il s'agit d'une surface réglée suivant l'axe y joignant la paroi côté interne du mât à l'intrados de la voilure. Ce plastron, défini et testé en soufflerie par Aérospatiale est appelé plastron A1. La forme en plan est donnée fig. 19 , 3 coupes en y (15.60 ; 16 ; 16.32 m) de l'ensemble plastron/voilure sont données fig. 20 et 3 coupes en x (10.8 ; 11 .4; 12.4 m) fig. 21. On note :

a) le bord d'attaque du plastron A1 consiste en une rampe faisant un angle de 5 à 6 degrés avec le profil de base ce qui a pour effet de réduire la courbure locale du profil et donc de diminuer les survitesses dues au contournement (fig. 20),
b) le plastron commence très tôt (x/c= 5 %) dans la section voisine du mât (y=16.32 m) de façon à ce que la réduction de courbure qu'il induit se produise au niveau de la survitesse max sur le profil à y=16.32 m (fig. 19),
c) le plastron s'étend dans la direction y (1 m à l'échelle avion) avec des pentes faibles de façon à réduire l'effet de coin entre le mât et le dièdre de la voilure (fig. 19 et 21),
d) le plastron s'étend jusqu'à la limite des volets dans la direction x (3 m à l'échelle avion ) afin d'avoir des pentes de rétreint suffisamment faibles et d'éviter de ce fait un décollement local sur la partie arrière (fig. 19 et 20).

#### *2.1.2-b Calculs*

La configuration avec plastron a été calculée avec le code EFTAS au point M=$M_{mo}$ à un $Cz_{croisière}$ ( fig. 22) et à un point de faible Cz (fig.23). Les répartitions de pression sur 3 coupes voisines du côté interne du mât montrent que le plastron A1 tend à réduire la survitesse au bord d'attaque intrados. L'effet est plus important au Cz de croisière qu'à faible Cz (fig.22 et 23).

*2.1.2-c Essais en soufflerie*

La configuration "avec plastron A1" a été testée à S1Ma par AS et à l'A.R.A. par BAe au cours des essais décrits au paragraphe 2-1-1-a. Dans les 2 cas on constate la disparition du décollement présent sur la configuration de base. Ce phénomène a été illustré à l'A.R.A. par des visualisations à l'huile de couleur (fig. 24 et 25) qui montrent pour les cas à grand Mach et faible Cz que le plastron A1 a pour effet de recoller l'écoulement à la jonction voilure/mât.

Les pesées globales effectuées sur les configurations avec et sans plastron à l'A.R.A. sont en bon accord avec celles réalisées par Aérospatiale à Modane. Le plastron a pour effet de réduire la zone décollée ce qui se traduit par rapport à la configuration de base par un gain $\Delta Cx$ d'autant plus fort que le Cz est faible.
L'effet du plastron A1 sur la portance reste faible.

*2.1.2-d Essais en vol*

Suite aux résultats des essais précédents, il a été décidé de tester le plastron en vol sur l'avion n°1. La forme a été réalisée sous forme de gabarits en bois dans les 2 sens x et y, collés à l'intrados de la voilure et remplis de mousse. La section la plus critique (y=16.32 m) contre le mât a été renforcée par une plaque de métal se terminant en biseau (fig.26). On remarque que le plastron A1 commence à la limite de la fente du bec n°4 (fig.26 haut).

Les essais en vol ont confirmé l'effet positif prédit par les essais en souffleries : on constate en présence du plastron A1 une suppression des vibrations aéroélastiques à faible Cz ce qui confirme que le décollement intermittent à la jonction voilure/mât a disparu.

Des prises de pression situées dans la section critique (y=16.32m) montrent que le pic de survitesse qui s'effondre sur la configuration de base se maintient en présence du plastron pour des Mach bien plus élevés et des Cz plus faibles.

A la suite de ces essais, l'avion n°1 a ouvert la totalité du domaine de vol et notamment le point le plus critique (M=0.93 / Vc=365 kts).

Le plastron A1 a été adopté comme solution de série sur les avions A340-200 et -300.

*2.1.3. Améliorations potentielles du plastron A1 : les plastrons B et C (calculs)*

Si le plastron A1 résout en partie les problèmes de vibrations en supprimant le décollement, on constate en examinant les prises de pression en vol qu'il ne réduit que faiblement l'intensité de la survitesse, ce qu'indiquait le calcul EFTAS à faible Cz (fig. 23). Une nouvelle famille de plastrons a donc été envisagée dans le but d'obtenir :

a) un plastron robuste au décollement à faible Cz ce qui se traduit par une réduction de la survitesse au bord d'attaque intrados,
b) un plastron de taille réduite au maximum pour libérer l'accès de certaines trappes de visite de la voilure et limiter les problèmes d'industrialisation.

*2.1.3-a Plastron B*

Les calculs EFTAS et les pressions mesurées en vol montrent une survitesse max située entre 2 et 3 % de la corde à y=16.32 m alors que le plastron A1 ne commence qu'à x/c=5 %. La modification de courbure induite par A1 est donc trop tardive, ce qui peut expliquer la faible réduction de la survitesse intrados.

Le plastron B possède les caractéristiques suivantes :

a) la trace sur la voilure est plus avancée que celle du plastron A1 (fig. 27) à 2.5 % de la corde à y=16.32 m : la courbure est réduite beaucoup plus tôt sur les sections de voilure (fig. 28),
b) dimension réduite en y (fig. 27),
c) génération réglée selon y.

Un calcul EFTAS au point critique montre que la survitesse induite par le plastron B est fortement réduite dans les sections proches du mât, notamment à y=16.32 m par rapport au plastron A1 (fig 29).

*2.1.3-b Plastron C*

Le plastron B donne jusqu'à présent les meilleurs résultats mais a un encombrement équivalent au A1. On a cherché à réduire la taille du B tout en conservant son effet positif sur la survitesse. Le plastron C présente les caractéristiques suivantes :

a) même trace sur le mât que le B,
b) forme en plan identique au B entre le mât et y=16. m au bord d'attaque et au bord de fuite (fig. 30),
c) dimension réduite en y par troncature de la forme en plan du B à y=15.9 m (fig. 30),
d) génération réglée selon y : le profil à y=16.32 m reste proche du B ; les autres sont fortement modifiés (fig.31).

Le calcul EFTAS à faible Cz montre que :

a) la survitesse n'augmente pas dans la section la plus critique (y=16.32 m) malgré la forte réduction de taille du plastron (fig.32)
b) la situation se dégrade à y=16. m (fig. 32) ce qui est logique lorsque l'on constate qu'avec le plastron C, le profil à y=16. m est très peu modifié (fig. 31).

Le plastron C semble donc prometteur car il offre des performances supérieures au plastron A1 avec un encombrement réduit de moitié.

## 2.2. Moteur à très grand taux de dilution

*2.2.1. Effet de taille par rapport à un moteur classique*

L'étude et la réalisation des avions bi-moteurs gros porteurs demande le développement de moteurs de plus en plus puissants. De plus, le désir de réduire la consommation spécifique des moteurs pousse les motoristes à augmenter le taux de dilution. Ces deux paramètres conduisent à l'augmentation de la taille des moteurs et notamment celle des fans. Ceux-ci atteignent désormais 100 pouces pour les avions volant actuellement et plus de 120 pouces pour les avions en étude.

Les moteurs de ces appareils sont généralement fixés sous les ailes. La place disponible sous voilure est limitée. Par conséquent, l'augmentation de la taille des moteurs rend de plus en plus critique leur intégration. Celle-ci fait l'objet d'une étude poussée comprenant une partie expérimentale et une partie théorique menées de front.

L'objectif de cette partie de l'étude est de comparer l'impact sur l'avion de deux moteurs différents : l'un de la génération actuelle d'un diamètre fan approchant les 100 pouces, l'autre de la prochaine génération atteignant les 115 pouces de diamètre. Cette étude a été menée pour plusieurs positions différentes sous la voilure du moteur de grande taille. L'impact sur l'intégration motrice a été estimé en termes de traînée d'installation et de modification de répartition de pression à la surface de la voilure.

Un des problèmes dominant de ce genre d'installation est la garde au sol restante sous le moteur. Pour cela, le paramètre hauteur relative axe nacelle / repère voilure est particulièrement intéressant.

La figure 33 montre les différentes positions en Z du moteur à fort taux de dilution vis à vis du moteur actuel. La localisation la plus basse correspond à l'alignement des deux nacelles sur le même axe et constitue la position de base.

La figure 34 illustre les écarts de traînée d'installation observés d'une configuration à l'autre. Ces effets sont relativement faible en amplitude. Les perturbations (et par suite la traînée d'installation) augmentent avec la taille du moteur, l'optimisation de la position en z ne parvient pas à compenser ce surcroît de traînée par rapport à un moteur de taille moyenne.

Les figures 35 et 36 représentent les distributions de Kp autour de la voilure pour les différentes configurations de l'étude : aile lisse, moteur classique installé, moteur fort taux de dilution position de base, moteur fort taux de dilution position rapprochée et moteur fort taux de dilution position très rapprochée. Les sections instrumentées montrées encadrent le mât moteur. Le nombre de prise de pression varie d'une configuration à l'autre en fonction des incidents d'essai. Ceci peut modifier l'allure des tracés de façon importante sans pour autant correspondre à une réalité physique. Seuls les symboles pointés indiquent les prises opérantes. D'autre part, ces répartitions de Kp sont interprétées en l'absence d'effet de jet : les nacelles utilisées durant les essais sont des nacelles perméables. Enfin, le point d'essai indiqué correspond à un cas de vol en croisière.

A l'extrados de la voilure, l'augmentation de taille du moteur amplifie les phénomènes liés à une installation classique. Ainsi, la décroissance de la zone de grandes vitesses du bord d'attaque est amplifiée alors que le plateau de pression faisant suite est légèrement rehaussé. Ceci est d'autant plus vrai que le moteur est proche de la voilure.

A l'intrados les phénomènes sont plus complexes : l'installation d'un moteur de taille normale fait accélérer plus rapidement l'écoulement après le bord d'attaque du côté interne du mât pour ensuite recomprimer lentement jusqu'au niveau de pression de la voilure lisse. La mise en place d'un moteur de grande taille en position basse permet à l'écoulement d'accélérer plus lentement au bord d'attaque. La recompression qui suit est plus brutale mais le niveau final est identique.

Le rapprochement moteur / voilure ne modifie pas l'allure de la recompression. Par contre, l'accélération faisant suite au bord d'attaque est de plus en plus brutale du côté interne du mât. Du côté externe du mât, les phénomènes sont plus modérés. Leur impact va dans le sens logique : plus le moteur est petit ou éloigné, plus la répartition de Kp est proche de celle de la voilure lisse.

### 2.2.2. *Influence sur la voilure et effet de jet (comparaison calculs / soufflerie)*

La simulation numérique fournit un complément intéressant aux essais en soufflerie, pour l'étude aérodynamique de nouveaux concepts tels que l'intégration de moteurs à fort taux de dilution. En effet, les résultats expérimentaux sont limités de par la relative pauvreté de l'équipement des maquettes. Par le calcul, on accède aux grandeurs aérodynamiques en tout point de la surface de l'avion, mais également en tout point de l'espace. Par des visualisations appropriées, la compréhension de l'écoulement peut alors être grandement facilitée. Mais, avant d'en arriver là, il importe de bien valider le code d'analyse aérodynamique utilisé, ce que l'on se propose de faire dans ce paragraphe à l'aide de comparaisons calculs essais.

Les contraintes d'encombrement introduites par ces nouveaux moteurs conduisent à les placer plus près de la voilure. Cette proximité se traduit par une interaction aérodynamique plus forte, en particulier entre le jet issu du réacteur et la voilure. Il est donc essentiel de soigner la modélisation du jet, si l'on veut évaluer l'interaction de façon correcte.

La technique habituellement utilisée, dite de jet figé, consiste à représenter ce dernier par une surface solide sur laquelle on écrit une condition de glissement (fig. 37). Cette technique simple, bien adaptée au code EFTAS, conduit dans la plupart des cas à de bons résultats. Pour plus de réalisme, il est nécessaire de passer au modèle Euler. Celui ci permet de représenter la géométrie exacte des tuyères et d'y imposer des conditions génératrices représentatives du fonctionnement du moteur. Le jet se forme alors naturellement, il est capturé.

Ces deux techniques ont été comparées à l'aide du code SESAME sur la configuration bimoteur à fort taux de dilution, dont on a étudié les essais en soufflerie au paragraphe précédent. Les maillages utilisés pour cette comparaison (fig. 38 et 39), relativement grossiers mais homogènes, comportent respectivement 260000 et 270000 points sur le demi-avion. Le point de calcul choisi, Mach=0.82 a=1.65°, pour un régime TPS de 38000 tours/mn, correspond rigoureusement à l'un des point soufflerie.

Les figure 40 et 41 montre l'évolution du Cp sur quatre sections voilure situées de part et d'autre du mât, respectivement pour les essais et pour les deux calculs précédents.

On constate que le modèle jet capturé conduit à de bien meilleurs résultats :

a) Sur le côté interne du mât, à l'intrados, la technique jet figé produit un système de double accélération recompression, très marqué près du mât (y/b=0.231) mais s'étendant également assez loin vers l'emplanture (y/b=0.134). Ce comportement, qui n'est pas du tout mis en évidence par les essais, disparait en modèle jet capturé pour lequel on obtient un meilleur recoupement.
b) A l'intrados côté externe du mât, le figeage du jet se traduit par une surévaluation de la pression qui s'étend sur une zone allant du bord d'attaque jusqu'à environ 30% de corde (y/b=0.271). Là encore la capture du jet permet d'obtenir des résultats plus corrects.
c) Les niveaux de survitesse calculés sur l'extrados de la voilure sont enfin assez nettement plus proches des essais lorsque le jet est capturé.

Au vu de ces résultats, il apparaît que le choix d'une modélisation par jet figé n'est pas adapté pour cette configuration où l'interférence jet voilure est importante. La forme arbitraire que l'on donne au jet n'est pas suffisamment réaliste et conduit à une dégradation des résultats, comme on a pu le constater non seulement sur l'intrados mais aussi sur l'extrados de la voilure. Pour ce type de configuration, la capture du jet est préférable même si cela doit se traduire par une plus grande complexité dans la génération des maillages.

Les résultats de calcul montrés précédemment font encore apparaître certaines différences par rapport aux essais. Si certaines d'entres elles peuvent être attribuées à l'absence de modélisation des effets visqueux (voisinage du bord de fuite), d'autres semblent dues à la grossièreté des maillages utilisés (chocs lissés, niveau des plateaux de survitesse extrados trop faible). Pour le vérifier, un calcul en maillage fin a été effectué sur la configuration motorisée complète, pour les mêmes conditions de vol. Le nouveau maillage est constitué de 51 domaines pour un total de 1400000 points. La figure 42 en visualise la trace surfacique et donne une idée, par comparaison avec la figure 39, de l'étendue du raffinement qui a été opéré.

Le champ de pression obtenu est illustré par les figure 43 et 44. On note la forme particulière de la poche de survitesse sur l'extrados voilure au droit de l'intersection avec le mât. Le jet issu du réacteur est représenté par des lignes iso pression totale dans un plan de coupe horizontal. La planche 44 montre le champ de Mach sur le moteur et sur le mât. La trace du jet secondaire sur le mât, dont la frontière est matérialisée par une discontinuité de vitesse, met en évidence un système complexe de détentes et de recompressions successives, que l'on retrouve aussi sur le capot moteur. Le jet primaire, moins énergétique conduit à des Mach locaux plus faibles, insuffisants pour amorcer la tuyère.

Pour quantifier le gain apporté par le raffinement du maillage, on présente maintenant les répartitions de pression sur les quatre sections voilure déjà exploitées précédemment (fig. 45 et 46) :

a) Pour ce qui est de la capture des chocs sur l'extrados de la voilure, on obtient bien l'effet de raidissement escompté.
b) Le niveau de la survitesse extrados, s'il est encore un peu faible par rapport aux essais, est néanmoins grandement amélioré en maillage fin. En particulier le pic très local qui apparaît entre 0% et 10% de corde sur la section y/b=0.231 n'était qu'esquissé en maillage grossier. Il est maintenant beaucoup mieux capturé.

Ces améliorations ne se réduisent bien évidemment pas à la seule voilure. Pour s'en convaincre, on a tracé l'évolution du coefficient de pression sur trois sections du capot moteur sur lesquelles des résultats d'essais étaient également disponibles (fig. 47).

Les courbes obtenues en maillage fin sont beaucoup plus contrastées :

a) Le comportement en double détente recompression révélé par la courbe expérimentale θ=330° (il n'est pas visible sur la courbe θ=180° en raison d'un trop faible nombre de prises de pression), est bien reproduit en maillage fin, avec néanmoins un petit décalage par rapport aux essais, alors qu'il avait été complètement lissé en maillage grossier.
b) La légère inflexion qui apparaît dans la première détente pour θ=180° n'est de même obtenue qu'en maillage fin.
c) Pour θ=30°, la comparaison est moins bonne, mais l'allure générale de la courbe reste satisfaisante.

Ces calculs montrent l'intérêt du modèle Euler pour la simulation d'écoulements autour de configurations motorisées en forte interaction. Pour ce type de configurations, la technique par jet figé habituellement utilisée en potentiel complet montre en effet ses limites.

Ce modèle permet en outre, par une représentation réaliste des tuyères et des jets qui en sont issus, d'accéder à des grandeurs caractéristiques comme la poussée, ce qui ouvre la porte à des études d'intégration motrice fines comme on va le voir au paragraphe suivant.

## 2.3. Vecteur poussée

### *2.3.1. Intérêt de l'étude*

Des mesures sur banc au sol ont montré que certains moteurs délivraient une poussée dont le vecteur s'éloignait de l'axe nacelle de quelques degrés. Cette constatation a amené les gens à s'interroger sur l'effet de cette déviation sur l'avion (fig. 48) : est-ce pénalisant, et, si oui, de combien en terme de consommation spécifique.

Ces questions font appel à des analyses aérodynamiques et à des problèmes de performance moteur.

Notre étude a pour but de déterminer les tendances pouvant mener à une optimisation de l'angle du vecteur poussée pour des considérations uniquement aérodynamiques.

Pour cela, deux étapes ont été définies :

- La première consiste à étudier la nacelle isolée par analogie avec l'étude au banc d'altitude des motoristes. L'objectif de cette partie est de calculer l'écoulement interne des tuyères (répartition de Mach/pression, calcul des débits) et de déterminer par le calcul l'angle du vecteur poussée de la tuyère. Cette étape est complétée par une campagne d'essai d'étalonnage de différentes tuyères motorisées afin de pouvoir valider la prédiction par le calcul de l'angle du vecteur poussée des tuyères. Cette étude fait l'objet d'un développement dans cet article.
- La deuxième étape sera l'étude de la nacelle installée. Nous nous intéresserons à l'impact sur la circulation autour de la voilure au voisinage de la nacelle et l'effet de l'installation sur l'écoulement interne et le jet en sortie de tuyère. Cette étude fera l'objet de développements dans des articles ultérieurs.

### *2.3.2. Prédiction de l'orientation du vecteur poussée (comparaison calculs / soufflerie)*

L'orientation de la poussée d'une tuyère peut être évaluée à partir d'un résultat de simulation numérique de l'écoulement avec le code SESAME.

Par définition, la poussée conventionnelle d'une tuyère débouchant dans une atmosphère de pression statique ambiante $p_a$ est:

$$\vec{F} = \int_S (p-p_a)d\vec{S} + \rho(\vec{V}\cdot d\vec{S})\vec{V}$$

Elle comporte l'intégral, sur une surface S, de la quantité de mouvement à laquelle on enlève le terme [ $p_a dS$ ] pour prendre en compte l'effet de la pression ambiante sur les parois externes du moteur.

Pour avoir un bilan global de toutes les forces agissant sur les parois internes de la tuyère, cette intégration est effectuée à la section de sortie, pour chacune des trois composantes de la poussée. En système de coordonnées cartésiennes, on obtient

$$F_x = \int_{S_{sortie}} [(p-p_a)dS_x + \rho(udS_x+vdS_y+wdS_z)u]$$

$$F_y = \int_{S_{sortie}} [(p-p_a)dS_y + \rho(udS_x+vdS_y+wdS_z)v]$$

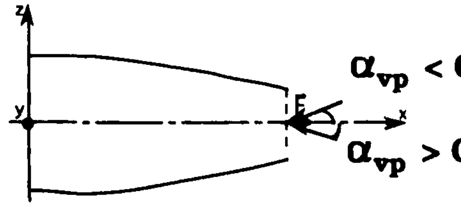
$$F_z = \int_{S_{sortie}} [(p-p_a)dS_z + \rho(udS_x+vdS_y+wdS_z)w]$$

Ces calculs sont effectués par un outil de post-traitement des résultats du code Sesame. Il détermine d'abord les points d'intersection entre le maillage et un plan de coupe, notamment le plan de sortie de la tuyère. Les variables, définies aux nœuds du maillage, sont transférées par interpolation aux points du plan d'intersection, et ensuite aux centres des cellules de ce plan. Il suffit alors de calculer la surface de chaque cellule pour évaluer les intégrales définissant les composantes de la poussée de la tuyère.

Par convention, la poussée est la force qui s'exerce sur la tuyère, et l'angle du vecteur poussée est donnée par rapport à l'axe du moteur. Si l'on considère que celui-ci correspond également à l'axe "x", l'angle du vecteur-poussée est alors calculé par :

$$\alpha_{vp} = -\tan^{-1}\left(\frac{F_z}{F_x}\right)$$

La figure ci-dessous illustre ces définitions.



Les écoulements autour de quatre différentes géométries de tuyère, également testées en soufflerie, ont été calculés avec le code Sesame. A partir de ces résultats, l'angle du vecteur-poussée $a_{vp}$ de chaque tuyère a pu être évalué et comparé aux résultats obtenus en soufflerie.

Les comparaisons pour ces quatre différentes géométries sont données dans le tableau suivant :

| géométrie | αvp calcul | αvp soufflerie |
|---|---|---|
| tuyère 1 | -0.566° | -0.7° |
| tuyère 2 | +3.272° | +3.5° |
| tuyère 3 | +4.348° | +4.4° |
| tuyère 4 | -6.061° | -6.15° |

La figure 49 représente, respectivement pour les tuyères 3 et 4, le champ de nombre de Mach sur une coupe verticale de la tuyère (un plan y=constante), passant par le mât interne. On observe que le jet de la tuyère 3 est orienté vers le bas, alors que celui de la tuyère 4 va dans le sens opposé.

On constate que le calcul à partir d'un résultat numérique et la mesure en soufflerie donnent des valeurs très proches pour l'angle du vecteur-poussée $a_{vp}$ de chacune des tuyères.

## CONCLUSION

L'utilisation des méthodes de calcul développées ces dernières années a permis au service Aérodynamique de Conception d'AEROSPATIALE-AVIONS de mener a bien les taches de conception qui lui sont dévolues au sein du programme AIRBUS A330/A340, notamment :

- L'optimisation de l'écoulement dans la zone d'intersection mat/voilure grâce au logiciel de C.A.O. MICA2 qui a permis de modéliser les formes de raccord dites "plastrons" et au code de calcul EFTAS qui a réussi à bien prédire le comportement des survitesses dans cette zone difficile, comme les essais en vol l'ont confirmé par la suite.

- L'effet de taille du moteur par rapport à la voilure et la modelisation de l'effet de jet par le programme SESAME.

- L'évaluation de l'orientation du vecteur poussée du moteur par rapport à l'avion pour une nacelle seule (SESAME).

La prochaine étape sera de calculer ce vecteur en présence non seulement de la nacelle, mais aussi du mat et de la voilure, ce qui permettra d'évaluer plus précisément l'impact sur les performances avion de l'orientation du vecteur poussée.

## BIBLIOGRAPHIE

[1] D. Bertin, J. Lordon, V. Moreux : *"A new automatic grid generation environment for CFD applications"*. AIAA-92-2720-CP, 10th AIAA applied aerodynamics conference, 1992

[2] O.P. Jacquotte, J. Cabello : *"A variational method for the optimization and adaptation of grids in computational fluid dynamics"*. Numerical grid generation in computational fluid dynamics '88. Edited by S.SENGUPTA et al

[3] Y. Vigneron, T. Lejal et R. Collercandy : *"Simulation d'écoulements par éléments finis"*. 6th international symposium on finite element methods in flow problems. Antibes, Juin 1986

[4] V. Moreux, D. Bertin et V. Rivoire : *"Simulation d'écoulements transoniques sur des géométries complexes d'avions de transport"*. à paraître dans la Recherche Aérospatiale, 1993

[5] V.Couaillier : *"Multigrid method for solving Euler and Navier Stokes equations in two and three dimensions"*. 8th GAMM conference on numerical methods in fluid dynamics, Delft September 27-29, 1989

[6] A.M. Vuillot, V.Couaillier, N.Liamis : *"3D turbomachinery Euler and Navier Stokes calculations with a multi-domain cell centered approach"*. 29th AIAA/SAE/ASME/ASEE joint propulsion conference, AIAA 93-2576

[7] J.L. Godard, O.P. Jacquotte et D. Gisquet : *"Detailed analysis of wing-nacelle interaction for civil transport aircraft"*. Symposium AGARD/FDP Fort Worth, TX (USA), October 7-10th, 1991.

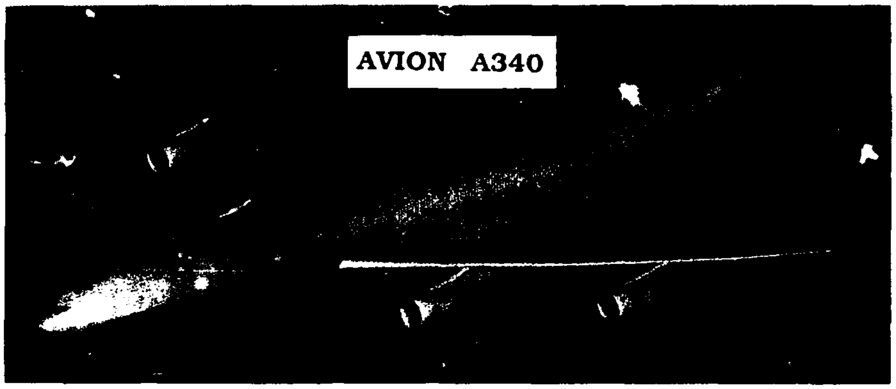



Figure 1

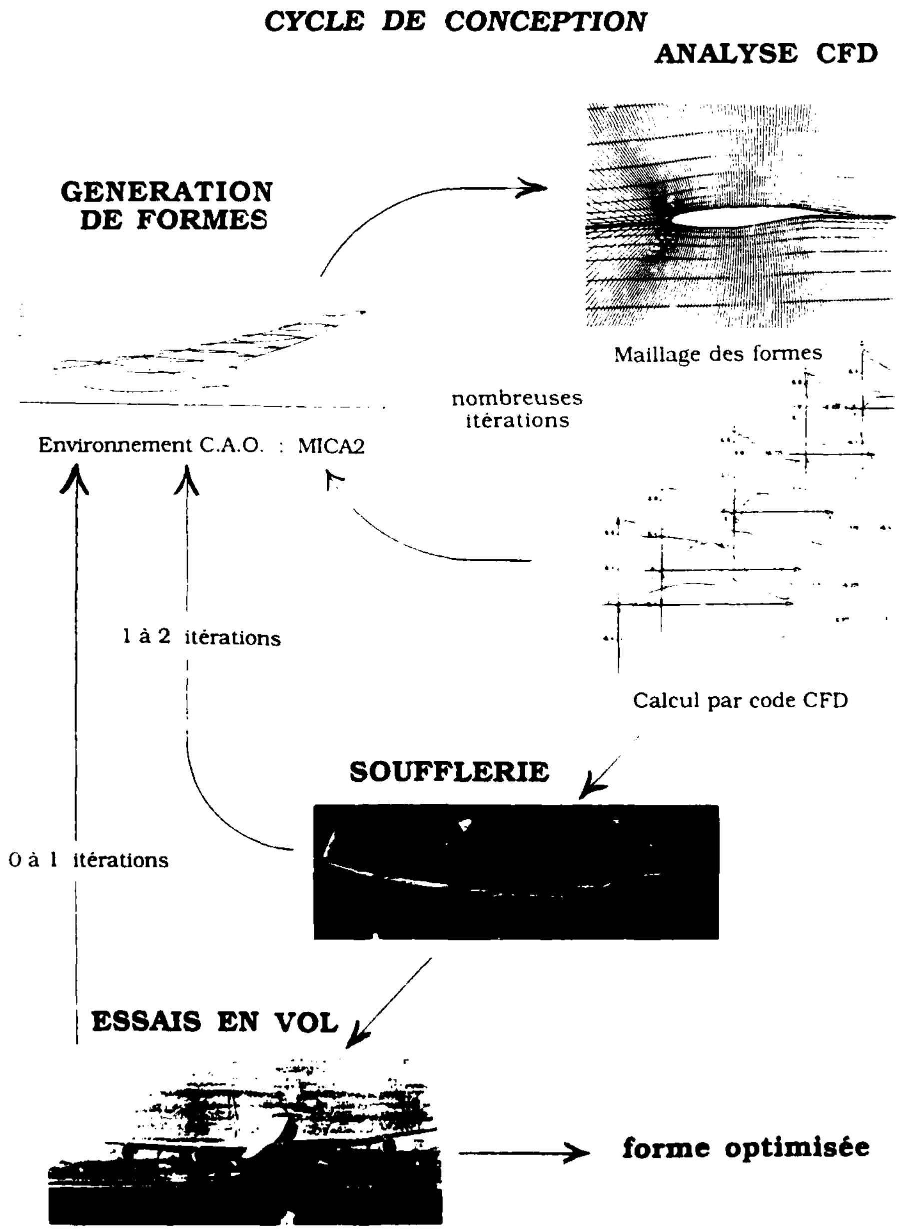



Figure 2

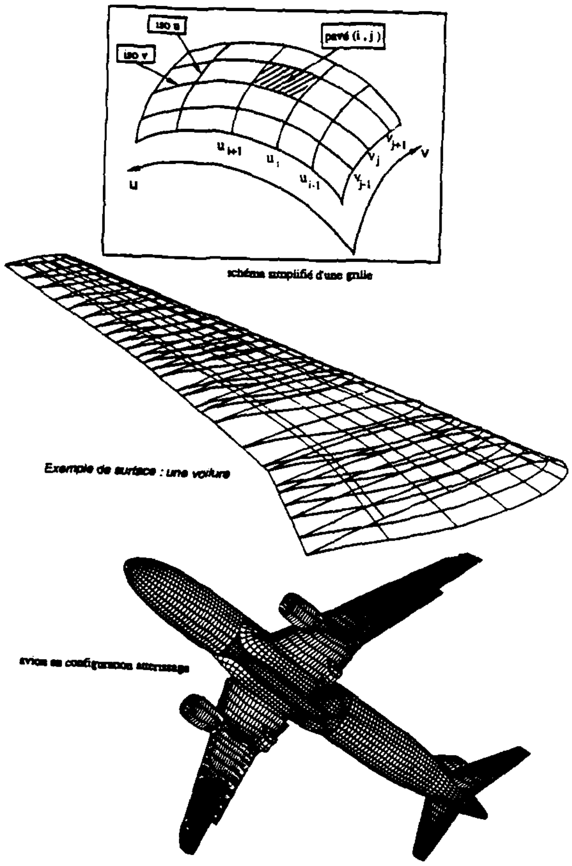



Figure 3

**MAILLAGE MULTI-BLOCS**
**AVION A340**
**(180 000 noeuds)**

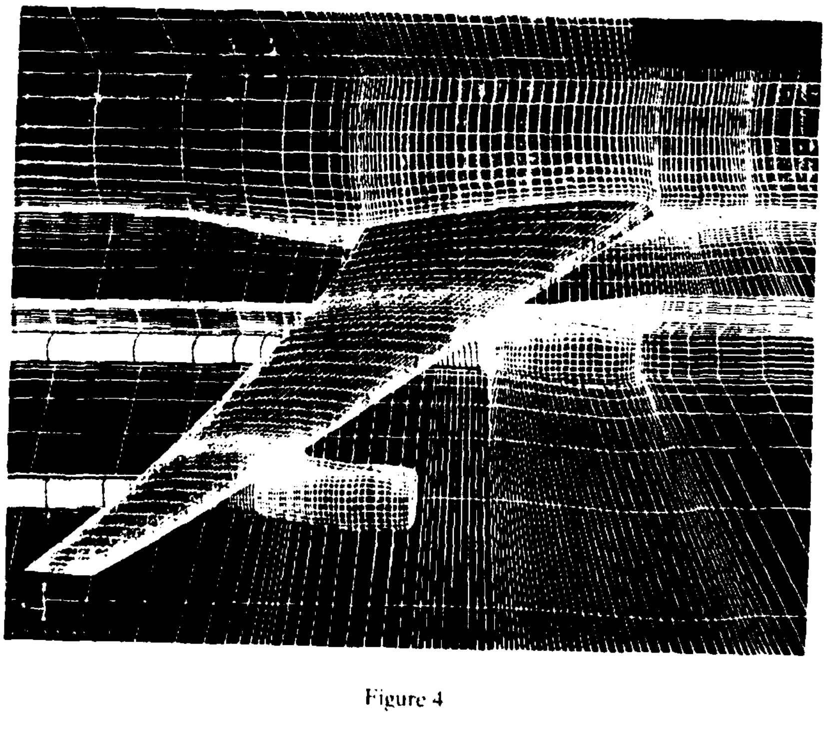
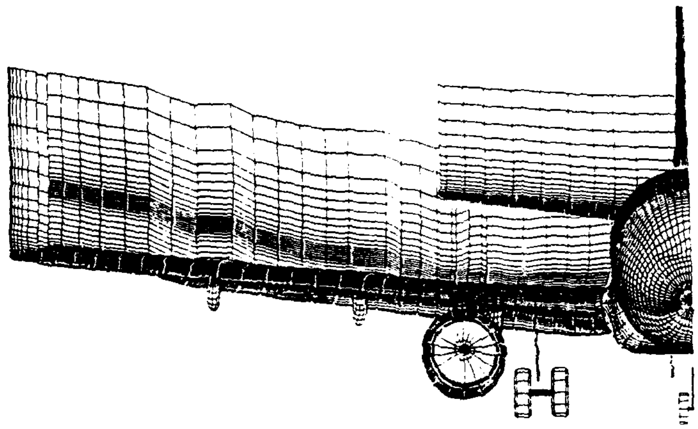


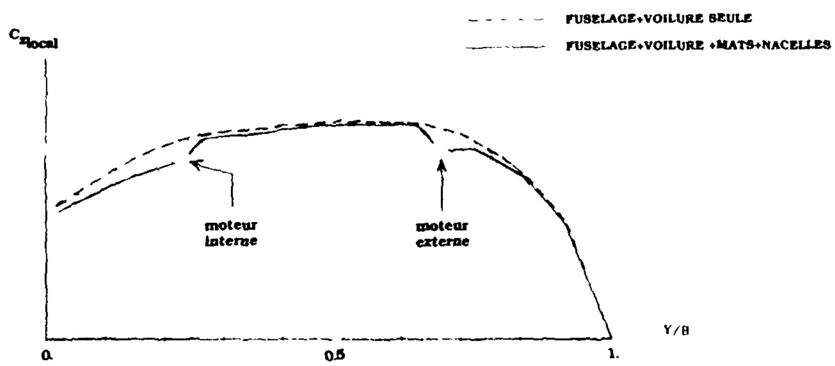
Figure 4



A320 - maillage surfacique + sillages tourbillonnaires

Figure 5

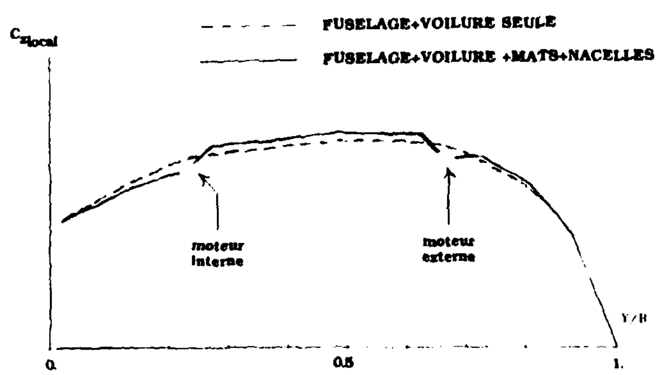
**LOI DE $CZ_{LOCAL}$ EN ENVERGURE POUR UN AVION QUADRIMOTEUR**




**COMPARAISON A ISO-INCIDENCE**

Figure 6

**LOI DE $CZ_{LOCAL}$ EN ENVERGURE POUR UN AVION QUADRIMOTEUR**




**COMPARAISON A ISO-CZ**

Figure 7

**ORIENTATION DU JET**
**A LA SORTIE DE LA TUYERE**

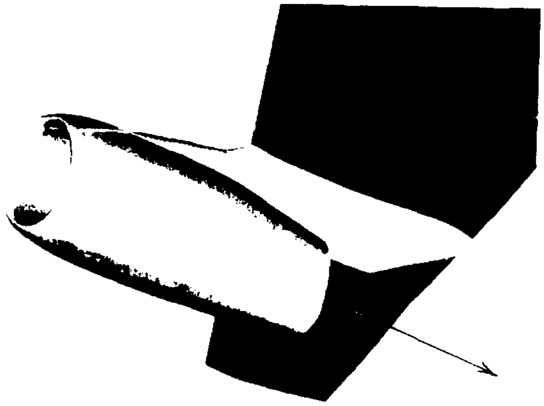


Figure 8

**POSITION DU JET PAR RAPPORT A LA VOILURE**

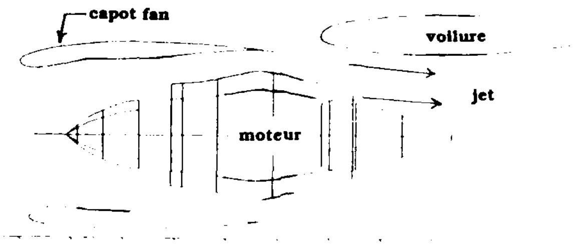



Figure 9

**CONTOURNEMENT DU MAT**

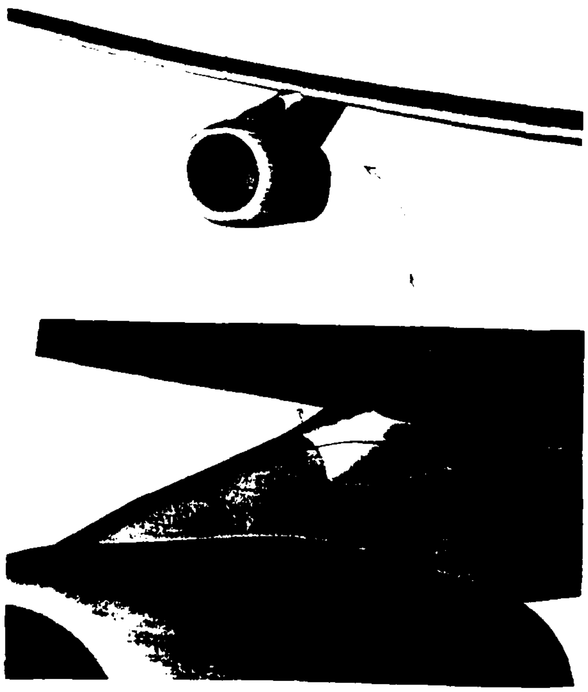


Figure 10

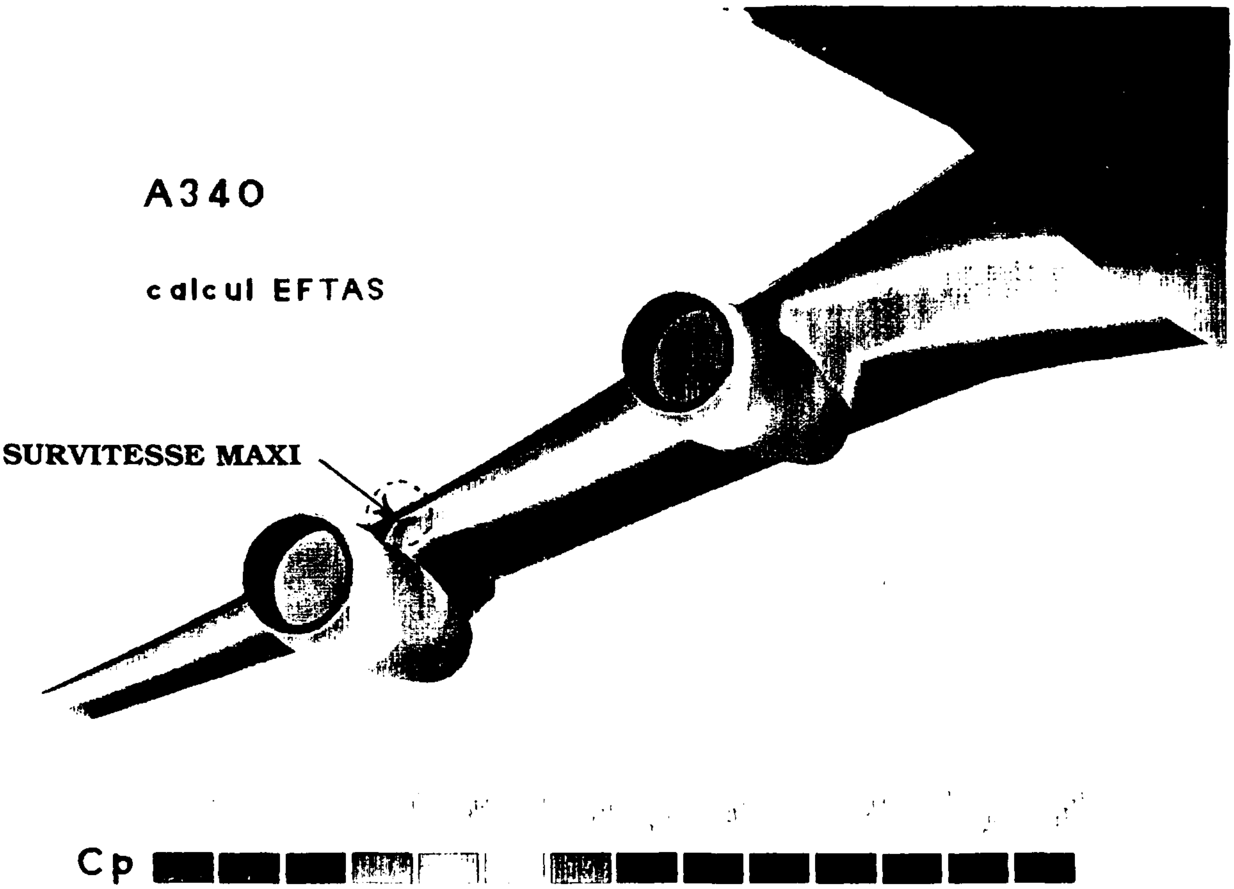
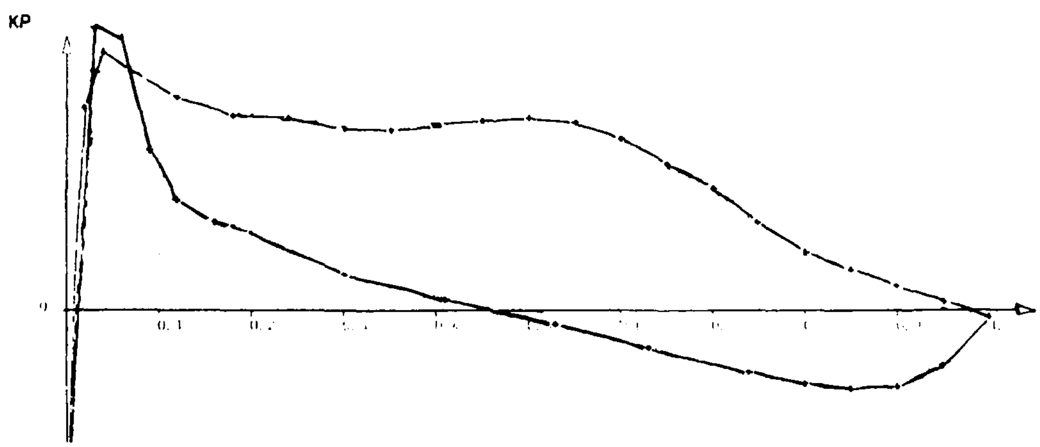



Figure 11

## ESSAIS SOUFFLERIE S1 (Modane, France)

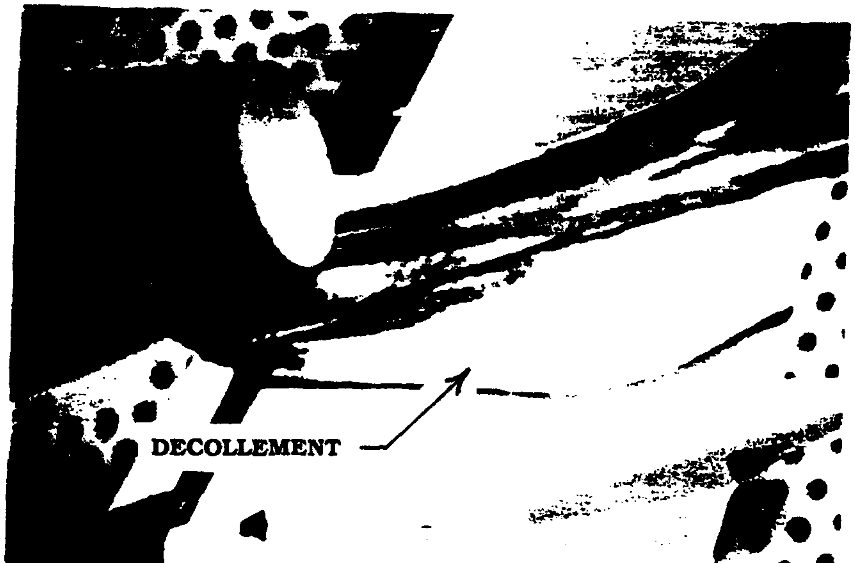



**section coté interne du mat externe**

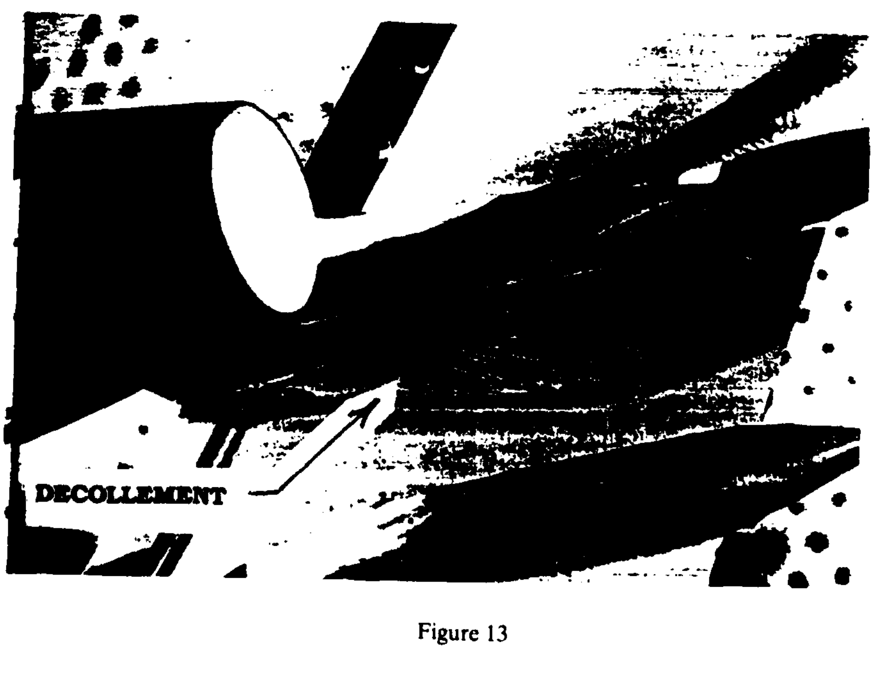
Figure 12

## ESSAIS SOUFFLERIE A.R.A. (Bedford, England)

**demi-maquette British Aerospace**




**visualisation à l'huile**




$C_Z$ décroissant

Figure 13

## ESSAIS SOUFFLERIE A.R.A. (Bedford, England)

**demi-maquette British Aerospace**

**visualisation à l'huile**

**CONFIGURATION DE BASE**
**(sans plastron)**

**$C_z$ croisière**

Figure 14

**ESSAIS EN VOL AVION n°1**

**section coté interne du mat externe**

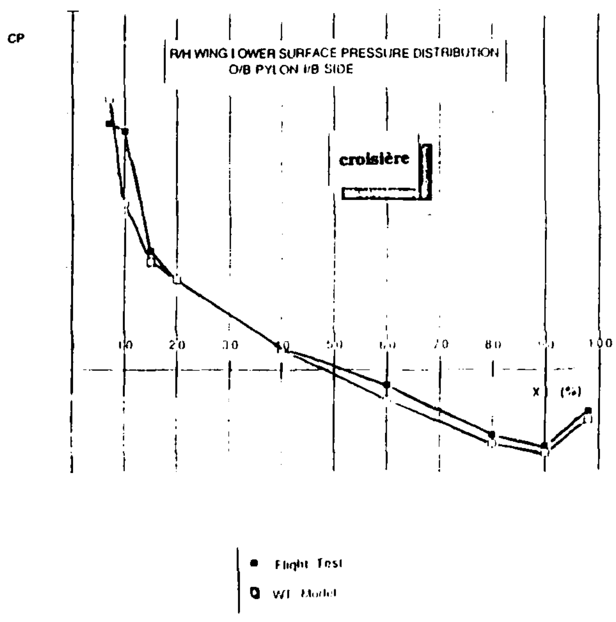



Figure 15

**ESSAIS EN VOL AVION n°1**

**section coté interne du mat externe**

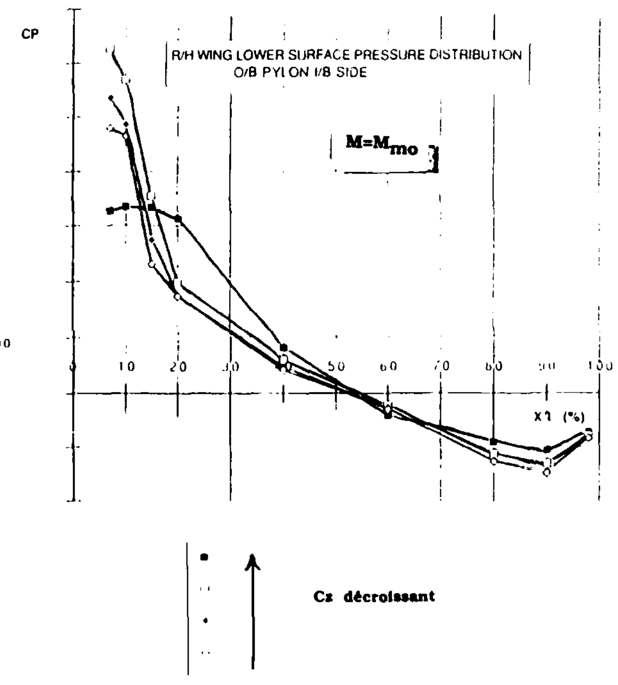



Figure 16

DATUM WING LOWER SURFACE PRESSURE DISTRIBUTION
M=Mmo Cz=Czcroisière
EFTAS CODE

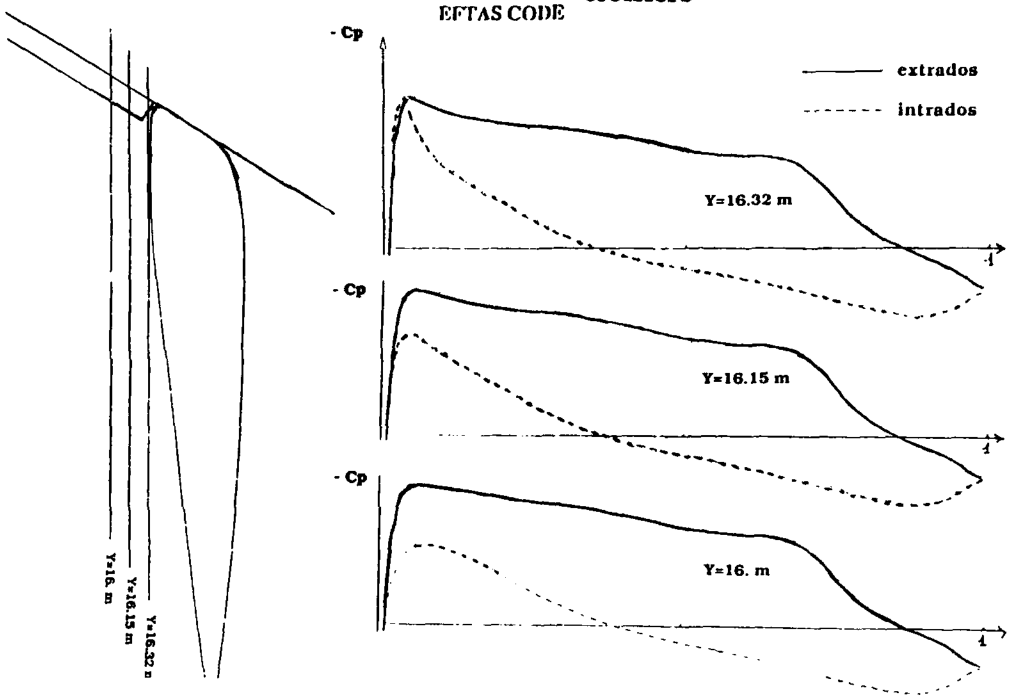



Figure 17

DATUM WING LOWER SURFACE PRESSURE DISTRIBUTION
M=Mmo faible Cz
EFTAS CODE

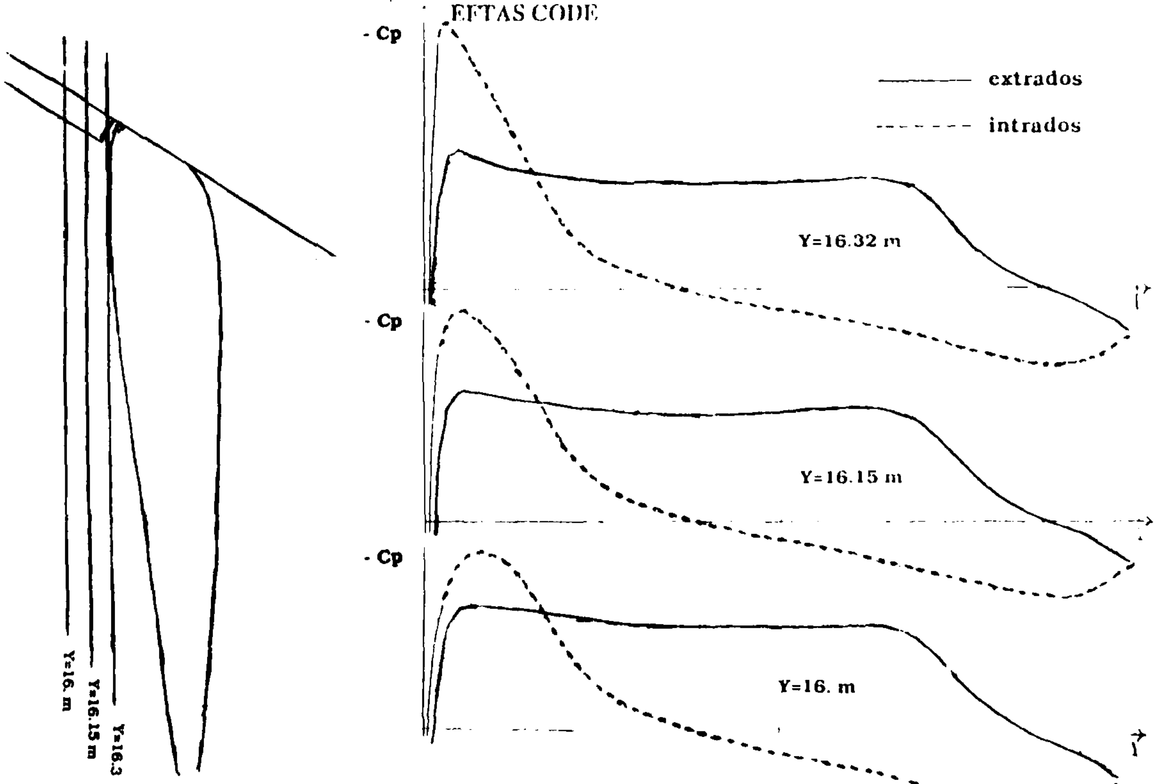



Figure 18

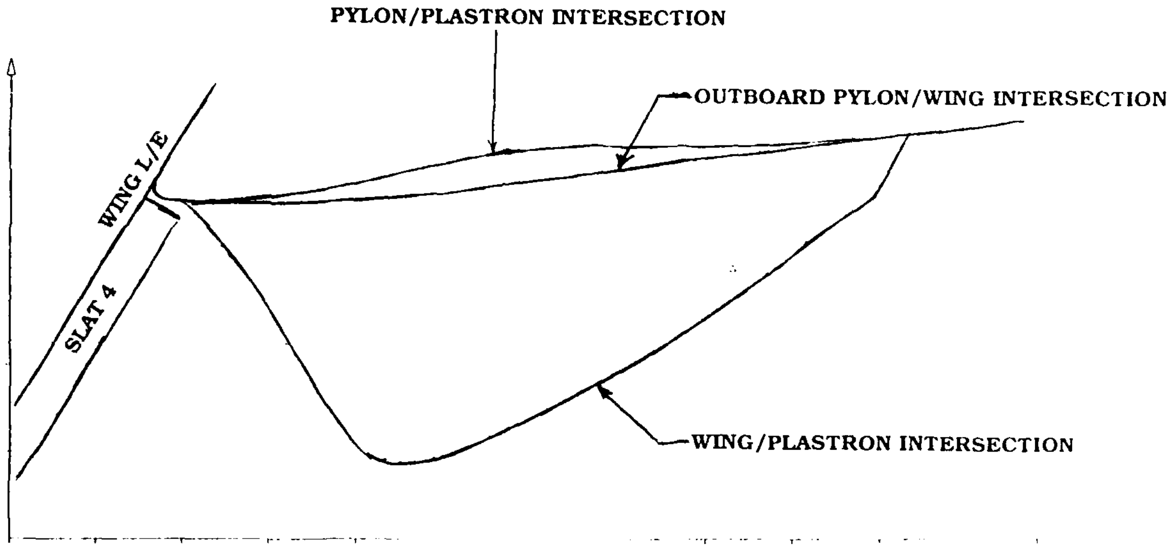



Figure 19

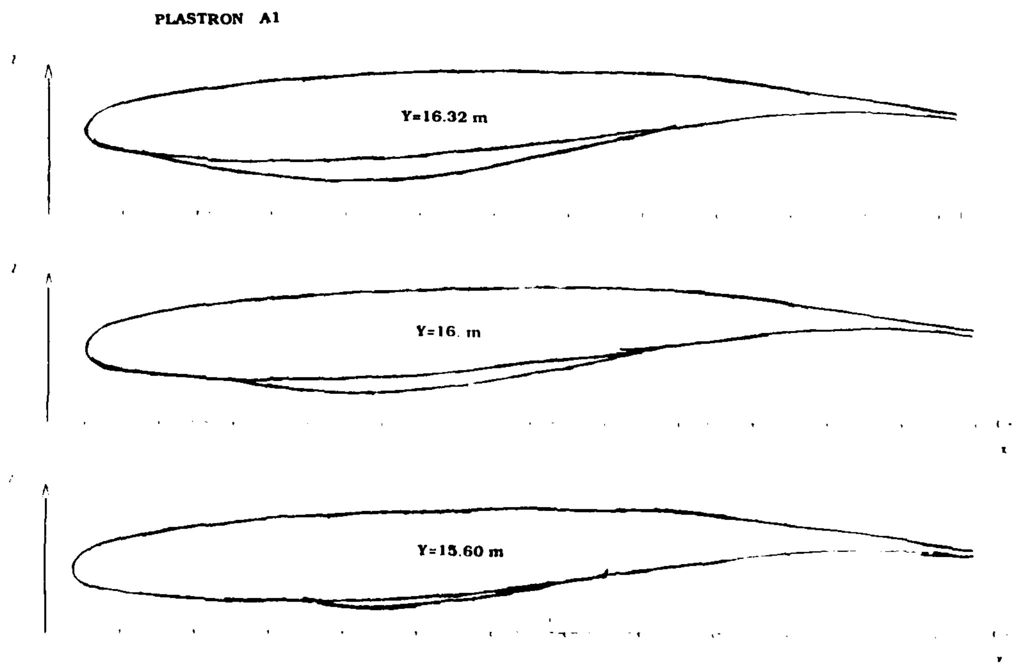



Figure 20

WING LOWER SURFACE PLASTRON GEOMETRY

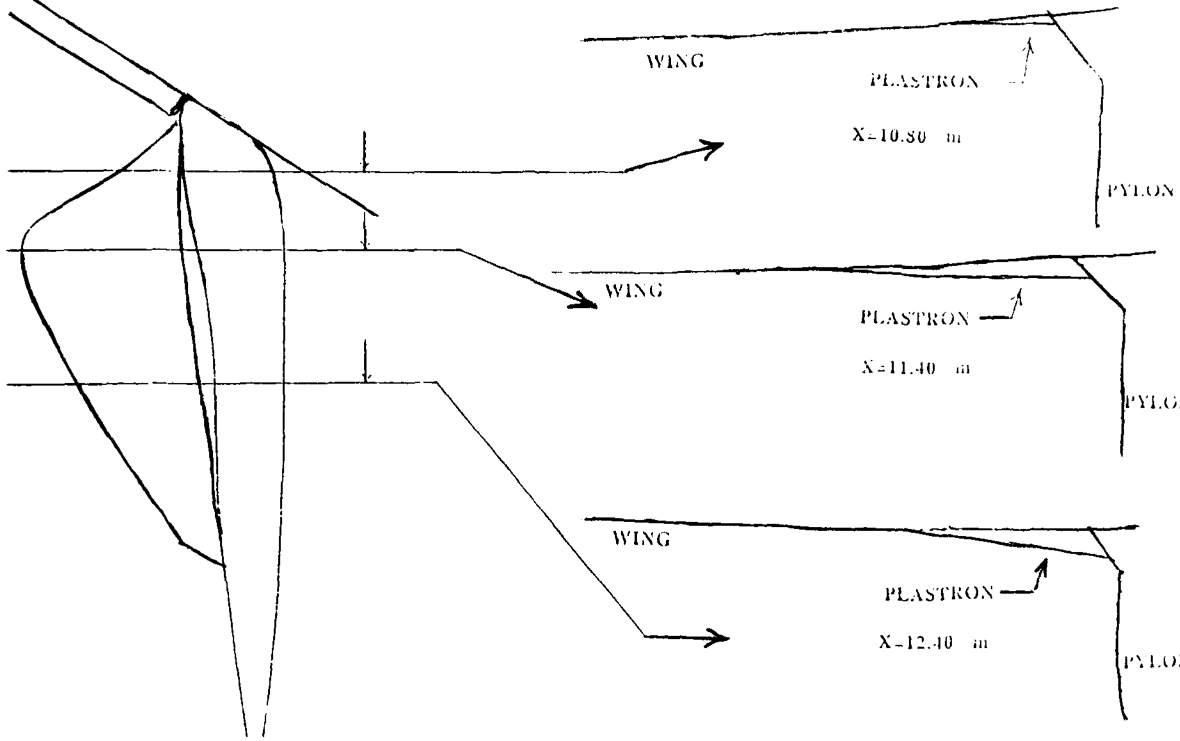



Figure 21

WING LOWER SURFACE "PLASTRON" EFFECT ON PRESSURE DISTRIBUTION

**M=M$_{mo}$ C$_z$=C$_{zcroisière}$**

EFTAS CODE

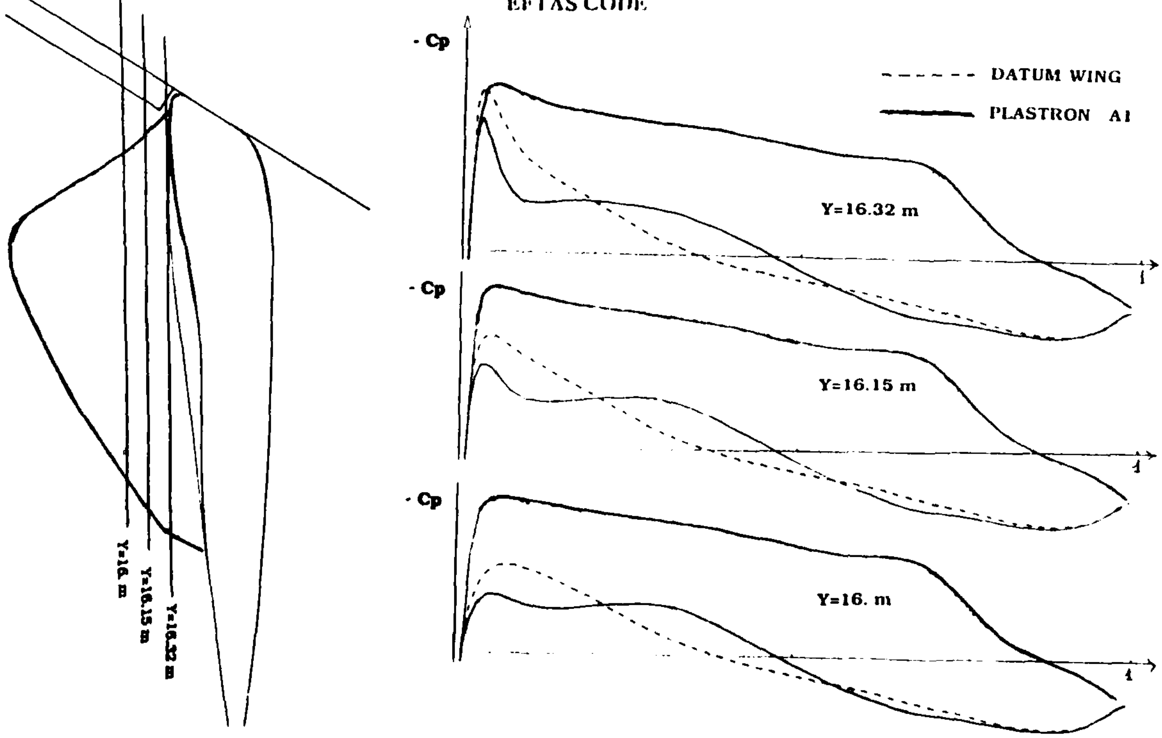



Figure 22

## WING LOWER SURFACE "PLASTRON" EFFECT ON PRESSURE DISTRIBUTION

**$M=M_{mo}$ faible $C_z$**

EFTAS CODE

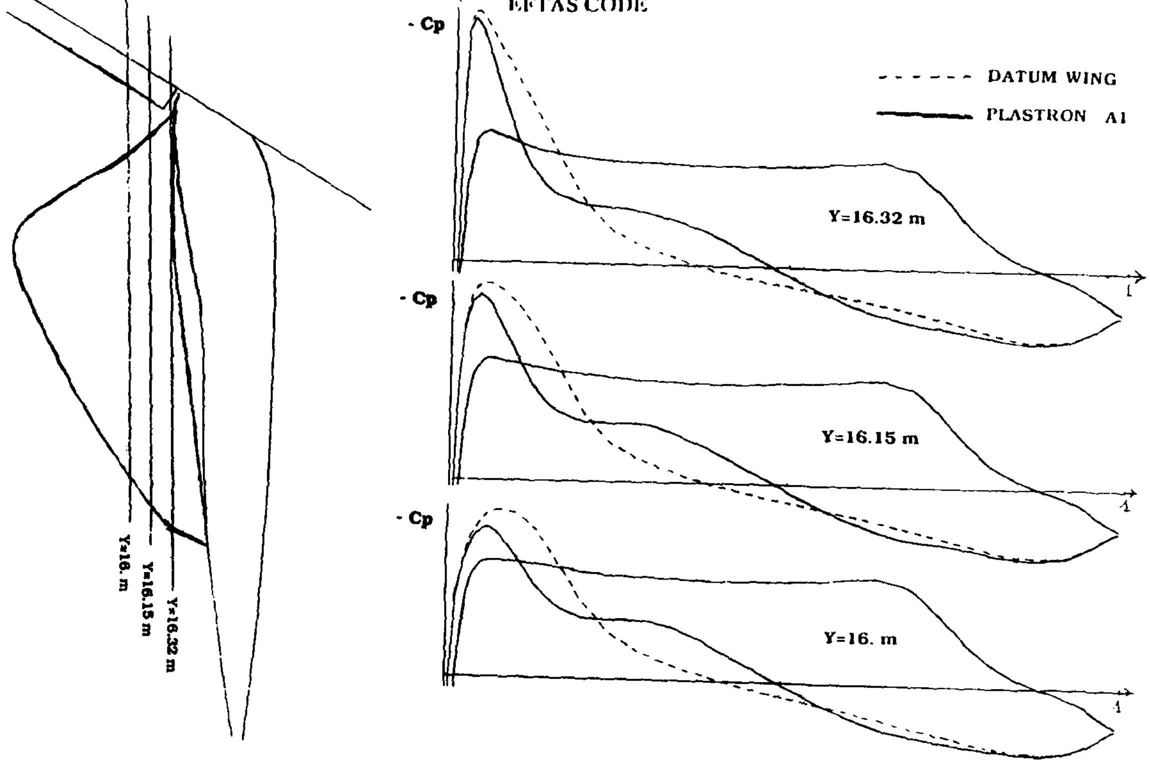
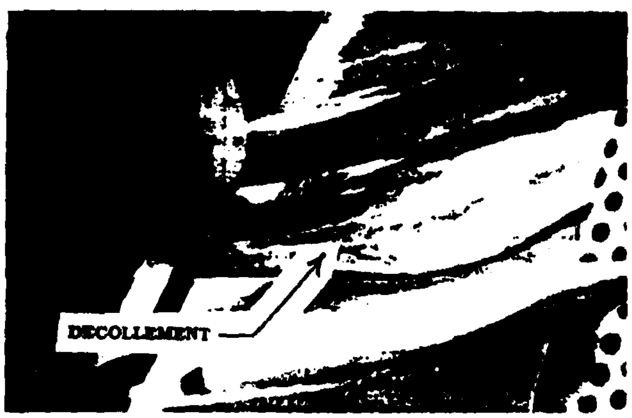



Figure 23

## ESSAIS SOUFFLERIE A.R.A. (Bedford, England)

**demi-maquette British Aerospace** **visualisation à l'huile**




**sans plastron**

**avec plastron**

Figure 24

## ESSAIS SOUFFLERIE A.R.A. (Bedford, England)

**demi-maquette British Aerospace**

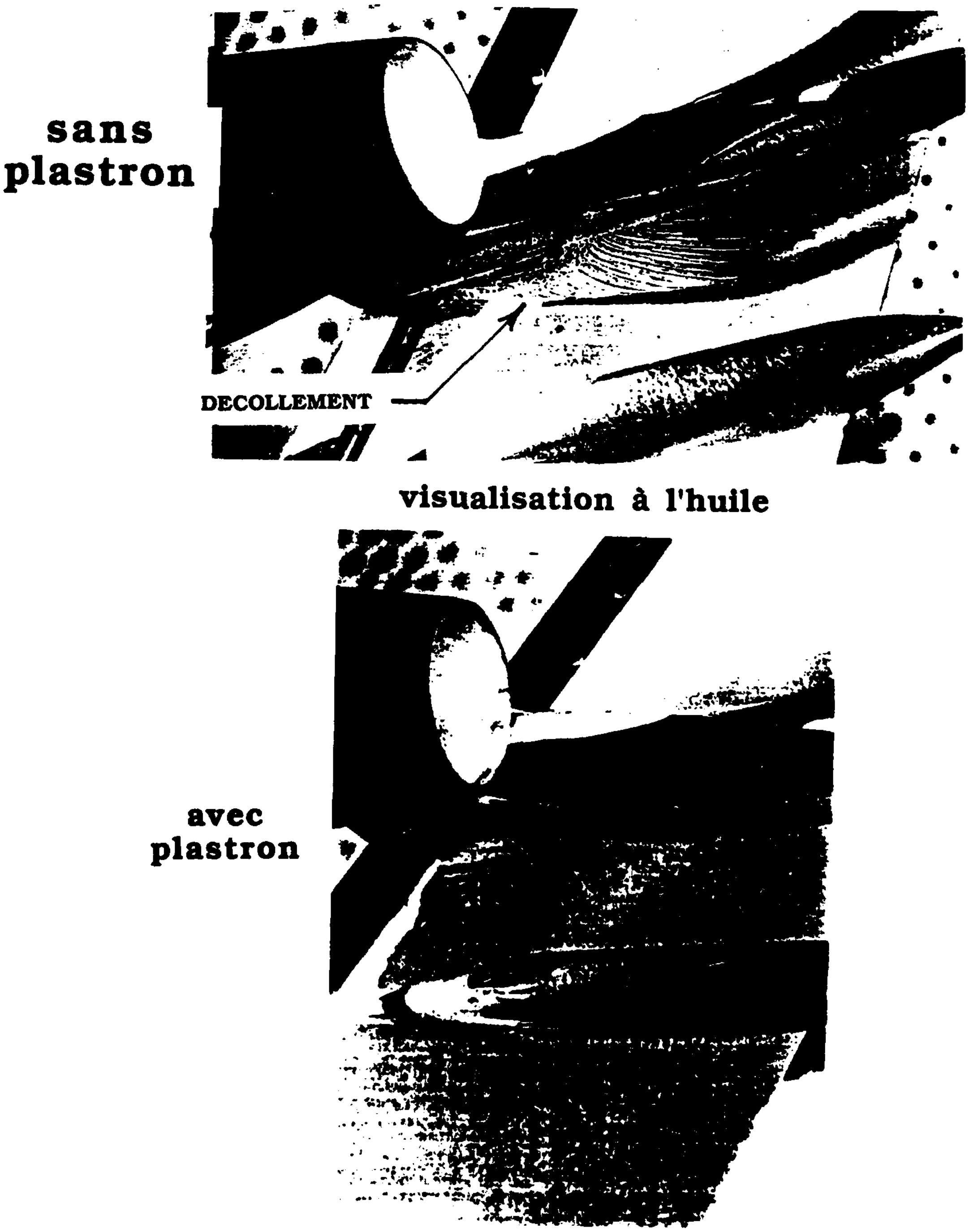



Figure 25

# PLASTRON A1 ( AVION n°1 )

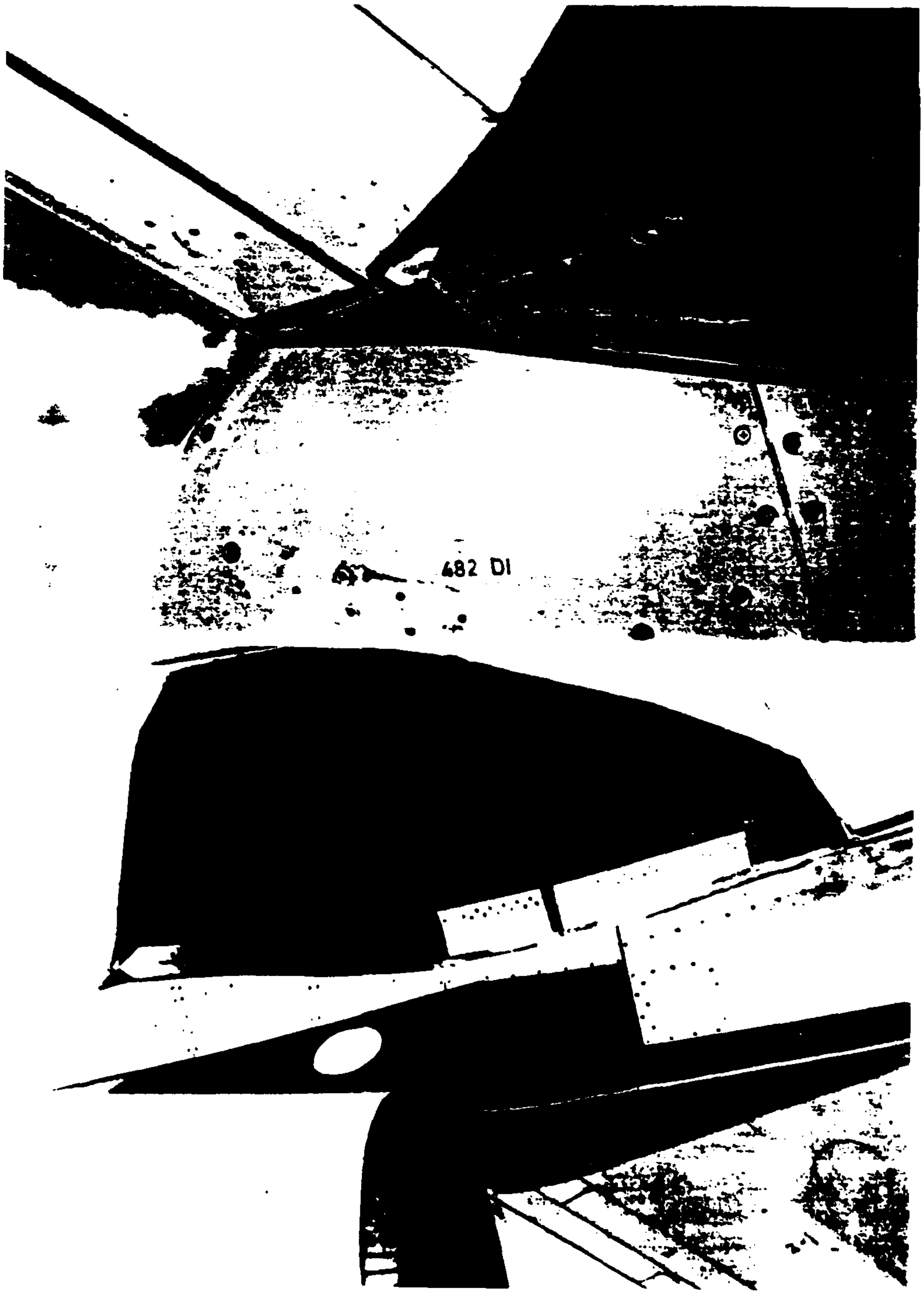



Figure 26

PLAN VIEW ON WING LOWER SURFACE TO ILLUSTRATE
PLASTRON COMPARISON

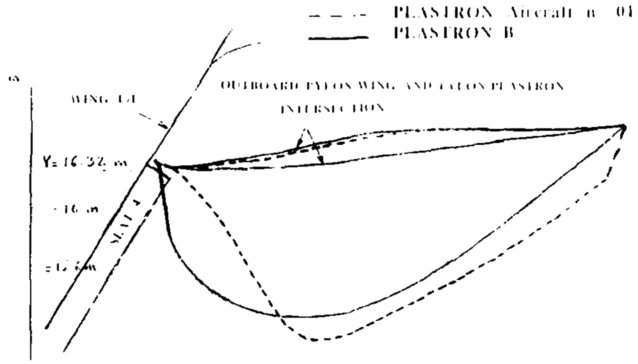



Figure 27

PLASTRON SECTION GEOMETRY

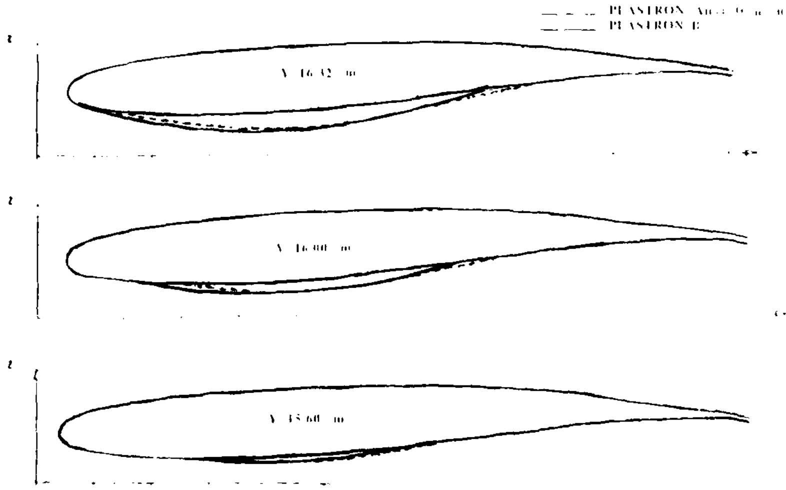


Figure 28

WING LOWER SURFACE "PLASTRON" EFFECT ON PRESSURE DISTRIBUTION
$M = M_{mo}$ $C_z = C_{z\,croisière}$

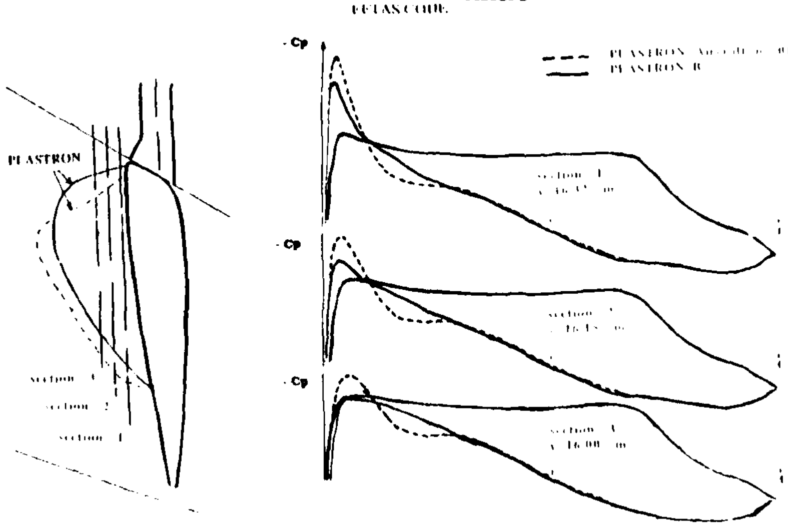



Figure 29

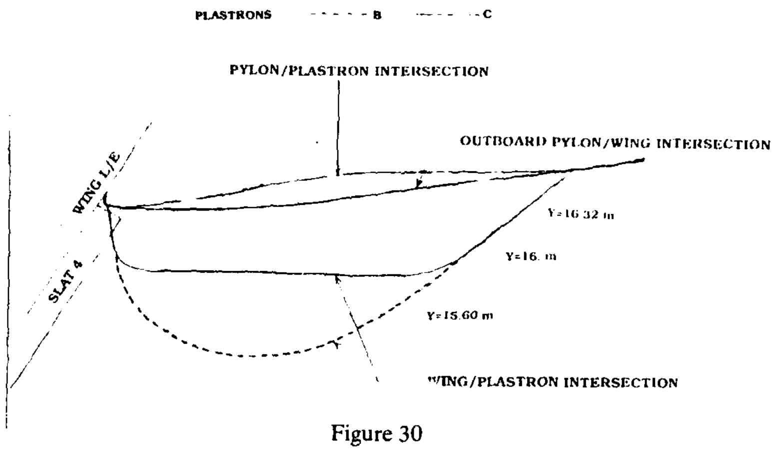



Figure 30

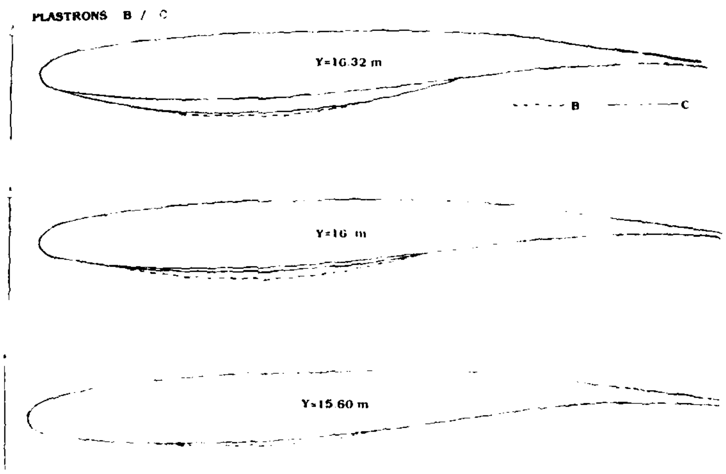



Figure 31

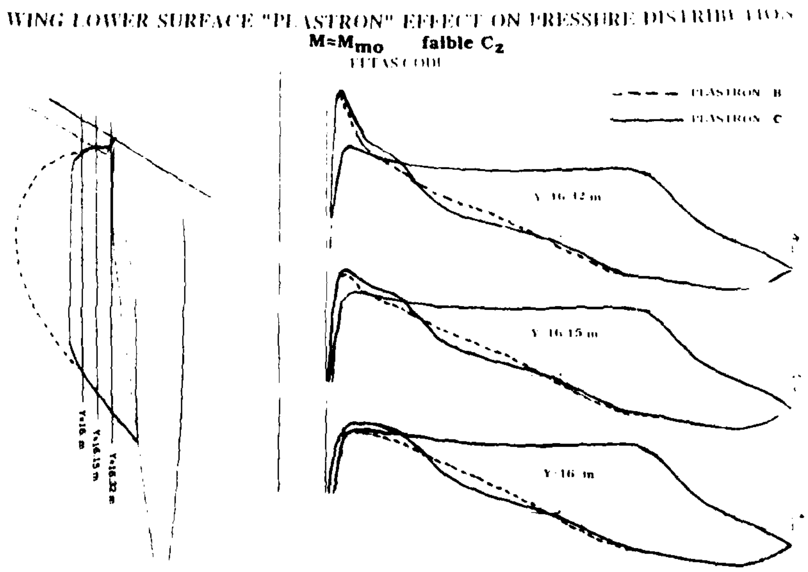



Figure 32

POSITIONS RELATIVES DES NACELLES

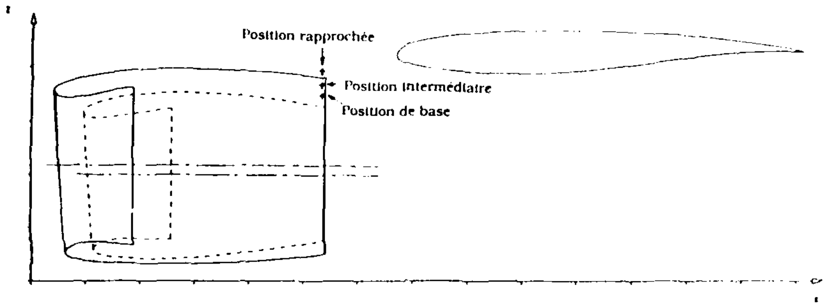



Figure 33

TRAINEE D'INSTALLATION
COMPARAISON DES CONFIGURATIONS

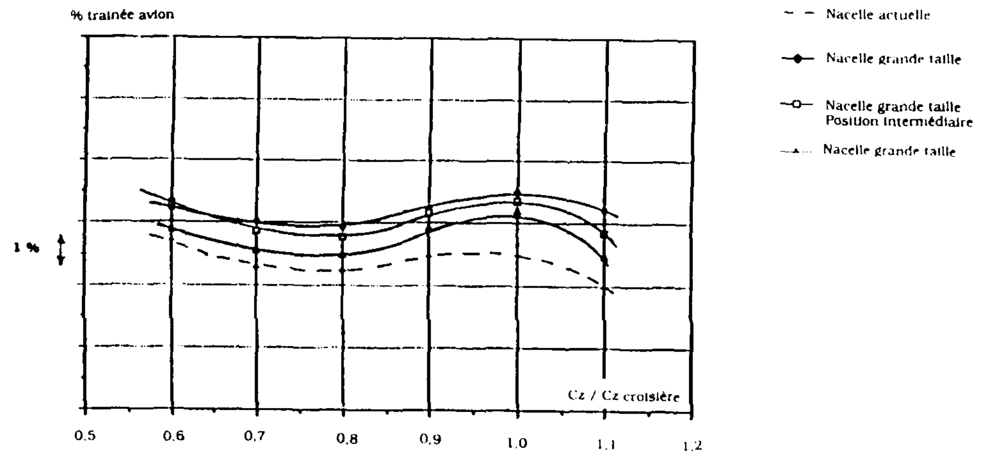



Figure 34

REPARTITION DE PRESSION STATIQUE SUR LA VOILURE
INFLUENCE DE LA TAILLE DU MOTEUR

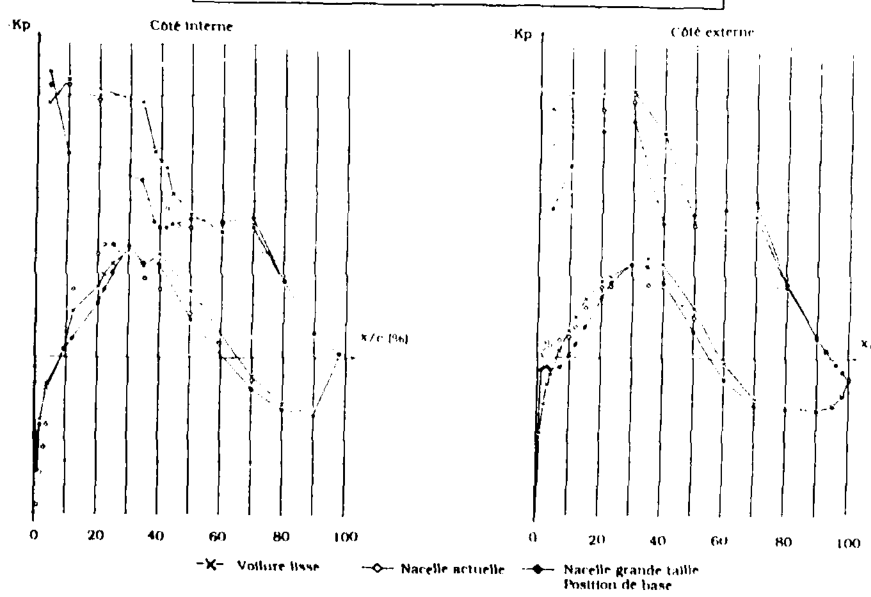



Figure 35

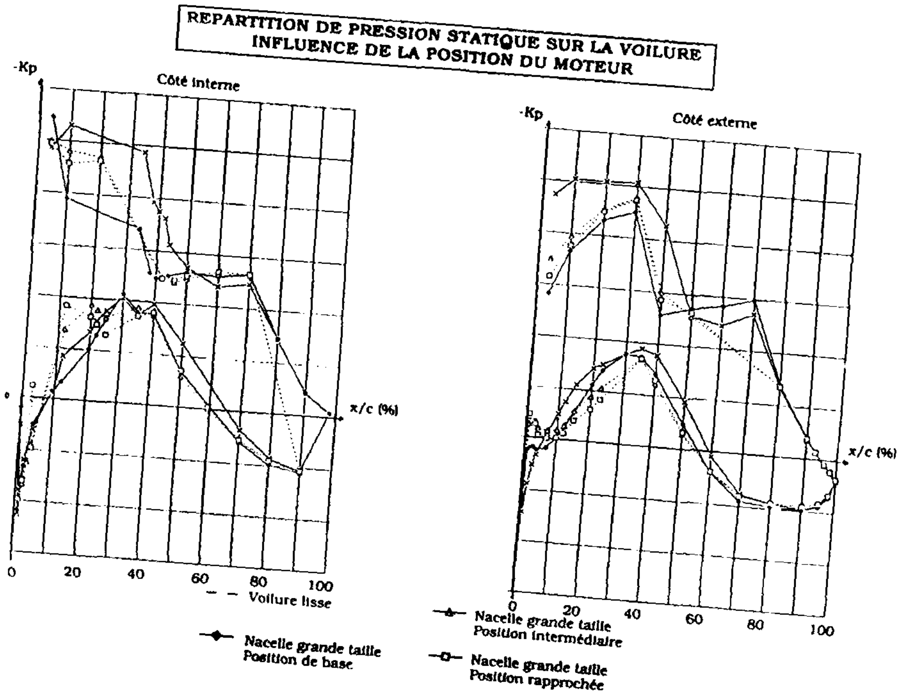



Figure 36

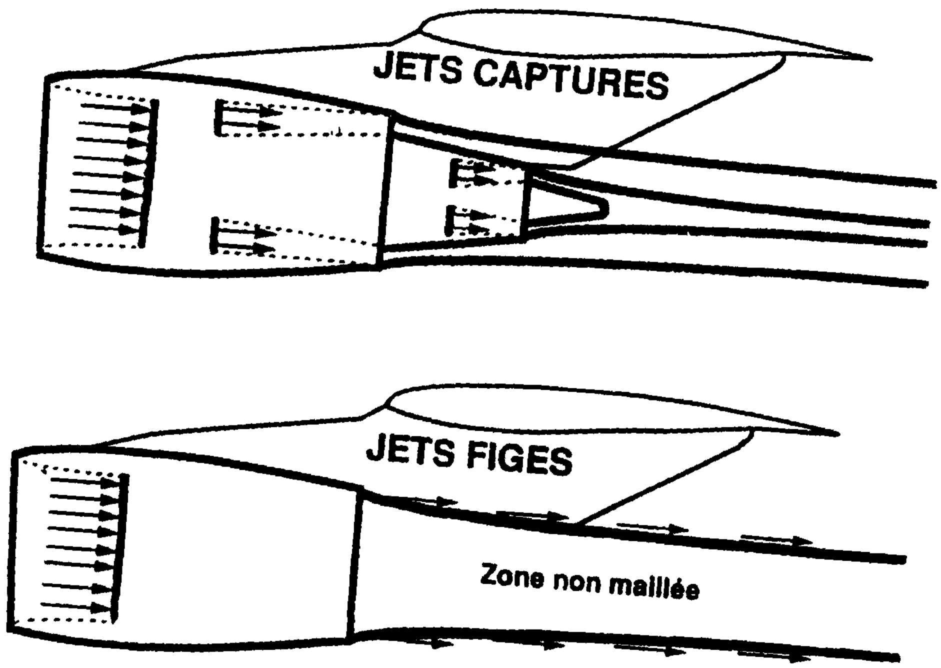



Figure 37

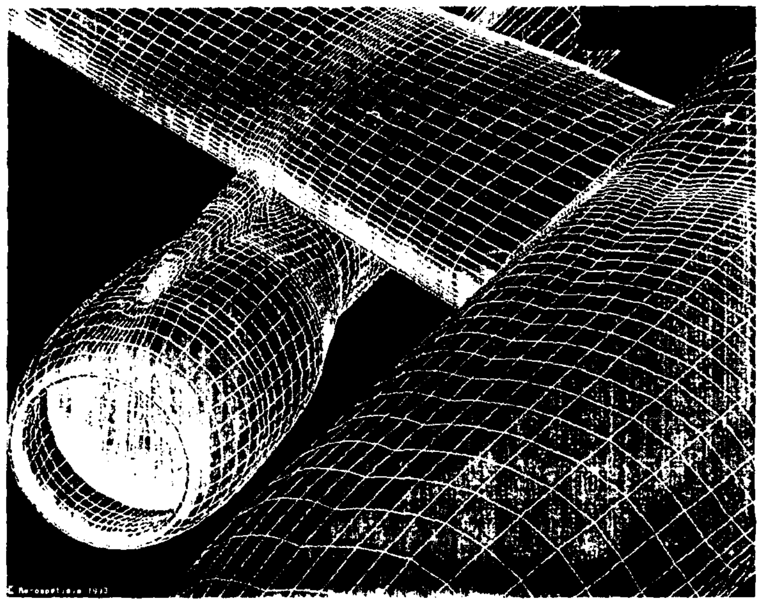


Figure 38

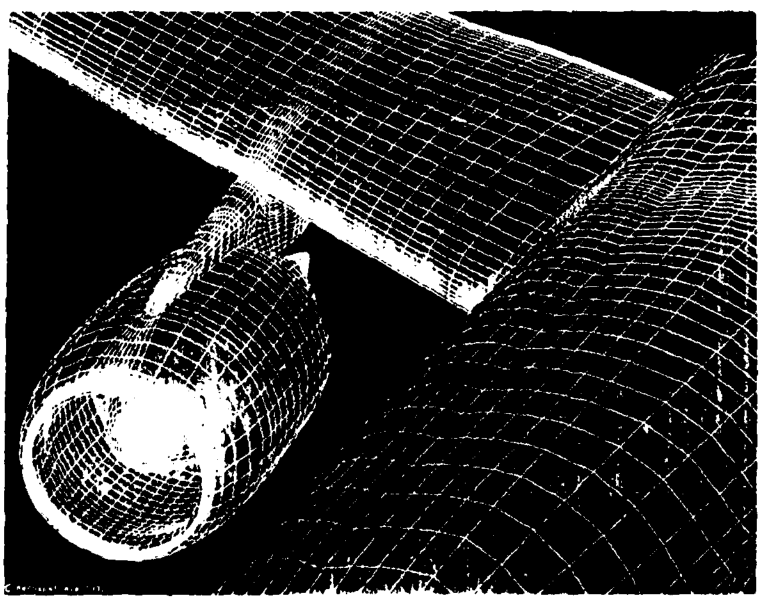


Figure 39

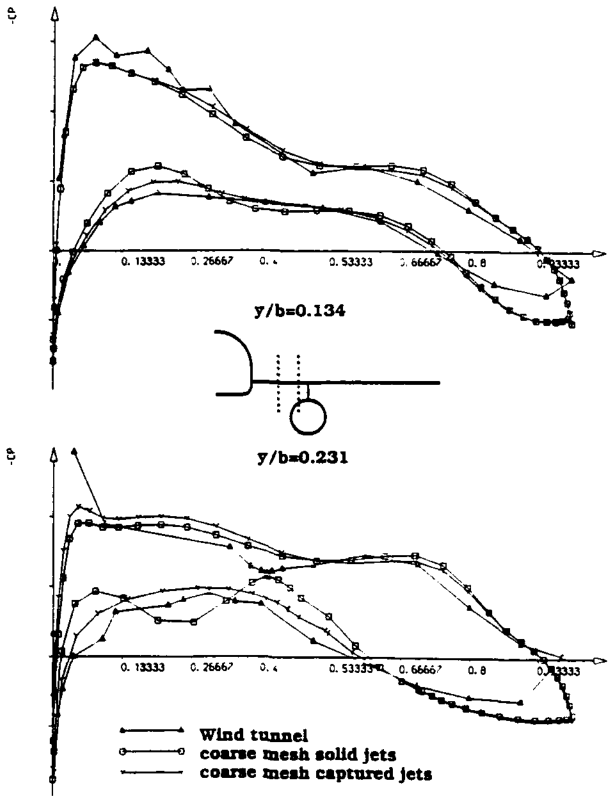



Figure 40

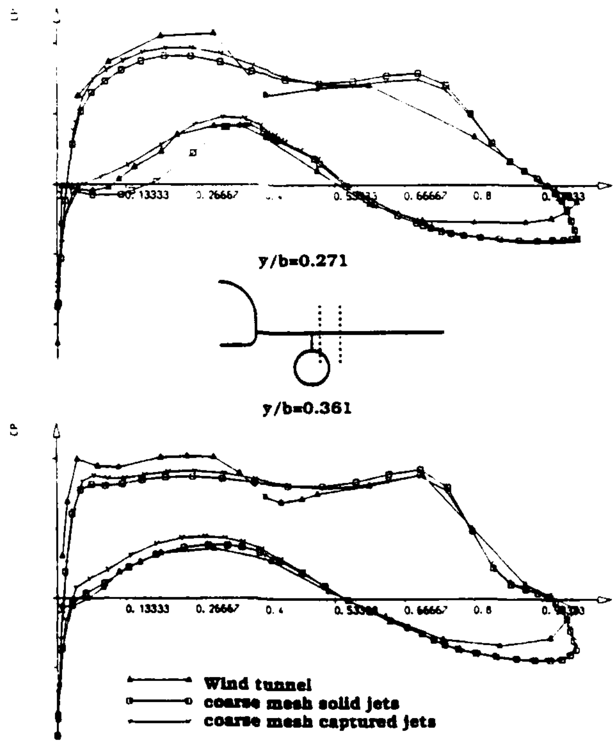



Figure 41

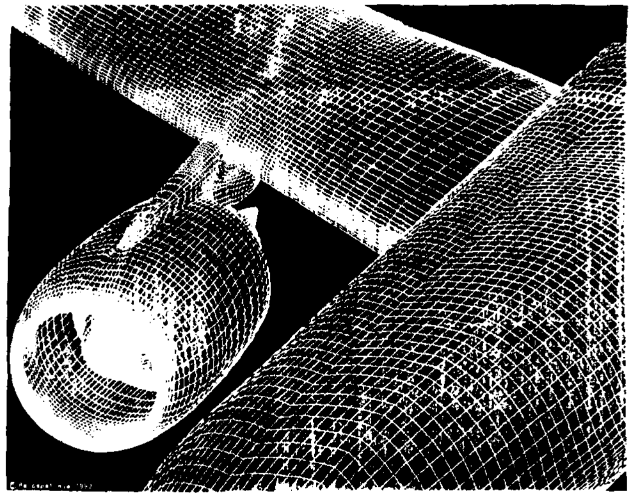


Figure 42

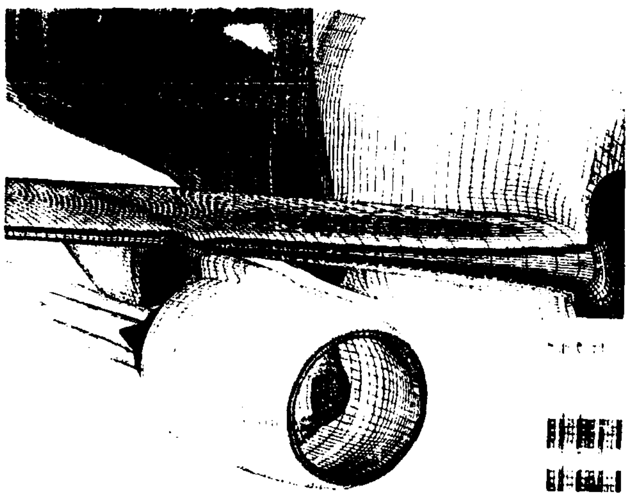


Figure 43

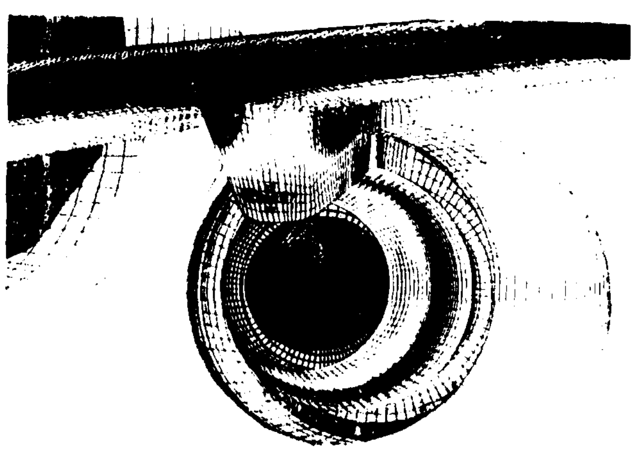


Figure 44

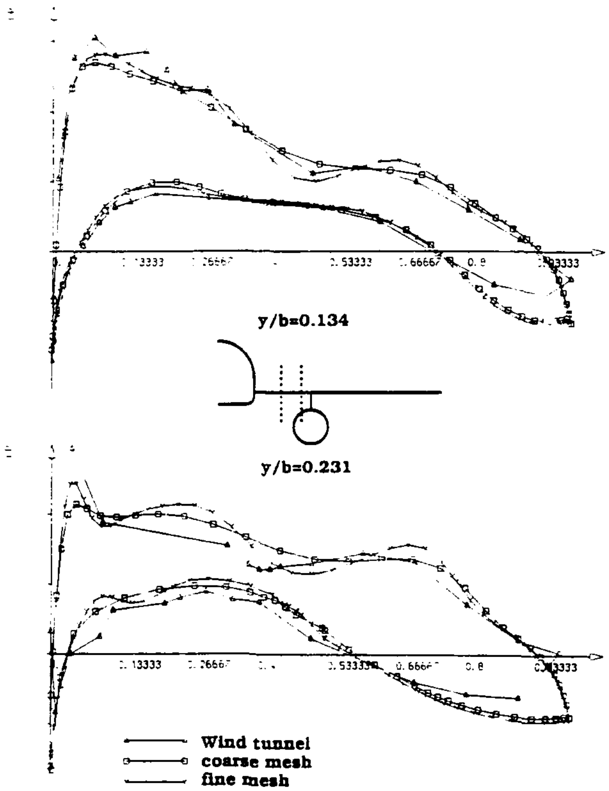



Figure 45

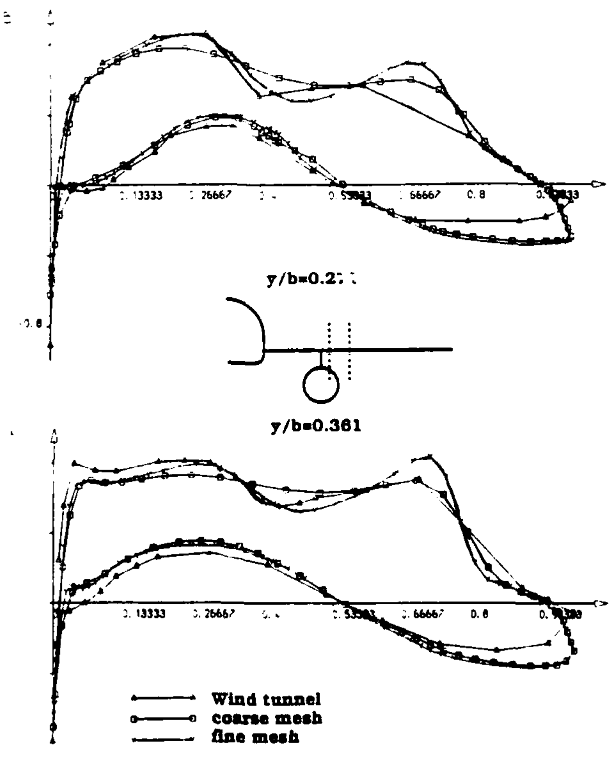



Figure 46

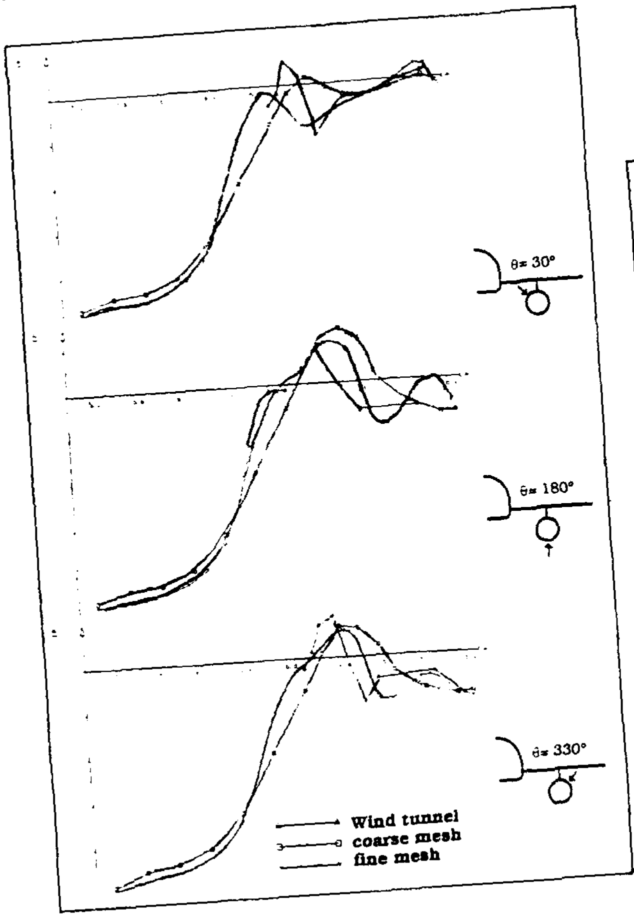



Figure 47

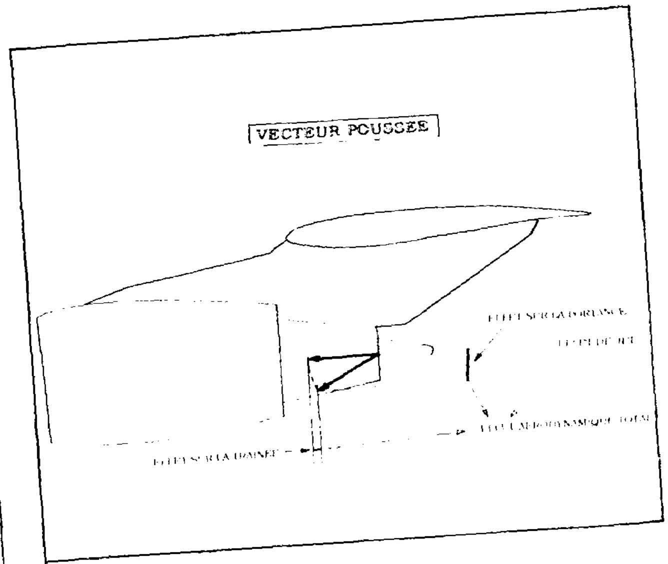



Figure 48

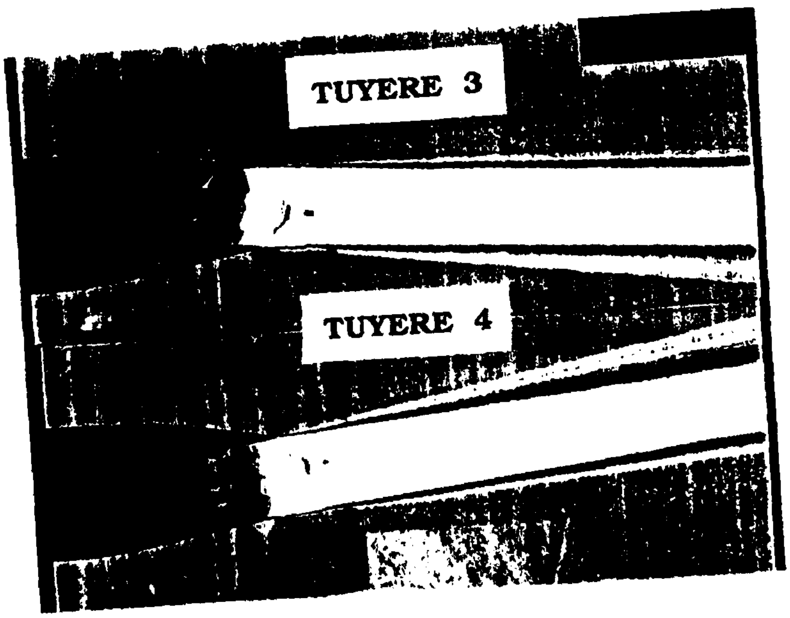



Figure 49

# PROPULSION SYSTEM SELECTION FOR A HIGH ALTITUDE LONG ENDURANCE AIRCRAFT

by

**John D. Cyrus**
**Joseph Franz**
Naval Air Warfare Center Aircraft Division
Code 6052
P.O. Box 5152, Warminster, PA 18974-0591
United States

**SUMMARY**

This paper addresses the major propulsion system options for High Altitude Long Endurance aircraft: internal combustion engines, turbine engines and fuel cells. The paper identifies the technology drivers for the vehicle and assesses the secondary equipment requirements for the various system options. Critical technologies and development requirements are addressed in terms of mission capability for both near-term and advanced systems. This AGARDograph was sponsored by the Flight Mechanics Panel.

**LIST OF SYMBOLS AND ACRONYMS**

| | |
|---|---|
| BSFC | Brake Specific Fuel Consumption |
| HALE | High Altitude Long Endurance |
| HP | High Pressure |
| HX | Heat Exchanger |
| IC | Internal Combustion |
| LHV | Lower Heating Value |
| LP | Low Pressure |
| NASA | National Aeronautics and Space Administration |
| PEM | Proton Exchange Membrane |
| SI | Spark Ignition |
| UAV | Unmanned Air Vehicle |
| VDC | Volts Direct Current |

## 1.0 DESIGN DRIVERS

The need for a fuel efficient propulsion system in a high altitude long endurance (HALE) aircraft is obvious. In fact, the importance of low **fuel consumption** and low **system weight** increases with an increase in mission loiter time. Good off-design engine performance is essential, because vehicle weight reductions as fuel is consumed during a mission cause a substantial reduction in thrust required to maintain a fixed loiter condition. For a mission with 100 hours endurance the turndown ratio (power at the start of loiter/power at the end of loiter) may approach three (See Figure 1). A highly fuel efficient propulsion system implies a complex, high **technology** system with high cycle pressure ratios and temperatures. This implies that the propulsion system for a long endurance mission will probably require a lengthy development program.

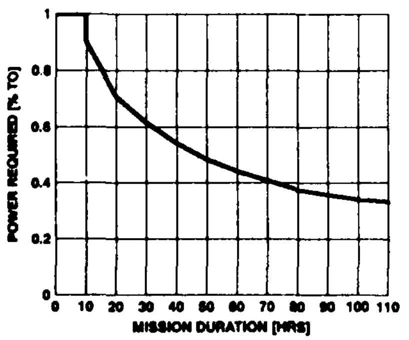



**Figure 1. Turndown Ratio for HALE Mission**

The mission location and the user may dictate the **fuel**. Atmospheric investigation missions such as the polar ozone depletion investigation missions or oceanic/atmospheric interaction missions being considered by NASA may not have access to high quality aviation fuels required by IC engines. Military users may favor or require heavy fuels such as JP or diesel.

A long endurance mission will also require a highly **reliable** propulsion system. In general, with additional **complexity**, vehicle reliability decreases. If the vehicle stays aloft for a long time there is simply more chance for the system to fail than if the mission duration were shorter. There are also several fairly strong implicit requirements for reliability arising from the HALE mission; (1) for mission durations of over twelve hours (the non-stop round-the-world Voyager flight notwithstanding) the vehicle will in all probability be unmanned--consequently, any component failure is more likely to result in the loss of the vehicle because no one is on board to take immediate corrective action; (2) the vehicle is likely to be extremely valuable--it has unique capabilities which provide it with excellent observational potential, it is complex and costly, and it is rather likely to be produced in limited numbers.

The rarefied atmosphere at high altitudes creates a number of problems for the designer. The low density atmosphere can cause losses in compressor or turbocharger efficiency due to Reynolds number effects and a falloff in energy output for a non supercharged system. In addition, **waste heat removal** from the propulsion system and vehicle avionics is a significant problem in the rarefied atmosphere.

## 2.0 CANDIDATE PROPULSION SYSTEMS

Numerous air breathing propulsion systems are candidates to power a HALE vehicle. These include:

- Gas Turbine Engines
  - Turbofans
  - Turboshaft Engines
- Internal Combustion Engines
  - Rotary Engines
  - Spark Ignition Engines
  - Diesel Engines
- Fuel Cells

In comparing the performance of the various propulsion systems, the aircraft designer and propulsion system designer will use two different figures of merit. The aircraft designer will quantify fuel consumption with Brake Specific Horsepower (BSFC) which provides a direct measure of the fuel being used. Because the engines in the above list use a variety of fuels, the propulsion system designer will use thermal efficiency (which eliminates the variation arising from differences in the lower heating value of the various fuels) as a figure of merit to assess how well his system converts energy. Equation 1 shows thermal efficiency is a constant divided by BSFC and fuel lower heating value.

$$\textbf{Thermal Efficiency} = 2546/(\text{BSFC} * \text{LHV}) \qquad \textbf{(Eq 1)}$$

Figure 2 shows the thermal efficiency of fuel cells and of turboshaft and internal combustion engines. In

*Presented at an AGARD Meeting on 'Recent Advances in Long Range and Long Endurance Operation of Aircraft', May 1993.*

this figure the lower boundary represents the state-of-the-art for existing engines of 100 to 600 HP, the hash marks the performance of near-term bare engines and the upper boundary marks the levels that are obtainable with engine development and the incorporation of turbocharging and turbocompounding. It can be seen that all of these engines offer the potential of achieving somewhat better than 40% thermal efficiency. It can also be seen that the up-side efficiency of fuel cells is significantly better than that of IC engines or gas turbine engines.

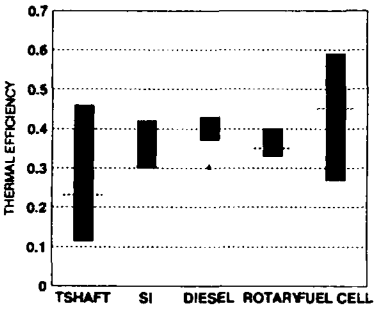



**Figure 2. Thermal Efficiencies for Various Power Sources**

Numerous authors have indicated that the merit of an engine can be established using the Breguet equation and its BSFC to establish endurance. This methodology would be precise if the HALE vehicle took off from a very tall mountain and did not have to climb to its loiter altitude. But since such takeoff sites do not exist, the prudent designer should consider the climb segment in his analysis.

A representative HALE vehicle will have a large wing, a high fuel fraction and multiple engines. To minimize the adverse effects of turndown ratio (part power operation) on the loiter segment the engine will be designed to provide a minimal rate of climb at the top of the climb/beginning of loiter segment. Since turbocharged IC engine systems and fuel cell systems produce essentially constant thrust throughout the flight envelope, the vehicle will also have minimal climb performance. Consequently, the climb duration and climb fuel consumption will be appreciable.

As an example, the climb fuel use for varying BSFCs were calculated for a vehicle with a takeoff gross weight (TOGW) of 16,000 lbs [7250 KG] with a lift/drag L/D ratio of 25:1 and multiple engines producing 800 HP. The vehicle was assumed to operate at a constant 0.25 Mach number during its climb to a loiter altitude of 60,000 ft. [18,300 M]. It is readily apparent from Figure 3 that a well designed HALE vehicle will require a high fuel fraction and an engine with low fuel consumption. A vehicle with a BSFC of 0.600 (which represents very good performance for a small turboshaft engine) will consume almost 50% of its fuel climbing to loiter--even with a 50% fuel fraction.

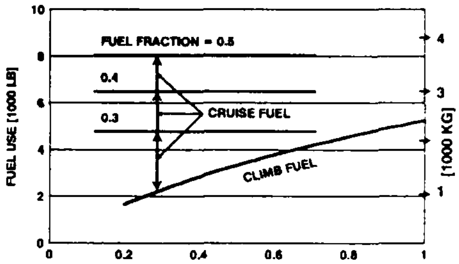



**Figure 3. Fuel Use on HALE Mission**

In generic terms, complexity varies directly with thermal efficiency as shown in Table 1.

**Table 1. PROPULSION SYSTEM CANDIDATE TRADES**

| | **Gas Turbine** | **IC Rotary** | **IC Spark Ignition** | **IC Diesel** | **Fuel Cell** |
|---|---|---|---|---|---|
| Fuel Consumption | High | Medium | Low | Low | Very Low |
| System Weight | Low | Medium | Medium | Medium | High |
| Fuel | JP | Multi | Av Gas | Diesel | Hydrogen JP* |
| Technology | Current | Dvl Near | Dvl Near | Dvl Near | Dvl Near Dvl*5-10 |
| Reliability | High | High | Medium | Medium | High |
| Waste Heat | Very Low | Medium | Medium | Medium-H | Medium |
| Complexity | Engine | Engine 2 Stg TC Cool Recup ControlsGB&Prop | Engine 2 Stg TC Cool Recup ControlsGB&Prop | Engine 2 Stg TC Cool Recup ControlsGB&Prop | Engine 3 Stg TC Cool Recup ControlsGB&Prop Burner Inverter Elec Mtr |

* Advanced Systems

### 3.0 GAS TURBINE ENGINES

The simplest propulsion system for HALE operations is a more-or-less stock turbofan engine or a turboshaft engine and propulsor. Perhaps as a consequence of this simplicity, one of the first HALE demonstrations was of a turbofan engine in Boeing's "Compass Cope" aircraft research program.

The engine size and lapse rate with altitude will establish its precise altitude; the thrust at the top of climb must be approximately 110% of the thrust required for the beginning of loiter. For a moderate bypass ratio turbofan, an altitude capability of 45,000 ft [14,000 M] is achievable; at this condition its thrust is approximately 1/10 of its thrust at sea level static (SLS) conditions and the engine has not experienced significant performance deteriorations due to operation at altitude. The substitution of a larger (oversized) engine will provide additional altitude capability. However, with increasing altitude, the fan or compressor of an existing engine will need to be redesigned to avoid a significant fall-off in airflow and efficiency due to Reynolds number effects. Increasing altitude may also require redesign of the combustor to avoid blow-out problems and to maintain efficiency.

The turbofan engine has good takeoff and climb performance. Consequently, it can get to its operating location quickly and efficiently; a turbofan powered vehicle can be expected to get to a 45,000 ft [14,000 M] loiter condition in one-third the time and with one-third the fuel as a vehicle powered by a turbocharged internal combustion engine propulsion system. For a vehicle with a moderately high bypass ratio turbofan engine (and, therefore, a SFC of 0.60 to 0.70) and a fuel fraction of 0.40 to 0.50, loiter durations of eight to sixteen hours are achievable.

For loiter durations longer than eight hours the designer should consider the incorporation of a regenerators and/or intercoolers. Allison, Boeing and Sundstrand have investigated turbo devices for use on long duration missions for altitudes up to 65,000 ft [20,000 M]. Allison[1] investigated the potential of modifying an existing turboshaft engine and adding a recuperator, while Sundstrand[2] and Boeing[3,4] have investigated the use of new turboshaft engines incorporating intercoolers and intercoolers and recuperators respectively. Their studies showed that these devices can improve specific fuel consumption by as much as 30%, but at a weight penalty of 30 to 60% of the basic engine weight.

### 4.0 SYSTEMS FOR INTERNAL COMBUSTION ENGINES

Internal combustion (IC) engine systems for HALE operations can be typically categorized as efficient but complex. These systems use multiple stages of supercharging and associated hardware to provide air to the IC engine at essentially sea level conditions. As shown in Figure 4 the supercharging ratio (SR) which is the inverse of the fall-off in atmospheric pressure increases markedly with pressure. With typical centrifugal compressor ratios of 5:1 to 6.0:1, two stages of supercharging are required to get to altitudes above 40,000 fT [12,500 M] and three stages may be required to get to altitudes above 65,000 ft [20,000 M]. With three stages of supercharging, it is theoretically possible to get to altitudes approaching 100,000 ft [31,000 M]. Because the air conditions supplied to the IC engine are essentially constant, the maximum performance of the IC engine system will be essentially constant throughout the operating envelope. As a consequence, the propulsion system will be designed to produce a minimum level of climb performance at the end of climb; at the initiation of loiter the power will be cut back to a level sufficient to maintain level flight.

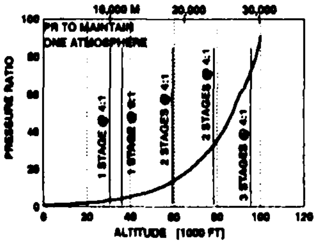



Figure 4. Fuel Use on HALE Mission

In addition to turbochargers the IC propulsion system will include an air induction system, one or two intercoolers and an aftercooler to provide good efficiency, an air bypass control, throttle control and waste gate control to provide a match between engine demand and air supplied by the turbochargers, a power transmission subsystem consisting of a multi-speed gear box and a propulsor, and an exhaust system. A two stage turbocharged exhaust system is depicted schematically in Figure 5. Because of the high degree of supercharging for a HALE system, the pressure ratio between the exhaust gases and ambient is extremely high. Consequently, a recouperator may be added to the exhaust system to provide additional horsepower derived from the exhaust gases.

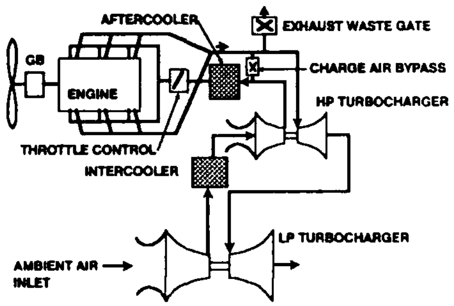



Figure 5. Two- Stage Turbocharged IC Engine

The choice of which type of internal combustion engine to use--rotary, spark ignition (SI) or diesel--has until now depended largely upon pragmatic decisions resulting from the sponsor's funding and the availability of an engine in a size class which could be used in the propulsion system with minimum development and/or modifications. Since there are limited numbers of extant aviation diesel and rotary engines, most applications have used spark ignition engines. Teledyne[5] has demonstrated the viability of gasoline powered spark ignition engines for HALE vehicles with their Voyager 300 liquid cooled spark ignition engine on the Boeing Condor and on the Rutan Voyager "Non-stop, non-refueled round-the-world flight.

In an ideal world both rotary and diesel engines would also warrant consideration. System studies of turbocharged two-stroke Diesel engines by Ricardo[6,7] of turbocharged four-stroke Diesel engines by Teledyne[8], and of turbocharged rotary engines by John Deere[9] have also shown that a development program could produce viable candidates. Diesel engines have inherently better brake specific fuel consumption rates than SI engines. Rotary engines have markedly fewer parts and run smoother than spark ignition engines and should therefore have inherently better reliability than SI engines. Both the diesel and rotary engines also have a heavy-fuel capacity (specifically the diesel can use diesel fuel and the rotary can use JP fuels) which means that they should be more supportable by military in the field. While the brake specific horsepower of rotary engines has been poorer than SI engines, development efforts at and sponsored by NASA Lewis have significantly improved their fuel consumption. In addition to pragmatic considerations and *ility* trades, the selection of engine type should also consider vehicle integration trades. The off-design match between the engine and turbocharger will vary between the three engine types.

**4.1 Two-Cycle Vs Four-Cycle Engines**

The four-cycle engine is self-aspirating whereas the two-cycle engine has no complete suction stroke. The two-cycle engine is not self-aspirating and requires some form of compressor to force fresh charge into the cylinder. The four-cycle engine also has a distinct exhaust cycle which drives the exhaust gases out of the combustion chamber. The two-cycle engine has no such positive exhaust expulsion. Because the two-cycle engine is not self-exhausting the fresh inlet charge driven in by the compressor is used to help force out residual exhaust gases. This process (called scavenging) is the key to successful operation of an efficient two-cycle engine. Two-cycle engines are very sensitive to the design of their exhaust system, since any residual pressure may impair the vital scavenging process. Care must be taken when turbocharging a two-cycle engine, since the exhaust turbine inherently increases pressure in the exhaust manifold. The system must be designed so that the boost pressure exceeds the exhaust pressure (by a suitable margin) during the scavenging process for the engine to operate well. Two-cycle engines typically exhibit low exhaust temperatures which will hinder effective turbocharging and may require an auxiliary combustor or other exhaust energy augmentation.

**4.2 Turbocharging**

Turbocharging introduces air (or air/fuel mixture) into an engine combustion chamber at a density greater than ambient. The increase in air mass allows a proportional increase in the fuel that can be burned and thus increases the potential power output. The principal objective is to increase power output, not to improve efficiency, however the efficiency may benefit.

**4.3 Turbocharger Turbines**

The requirements for an efficient turbine for the first stage of a high altitude turbocharger system necessitate the accommodation of a wide range of mass flows, high gas temperatures and high rotational speeds.

**4.4 Turbocharger Compressors**

The high pressure ratio requirements of a high altitude turbocharger compressor may lead to internal duct velocities that exceed the speed of sound with a resultant shock field that reduces efficiency. High altitude turbocharger compressors are invariability radial designs which provide the opportunity for high pressure ratio operation at the cost of limited mass flow capabilities. Centrifugal compressor performance is limited to a region of the map bounded on the left by flow surge conditions and on the right by choked conditions at either the inducer inlet or the diffuser outlet. Surge occurs when local flow reversal occurs in the blade boundary layer and a decreased flow rate relieves the adverse pressure gradient which then permits a flow rate increase and the process repeats the cycle at a fixed frequency. Uncooled turbine temperatures as high as 1000 K for diesel engine applications and 1200 K for gasoline fueled engines require the utilization of high temperature alloys. Compressor performance losses will occur at high altitude due to Reynolds number effects. The low density atmospheric conditions at high altitude will decrease the effective efficiency, air flow and pressure ratio and will require an increase in turbocharger speed to compensate for the reduced performance.

**4.5 Charge Cooling**

Compression of air by a compressor is accompanied by a temperature rise. This temperature rise will depend on the pressure ratio and the efficiency of the compressor. A reduction of engine inlet manifold air temperature will increase the density of the air and consequently increase the mass of air in the cylinders. Reducing the manifold air temperature will enable more fuel to be burned and the power output to increase. The compressor outlet temperature can be effectively reduced by an air-to-air or air-to-liquid heat exchanger. The performance of a charge cooler is measured by its effectiveness, which is the temperature drop of the compressor outlet air through the heat exchanger divided by the maximum possible temperature drop (inlet temperature of air minus inlet temperature of coolant). Typical performance of charge coolers will depend on effectiveness and the mass flow rate and pressure drop of compressor air and coolant. The flow of air through the complex passages of a typical cooler will result in some air pressure loss, however the losses are usually small. Turbocharger heat exchangers lose effectiveness at high altitude conditions where the air density reduces the thermal conductivity and heat transfer rates. In order to compensate for the reduced performance, heat exchangers must increase in size and weight. A typical heat exchanger system designed for high altitude will be larger in volume than the engine and turbochargers combined.

**4.6 Propellers**

The propulsive thrust for vehicles designed for high altitude operation generally is derived from a large propeller operating at low forward speed and low rotational speed. Figure 6 shows three different designs developed for varying speed ratios. It is desirable to operate the tip speed of the blades at high subsonic conditions in order to maintain maximum efficiency. If the propeller were to operate in a limited speed range, the Curve A would be used for maximum efficiency. However, in order to maximize efficiency, propeller integration requires a low blade lift coefficient for take-off and climb and a high lift coefficient for high altitude cruise. A compromise usually results in a blade design which provides acceptable climb performance with good performance during the long loiter cruise segment of the mission such as that depicted in Curve B or C.

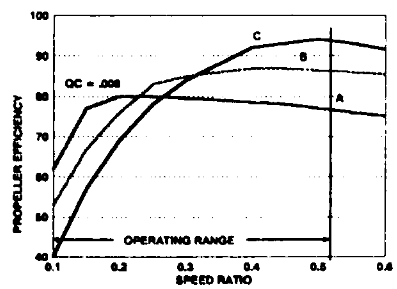



Figure 6. Theoretical Propeller Efficiency for Three Designs

**4.7 Gear Box**

Climb performance can also be improved by utilizing a two stage gear drive or a continuously variable gear drive which will match engine and propeller to the most efficient operating conditions. The loiter segment of a typical mission can last 100 hours and result in a considerable decrease in vehicle weight through depletion of fuel, therefore the thrust power required during loiter will decrease dramatically. Propeller efficiency can be maximized during loiter through reductions in blade speed and blade pitch angle to match the changing power requirements. Propellers which operate at high altitude will experience thrust losses due to the low Reynolds number environment and will require corrections of blade speed and pitch angle.

**4.8 Controls**

Integrating the performance of engine, gear drive, propeller, turbochargers and system heat exchangers of a high altitude long endurance system requires a very complex control system. The controls required for a multi-stage turbocharger system includes an exhaust gas waste gate valve, an air bypass valve and possibly an air throttle valve. The air bypass valve regulates flow through the multi-stage compressor and multi-stage intercooler/aftercooler to provide an acceptable combination of air pressure, temperature, and mass flow to the engine inlet manifold. The bypassed air is typically delivered to the engine exhaust manifold where it mixes with the exhaust gas stream. The air manifold pressure must be maintained higher than the exhaust pressure to avoid recirculation of exhaust products. The waste gate valve operates in consort with the bypass to divert exhaust gas energy from the turbine inlet stream to an overboard dump and thus match the turbine work and speed to that of the compressors. Various operating conditions within the compressors and turbines must be maintained in order to avoid surge, choking or overspeed in the compressors and limit the temperatures in the turbines. The turbocharger heat exchangers are typically separate from the engine heat exchangers. The separate systems are required as a result of large difference in coolant operating temperatures between the engine and turbocharger system. The two separate coolant systems are linked together with control valves which regulate the low temperature of the turbocharger coolant loop within acceptable limits by mixing high temperature engine coolant flow.

**4.9 Recuperators**

Significant potential energy resides in the exhaust of all of the various types of proposed core engine systems. The exhaust pressure from a high altitude propulsion system can be forty to fifty times greater than the ambient pressure at the operating altitude. A substantial portion of the pressure potential could be recovered as power by increasing the exhaust temperature in a burner and utilizing a separate recovery turbine. The recovery turbine could be compounded to the engine or it could be utilized to produce electrical energy and therefore increase the overall efficiency of the propulsion system.

**5.0 FUEL CELL SYSTEMS**

There are five major groups of fuel cells:

| CELL TYPE | TEMP | F |
|---|---|---|
| Alkaline Fuel Cells | 250 C | H |
| Phosphoric Acid Fuel Cells | 250 C | H |
| Proton Exchange Membrane | 250 C | H |
| Molten Carbonate Fuel Cells | 600 C | HC |
| Solid Oxide Fuel Cells | 600 C | HC |

Of these groups, the Molten Carbonate and Solid Oxide Fuel Cells are in the early stages of development. Alkaline fuel cells require pure hydrogen and oxygen; they react with $CO_2$ in the fuel or oxidant. Since equipment to eliminate $CO_2$ from the atmosphere and fuel would be heavy and complex, the alkaline fuel cell is not a viable option for a HALE vehicle. Phosphoric acid fuel cells and proton exchange membrane (PEM) fuel cell are potential near term options for an air vehicle. But, Bentz[10], Aurora Flight Sciences[11] and International Fuel Cells[12] have shown that the BSFC of phosphoric acid cells is up to 30% greater than PEM cells. Consequently the PEM cell is the near term fuel cell of choice.

**5.1 PEM CELLS**

Aurora Flight Sciences[11] and International Fuel Cells[12] have conducted system studies of the PEM cell in a HALE vehicle. These studies showed that a hydrogen powered PEM cell could provide power for flights of 100 hr. duration, producing power at a thermal efficiency exceeding 45% at rated power. And, unlike other candidate systems, their part power efficiency actually improves as shown in 7 as load decreases.

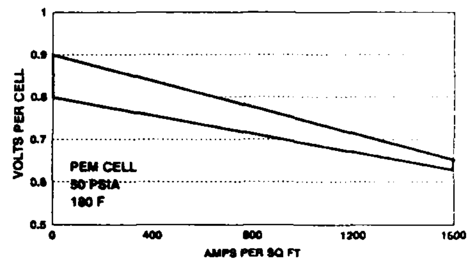



**Figure 7. Fuel Cell Part Power Performance**

These systems use multiple stages of supercharging and associated hardware, similar to the hardware described above for IC engines, to provide air to the fuel cell. Because of the weight and complexity of the fuel cell system, air is likely at greater pressure than sea level conditions to improve the power output of the cell. In addition to turbochargers and intercoolers, the fuel cell system will require inverters to convert the fuel cells electrical output into 270 VDC power and electric motors which drive propulsors for the vehicle. (See Figure 8.) In addition the generic hardware requirements the Proton Exchange Membrane (PEM) fuel cell requires humidified air which is supplied by saturators. Because the waste energy of the fuel cell is not sufficient to power the turbochargers, a supplemental burner is required to supply energy to the turbocharger.

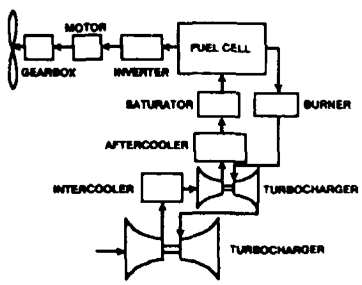



**Figure 8. Fuel Cell Propulsion System**

**5.2 Fuel Cell Tankage**

The PEM cell uses cryogenic hydrogen and air to generate power. International Fuel Cells[12] have examined the tankage requirements and found that tankage weights, based on air vehicle technology, varied between 1.0 lb. [.45 KG] of tank per pound of H2 at current technology levels to 0.25 lb. [.11 KG] of tank per pound of H2 with advanced technology.

**5.3 Advanced Fuel Cells**

High temperature fuel cells offer the potential of high thermal efficiencies and the use of hydrocarbon fuels; however, they are in the early stages of development and may not be viable options for use before the turn of the century. Allied Signal reports that EPRI/GRI Workshop on Fuel Cell Technology R&D indicated that the performance potential of Solid Oxide Fuel Cells could reach 55 to 59%.

**6.0 HYBRID-ELECTRIC PROPULSION SYSTEMS**

A hybrid-electric system, shown in Figure 9, has been considered as a potential step in developing a fuel cell powered vehicle. This system uses a turboshaft engine or a set of turbochargers and an IC engine to drive a generator which supplies 270 VDC electrical power to an inverter and electric motors which drive a fan/propulsor. The propulsion system efficiency is lower than that of turboshaft or IC engine system due to the electrical losses in the generator, inverter and electric motor. These losses will vary as shown in Table 2:

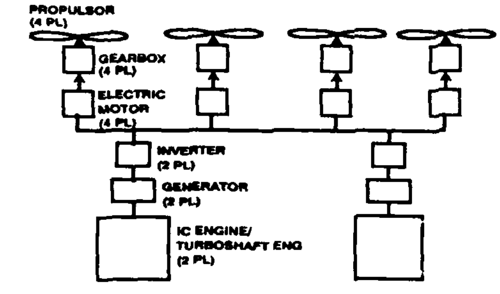



**Figure 9. Hybrid - Electric Propulsion System**

**Table 2. Electrical Component Losses for a Hybrid-Electric System**

| COMPONENT | LOSS |
|---|---|
| Generator | 2 -4% |
| Inverter | 8-15% |
| Motor | 2-4% |

Gonhalekar, et al.[13], have studied a variable speed electric drive in combination with a propeller for HALE operations. Their analyses has shown that the variable speed capability of the electric drive allows the propeller to be operated in a narrow high efficiency region throughout the loiter segment. The power transmission efficiency with a propeller and a variable speed electric drive was 26% higher than the efficiency with a propeller and a single speed gearbox and 20% higher than the efficiency with a propeller and a two speed gearbox. They cited a weight penalty of 1.8% of vehicle weight for the electric equipment.

In addition, the electric drive system uncouples the propulsor from the engine allowing the use of multiple small propulsors and providing significantly enhanced control authority during engine out operations. In the event of an engine failure, power from the remaining generator can be routed to all the propulsors.

**7.0 THERMAL MANAGEMENT SYSTEM**

The heat exchanger system for a HALE vehicle must provide cooling for the engine or fuel cell, avionics and for the turbocharger heat load (consisting of the intercooler and aftercooler heat) if applicable. As shown in Figure 10, the heat exchanger load for a gas turbine is markedly less than the heat exchanger load for a IC engine. There are also significant differences between IC engines; the heat exchanger loads for spark ignition engines will be significantly less than for rotary or Diesel engine systems. Because the heat must be rejected to low density ambient air, HALE heat exchangers will be large and heavy. Patel and Lents[14] showed an optimized system for a HALE vehicle would weigh approximately 2.7% of takeoff gross weight.

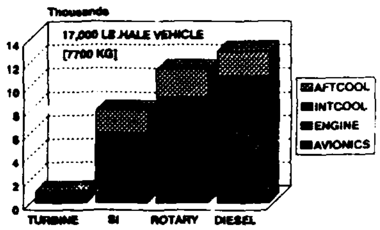



**Figure 10. Heat Load for HALE Vehicle**

Patel and Lents[14] have examined a number of cooling options have been examined for handling the heat load. These include conventional systems which reject all their waste heat to ambient air through ram air or wing mounted heat exchangers. Figure 11 shows a single loop thermal management system. In this system heat from both the low temperature loads (the avionics and turbomachinery) and the engine heat are rejected in one loop. Dual cooling loop systems reject heat from the low temperature loads in one loop and engine heat is rejected in a second.

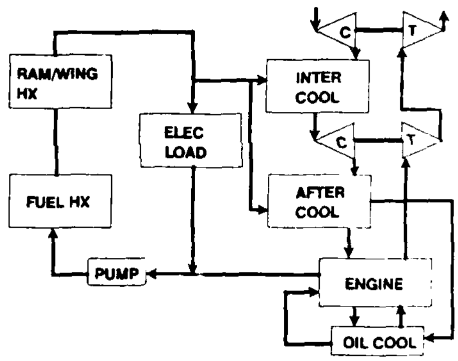



**Figure 11. Single-Loop Thermal Management System**

A co.. .ptual alternative to the conventional sy:tem is the addition of a v. .e heat recovery (WHR) system to the conventional system shown schematically in Fig. e 12. In this system part of the waste heat is converted by a Rankine bottoming cycle into electricity which can be used to power the avionics.

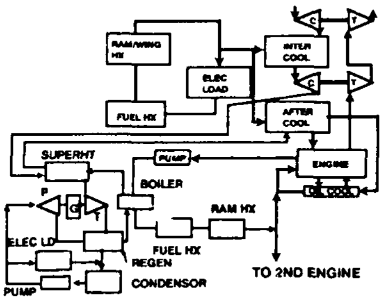



**Figure 12. Waste Heat TM System**

The Rankine cycle loop collects waste heat from the engine(s) and uses a portion of it to evaporate a refrigerant in a boiler. The refrigerant is then superheated by hot air from the turbocharger. The superheated air expands through a turbine converting its thermal energy into mechanical energy. The turbine drives a generator producing electric power. The fluid subsequently passes through a condenser and then returns to the boiler.

This reduces the power extraction from the engi.. and improves the endurance of the vehicle.

Nagurny[15] examined conventional and waste heat recovery systems for HALE vehicles with gasoline powered spark ignition engines; he found that a vehicle using a waste heat recovery system can achieve an endurance gain of up to 7% over a vehicle with a conventional heat exchanger system. Patel and Lents[14] extended this analysis to include rotary and Diesel engines as well as spark ignition engines. Their studies confirmed Nagurny's benefits and showed slightly larger gains for the rotary and Diesel engines.

## 8.0 CONCLUDING REMARKS

A number of near-term propulsion systems have been identified for high altitude application. Selecting the best propulsion system for a high altitude long endurance mission will depend strongly on factors such as mission definition, payload requirements, propulsion system reliability and overall mission reliability. Turbofan engines provide a simple option of getting to a moderate altitude for a short duration mission with little development risk. But, for true HALE missions, a propulsion system is required. Intermittent combustion designs (two-cycle and four-cycle reciprocating engines and stratified charge rotary engines) with their associated turbochargers can achieve greater than forty percent thermal efficiency and acceptable system reliability with moderate to minimal developmental risk. Continuous combustion designs (turboshaft gas turbine systems with intercoolers and/or recuperators) can also achieve these efficiencies with moderate t minimal developmental risk.

But, for the HALE designer, even greater efficiencies can be obtained with increa.ing developmental efforts. Near-term fuel cell systems (with their associated turbochargers, supplemental burners, humidifiers and unique tankage requirements for hydrogen fuel) have been shown to provide up to forty-five percent efficiency. Waste heat recovery systems using thermal bottoming cycles offer up to seven percent additional endurance over convention thermal management systems. Variable speed electric motors can allow propellers to operate in a narrow high efficiency region thereby significantly increasing overall power transmission efficiency. And, advanced fuel cells have the potential of exceeding fifty-five percent thermal efficiency. Although successful development of these technologies is in no way assured, and work to bring them to fruition remains considerable, their potential cannot be ignored.

## 9.0 REFERENCES

1. Allison Gas Turbine Division of GM, "HALE Advanced Propulsion Studies," Final Report NADC contract N62269-90-C-0039, May 1991.

2. Rodgers, C., "High Pressure Ratio Intercooled Turboprop Study," ASME Paper 92-GT-405, June 1992.

3. Boeing Defense & Space Group, "Advanced System Propulsion Studies," Final Report NADC contract N62269-90-C-0034, February 1991.

4. Kolden, J. J., W.J. Bigbee-Hansen and [illegible], "A Compact, Intercooled and Regenerated Gas Turbine for HALE Applications," ASME Paper 92-GT-[illegible], June 1992.

5. Wilkinson, R.E. and R.B. Benway, "Liquid Cooled Turbocharged Propulsion System for HALE Applications," ASME Paper 91-GT-399, June 1991.

6. Ricardo Consulting Engineers Ltd, "Study to assess the feasibility of a Two-Stroke Turbocompound Diesel Engine for a High Altitude Long Endurance Propulsion Unit," Final Report Ricardo DP91/0106, February 1991.

7. Jackson, N.S., N.J. Owen and T. Mc[illegible], "The [illegible] Valve Two Stroke Diesel--A Practical HALE [illegible]," Oral Presentation at ASME Gas Turbine and Aeroengine Congress and Exposition, Cologne, Germany, June 1992.

8. Teledyne Continental Motors, "Advanced Propulsion System Studies," Final Report NADC contract N62269-90-C-0040, February 1991.

9. John Deere Technologies International, "Advanced System Propulsion Studies," Final Report NADC contract N62269-90-C-003, March 1991.

10. Bentz, J.C., "Fuel Cell Powered Electric Propulsion for HALE Aircraft," ASME Paper 92-GT-404, June 1992.

11. AeroVironment Inc., "Advanced Electric Propulsion System Study," Final Report NADC 92005-60, January 1992.

12. International Fuel Cell Corporation, "Investigation of Fuel Cell Power System for Aircraft Electric Propulsion," Final Report NAWCADWAR 92014-60, March 1992.

13. Gonhalekar, Vijay, Darius [illegible] and Stanley Drasky, "Electric Propulsion [illegible]," Batelle Technology Corporation Document [illegible], 13 February 1993.

14. Patel, R.S. and C.E. Lents, "Optimal Thermal Management System for HALE UAV," ASME Paper 91-GT-336, June 1991.

15. Nagurny, N.J., "Waste Heat Recovery System for High Altitude Application of Liquid Cooled Piston Engines," AIAA Paper 87-2114, July 1987

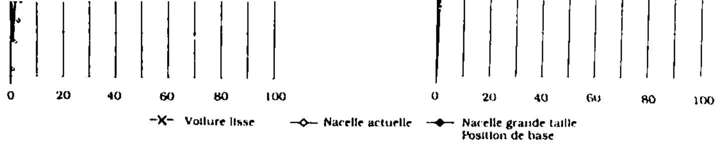



Figure 35



**PROPULSION SYSTEM TECHNOLOGIES FOR LONG RANGE AND LONG ENDURANCE AIRCRAFT**

by

**K.R. Garwood**
Rolls-Royce plc
P.O. Box 3
Filton
Bristol BS12 7QE
United Kingdom

## INTRODUCTION

The NATO requirement for increased range and endurance of aircraft is also associated with the necessity to reduce the initial and life cycle costs of these aircraft. Consideration of these conflicting requirements leads to the prioritisation of engine technologies for different vehicle types and presented here are views of engine manufacturers addressing these challenges over the range of aircraft.

Traditional views of engine optimisation are being challenged by the growing acknowledgement of limited budgets and questions of affordability. No longer can the engine producer rely on thrust and specific fuel consumption being the main design drivers in the engine. It is necessary to balance those traditional technology comparators with at least equal consideration being given to reliability, maintainability and operability. Initiatives such as R&M 2000 and ENSIP have created a change of culture in the engine design houses throughout the western world with maintenance and overhaul easements being made at the design and development stage. Complimentary programs such as Integrated High Performance Turbine Engine Technologies (IHPTET) are progressing the basic improvements on component efficiencies, cycle improvements and efficient and effective design methods utilising advanced high specific strength or high temperature materials. By the nature of Technology Demonstration Programs (TDP's), a high degree of testing, design verification and lifing methodology of integrated components in real engine environments is established. This leads to a more secure and realistic database for the components when committed to a production engine design. Such understanding leads to a more rapid maturity of the propulsion unit, which has significant benefits on the reduction in unscheduled removals and in-flight shut downs, with the resultant advantages for the operator of early reliability. This has an additional advantage since such reliability of product minimises the financial outlay required in the early days of introduction to service, at a time when finances are best focused to the procurement of the required fleet numbers.

The above factors all contribute to the design of propulsion units for air vehicles operated by the NATO armed forces. This paper will discuss the prioritisation of technologies required for the range of air vehicles and examine how increases in endurance and range affect the balance of technology within each propulsion unit type. It is convenient to group the vehicles in the following way:

- Transport, Tanker, AWACS
- Maritime Patrol,
- Combat, and
- Special purpose

Each grouping has the challenges of range or duration subject to its class, although clearly in absolute terms the range of transport vehicles is significantly different from that of a combat aircraft. It is primarily these differences in the groupings that give rise to the differences in technology prioritisation.

## TRANSPORT, TANKER AND AWACS

This grouping of air vehicles is characterised by their size and flight pattern. Under most circumstances even during times of conflict, the majority of their flight can be achieved at altitudes and mach numbers best suited to the achievement of greatest range or endurance of the aircraft.

Transport aircraft are ideally required to operate out of semi-prepared runways, with adequate size and volume and minimal journey time. Being a workhorse of the forces only minimal logistics support is wanted for these vehicles, their purpose is to maximise the delivery of goods and men for combat, and any significant support systems such as fuel, oil, parts or mechanics required by these aircraft detract from their prime purpose. As concepts such as Rapid Deployment Forces are adopted so improvements in carrying capacity are required.
These can be achieved in two ways:

- Same fleet size and container volume with reduced flight times
- Increased container volume or fleet size

*Presented at an AGARD Meeting on 'Recent Advances in Long Range and Long Endurance Operation of Aircraft', May 1993.*

As deployment range increases due to the nature of perceived future conflicts so flight speed becomes more dominant in the balance of time to deploy the required equipment. This is driving the transport vehicle away from the propeller driven 250kts vehicles towards the high bypass ratio 500kts vehicles.

Such increases in flight speed bring benefits to the whole operation, not just by reduced time to deploy but also by minimising crew and personnel fatigue, and reducing the probability of double crews with associated infra-structure costs.

Operation of in-flight refuelling tankers and Airborne Warning and Command Systems aircraft is very similar in style. Aircraft are deployed from safe runways with no limitations on runway length, position in convenient and safe airspace, maintain station for required time then return to base in safe airspace. This requirement is to deploy from base to station in minimal time, to be able to reposition in minimal time, but then hold station for maximum duration. Such requirements are ideally met by the high bypass ratio engines of today's civil aircraft.

The key requirements of such high bypass ration engines are

- meet the thrust requirements
- high reliability
- high performance retention
- long life
- adequate fuel burn

with these to be achieved at the right unit and certification costs.

## MEETING THE THRUST

Aircraft configurations for the Transport/Tanker/AWACS group tend to utilise 'podded' engines similar to civil airliners. This allows greater degree of freedom in design changes than a combat aircraft where the engine(s) are buried in the fuselage, with structural frames in very close proximity. In general, the thrust requirements can be readily achieved. Engine sizing tends to be at the hot and high take off/climb out condition with most other engine ratings causing less distress to the engine. The choice between two and four engines also tends to conflict in engine designs. Twin engined aircraft are required to continue take off and climb out with one engine not functioning, and likewise four engined aircraft have to be able to continue take off and climb out with one engine inoperative. Such margins of thrust reserve lead to the four engines aircraft utilising higher throttle settings at their cruise condition and consequently consuming more turbine life than an equivalent twin engined solution!

## RELIABILITY

The operator sees reliability in two clearways (Figure 1). First in-flight shut down rates indicate annoying but mechanic fixable problems without having to change the engine. Such problems are usually associated with external dressings, electrical harnesses and sensors. With adequate and responsive timely changes made to the productionised engine the classic 'learner curve' should be invisible to the operator. There is clear evidence from civil operations that this has not necessarily been the case. However, with twin engine large aircraft becoming more widely used, the airframer and engine manufacturers are forced to work even more closely together such that the aircraft can quickly be certified for extended time and range operations.

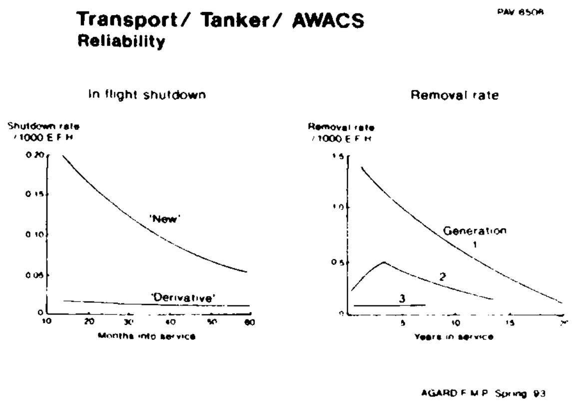



Figure 1.

This gives such substantial commercial advantages to the operators who then can utilise EROPS in their flight schedules. The commercial pressure to achieve this is causing reliability to play a key role in the design of the engine, control system and aircraft interfaces. Such understandings are available for rapid application of these types of engines to Military usage in the Transport/Tanker/AWACS aircraft.

Reliability is contained in the engine design in many facets. These can be considered in the three stages of the productionised process. Firstly, there is reliability by concept. This is achieved by basic system architecture. For turbomachinery components, the use of wide chord blading has significantly improved reliability by concept. In like manner engine control units, now essentially Full Authority Digital Engine Controls (FADECS) need built into them the logic of spurious signal suppression from sensors and electro magnetic interfaces, reversionary control and the essential computer to computer, sensor to sensor and actuator to actuator signal comparisons.

Reliability by application brings into question the way in which engines are designed to achieve their conceptual performance.

This involves such things as knowledge of the margin between peak stresses and temperatures and those sustainable by the material. In recent times, advanced aerodynamics and structural computational models have made great advances to the inherent reliability by application with greater inside and understanding being gained in early phases of the design process. It must however, be acknowledged that engineering judgement must still be made despite the complexities of computer codes. Such capabilities are but one spanner in the propulsion engineers tool box and should not be seen as the unique and perfect answer. With the introduction of greater process control and measurement during the manufacturing process, along with process modelling improvements in consistency in parts have been realised. This reduces the randomness of failures and has contributed greatly to this facet of reliability.

Reliability by development builds on the two prior forms of reliability, those of concept or application. In this stage realistic testing is required to identify weak points in designs either by concept or application, and ensure realism to the way in which the product will be used in service.

The quality of this reliability improvement is realised by the maturity of the product when actually used by the operator. Engine companies are tending to adopt Technology Demonstrator Programs to give early and realistic indications of the reliability challenge associated with upgraded or new engines.

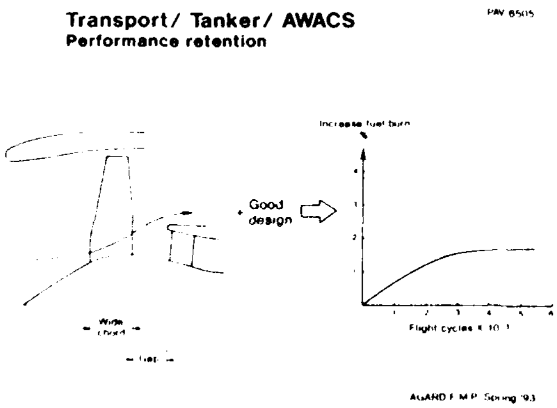



Figure 2.

Performance Retention

In order to consistently fulfil the roles required of this group, performance retention, particularly with respect to specific fuel consumption is of high priority. Design features that limit the ingress of debris into the core engine offer significant advantages (Figure 2) by minimising erosion of the aerofoils.

Associated with this must be sub systems that are tolerant to the axial and radial excursions that the rotating spools make during throttle movement and flight induced loads. In particular, increases in blade and vane clearances are the normal major performance loss mechanisms once an engine has been configured. Special effort is made in the design and development phase to compensate for those movements. Two types of tip clearance control are in common usage today and they are passive thermal matching or active control. In passive thermal matching the growth rate of the static members is thermally matched to the thermal growth rate of the rotating member. However, spool speed variations are faster than their thermal movements and this does not permit the absolute minimum clearances to be set. Such systems do however have the advantage that they consume no additional high energy air and require no control system and valves to be effective. The alternative system is the active clearance control. This system uses air tapped off the relevant stage of HP compressor and by a series of valves and circumferential pipes pumping air onto the outer skin of static members in clearance areas.

It has the advantage of being able to close clearances to their minimum during steady state conditions, but must be able to respond in adequate time to throttle and flight inducted variances in clearance. Recent developments in this field are using sensors to measure the running clearances and adjust the air flow rate, hence modify the cooling and shrinkage of the static member. Over a limited radial height this also serves to reduce performance loss, although system reliability, which should not be made flight critical, is degraded with this type of clearance control.

Inside of the gas path, the secondary air system is reliant on the distribution of small quantities of air to strategic areas of the engine, the retention of oil/air mist in small volumes and the balancing of bearing loads by pressure loads. Such systems rely on the maintenance of good seal performance between the overhaul lives of the engines. It is not feasible to consider active clearance control for these features and compliant systems such as brush seals are being rigorously pursued. The other major feature which causes rapid performance deterioration is the ingress of water and hail from atmospheric conditions. These have the effect of significantly changing the thermal matching of the rotors and statics with a subsequent after rainstorm increased clearance, due either to blade length reduction or wear of abradable coating. Design detail of the front of the engine which aid the removal of dirt from the core is also helpful in removal of water and ice.

Some airborne dust is of such size (3-10 micron) that it does not act ballistically but follows the path of the air. Such dust is prevalent in certain areas of the world, and the time of year, type of dust, and anticipated dispersal paths are reasonably well known. By choice, these areas would be avoided but in the military operation, they may well have to be encountered.

Since the dust remains airborne and is silica by composition, it has two main effects. Firstly, that which goes through the main gas path can then be adequately heated to glasify and form a coating typically on the HP turbine nozzle and rotor leading edge. Secondly, some will enter the HP turbine cooling air feed system. This dust may then glasify, and accrete onto the internal surface of the blade. This can result in very short life blades since they are attempting to operate with reduced cooling flow but worst heat transfer coefficients. Usually transport engines are of sufficient size to be able to minimise such effects, but the internal accretion is feature dependent and the design needs to acknowledge the requirements to operate in this hostile condition.

Long Life

There are really two facets of life to the engine. Firstly, the most obvious is the total design life of the component and secondly the inspection period required to ensure that life. As may be anticipated the key areas for life limiting parts as the HP turbine blade, disc and the combustor. These components suffer the highest temperatures, pressures and densities in the engine and are subject to cyclic usage. Each part will have a declared life, which is normally on a statistical basis and is built up progressively via safe inspection periods. Critical parts, such as HP turbine discs are usually assumed to generate a surface or sub-surface defect during the first flight cycle after each inspection. The period of time between inspections is then based on flight or throttle cycles, disk design style and the material properties of the disc at operating condition. This has given rise to lifing methods based on crack propagation and in some regions of the disc of crack propagation with dwell imposed in the cycling of the disc.

Such measurements of material properties are expensive to make and difficult to simulate. Significant differences can be found by changes in rate of loading, dwell time verses relax time and duration of cycle. To the operator the most important aspect is more likely to be how often he needs to strip the engine for inspection and not necessarily on absolute life component. Turbine blades and vanes and combustors are more easily inspected without necessitating engine removal. This is achieved by use of boroscope ports at various locations through the engine.

Under normal circumstances, the compression system will last the life of the engine. Localised damage from ingested hard foreign objects can usually be dressed out of the damaged blade, which is usually limited to the front three rows of the compression system. The fan rotor blade, being the first aerofoil and having the highest velocity is subject to the maximum probability of damage. Recent designs have allowed for 'in field' replacement of seriously damaged blades and in-situ balancing procedures have been made viable thus eliminating the strong out-of-balance forces that would potentially damage both the engin and its mounting system.

Fuel Burn

The competitive field of the civil operated high bypass ratio turbo fan ensures that each engine manufacturer is capable of similar fuel burn, particularly when considering the fuel consumption after a few thousand flight hours. By comparison to the previous discussions on reliability and life then the equitable situation of fuel burn brings this technology low down the list. There have been engine demonstration programs of significantly reduced fuel burn configuration, with implicitly range and endurance enhancements, such as the variable pitch fan (ducted) by Rolls-Royce, the UDF (unducted fan) by General Electric and the Advanced Ducted Propulsor by Pratt & Whitney. Each of these have fuel burn merits but failed to gain acceptance by the airframe community. They must therefore be considered as immature solutions against a requirement that is dominated by reliability and cost.

**MARITIME PATROL AIRCRAFT**

These aircraft are characterised by the requirement to operate in all weathers from prepared unrestricted runways, journey out to position on minimum time, then maximum time on station at very low engine power setting and low altitude and return at optimum speed. Dependant on the flight distance to station so the idealised choice of propulsion unit changes from propeller driven for relatively close range, to the higher bypass ratio turbo fan for the greater radius of operation. Since the loiter thrust is such a small proportion of the required take off, and normal in flight thrust requirements, so the currently adopted practice of selectively shutting down one or more of the engines in a multi-engined aircraft would appear very effective. The adoption of such a practice to minimise thrust and fuel flow could not be matched by enhanced cycle and component efficiencies. The real challenge to the engine designer is not so much in performance, but in the protection systems against the corrosive attack by salt water. The presence of salts in the turbine region can dramatically alter the declared life of the component, since temperatures are achieved that permit infiltration and chemical change within the blade and disc alloys.

Some re-alloying and/or surface protection coating development is usually necessary to accommodate this hostile environment.

Regardless of the idealised propulsion unit characteristics, it must be recognised that the maritime patrol aircraft, in common with the AWACS carries equipment and sensors that are far more expensive than the typically military aircraft. The purpose of the aircraft is purely as a platform from which such equipment can work, and although both airframers and propulsion engineers can clearly see improvements that can be made to their parts of this system, it is usual that a pragmatic economic solution is found which is not driven by the technically elegant solution.

## COMBAT AIRCRAFT

One of the major differences between combat aircraft and those discussed in the preceding scheme is the wide range of operations - altitude, flight mach number - and the fact that for operational reasons they are forced to operate in areas of their flight envelope where neither the aerodynamics of the airframe, nor the characteristics of the propulsion unit are best for maximising the range or endurance. Each vehicle needs clarity in the design phase of primary and secondary roles and their relative weightings. Combat vehicle propulsion however can be ordered in the following way:

- adequate reheat and dry thrust
- fuel burn balanced over mission type
- high reliability
- long time between inspections
- stability and performance retention

Differently from the Transport/Tanker/AWACS and maritime patrols, the combat engine tends to be more highly integrated with the airframe, reducing the economics of alternative engine installations within the same airframe.

In Figure 3 a typified supersonic combat vehicle with wing loading selected as a compromise between high and low altitude operations and subsonic turn capabilities is shown. For maximum range and endurance the majority of flight should occur at 0.9 mach number and 27,000ft altitude. Operationally such an aircraft is likely to be flown in conditions such as supercruise (i.e. 1.4 Mach No. Trop & dry engine) or 0.9 Mach Number, 200ft, dry and reheated. Such operational requirements are reducing the range of the aircraft by between 40 to 60% relative to what could be achieved by the same aircraft, engine and weapons fit when flown at optimum condition.

Increases in loiter time, where loiter is achieved at close to optimum altitude and flight mach number are primarily achieved by increased fuel tankage in the aircraft, although as this condition becomes a greater proportion of fuel burn so the optimum cycle pressure ratio, the bypass ratio, and the component efficiency requirements all start to rise. This must be weighed against the performance of the whole machine in the combat phase of its mission. In general the combat phase dominates the loiter in terms of priorities since it is ultimately the most important phase of the flight.

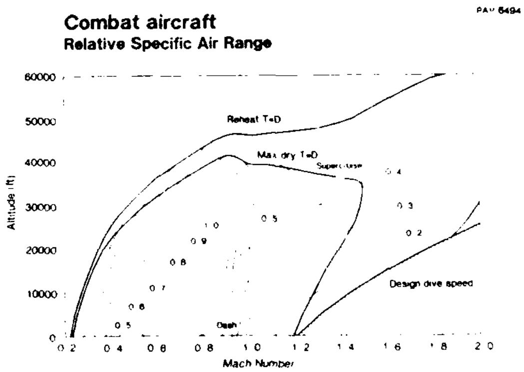



Figure 3.

Concepts of propulsion with various degrees of variability either by cycle or component match via adaptive engine controls are under current developments. Their target is to be able to optimise the engine performance to a significantly better level than could be achieved with "fixed" engine with the same combat capabilities. A range or endurance improvement will then result. Such propulsion characteristics are more dominant in the design phase of a new platform where considerable size and weight savings can be made than where an aircraft is already configured and only propulsion unit changes are made. Figure 4 shows how, with a new aircraft, new engine combination the overall weight hence unit size and cost for future more capable combat aircraft can be contained to acceptable levels by the advances in propulsion technologies that are actively being pursued within the NATO countries.

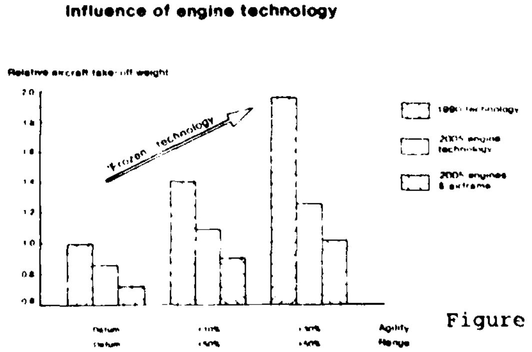



Figure 4.

## Life Consumption

Within the scope of the combat vehicle there are the two major facets of combat capability and range capability. As combat capability increases so the aircraft thrust:weight ratio tends to rise, and hence the loiter thrust requirement is proportionally smaller. Without advances in propulsion system efficiencies the range of these more agile vehicles would be significantly reduced, which is contrary to requirement. Two types of range enhancements are currently considered, they are the increased use of subsonic near optimum cruising, and the use of supercruise. This diversity leads to different challenges within the engine, particularly in the utilisation of life in the hot section of the engine. These different modes of operations can radically change the inspection period and the projected life of these parts.

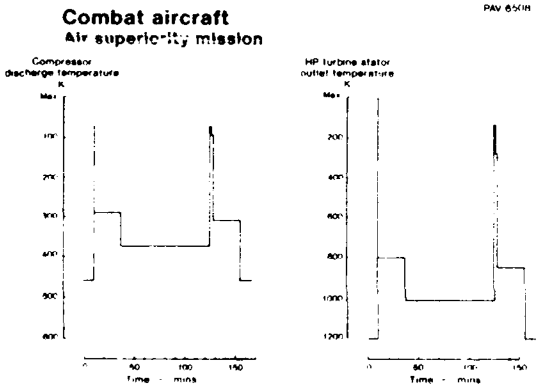



Figure 5.

In order to illustrate differences a model of an advanced combat aircraft has been used to synthesise two mission profiles; that of a long range interceptor and that of air superiority. Figure 5 shows the compressor discharge and the high pressure turbine temperatures for an air superiority mission.

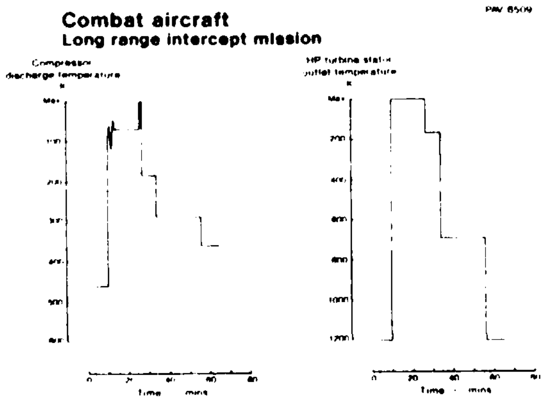



Figure 6.

This same aircraft configuration has then 'flown' a (European) long range interception mission and the same temperature/time histories are show in Figure6. The combination of compressor discharge, ie blade cooling flow supply temperature, and turbine temperature can then be used to assess the level and duration of likely thermal damage to the HP turbine rotor blade. The resulting potential damage time history in Figure 7 shows clearly the differences between the missions. Air superiority has two damage times, one at take off and the other at combat. Although the elapsed mission time is the order of $2\frac{1}{2}$ hrs, damage time is limited to approximately 3 minutes. Conversely, the long range interceptor with supercruise to target mission has a duration of 1 hr, and a damage exposure of over half that time.

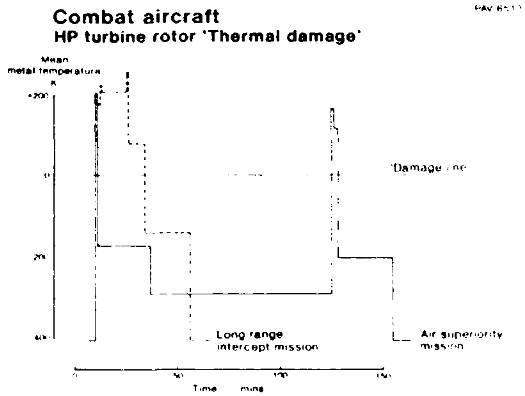



Figure 7.

Life variations with missions have always been noted but what is new here is the extended use of high power settings required for the supercruise requirement, which is similar to the life consuming operation of the I.D.S. Tornado fleet. These differences in usage lead to the necessity to re-alloy the turbine blade material such that the balance of creep resistance, oxidation resistance and thermal/direct stress damage are satisfactory for the type of missions required to be flown, and the blade life and inspection periods are consistent with the requirements of operational readiness and life cycle costing.

## SPECIAL VEHICLES

In this group of vehicles the dominant feature is capability. Cost, although a consideration comes a poor second. Special vehicles exist to give strategic or tactical advantage to enable an ultimate win situation. At this time such vehicles tend to be either very high speed or very controlled on all forms of signature. For the propulsion engineer the high speed vehicles give the greatest challenges.

Firstly, just as in the combat supercruise vehicles use is made of high throttle settings at high inlet temperatures. This is a life consuming situation and some degree of bleed flow network compromising is usually required to restore life at the expense of optimum performance.

When flying at the high mach numbers skin heating can be controlled by using the fuel in the tanks, pumped to the hot areas then on to the engine. On occasions the engine fuel flow is not high enough to consume all of the fuel so pumped, with the unused fuel returned to tank. Over an extended period of time the tank temperature will have elevated to a point where inadequate skin cooling can be affected. Studies are in hand on Endothermic fuels which will store more heat energy than previous fuels. With hot fuel the next section of the propulsion unit liable to difficulties is the fuel system components. Development work on higher temperature seals and improved lifing at elevated temperatures for these components are necessary activities.

Oil and lubrication systems of the high speed vehicles are always areas of concern. In an engine for lower speed flight oil is often cooled in the bypass stream air. This prevents the progressive build up of temperature in the lubrication system which can eventually lead to premature coking in oilways and the potential of air/oil mist flash fires. As flight mach number is increased, and endurance at that mach number so the sink to which the oil can loose its temperature becomes more limited. These considerations have given rise to the search for the higher temperature oils. Currently oil is capable of long lives up to 200 to 250° for conventional oils, and up to 450° for unconventional. Unfortunately this high temperature oil is a solid at room temperatures which brings very limiting operating procedures should such oil be necessary. Ideally a 50 to 100° increase in oil temperature capabilities with normal operational procedures would be of significant benefit to such vehicles.

## CONCLUSIONS

A review of the propulsion system technologies for long range and endurance aircraft has indicated some of the priorities that should e addressed when developing these units. There is a difference in the order of technologies between different operational requirements. Transport type vehicles would best be powered by minor derivatives of civil airlines, bringing with them the benefits of longevity, reliability and a worldwide technician infrastructure. As range is increased and deployment time reduced so the need to increase flight speed becomes inevitable.

Combat aircraft with increases in range or endurance will, without adoption of advanced propulsion systems, become larger, heavier and significantly more expensive to own and operate. The currently favoured supercruise consumes turbine and hot section lives considerably faster than cruise at optimum aircraft altitude and speed.

Special vehicles with sustained high flight mach number are challenging the capabilities of fuels and oils, both from a thermal capacity and system operating viewpoint.

# The STRATO 2C Propulsion System
# A Low Cost Approach for a High Altitude Long Endurance Aircraft

H. Tönskötter

Industrieanlagen-Betriebsgesellschaft mbH
Einsteinstraße 20
8012 Ottobrunn
Germany


## SUMMARY

For the STRATO 2C - a High Altitude Long Endurance Research Aircraft - a low cost propulsion system was designed and is now under development.

The approach to achieve the aim of low development, procurement and in-service costs is a compound propulsion system based on a highly supercharged liquid cooled piston engine with charge air inter-cooling and the extensive usage of available components.

The concept of the propulsion system and the main components are described. Aspects of controlling the three-stage turbocharger system are discussed. The way how to realize the power plant in three years is presented and the test program is addressed.


## 1. INTRODUCTION

The STRATO 2C is a High Altitude Long Endurance Aircraft which is developed by GROB* on behalf of the German Ministry of Research and Technology. The aircraft will be operated by the DLR** and is part of a stratosphere research program.

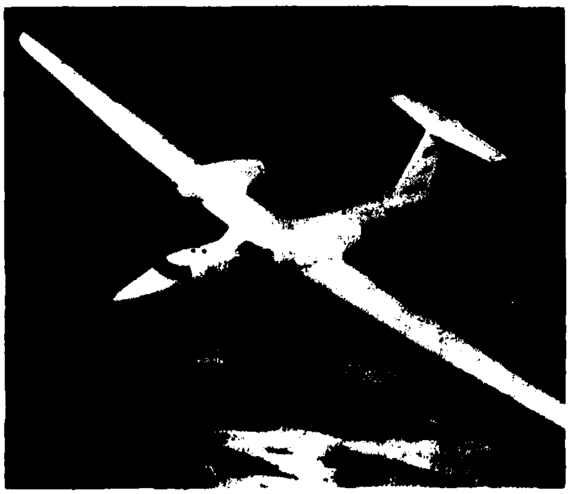


Fig. 1: STRATO 2C

The STRATO 2C has a takeoff weight of about 12 000 kg and a wing span of 56 m. The pressurized cabin is designed for 2/3 scientists and provides maximum flexibility with respect to the installation of measuring equipment and to the performance of research work during high altitude long endurance missions. The aircraft is powered by two 300 kW compound engines installed in nacelles above the wing driving two 5 bladed propellers in a pusher configuration (Fig. 1).

The aircraft is designed for a cruise of 8 hours at 24 km and at Mach 0.5 with a range of 7000 km without refuelling or 48 hours at 18 km altitude (Fig. 2).

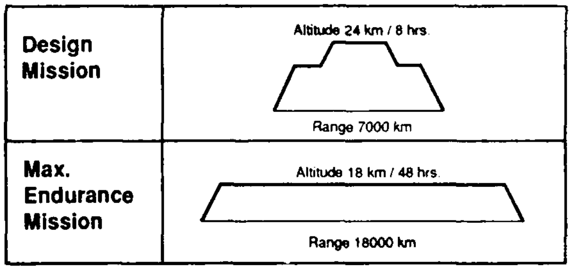



Fig. 2: Mission Profiles

## 2. STRATO 2C PROPULSION SYSTEM

During the concept phase various propulsion systems have been evaluated. The result was, that the compound engine as described below is the most suitable one (Ref. 1).

The term "compound engine" is used for this propulsion system as the 300 kW piston engine is combined with the gas generator of a 2000 kW turboprop engine which serves as a turbocharger and provides an additional jet thrust of about 12 % of the propeller thrust.

---

* BURKHART GROB Luft- und Raumfahrt GmbH & Co KG, 8939 Mattsies

** Deutsche Forschungsanstalt für Luft- und Raumfahrt e.V., Köln

*Presented at an AGARD Meeting on 'Recent Advances in Long Range and Long Endurance Operation of Aircraft', May 1993.*

## 2.1 Propulsion System Concept

Initial studies showed that the requirement of low cost, low risk and short development time can only be met by the extensive usage of available mature components. Therefore, a liquid cooled Teledyne Continental piston engine and a Pratt & Whitney Canada PW127 gas generator were choosen as the main propulsion system components.

The propulsion system consists of two major propulsion groups.

The first group consists of the piston engine with a standard turbocharger, the reduction gearbox and the propeller. This system is controlled by three levers (propeller speed, manifold pressure and fuel/air mixture) which are operated by the pilot. A standard hydraulically driven exhaust wastegate controls the turbocharger. Hence, during takeoff and landing and up to about 7 km flight altitude the propulsion system works like a conventional piston engine with propeller.

For higher altitudes the second propulsion group - the LP charger - is switched on. The LP charger provides charged air at a pressure that allows the piston engine to maintain 300 kW shaft power up to about 24 km. This propulsion group is controlled by a new digital control unit and provides an additional thrust of about 12 % at design altitude. The LP charger has its own oil system and integrated charge air coolers and is installed at the front of the nacelle. The inlet can be closed to avoid FOD and icing problems.

Fig. 3 shows the propulsion system and the arrangement of the components.

## 2.2 Propulsion System Components

*Piston Engine*

The piston enigne is a certified Teledyne Continental Motors (TCM) TSIOL-550-A direct drive liquid cooled opposed cylinder engine with a displacement volume of 9 litres and a compression ratio of 7.5:1. This engine provides 260 kW at 2700 rpm. For STRATO 2C the engine operates at 3100 rpm to provide 300 kW shaft power. The engine has the potential of 340 kW at 3400 rpm.

Teledyne was selected as they are the only company offering certified liquid cooled piston engines for aircraft. Furthermore, they offer high altitude experience gained during the Condor program (Ref. 2).

In a pretest TCM demonstrated the performance of the engine and defined the necessary modifications for the high altitude application. The heat of the engine is rejected by a water cooler (Ethylen Glycol/water) and by an oil cooler.

The turbocharger is a standard Garrett unit with increased compressor and turbine capacity compared to the basic engine. The required manifold pressure is controlled by a standard hydraulic system with an exhaust wastegate at turbine inlet.

The capacity of the oil sump is increased for the long endurance mission and the crankcase is pressurized to avoid oil pump cavitation and unacceptable flow degradation. The engine is started with an air turbine starter mounted on the engine. A flywheel and elastomer couplings are integrated in the drive system to reduce torsional vibration.

*Gearbox*

The Gearbox is a new design and is developed by ZF (Zahnradfabrik Friedrichshafen). It is a two-stage gearbox with an integral oil system and drive pads for the oil cooled variable speed DC generator and the propeller governor. Magnesium casting for the gearbox case and a titanium propeller shaft are used to reduce weight.
Turbine oil according to MIL-L-23699C Amend. I is used to improve starting at low temperatures and to cover maintenance aspects (same oil for gearbox and LP charger). A separate gearbox instead of an integral version based on the geared GTSIO-520 engine was choosen as the separate gearbox allows an individual mounting of the gearbox and of the piston engine according to the different stiffness and frequency requirements.

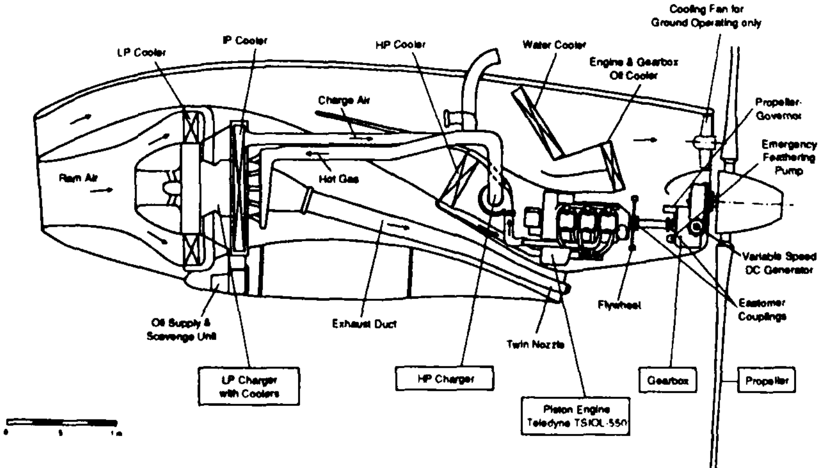



Fig. 3: STRATO 2C Propulsion System

*Propeller*

Due to the low air density at 24 km the propeller has a diameter of 6 m and five light weight composite blades. For the demonstrator aircraft a low risk design featuring a wooden spar and a composite shell was choosen by the manufacturer MT-Propeller, Straubing. The propeller design will be verified in a wind tunnel test under simulated pusher conditions.

Control of the propeller is accomplished by a hydraulic governor which is driven by the propeller gearbox and integrated into the oil system of the gearbox. Due to the very low propeller speed (640 rpm) a conventional feathering system with counter weights is not very effective. Therefore, an all hydraulic system with a separate emergency feathering pump supplied with oil out of a separate volume in the gearbox oil sump is considered.

An originally specified all electrical propeller control system was rejected due to cost reasons.

*LP Turbocharger*

Within the given cost and time frame the development of a new turbocharger was not possible. Therefore, is was necessary to find an available system, which could be adapted to the STRATO 2C application. As the performance of radial compressors is less sensitive to low Reynolds Numbers a two-stage radial compression system was preferred. The biggest and most suitable available system was the gas generator of the Pratt & Whitney Canada (P&WC) PW127 turboprop engine. It is a two-spool gas generator with a radial compressor and a single axial turbine stage on each spool.

Due to the two-spool arrangement and the externally mounted LPC diffuser tubes only limited modifications for the integration of the intercooler (LP cooler) were necessary (Fig. 4).

The original bow diffusers are replaced by straight diffusers connected to a carbon fibre collecting case. To compensate for different thermal behaviour of the

Modification of PW127 Gas Generator

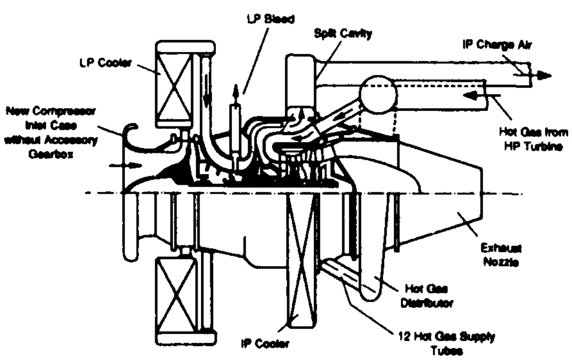



Fig. 4: Modification of PW127 Gas Generator

metal diffuser case and the composite collecting case the new diffuser tubes are partially made of a silicone based rubber material already used in aircraft applications.

To minimize the front area and hence the diameter of the engine nacelle the LP coolers are top and bottom mounted and the IP coolers are side mounted (Fig. 5).

LP Turbocharger System

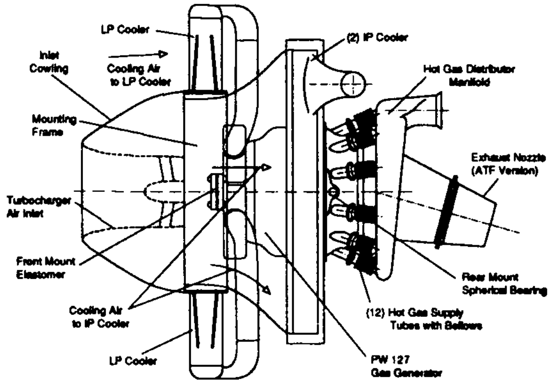



Fig. 5: LP Turbocharger System

The former combustion chamber is divided into two cavities. The air from the intermediate compressor passes the outer cavity and is directed through 14 holes in the gas generator case to the IP coolers (Fig. 4).

The exhaust gas coming from the turbine of the HP turbocharger is distributed in a manifold outside of the LP charger and enters the inner cavity through 12 tubes integrated into the turbine support case. To allow different thermal growth the tubes are equiped with bellows. All hot parts and modifications in the turbine section are made of Inconel 718 and 625.

Compared with the turboprop application the PW127 gas generator operates at lower air (inter-cooling) and lower gas temeratures. Therefore, oil flow to the bearings and turbine cooling flow could be reduced.

To rematch the compressors P&WC has increased the IP turbine capacity by about 4.5 % and reduced the LPT capacity by 12 %.

Due to the low pressure in the bearing chambers at high altitude the blow down oil scavenge system is replaced by individual oil scavenge pumps for each bearing chamber. The oil pressure and scavenge pumps are part of a separate oil unit, which also incorporates the oil tank, the oil filter and the air/oil separator. The design of the oil pumps was verified at IABG in an altitude test facility.

*Heat Exchangers*

A total heat rejection of about 300 kW at an altitude of about 24 km requires very large heat exchangers with a total front area of 3.5 m². Inter-cooling of the charge air is accomplished by air-to-air heat exchangers. The piston engine is cooled by liquid-to-air heat exchangers (Table 1).

(Design Point 23.5 km / M 0.48)

| | | * LP Charge Air | IP Charge Air | HP Charge Air | Engine Water | Engine & Gearbox Oil | LP Charger Oil |
|---|---|---|---|---|---|---|---|
| Number of Coolers | - | 2 | 2 | 1 | 1 | 1 & 1 | 1 |
| Total Heat Rejection | kW | 49 | 53 | 43 | 90 | 55 | 10 |
| Front Area of one Cooler | $m^2$ | 1.28 x .28 | 1.12 x .34 | 1.21 x .50 | 1.12 x .72 | 1.08 x .50 | .50 x .23 |
| Efficiency | % | 74 | 72 | 69 | 84 | 86 | 86 |
| Pressure Loss of Cooling Flow | % | 5.3 | | | | | |

Table 1: Heat Exchangers

The aluminium coolers are manufactured by Behr, Stuttgart. The heat exchangers were optimized taking into account the weight, the front area (nacelle drag) and the pressure losses (drag and exhaust thrust of the LP charger). As the nacelle flow is heated when passing the heat exchangers the internal drag of the nacelle is very low.

## 2.3 Control System

To reduce risk and cost the standard control system of the piston engine is used.

The piston engine is controlled by the pilot versus three levers (propeller speed, manifold pressure and fuel/air mixture). A standard exhaust wastegate at turbine inlet which is operated by engine oil controls the manifold pressure in the air inlet of the piston engine The hydraulic propeller governor at the gearbox adjusts the propeller blade angle such that the required propeller speed is constant.

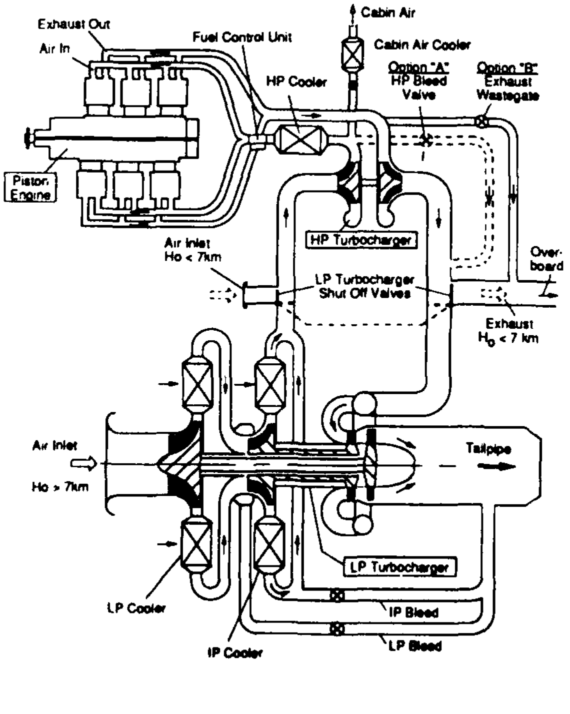



Fig. 6: Turbocharging System and Control

Above the flight altitude of 7 km the LP charger is switched on (Fig. 6).
While the turbine sections of both chargers are controlled by the exhaust wastegate (Option "B") of the HP charger matching of the LP charger compressors is achieved by LP and IP bleed (Fig. 6).

LP charger and oil unit switching on and off, bleed valve positioning and overspeed control is carried out by a new digital control unit. The valves are operated by stepper motors.

Instead of the exhaust wastegate an HP bleed valve (Option "A") can be used to control the turbocharger system. The advantage is that the spool speeds of the LP charger at low altitudes are much higher (Table 2). If the LP charger operates at too low speeds sealing of the bearing chambers may become a problem.

| | Dimension | Design Point | Option "A" HP Bleed | Option "B" Exhaust Bleed |
|---|---|---|---|---|
| Altitude / Mach Number | km/- | 23.5 / 0.48 | 9 / 0.15 | 0 / 0.15 |
| Equivalent Shaft Power (constant manifold pressure) | kW | 334 | 328 | 340 |
| Equivalent Specific Fuel Consumption | g/kW·h | 214 | 236 | 231 |
| Piston Engine Pressure Ratio (cylinder out / cylinder in) | - | 0.90 | 1.10 | 0.84 |
| Total Compressor Pressure Ratio ($\pi_{LPC} * \pi_{IPC} * \pi_{HPC}$) | - | 39 | 4.3 | 4.1 |
| LP Compressor Pressure Ratio | - | 5.8 | 1.6 | 1.2 |
| LPC Corrected Speed | $min^{-1}$ | 29790 | 13390 | 9070 |
| LP Bleed *) | % | 0 | 9 | 11 |
| IP Bleed *) | % | 0 | 22 | 22 |
| HP Bleed*) | % | 0 | 25 | - |
| Exhaust Bleed (wastegate) *) | % | 0 | - | 12 |
| Nozzle Pressure Ratio | - | 3.6 | 1.14 | 1.08 |

*) relative to LP charger inlet flow

Table 2: Comparison of STRATO 2C Propulsion Control Options

On the other hand a power increase e.g. for takeoff and for climb/manoeuvering at high altitudes by operating the piston engine with a rich fuel/air mixture is not possible as afterburning of the unburned fuel downstream of the HP bleed air injection into the exhaust system cannot be excluded.

Although the nozzle pressure ratio of Option "B" is lower at low altitudes, the equivalent shaft power (shaft power plus the equivalent power of the exhaust thrust) is higher and fuel consumption is reduced compared with Option "A". This is because Option "B" provides less throttling to the piston engine at the exhaust side resulting in higher shaft power at constant manifold pressure. Furthermore, the total amount of bleed flow (air & exhaust) is lower.

The operating lines in a typical HP compressor map at given LP and IP operating lines are shown in Fig. 7.

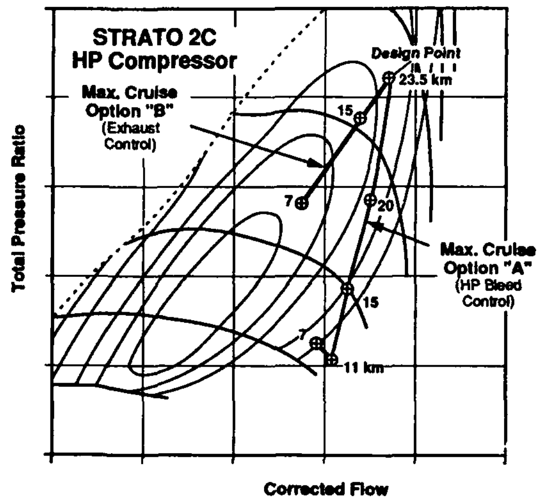



Fig. 7: HP Compressor Operating Lines

## 2.4 Engine Rating

As the propeller is designed for optimum cruise at 24 km the efficiency of the propeller decreases rapidly at low altitudes and low flight velocities. Therefore, a two speed gearbox allowing the propeller to run at reduced speed at low altitudes would be desirable.

To avoid the complexity of a two speed gearbox the potential of the piston engine to provide for a short time the same shaft power at lower speed by increasing the manifold pressure and by rich fuel/air mixture is used for STRATO 2C.

Table 3 shows the engine ratings.

| | Shaft Power kW | Engine Speed rpm | Manifold Pressure bar | F/A Mixture |
|---|---|---|---|---|
| Ground Idle | as necessary | 1200 | as necessary | |
| Takeoff (hot day) | 300 | 2700 | 1.35 | rich |
| Max. Continuous | 320 | 3100 | 1.22 | rich |
| Max Cruise | 300 | 3100 | 1.22 | lean |

Table 3: Engine Ratings

## 3. PROPULSION SYSTEM DEVELOPMENT

The GROB Luft- und Raumfahrt GmbH is the main contractor for the development and the production of the STRATO 2C aircraft (Fig. 8).

IABG is contracted by GROB to design the STRATO 2C propulsion system, to carry out the performance calculation, to define the control schedules and the control system, to integrate the propulsion components, to prepare and carry out the verification testing in the altitude test facility (ATF) and to coordinate the development and the hardware supply of the subcontractors.

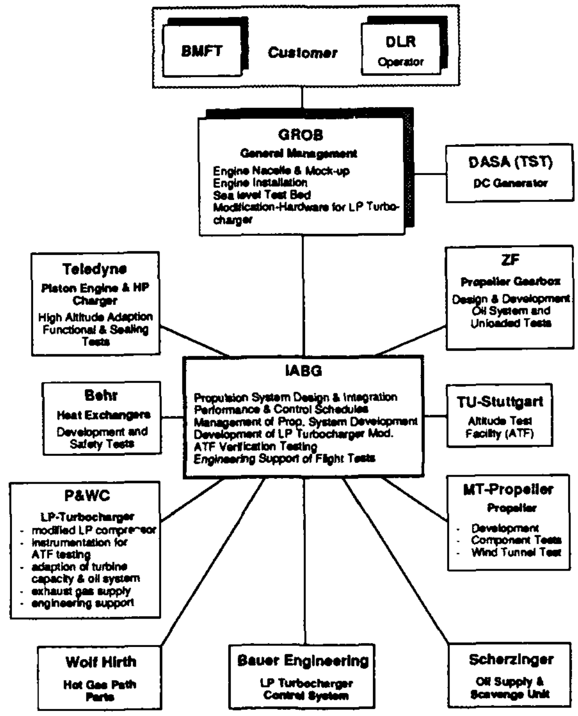



Fig. 8: Organization of STRATO 2C Propulsion System Development

The engine nacelle, the frame for mounting the propulsion components and the hardware that is not supplied by subcontractors are manufactured by GROB. Furthermore, GROB assembles the propulsion systems and carries out the propulsion installation into the aircraft.

As shown in Fig. 9 the development started in May 1992.

The first batch of contracts covers the development and supply of hardware for ATF testing. After the verification of the design by the ATF tests a second batch of contracts will be issued covering the hardware supply for the demonstrator aircraft (POC).

Following the design verification by POC flight testing final improvement of the propulsion system as capacity increase of first LP charger compressor by about 8 % and reduction of fuel consumption of the piston engine which are not necessary for the demonstrator will be carried out and integrated in the ATF and flight versions of the propulsion system.

## 4. VERIFICATION TESTING

Due to the high altitude application the main design verification can only be accomplished by ATF testing. This is done in the Altitude Test Facility at the University of Stuttgart.

ATF testing of the complete LP charger system incl. heat exchanger and oil unit has started in May 1993. Fig. 10 shows the test arrangement. The LP charger is driven by hot gas generated with a 600 kW natural

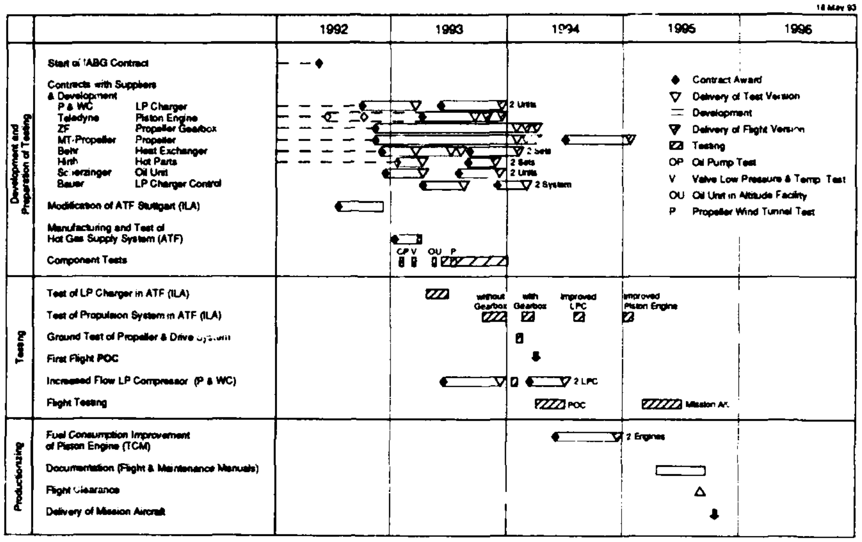



Fig. 9: Schedule of STRATO 2C Propulsion System Development

gas burner. The capability of the test facility is extended to 25 km altitude by the introduction of an ejector.

The first run was carried out at an altitude of 15 km. On the following day 22 km were reached without problems except an external oil leak. In June testing will be continued up to 24 km.

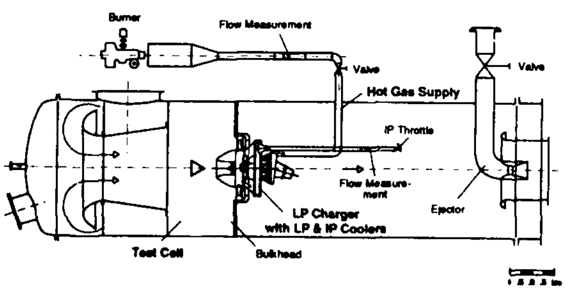



Fig. 10: ATF Testing of the LP Charger System

The aim of the tests is to verify the gas generator modifications, the secondary air and oil system, the hot gas supply components, the heat exchangers and the compressor behaviour under high altitudes conditions.

The next step is ATF testing of the complete propulsion system installed in the nacelle except the propeller. By this test the matching of the various propulsion components and the control system will be investigated and adjusted.

In parallel limited component tests are carried out by the subcontractors and in the static altitude test chamber (low pressure, low temperature) at IABG.

## CONCLUSIONS

The propulsion system of the 24 km long endurance aircraft STRATO 2C is the next milestone after the Condor 21 km - engine on the way to a 30 km power plant. For 24 km a three-stage turbocharging system was necessary with larger heat exchangers - compared to 21 km - and increased control effort.

The STRATO 2C compound engine is a compact design which can be realized with relatively low cost and in a short time by the extensive usage of available hardware.
At low altitudes the engine operates similar to a conventional turbocharged piston engine with propeller. At higher altitudes a self-contained LP charger system is switched on. Individual air-to-air coolers are integrated to avoid the additional weight of a liquid heat transfer system for the charge air cooling.

ATF testing of the LP charger system with integral heat exchangers and the new oil supply & scavenge unit has started in May 1993 and the first runs up to 22 km have been successfully completed.

## ACKNOWLEDGEMENTS

The author would like to thank Mr. K.-H. Fischer, H.-J. Hölzel and G. Klinger from the GROB company for the very successful cooperation during the ATF test preparation phase and the scheduled supply of excellent hardware.

## REFERENCES

Ref. 1 H. Künkler "Antrieb der STRATO 2C - Integraler Bestandteil einer Systemlösung", DGLR 92-03-044

Ref. 2 Wilkinson, R.E. and Benway, R.B., "Liquid Cooled Turbocharged Propulsion System for HALE Application", Unmanned Systems, Summer 1990

# REVIEW OF HUMAN FACTORS PROBLEMS RELATED TO LONG DISTANCE AND LONG ENDURANCE OPERATION OF AIRCRAFT

Ries M. Simons, M.D. and Pierre J.L. Valk, psycholgist
Netherlands Aerospace Medical Centre
Research Department
PO Box 22, 3769 ZG Soesterberg,
The Netherlands.

## SUMMARY

Long distance operations are characterized by rapid multiple time-zone changes and long irregular work schedules. Performance and alertness of aircrew engaged in these operations might be affected by circadian disruptions, sleep loss, workload, and cockpit-environmental factors, such as lower pressure, low relative humidity, and constant background noise. Recent literature on the various factors, which contribute to fatigue and reduced alertness of pilots, is reviewed.

## 1. INTRODUCTION

Technological developments and operational requirements result in an ever increase of distances flown non-stop and an increase of duration of missions. In emergency situations Air Force pilots must perform extremely fatiguing missions over a considerable period of time. Although Air Force flying schedules are not commonly flown by commercial airline pilots, the airline industry is also concerned about the effects of long-haul operations on performance and wellbeing of pilots. Long-haul operations are characterized by rapid multiple time zone changes, sleep disturbances, circadian disruptions, and long irregular work schedules. These factors can result in pilot fatigue, wich might have adverse effects on safety and operational effectiveness. Long-haul wide-body flight operations have almost a three times higher loss ratio compared to short- and medium-range flights (1). Many pilots will describe anecdotally the overwhelming fatigue and sleepiness associated with trans-atlantic all-night flying and Aviation Safety Reporting Systems receive reports of long-haul crews on the role of fatigue, sleep loss, and sleepiness in relevant operational errors. The reported errors include altitude deviations, improper fuel calculations, track deviations, landing without clearance, and landing on an incorrect runway (2). The cockpit environment with lower pressure, low relative humidity, constant background noise, dim lighting, and a low workload during cruise-flight can contribute to the difficulty of remaining vigilant and awake (3). On long-haul operations a pilot has to remain vigilant for long periods of time in a relatively monotonous environment. Piloting modern aircraft requires complex psychomotor coordination, high rates of information processing, and high speed of decision making. These capacities are particularly affected by fatigue and sleep loss (4).

After discussion of the concept of fatigue, the relevant factors which affect performance of aircrew on long-haul and long-duration operations will be described. In this context the following categories of factors will be dealt with: circadian disruption, cockpit environment, and workload.

## 2. THE CONCEPT OF FATIGUE

Most literature on the effects of long distance and long endurance operation of aircraft considers fatigue as a major cause of impairment of pilot performance. However, the definition of fatigue is subject to much disagreement. The inability to develop an adequate definition of fatigue has always plagued research on rest-activity schedules. Fatigue can be defined in terms of performance decrement, of subjective feelings of fatigue, and in terms of physiological changes. At present, subjective feelings of fatigue are made the primary emphasis of the definition. Subjective fatigue is that subjective sense of weariness resulting from the duties of piloting an aircraft which is considered to be excess of the expected normal fatigue. Perelli (4) states that the concept of fatigue is best defined as a subjective feeling; and, provided that the intensity of the fatigue stressor is severe enough, the subjective report of

*Presented at an AGARD Meeting on 'Recent Advances in Long Range and Long Endurance Operation of Aircraft', May 1993.*

This has an additional advantage since such reliability of product minimises the financial outlay required in the early days of introduction to service, at a time when finances are best focused to the procurement of the required fleet numbers.

These can be achieved in two ways:

- Same fleet size and container volume with reduced flight times

- Increased container volume or fleet size

*Presented at an AGARD Meeting on 'Recent Advances in Long Range and Long Endurance Operation of Aircraft', May 1993.*



fatigue should be expected to be correlated with a wide range of performance decrements. In most real-world situations, the direct relation between subjective feelings of fatigue and performance decrement is difficult to demonstrate. In laboratory research, results on a wide range of performance tests show various levels of correlation with subjective data on fatigue. In most cases, these tests lack face-validity in the context of pilot performance. Results on tests of pilot performance in a flight-simulator often fail to demonstrate a direct relation between subjective fatigue scores and pilot performance, because in this kind of tests a variety of factors, which influence results, is involved (proficiency on the simulator, motivation, difficulty of the simulated flight). A shortcoming of all pilot-performance evaluation systems is that the flight profiles flown are often extremely simple and highly repetitive due to the nature of the scoring system.

For practical purposes fatigue can be subdevided in three categories (5):

1. acute fatigue, which normally occurs between a pair of sleep periods. Acute fatigue would cause performance decrement only on tasks requiring the highest degree of performance capability.

2. cumulative fatigue, which accumulates over a period of days or weeks owing to the inadequate recovery from successive periods of acute fatigue. During cumulative fatigue, the most operationally significant performance decrement would occur.

3. chronic fatigue, which is a psychoneurotic syndrome characterized by difficulty in committing oneself to an agressive course of action, and by generalized withdrawal or retreat from conflict which is intolerable for situational or personality reasons. Chronic fatigue is rarely seen in pilots.

In the context of performance decrement during long-haul and long endurance operations cumulative fatigue plays a major role. In these operations cumulative fatigue is caused by circadian disruption (sleep loss), long irregular work schedules, and accumulation of acute fatigue (caused by long daily missions, cockpit environmental conditions, workload).

## 3. CIRCADIAN DISRUPTION

Human circadian rhythms (i.e. about 24 hour) are internally controlled by a biological clock in the brain. It has been demonstrated that many biological functions, such as sleep, wakefulness, body temperature, activity, hormone secretion, etc. fluctuate over a 24-hr period. As most long-haul operations involve rapid crossing of multiple time-zones, the human circadian clock has to adjust quickly to a new environmental time. However, the internal biological clock can only adjust to a new external time at a slow rate. The result is a mismatch between biological rhythms and environmental synchronizers ("zeitgebers" such as daylight, meals), leading to a disorganization of internal physiological and psychological rhythms ("jet lag"). The more time-zones crossed, the greater the adjustment required by the circadian clock. It is known that there are wide individual differences in the ability to adjust to new time-zones. It is also known that, generally, adjustment will be slower and more difficult when flying eastward as compared to westward flights.

### 3.1. Sleep loss

An important consequence of circadian disruptions by rapid time-zone changes is that the sleep-wakefulness rhythm is desynchronized with the new environmental time. The result is usually sleep loss caused by a short duration of sleep. Several studies have provided objective evidence for the occurrence of disturbances of the physiological sleeping pattern in cockpitcrew after a transmeridian flight (6, 7). In 1988 the Netherlands Aerospace Medical Centre conducted an inquiry into the occurrence of sleep disturbances among cockpitcrew of two Dutch airlines (8). Anonymized questionnaires, comprising 24 items concerning sleep and the use of sleeping aids/methods, were mailed to 1191 cockpit-crewmembers. The Groningen Sleep Quality Scale (GSQS, 9) was used to evaluate sleep quality. On all items the home situation was compared to the layover situation. The response was 60%, and a positive correlation between operating on transmeridian flights and complaints about sleep duration and the quality of sleep was demonstrated. Sleep quality during layovers was significantly worse than at home (p<.0001). 47% Of the transmeridian flying crewmembers with sleep disturbances judged their disturbed sleep to affect their performance in the cockpit. Sleeping aids used during layovers included alcohol and hypnotics. An example of disrupted sleep during layover is presented in figures 1 and 2. These figures represent results of a study by Simons and Valk (10) in which quantity and quality of sleep at home, onboard, and during layovers have been studied in 20 crewmembers performing their normal operational tasks on trips from Amsterdam to Singapore (AMS-SIN-AMS, flight time: approx. 12 hr; time difference: 7 hr) and to Bangkok (AMS-BKK-AMS, flight time: approx. 11 hr; time difference: 6 hr). In a within subjects design aircrew was studied on each of both trips (40 cases). Time in bed was assessed subjectively (daily logs) and objectively (wrist worn actigraph), while sleep quality was measured by the GSQS. As is shown in figure 1, sleep was significantly shorter on the 2nd and 3rd layover night, while sleep quality was poor on the 2nd layover night.

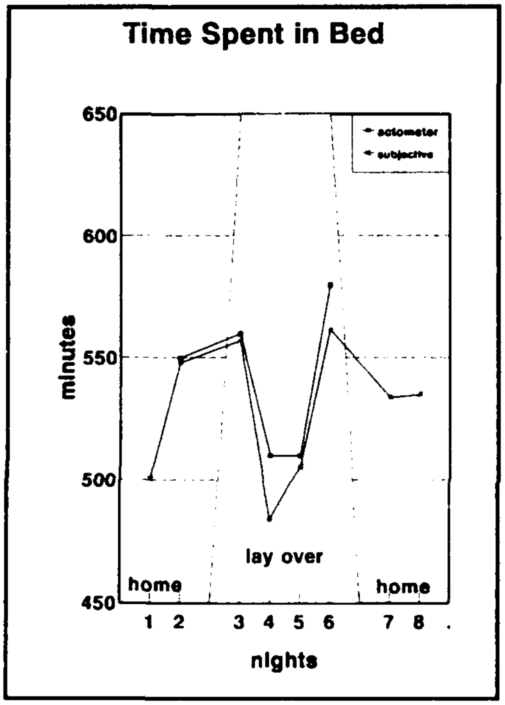



Figure 1: Time spent in bed at home and during layovers

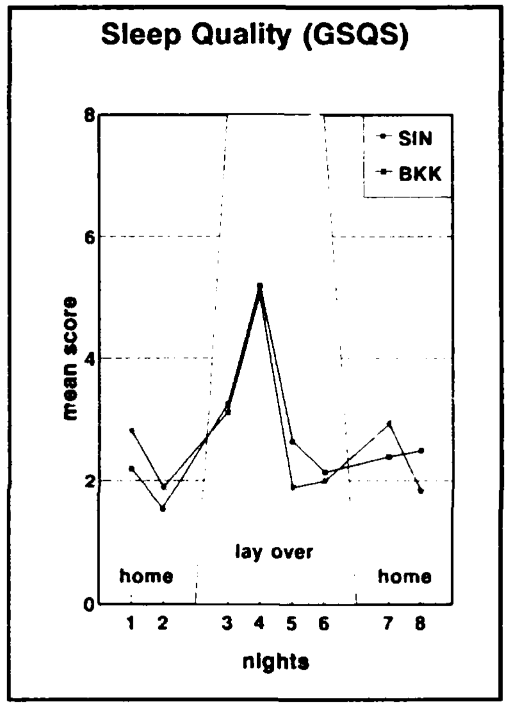



Figure 2: Sleep quality at home and during layovers. Highest score represents poorest quality.

Over time disrupted and shortened sleep results in a cumulative sleep loss and sleep debt. The potential results of sleep loss are performance lapses, slowed mental processing and decision-making, and reduced memory function (11).

### 3.2. Irregular shift work

Scientific research has shown that the biological c' .. not only organizes nocturnal sleep, but also regulates the daily level of sleepiness and alertness. In a 24-hr period there are two distinct periods of maximal sleepiness (minimal alertness) for a normal, healthy, non-sleep deprived individual: during early morning hours (about 4-5 a.m.) and during mid-to-late afternoon hours (about 3-5 p.m.) (12). While various strategies are used to combat these periods of biological sleepiness, it is clearly a window of increased vulnerability to reduced performance and alertness. It is known that sleep loss exacerbates this situation by increasing the level of sleepiness at all times of day. In irregular shift-work, a night flight might coincide with a window of maximal sleepiness which creates an increased vulnerability to impaired performance and reduced alertness.

The quality of performance is, in part, a function of the time of day. Generally, performance has been found to improve steadily from morning to early evening, then plateau, and next decline, reaching its lowest level around 04.00 a.m. (13).

Perelli (4) and many others showed that time awake prior to flight is a major determinant of aircrew performance. Therefore, it is recommended that flight scheduling personnel as much as possible take this factor into consideration, when planning missions. Moreover, aircrew involved in long-haul operations should be advised on rest schedules prior to a flight and during layovers.

## 4. COCKPIT ENVIRONMENT

Extended flight times also implicate prolonged exposure to physical cockpit-conditions which might affect the physical and psychological condition of aircrew. These physical cockpit-conditions include lower cabinpressure, low relative humidity, ozone, and noise (3).

### 4.1. Cabinpressure

In practice, during a long-haul commercial or military transport flight, the pressure in the cabin is maintained at a cabin altitude equivalent to an altitude of about 6000-8000 ft., which corresponds with an atmospheric pressure between 81.2 and 75.2 kPa (pressure at sea level: 101.3 kPa). The lower ambient pressure leads to expansion of the gases entrapped in the cavities of the body. For a healthy individual operating at 8000 ft this may result in only minor symptoms (mild abdominal discomfort, flatulence, belching).

Table 1: Atmospheric pressure, partial oxygen pressure, arterial oxygen pressure, and oxygen saturation of haemoglobin ($SaO_2$) of resting subjects acutely exposed to various altitude (14)

| Altitude ft | Pressure kPa | P.Part.$O_2$ kPa | $PO_2$-art. kPa (mmHg) | $SaO_2$ % |
|---|---|---|---|---|
| 0 | 101.3 | 21.2 | 12.7 (95) | 98 |
| 6000 | 81.2 | 17.0 | no data | 93 |
| 8000 | 75.2 | 15.7 | 7.5 (56) | 90 |
| 15000 | 57.2 | 11.9 | 4.9 (37) | 77 |

As is shown in table 1, at 8000 ft the partial pressure of oxygen (P.Part. $O_2$) is 15.7 kPa and the pressure of oxygen in arterial blood comes to 7.5 kPa (56 mmHg) in a healthy individual. The oxygen saturation of haemoglobin ($SaO_2$) at this altitude will be 90-93 % indicating a mild degree of hypobaric hypoxia. It should be emphasized that $SaO_2$ values in healthy subjects under hypobaric hypoxic conditions show marked inter-individual differences and values below 90% are not uncommon at 8000 ft. The Aviation Safety Institute stated that "low cabin oxygen levels may be more of a threat to safety than previously believed" (15). This statement was based on results of measurements which showed $SaO_2$ values to come below 90 % in passengers and crewmembers at cabin altitudes of 7000 ft. The effects of hypobaric hypoxia occurring at a cabin altitude of 8000 ft include subjective complaints, physiological effects, neuro-sensory effects, and psychological effects. Subjective complaints include mild headache, lightheadedness, and fatigue. The complaints become more frequent as duration of exposure increases. Respiratory as well as cardiovascular reactions to increasing hypoxia can be observed already at 6600 ft (16), and include increase of respiratory minute volume, increase of heart rate, increase of systolic blood pressure, and increase of cardiac output.

Neuro-sensory effects of mild hypoxia, observed at altitudes of 5000-8000 ft include impairment of postural stability (17), impairment of brightness discrimination (18), impairment of night vision (19), impairment of colour detection (20), and decrement in the cortical processing of the auditory stimulus (21, 22).

The minimum altitude at which perceptual-motor decrements due to hypoxia can be detected is a controversial issue having implications for flight safety. Ernsting (23, 24) recommended that cabin altitudes should be maintained at or below 8000 ft in the interests of safety. This suggestion was based primarily on a study by Denison et al. (25), who reported increased response times at 8000 ft using a spatial transformation task (the Manikin test). Based on his study Denison stated that "mild hypoxia affected performance while the task was being learned, but not after practice", which means that mild hypoxia affects novel tasks. In the same study Denison found that even at 5000 ft a significant increase in response time could be demonstrated while the task was being learned. Supporting evidence for the results of Denison is provided by an experiment of Crow and Kelman (26). Ledwith (27) reported significant impairment of total reaction time at altitudes as low as 5000 ft using a variety of novel tasks with simple and complex spatial and code relationships between stimulus and response.
Concerning the relationship between the duration of exposure to mild hypoxia and impaired performance, no firm data exist. At present, no study has been attempted in which performance has been assessed over time during an 10-14 hour stay at 8000 ft, which condition represents the working condition of aircrew on long-haul flights.

### 4.2. Relative humidity

Relative humidity (RH) is the ratio of the amount of water vapour in the air at a given temperature to the capacity of the air at that temperature. The term is used to mean the percentage of moisture present, relative to the amount the air can hold (at a given temperature and pressure). In most aircraft, fresh air is brought in from outside through the engines, cooled, and delivered directly to the cabin with no humidification. Available water from this source remains at approximately 0.15 g/kg, and at 20-22 °C the relative humidity of the fresh air is less than 1 percent. Moisture from the passengers and crew will cause relative humidity to increase, depending on the outside-air ventilation rate and the load factor, and it will decrease as rate of outside ventilation increases. Measurements of Simons and Valk (10) in the cockpit and crew rest area of a B 747-400 show RH values ranging from 3-12% throughout long-haul flights. RH in the aircraft cabin can get very low, as is shown in table 2. These values are well below the lower limit standard set by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (28). For heated rooms, a RH of 40-45 % is considered to be comfortable.

Table 2: Lowest Relative Humidity measured in aircraft cabins.

| Study | Aircraft | lowest RH % |
|---|---|---|
| Hawkins (31) | DC 10 | 3.0 |
| Lufthansa (32) | B 747 | 8.5 |
| Applegate (33) | B 747 | 6.0 |
| | DC 10 | 5.0 |
| NAMC (10) | B 747-400 | 3.0 |

Documented direct effects of low relative humidity on crewmembers are few. Complaints caused by a low RH include dry eyes and redness, dry throat, and dry nose. Corneal ulcerations have been reported in wearers of contact lenses after long flights. A study by the Netherlands Aerospace Medical Centre, in which subjects stayed for 8 hours at 8000 ft simulated altitude, and RH = <20 % in a low pressure chamber, demonstrated the development of punctate keratitis in wearers of contact lenses (29). Evidence on the common belief that low relative humidity increases the risk of respiratory infection is conflicting (30).

Hawkins (31) emphasizes that a low cabin RH might cause systemic dehydration in aircrew. He emphasizes that it is necessary to learn how much to drink and then take fluids whether thirsty or not. He further emphasizes that the sensation of thirst is not a good indicator of the amount of fluid needed as replacement to avoid dehydration. In a study at the Netherlands Aerospace Medical Centre, in which 6 healthy subjects were exposed during 8 hours to a simulated altitude of 8000 ft and a RH <10%, systemic dehydration was evidenced by an increase of the mean plasma osmolality (289 mosml/kg to 295 mosml/ kg), mean urine osmolality (410 mosml/kg to 807 mosml/kg), and urine specific gravity (1012 to 1022). In the control condition (8 h. at sea level and RH: 30-40%) a slight fall in these parameters was observed during the session. Dehydration might cause fatigue and impairment of performance, as has been shown by the results of a study by Gopinathan (34).

### 4.3 Ozone

Measurements of inflight ozone concentrations have produced variable results. This might be caused by the fact that the amount of ozone in the cabin varies with the type of aircraft, flight level, season, weather condition, latitude, and the stretch on which the measurements were performed. Results of measurements are represented in table 3.

Table 3: Inflight ozone concentrations (ppm).

| Study | Aircraft | Ozone conc. |
|---|---|---|
| Benett (35) | B 707 | 0.05-0.12 |
| Daubs (36) | B 747-100 | 0.30-0.50* |
| van Heusden (37) | D 10-30 | 0.20-0.40 |
| GASP (38) | B 747SP | 0.05-0.65 |
| | B 747-100 | 0.04-0.40 |
| Preston (31) | unknown | 0.57** |

* cumulative exposition densities (ppm/hour)
** peaks measured on the polar route (ppmv)

The FAA established a standard for cabin ozone concentration (39). These regulations state: "The airplane cabin ozone concentration during flight must be shown not to exceed 0.25 ppm (parts per million), sea level equivalent, at any time above flight level 320 (32.000 ft at standard atmosphere); or 0.10 ppmv (ppm volume) during any 3-hour interval above flight level 270 (27.000 ft at standard atmosphere)". In fact, in 1978-1979 FAA monitored ozone on flights (mostly at 30.000-40.000 ft) and found that 11 % were in violation of FAA's ozone concentration limits (40).
The generally accepted Threshold Limit Value of ozone in industry is 0.1 ppm (max. average concentration to which workers may be exposed for an eight hours working day without harmful effects on health).

Symptoms of ozone intoxication include cough, upper airway irritation, chest discomfort, retrosternal pain, pain in taking a deep breath, dyspnea, wheezing, headache, fatigue, nasal congestion, and eye irritation.
Controlled human studies, using ozone concentrations of 0.14 up to 0.50 ppm, have reported respiratory symptoms and significant decrements in pulmonary function (41). Nowadays, many airlines use catalysts or adsorbers to control cabin ozone concentrations.
The effects of ozone exposure on flying performance have not been studied as yet. The developments in long-range aviation necessitate the assessment of effects of prolonged exposure to low ozone concentrations (0.10-0.25 ppm) on pilot performance, using vigilance and monitoring tasks.

### 4.4. Noise

For practical purposes, noise may be taken to mean continuous broad-band sound with a sound pressure level (SPL) over 80 dB. In the long term, continuous noise may damage the mechanism of hearing, at first reversibly but later permanently. It is difficult to establish an "acceptable" or "safe" noise level whether by retrospective or prospective means, because such a survey depends on a population which has been exposed to a reasonably constant source of noise for a long time. It is generally agreed that exposures to noises of less than 80 dBA (A scale-weighted SPL) produce no increase in deafness in a population. In industry a SPL of 85 dBA is generally considered to be the upper limit of acceptable ambient noise. Final conclusions, about what is to be considered as a safe noise level, can only emerge from the study of regular audiograms of flight crew and controls over a long period.

The results of measurements of noise levels in the cockpit depend on the type of aircraft, position in the cockpit where the measurement was taken, airspeed, airconditioning, and phase of flight. In a study performed by the Netherlands Aerospace Medical Centre (42) noise was measured in the mid-position between captain and first officer, without radio-telephony (RT) sound, in aircraft

during cruise-flight. Weighted sound pressure levels (dBA) found in this study were 75 dBA in a DC 10, 76 dBA in A 310, and 78 dBA in B 747-200/300. These noise levels are below the generally accepted limit of 85 dB. However this limit value represents the total noise, whereas in this study, RT-noise was excluded. Flight crew operating noisy aircraft state that the noise causes fatigue, makes them irritated, and effectively increases their workload. Studies on the effects of continuous noise on vigilance and cognitive task performance have yielded inconclusive results.
As long-haul aircrew spends 10 hours or more in an environment with sound pressure levels of 75-80 dBA, this sound pressure might contribute to fatigue.

## 5. WORKLOAD

There has been considerable difficulty in defining the nature of the term "workload". Many definitions of workload have been proposed by various investigators, differing primarily in the presumed source of stress on the individual. However, the concept of workload has no independent existence. It is a summary term for several factors which cause an individual's performance to be task limited (43). Task requirements, mental operations, and subjective feelings all combine with a multitude of state variables such as training, fatigue level, motivation, and physical condition to produce a final performance capability in the individual. The workload of a mission cannot be thought of independent of the mission, the system, or the individuals engaged in the operation. Unfortunately no widely accepted standards for workload measurement presently exist. Physical or mental workload that is too high might cause physical or mental fatigue, wich consequently might affect performance. However, research on direct relations between workload and performance have yielded inconclusive results and often performance decrement cannot be demonstrated even though performance requirements or workload are increased. This problem can be explained by the concept of reserve capacity (44). The concept proposes that man rarely works at his maximum output level, and can thus momentarily absorb additional cognitive or physical workload and maintain his baseline performance, providing his reserve capacity is not exceeded. For practical use, the increase of fatigue can best be viewed as reducing man's reserve capacity, and the concepts of workload and fatigue should be considered highly interrelated. Performance decrement observed due to fatigue is considered to be a function of both the time at task and the total amount of work performed in a given unit of time (4). Overload of mental or physical load factors can cause performance decrement.

In long-haul transport operations, it is not so much the difficulty of the tasks or the amount of work, that results in fatigue. Fatigue in this kind of operations is primarily caused by long, irregular, working hours. In long-haul operations, pilots often experience workload being too low during cruise-flight. A long cruise-flight is monotonous and, combined with advanced cockpit automation, results in low arousal levels in flight-deck crew. In this situation, alertness might be reduced. This is especially true for long night-flights, where reports of pilots fighting sleepiness are legion. To increase alertness during monotonous cruise-flights, feasibility on aircrew alerting systems is studied.

In military operations, where pilots must perform extremely fatiguing missions over a considerable time period, acute fatigue will be caused by long time periods on difficult and stressful tasks. In these situations fatigue will rapidly accumulate when time to recover between missions is too short, and rest facilities are of low quality.

## 6. CONCLUSION

In long-haul transport operations safety and operational effectiveness may be compromised due to reduced pilot performance and alertness. This is caused by:
- cumulative sleep loss due to desynchronization of the pilot's sleep rhythm with the new environmental time.
- all-night flights with consequent conflicts of operational demands with normal sleep-wakefulness, and performance rhythms.
- cockpit automation and monotony during cruise-flight resulting in reduced alertness.
- cockpit environmental factors, such as lowered pressure, low relative humidity, ozone, and constant background noise, which contribute to fatigue and reduced performance.

In military missions extended over several days, cumulative fatigue plays a major role. In this situation, cumulative fatigue is caused by inadequate sleep between missions (due to mission demands and, in many cases, circadian disruption) and very stressful missions.

It is recommended that these factors are taken into account when planning long-haul operations. Moreover, aircrew should be aware of these factors and plan their own strategies to cope with these difficulties, i.e. take adequate rest and naps. In the course of some missions, like the South Atlantic Campaign (1982)(45), the use of hypnotics to guarantee adequate sleep of aircrew is recommendable.

REFERENCES


1. Caesar H. Long-term statistics and their impact on safety management and operational procedures. Proceedigs of the 39th International Air Safety Seminar. Arlington, VA: Flight Safety Foundation, 1986.
2. Rosekind MR, Curtis Graeber R, Dinges DF, Connell LJ, Rountree MS, Spinweber CL, Gillen KA. Crew Factors in Flight Operations: IX. Effects of Preplanned Cockpit Rest on Crew Performance and Alertness in Long-Haul Operations. NASA Technical Memorandum 103884. Moffet Field, CA: NASA-Ames, 1992.
3. Simons M. Environmental factors influencing flight crew performance. In: Human Factors Digest No.4: Proceedings of the ICAO Human Factors Seminar. Leningrad, USSR, 3-7 April 1990. Circular 229-AN/137. ICAO, Montreal, 1990.
4. Perelli LP. Fatigue stressors in simulated long-duration flight. Technical Report 80-49. Brooks AFB, TX: USAF School of Aerospace Medicine, 1980.
5. Hartman BO. Psychological factors in flying fatigue. In: C. Perry (ed.), Psychiatry in Aerospace Medicine (Vol. 4). Boston: Little, Brown & Co., 1967.
6. Curtis Graeber RC, Lauber JK, Connell LJ, Gander PH. International aircrew sleep and wakefulness after multiple time zone flights: a cooperative study. Aviat. Space Environ. Med. 1986; 57(12,Suppl.):B3-9.
7. Klein KE, Wegmann HM. Significance of circadian rhythms in aerospace operations. AGARDograph No. 247. Neuilly-sur-Seine: NATO-AGARD, 1980.
8. Simons M, Valk PJL. Enquête slaapproblematiek cockpitpersoneel (Survey on sleep disturbance in cockpit crew). Report RLD-87-10. Soesterberg, The Netherlands: National Aerospace Medical Centre, 1988 (in Dutch).
9. Meijman TF, de Vries GM, de Vries-Griever AHG, Kampman R. The evaluation of the Groningen Sleep Quality Scale. Department for experimental and occupational psychology, Biological Centre, University of Groningen, The Netherlands, 1987.
10. Valk PJL, Simons M. Actigraphy and logbooks during long-haul flights: a feasibility study. Paper presented at the 7th International Symposium on Aviation Psychology, Columbus, OH, April 1993.
11. Dinges DF, Kribbs NB. Performing while sleepy: Effects of experimentally induced sleepiness. In: T. Monk (ed.), Sleep, Sleepiness, and Performance. Chichester, UK: John Wiley and Sons Ltd., 1991.
12. Carskadon MA. Measuring daytime sleepiness. In: M.H. Kryger, T. Roth, & W.C. Dement (eds.), Principles and Practice of Sleep Medicine. Philadelphia, PA: Saunders, 1989.
13. Colquhoun W.P. (ed.). Biological rhythms and human performance. New York: Academic Press, 1971.
14. Ernsting J, Sharp GR. Hypoxia and Hyperventilation. In: Sir G. Dhenin, ed. Aviation Medicine I.Physiology and Human Factors. London: Tri-Med Books Ltd.; 60-84; 1978.
15. Anonymous. Aviation Week and Space Technology; March 21, p.79, 1988.
16. Lagica P, Koller EA. Respiratory, circulatory, and ECG changes during acute exposure to high altitude. J. Appl. Physiol. 41:159-167; 1976.
17. Fraser WD, Eastman DE, Paul MA, Porlier JAG. Decrement in postural control during mild hypobaric hypoxia. Aviat. Space Environ. Med. 1987; 58:768-772.
18. Hecht S, Hendley CD, Frank SR, Haig C. Anoxia and brightness discrimination. J. Gen. Physiol. 1946; 29:335-351.

19. Mc Farland RA, Evans JN. Alterations in dark adaptation under reduced oxygen tensions. Am. J. Physiol. 1939; 127:37-50.
20. Kobrick JL. Effects of hypoxia and acetazolamide on color sensitivity zones in the visual field. J. Appl. Physiol. 1970; 28:741-7.
21. Gellhorn E. Sensitivity of the auditory projection area to anoxia. Am. J. Physiol. 1951; 164:748-751.
22. Fraser WD, Eastman D, Gee T. The effect of mild hypoxia on the latency and topographical distribution of the auditory evoked response. Paper presented at the Annual Scientific Meeting of the Aerospace Medical Association. New Orleans, May 8-12, 1988.
23. Ernsting J. Prevention of hypoxia-Acceptable compromises. Aviat. Space Environ. Med. 1978; 49:495-502.
24. Ernsting J. Mild hypoxia and the use of oxygen in flight. Aviat. Space Environ. Med. 1984; 55:407-410.
25. Denison DM, Ledwith F, Poulton EC. Complex reaction times at simulated cabin altitudes of 5000 feet and 8000 feet. Aerospace Med. 1966; 37:1010-3.
26. Crow TJ, Kelman GR. Psychological effects of mild hypoxia. J. Physiol. 1969; 24:204.
27. Ledwith F. The effects of hypoxia on choice reaction time and movement time. Ergonomics. 1970; 13:465-82.
28. American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc. Thermal Environmental Conditions for Human Occupancy. ANSI/ASHRAE 55-1981. Atlanta, Ga.: American Society of Heating, Refrigeration, and Air Conditioning Engineers, Inc., 1981.
29. Punt H, Heldens DJJ, Valk PJL, van Heijnsbergen P. The behaviour of hard contactlenses in conditions of low relative humidity and low atmospheric pressure. Report OR-88-01/R. Soesterberg, The Netherlands: National Aerospace Medical Centre, 1988.
30. Simons M. Cockpit-environmental factors during long-range flights. Report 89-02-RLD. Soesterberg, The Netherlands: Netherlands Aerospace Medical Centre, 1989.
31. Hawkins FH. Human Factors in Flight. Aldershot: Gower Technical Press, 1987.
32. Lufthansa German Airlines. Report on Air Quality Study with Half Pack Operation: 747. 1982.
33. Applegate WC. Aircraft Cabin Air Quality Study. 1982 (unpublished document, United Airlines).
34. Gopinathan PM, Pichan G, Sharma VM. Role of dehydration in heat stress-induced variations in mental performance. Arch. Environ. Health. 1988; 43(1):15-7.
35. Bennett G. Ozone contamination of high altitude aircraft cabins. Aerospace Med. 1962; 33:311-8.
36. Daubs J. Flight crew exposure to ozone concentrations affecting the visual system. Am. J. Optom. & Physiol. Optics. 1980; 57(2):95-105.
37. Van Heusden S, Mans LGJ. Meting van ozon in een vliegtuig. Philips Techn. Tijdschr 1978/79; 38(3/4):97-100.
38. Committee on Airliner Cabin Air Quality. Health effects associated with exposure to airliner cabin air. In: The airliner cabin environment: air quality and safety. p. 113-118. National Research Council Report. Washington D.C.: National Academy Press. 1986. ISBN 0-309-03690-9.
39. Cabin ozone concentrations. Code of Federal Regulations, Title 14, Pt. 25.832. Washington D.C.: U.S. Government Printing Office, 1985.
40. Rogers JW. Results of FAA Cabin Ozone Monitoring Program in Commercial Aircraft in 1978 and 1979. FAA-EE-80-10. Washington DC: US Federal Aviation Administration, Office of Environment and Energy, 1980.
41. Horvath SM, Gliner JA, Matsen-Twisdale JA. Pulmonary function and maximum exercise responses following acute ozone exposure. Aviat. Space Environ. Med. 1979; 50:901-5.
42. Blom J. Preliminary Report on RT-Intelligibility and aircraft noise. Soesterberg, The Netherlands: National Aerospace Medical Centre, Dept. of Audiology,1988.
43. O'Donnell RD, Eggemeier FT. Conceptual framework for the development of workload metrics in sustained operations. AGARD Conference Proceedings No. 338. Neuilly-Sur-Seine: AGARD, 1983, Paper 4.
44. Brown ID. The measurement of perceptual load and reserve capacity. Transactions of the Association of Industrial Medical Officers, 1964; 14: 44-49.
45. Baird JA, Nicholson AN. Human Factors of Air Operations in the South Atlantic Campaign. AGARD Conference Proceedings No. 338. Neuilly-Sur-Seine: AGARD, 1983, Paper 28

# EXTENDED RANGE OPERATIONS – A REVIEW OF RECENT DEVELOPMENTS

by

**A. Samel** and **H.M. Wegmann**
DLR-Institute for Aerospace Medicine
Postfach 90 60 58
Linder Höhe, D-5000 Köln 90
Germany

## SUMMARY

The introduction of long-haul aircraft which can be operated by a 2-crew flight deck over expanded duty hours, raises serious concerns about flight safety. It is a matter of intense discussions between authorities, operator and pilot associations in the USA, in Japan and in Europe whether the legal standards of flight duty limitations presently in force are still adequate or must be modified for minimum crew operations under the changing conditions.

In cooperation with various air carriers, different approaches have recently been undertaken by international scientific laboratories to investigate physiological and psychological responses of the human element to the new technology in the cockpit during long-haul operations: (1) In the conventional 3-man cockpit, pre-planned controlled rest on the flight deck has been investigated. (2) In augmented crews, comparison have been made between the 3-man flight deck and the newly introduced 2-crew cockpit. (3) The efficiency of onboard rest facilities has been investigated during long-haul augmented 2-crew operations. (4) Workload, alertness and fatigue are under investigation in single 2-crew operations with non-stop flights of up to 14 hours flight duty time.

Because not all of these investigations are completed, scientific contributions for discussions about flight time limitations and rest requirements must still be limited. However, in certain countries, scientific results have already led to recommendations for amendments in the actual legislation.

## 1. INTRODUCTION

Worldwide, air operations have significantly incre..ed during recent years. In relation to the number of sectors flown, flight safety has improved substantially. However, when excluding yearly fluctuations of aircraft accidents, absolute numbers of total hull losses did not change during several years. A primary factor of all accidents with known causes are attributed to the flight crew, i.e., human errors are found to be the main factor of hull loss accidents (Ref 1). Neither the average yearly rate (12.1 losses per year) nor the primary factor (ca. 75%) of total losses have changed during the last thirty years. Although a detailed analysis of the reasons why the human operator failes is not available, it can be concluded from other investigations that aircrew fatigue and impaired performance contribute to accidents. When comparing long- and short-haul operations, several conditions are typical for both: Operations can require long duty days, early reporting times, late arrivals and night flights. Under these conditions, aircrew fatigue must be viewed primarily as a function of flight duty time and workload intensity. However, in most long-haul flight operations a second dimension is added to the problem of aircrew fatigue, because they frequently require transmeridian crossings and thereby impose the additional burden of circadian desynchronisation and sleep disruptions. The operational significance of these factors has not completely been identified. However, the likely impact on performance is evidenced by the consistently higher accident rates for long-haul versus short-haul commercial flights. While short- and medium-range aircraft performed 3.34 times more take-offs and landings worldwide than long-range aircraft during
the years 1979 to 1985, their loss ratio was only 1.38 times that of the long-haul fleet. The operational total loss ratio of
the latter (based on sectors flown) was 2.83 times that of the combined short- and medium range fleet (Ref 2). Similar statistical records are reported for the prior 20 years.

During recent years, flight operations on long-haul routes (extended range operations, EROPS) have drastically changed. Three factors are responsible for this change. First, with the introduction of new aircrafts (B747-400, A340, MD-11), automation of the aircraft systems is accompanied by a reduction of the crew on the flight deck, as was the case in short-haul operations 25 years ago. Second, increased reliability in the technical systems has led to an alteration of provisions for the operation of two-engine aircrafts (B757, B767-300, A330), which are now permitted to be flown over extended oversea sections (ETOPS). Third, the opening of the European market permits deregulation and will lead to more competition among air carriers; thus, the growing economic pressure and an increasing demand for more frequent flights will only serve to enhance the potential for producing operational inadequacy and decreased flight safety.

## 2. REGULATORY ACTIONS

Aviation authorities in variuos countries are reacting to the substantial changes in air traffic. In addition, because of the unification of the European market, the fundamental rules for business have to be established by European authorities. Therefore, national authorities have formed a group called Joint Aviation Authorities (JAA) in order to harmonize national regulations with the goal to create a supranational regulatory system. In the case of flight time limitations and rest requirements for aircrew, the JAA Flight Time Limitation Study Group (JAA-FTLSG) has held a number of meetings since 1990 to elaborate regulations which meet the requirements of flight safety, economic demands and national and cultural pecularities as well. They called for advice from several organizations as they are represented by operator and pilot associations. However, an agreement among the lobbying organisations could not be achieved. For example, the wide divergence of opinions between aircrew and operator representatives can be illustrated by the discussions on flight time limits in 2-crew operations. Pilot organisations insisted that such flights should be limited to a maximum of nine hours flight time, whereas some operator organisations required 13 h as the limit. This kind of dispute raised the willingness to consult research institutions which are able to provide medical advice for the formulation of the new provisions. As for 2-crew operations, the JAA-FTLSG is currently proposing 11 h flight time, but it was explicitly stated

*Presented at an AGARD Meeting on 'Recent Advances in Long Range and Long Endurance Operation of Aircraft', May 1993.*

that this figure may be modified pending the results from medical research.
The supranational regulations will be elaborated further in different committees before they will be presented to the EC council of Ministers. After the consultation procedure, it is foreseen to adapt them as a regulation applicable to all 12 EC member states in 1995 or 1996. The main issues of the currently proposed JAA-scheme (Document 19) are presented in table 1 (Ref 3, Ref 4).
In Japan, the current standards regarding flight time limitations for flight crews engaged in international flight operations differentiate between the required minimum flight crew of two pilots and that of two pilots and one flight engineer. These interim standards came into effect with the introduction of B747-400 aircrafts on pacific routes. For a minimum flight deck crew of 2 pilots, the scheduled flight time is not allowed to exceed 8 h; for a flight crew augmented by one pilot, flight time up to 12 h is permitted; for a crew augmented by more than one pilot, flight times of more than 12 h are allowed. For the 3-person cockpit, flight time should be 12 h or below; if the flight crew is augmented by at least one pilot and one flight engineer, more than 12 h flight time are permitted.
In the USA, in Japan and in Europe, recommendations by scientific organisations have recently been made as a result of in-flight investigations. However, further investigations are necessary to establish prenormative standards worldwide and especially in Europe.

## 3. SCIENTIFIC ACTIONS

Since a couple of years, world-wide collaboration between scientific institutions have led to a significant increase of knowledge on human behavior in the cockpit. A first cooperative effort was the "International Aircrew Sleep/Wakefulness Study" (Ref 5), which led to considerable insights concerning sleep and circadian rhythms in aircrews on transmeridian routes. The ongoing research in this field has led to the formation of the "International Research Group on Aircrew Alertness (IRGAA)" in which several institutions from around the world are working together to identify the human factor related problems of the modern cockpit and to investigate means which can support the human operator in maintaining or regaining sufficient capabilities to perform his task optimally over extended duty hours. The results derived from the different investigations are leading to conclusions and recommendations that have contributed and will contribute to regulatory actions and to amendments of present regulations when becoming necessary.
Present scientific efforts are mainly focussed on extended range operations (EROPS) in the 3- and 2-crew flight deck. The main purpose in the 1980's was to investigate sleep and circadian rhythms in the 3-person cockpit crew when single or multiple time-zone transitions were operated (Ref 5 - Ref 12). These field investigations have shown that on-the-job fatigue is caused by sleep loss, sleep disruptions and disturbances of the circadian system (Ref 5 - Ref 7). Thus, alertness and vigilance in the cockpit are affected by restraints of the human biological system (Ref 13). Longer rotation patterns tend to magnify these effects (Ref 8 - Ref 12). The implications for the flight deck during EROPS are that manufactures and carriers must assume that at least one crewmember is very likely to be in a low state of alertness during a substantial portion of the flight. The increased range of long-haul aircraft with reduced crew sizes and highly automated cockpits can be expected to heighten concerns about crew fatigue and the need to plan for sleepiness on the flight deck.

### 3.1 Investigations of Onboard Rest

Several approaches have been undertaken by the scientific community to identify these problems and to contribute to possible solutions.
In the USA, NASA-Ames Research Center established a Fatigue/Jet Lag Program in order to collect systematic, scientific information on fatigue, sleep, circadian rhythms and performance in flight operations (Ref 14). These efforts have recently been pursued by launching the Fatigue Countermeasures Program. One of the actions was to conduct a joint NASA/FAA study of controlled cockpit rest in the non-augmented *three*-person long-haul flight crew (Ref 15, Ref 16). The primary goal in this study was to determine the effectiveness of a pre-planned cockpit sleep for improvement of performance and alertness. The participating pilots were randomly assigned to either a rest group or a non-rest group condition. The rest period was planned well in advance and lasted 40 min, alternating between pilots, during the low workload, cruise portion of flight. Focussing on brainwave and eyemovement activity reflecting changes in physiological alertness and sleepiness, the results from the last 90 min of flight have shown that the rest group had signifcantly less microevents of reduced alertness than the non-rest group (Ref 16). This result as well as findings from other measurements of this study support the conclusion that even short sleep periods obtained on the flight deck can help to improve physiological alertness and therefore increase flight safety during subsequent hours of flight. It has to be emphasized that the recommendations to implement rules for pre-planned short rest periods in the cockpit are only considering the conventional 3-person flight deck.
Currently, another activity of NASA-Ames is to study onboard crew rest facilities on long-haul aircrafts. Several hundred surveys with pilot assessments of onbord facilities have been received already.
Additional and complementary investigations on bunk sleep are currently carried out by British and Dutch research institutions (Ref 17).

### 3.2 Investigations on Augmented Crews

A further approach to deal with problems of changes in alertness and performance on the flight deck is based on the comparison between the conventional 3-man cockpit and the newly introduced 2-crew cockpit on long-haul operations. In 1992, Japanese researchers studied several vigilance and stress related physiological functions (but not brainwave and eyemovement activity) in ***augmented*** 3-person cockpits (double crew) and ***augmented*** 2-crew flight decks (double crew) on transpacific routes (Ref 18). Inflight findings have shown that the comparison of the physiological and psychological results do not reveal significant differences between the two crew configurations. Furthermore, the degree of fatigue of the pilots engaged in long-haul flights on B747-400 and conventional B747 aircrafts did not show significant differences between those two aircraft types under the conditions these investigations were conducted. Therefore, Japanese organisations have concluded that the flight time limit within consecutive 24 h for modern 2-man aircraft operations on long-range international routes should be

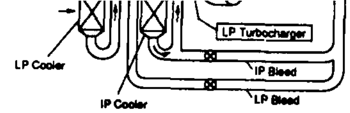



Fig. 6: Turbocharging System and Control

duced compared with Option "A". This is because Option "B" provides less throttling to the piston engine at the exhaust side resulting in higher shaft power at constant manifold pressure. Furthermore, the total amount of bleed flow (air & exhaust) is lower.

The operating lines in a typical HP compressor map at given LP and IP operating lines are shown in Fig. 7.



the same as for the 3-man aircraft. They recommended to amend the legislation currently in force by the following statement: For flight operations requiring only 2 pilots as the minimum crew, the scheduled flight time may be increased to 12 h within consecutive 24 h for the minimum crew (1 captain and 1 pilot), and can be further increased beyond 12 h for an augmented crew (1 captain and 2 pilots). Because these conclusions are derived from investigations on augmented crews only, but recommendations are also made for minimum crew flight operations, some criticism may be permitted. First, results from augmented crew operations may not be transferable to single crew operations without restrictions. In particular, minimum 2-crew operations require sustained presence at the controls for the two crew members, and this, in turn, induces physical inactivity and monotony that may lead to problems during EROPS which cannot be assessed in augmented crews. Second, the investigations were conducted on a route with only one sector flown during the flight duty period. Deviating results can be expected when more sectors must be operated. Third, layover times at the destination were considerably longer than the minimum required by current legislation, i.e., layover lasted more than 2 days including two local nights.

### 3.3 Investigation of Single Crew Operations

Within a broader program to evaluate physiological and psychological factors in aircrew on long-haul routes, the DLR-Institute for Aerospace Medicine was asked by the JAA and the German Ministry of Transport to investigate inflight alertness, vigilance and fatigue as well as related factors, as such as circadian rhythms and sleep, during minimum 2-crew EROPS. The main purpose of these investigations is to establish standards of flight time limitations and rest requirements for the single 2-crew flight deck. In 1991, DLR started inflight measurements on the route Düsseldorf (DUS) - Atlanta (ATL), because this rotation was considered to be normal and save during EROPS with respect to flight duty times in Germany (Ref 19). Data being collected during this schedule (table 2) will serve as control for the subsequent research on routes going beyond normal flight duty time of 10 h. Because it is permitted in Germany, to expand the normal flight duty period of 10 h to 14 h (within certain restrictions) for a single crew (Ref 19), investigations have been extended to the routes Hamburg (HAM) - Los Angeles (LAX) and Frankfurt (FRA) - LAX/San Francisco (SFO) in 1992. The duration of the outgoing (westbound) flight is more than 11:45 h, i.e., the corresponding flight duty periods (FDP) are exceeding 13 hours (FDP is currently calculated by blocktime plus 1:15 h for pre- and postflight activities), and the flights take place during day time. The homegoing, eastbound flights are 0:45 h shorter, however, they have to be operated during night hours (table 2). During these transatlantic rotations, layover times are longer than 2 days. Thus, sufficient time is available for recuperation, although the adverse effects of time-zone transitions on circadian rhythms and sleep for the subsequent flight duty have to be taken into consideration (Ref 6, Ref 13, Ref 20). It can be expected that human factors affecting the safe operation of aircrafts may became even more important, when the time schedule is shortened. Therefore, DLR is currently conducting investigations on the route FRA - Mahe (SEZ), since this rotation involves two consecutive night flights separated by a scheduled layover period of only 13:20 h (table 2). The scheduled flight duty times are between those of the ATL-rotation and the U.S. westcoast rotations. However, the rest period between the two flight legs is very short, coming close to the required minimum of 12 h (Ref 19, Ref 21), as, due to delays, the actual flight duty period often exceeds 11 h during the outgoing flight FRA-SEZ, causing also delayed arrival times in SEZ. (German rules require that minimum rest duration is 10 h (Ref 19), and must be extended to 12 h when the FDP goes beyond 11 h.)

#### 3.3.1 *Methods*

Physiological alertness was assessed by means of electroencephalogaphy (EEG) and electrooculography (EOG). EEG and EOG signals were continuously recorded during flight on analoguously registrating tapes (Ref 22). Simultanously, electrocardiogramme (EKG) was recorded for evaluating physical and mental load. Because data analysis is not yet completed, data and results of these measurements will be published elsewhere.

In addition to electrophysiological recordings, also subjective estimates were considered for identifying overall operational loads. For assessing load levels and psychological factors, three different types of questionnaires were administerred to the pilots. The first one was a checklist, reflecting momentary subjective feeling of fatigue (Ref 23 - Ref 25), and two analog scales regarding tenseness and alertness (Ref 26). This questionnaire had to be filled in before each flight, at 1-h intervals during flight, and after landing. The checklist for assessing fatigue results in scores ranging from 20 (very alert) to 0 (exhausted). These scores are related to categories of operational significance (Ref 23). Four ranges of fatigue are identified: As long as the fatigue scores remain beyond a limit of 12, it is assumed that pilots are sufficiently alert and performance decrement does not occur. Ratings between 8 and 11 imply mild fatigue, and performance impairment is possible, but not significant. When the scores are rated between 4 and 7, moderate to severe fatigue must be assumed, and some performance decrements possibly do occur; flying duty is still permissible, but not recommended. Below a scoring of 4, severe fatigue must be expected, performance is definitely impaired, and flight duty cannot be recommended. This system was derived from investigations on military aircrews in field and simulation experiments (Ref 23). It was also utilized in studies on civil air carrier operations (Ref 20, Ref 24).

Except for administration before a flight, the two other types of questionnaires were given during flight jointly with the fatigue checklist: the Bedford workload rating scale (Ref 27), covering 10 workload levels, and the NASA-Task Load Index (NASA-TLX), a six-scale rating list regarding "mental demand", "physical demand", "temporal demand", "performance", "effort", and "frustration level" (Ref 28). Once during the rotation, pilots had to rate the six scales with respect to personal importance. For evaluation, the six different scales are weighted by the personal ranks and added to a sum. The range of the taskload index is between 0 and 300 points (the higher the points, the higher the load).

Disturbances of sleep can be expected when flying long-haul missions, operating on transmeridian routes and conducting night flights. They can be anticipated to affect alertness and vigilance during subsequent flight duty periods. For the assessment of disturbances, expressed by changes of sleep quantity and sleep quality, a daily log was used (Ref 11, Ref 20). The crew had to fill in different sleep parameters beginning the recordings three days before the start and finishing three days after the end of the rotation. Not only "normal" sleep had to be reported, but also naps whenever they took place. The data of the first two days (when pilots should be at home base) were used as baseline days, and the different sleep parameters derived from subsequent days, were investigated for changes from these baseline data.

### 3.3.2. *Results*

In this report, results are presented from the investigations of the rotations DUS-ATL and HAM-LAX (table 2).

Figures 1 to 3 present the mean sleep duration of cockpit crew members during these rotations. Flight times and local nights (assuming to be between 2300 and 0700 local time LT) are also illustrated for comparison. During the DUS-ATL schedule overseas layover periods lasted 2.5 days and the same cockpit crew (N=12) performed both, the outgoing and homegoing flight duties (one crew (N=2) had to stay 1 d longer in ATL because of technical problems with the aircraft, and therefore was not considered in figure 1). However, when operating the flights on the HAM-LAX route, crew members were studied only during one flight leg of that route, but performed additional flights within America, either after the flight HAM-LAX (figure 2) or before the flight LAX-HAM (figure 3). These schedules lasted 8 and 5 d, respectively. In each of the two LAX-rotations, 10 pilots volunteered for the investigation, and 9 of them participated in both parts.

Results from the self-reported sleeps (daily log) indicate that already during baseline days sleep duration differed among pilots and days, but not between different rotations. Sleep duration decreased in the second night before departure when compared with the third night before, and increased in the last night before departure. In the ATL-group, the average sleep duration was 8.6 h (figure 1, day 1) and decreased in the second night to 6.8 h. The sleep during the night preceding the outgoing flight lasted 7.4 h. Before the flight HAM-LAX, pilots went to bed for 8.0 h in the first night of reporting and slept only for 5.8 h in the second night (figure 2). Before going on trip, sleep duration increased to an average of 8.2 h. Finally, the LAX-HAM group also slept longer in the first (8.0 h) than in the second night (5.2 h). Sleep during the night before the first trip (FRA-MIA) lasted 6.6 h (figure 3). On average, after the outgoing westbound flight to the U.S. east coast (ATL and MIA), the subjects went to bed 4 h later compared to home base, but 7 h later after the flight to the west coast (HAM-LAX). In all three rotations, sleep duration significantly increased to an average between 9.0 h and 9.6 h. During the following days overseas, sleep adapted to normal length. Depending on the flight pattern, subjects tried to nap before the homegoing flight. In the ATL-rotation, pilots got up at normal time in the morning and tried to nap in the afternoon and early evening, before the return flight commenced about midnight LT in ATL. However, only 6 pilots were able to sleep during this nap period (figure 1, day 6). Before the return trip of the HAM-LAX rotation, pilots shifted their sleep to later hours, thus getting up later in the morning and trying to shorten the wake period until the departure of the flight MIA-MUC which was scheduled for 1640 LT (figure 2, day 11). Because departure was at 1800 LT LAX, both kinds of sleep strategy were undertaken in the LAX-HAM group when pilots either delayed their sleep or napped in the early afternoon (figure 3, day 7). After the last flight of each rotation, most pilots stayed awake until evening, but advanced their sleep onset by several hours. In the HAM-LAX group, however, several pilots went to bed after arrival at home and tried to overcome sleep deficit by napping in the late local morning (figure 2, day 12). They were the earliest of the three groups to arrive in Germany and they had the longest wake period before returning, because they did not nap before the last duty period. During subsequent days, sleep normalized to baseline values.

Figures 4 to 6 illustrate the sleep balance; i.e., the sum of deviations in sleep duration from the average of the two baseline days. Thus, the curves reflect sleep deficit or surplus accumulated each consecutive day over the entire reported period. In general, all groups exhibited similar patterns. Westward flying did not result in significant sleep duration changes. However, a sleep deficit between 7 h and 8 h was observed upon returning to Germany. The reason for this sleep loss must be seen in the fact that the eastbound flight took place during night hours. On average, only 1.6 h of sleep could be gained by napping before the return flight ATL-DUS (figure 4), whereas no naps were taken before the MIA-MUC return flight, and only two naps before the LAX-HAM leg. After the MIA-MUC flight (figure 5), some improvements of the sleep balance curve occurred through napping in the late morning.

The results of the fatigue questionnaires are presented in figures 7 to 10. They reflect subjective ratings of fatigue during the operation of the flights DUS-ATL (figure 7), ATL-DUS (figure 8), HAM-LAX (figure 9) and LAX-HAM (figure 10) when inflight investigations were performed. During the outgoing flight DUS-ATL, pilots showed a low level of fatigue during the entire flight. The scores remained in an uncritical region with respect to operational implications, although a trend to higher fatigue with ongoing duty can be observed, but no individual rated fatigue scores less than 9. Before the return flight ATL-DUS and for 3 h after departure, pilots rated their fatigue again quite well. However, as can be seen from the standard deviation (figure 8), some pilots felt so fatigued during the second portion of the flight that their ratings dropped below the critical limit of 8, indicating possible performance impairments. Individual values show that one pilot rated lower than 8 after 3 h of flight already. Afterwards, the scores of at least two pilots went below the critical limit. Although subjective fatigue scores on average indicate a course for the first 10 h of the flight HAM-LAX very similar as during the outgoing flight of the ATL-rotation, ratings decreased after 10 h (figure 9). Two pilots were so fatigued after 11 h of flight that their scores dropped below 8, and possible performance impairment can be assumed. This effect was much more pronounced during the second LAX-rotation when the LAX-HAM leg was investigated (figure 10). Already after 6 h of flight, some pilots rated their fatigue being in the critical region. The lowest fatigue scores (i.e., a maximum in fatigue) were observed after 9 h of flight when ratings of four pilots went below 8. Towards the end of the flight, some recovery from fatigue was reported, but after landing in HAM, fatigue increased again.

### 3.3.3. *Discussion*

The results presented in this report reflect a subsample of the measurements being obtained during the DLR-investigations concerning the 2-man cockpit. Conclusions drawn from this limited part of data are preliminary and must be confirmed by the complete set of measurements, in particular by the findings from the physiological data.

The results from the daily log, i.e., sleep quantity and sleep distribution over the 24-h cycle, reflect subjective assessments. Previous studies with similar pilot populations (Ref 5, 10) showed that evaluation of sleep by subjective ratings and by polysomnographic recordings led to nearly congruent results. Thus, the presented findings should reflect real and actual sleep conditions associated with flight schedules on transmeridian routes.

Our sleep data indicate that the westward flights are associated with an increase of sleep duration during the following local night. The reason for this extension is the delay of sleep onset due to the shifted environmental time which supports staying awake for longer times, and thus a certain state of sleep deprivation by several hours. The second layover night sleep was on average not shorter than normal indicating that the adverse effects by disturbances of the circadian rhythmicity did not severely influence sleep as have been observed in 3-man cockpit studies (Ref 5, Ref 6, Ref. 20).

The most striking result concerning sleep quantity is the sleep loss after the return flight to Germany. It demonstrates that eastward transmeridian flying over several time zones is associated with night duty even when departure time is in the early hours of the local time. The sleep loss of 7 h to 8 h as shown in these studies is in agreement with several studies performed in recent years (Ref 5, Ref 9, Ref 20). The resulting sleep loss could only partly be compensated during subsequent days. Some pilots napped after returning to home base and sleep duration during the following night was extended by several hours. In the present study, sleep length normalized during the second night and was not shortened as was observed in similar investigations on pilots in the 3-man flight deck (Ref 20). A reason might be that not so many naps were taken as in the earlier study.

Changes in fatigue as observed in our study depend on several factors characteristic not only for the aviation environment. The main influence on fatigue is the duration of wake time since the last sleep. When the DUS-ATL flight was conducted, pilots were awake for only 2 h before departure and the fatigue level remained in the operationally uncritical region for the entire flight which, in addition, was performed during normal day time. During some portions of the other flight operations investigated in our study, subjects were sleep deprived to a certain extend. Before departing from HAM to LAX, pilots were awake for 7.8 h on average, because the flight commenced during local afternoon. The first occurance of fatigue scores being below the critical region was observed after 11 h of flight, i.e. after 19 h of being awake.When commencing the flight LAX-HAM, pilots were awake for 10 h on average. Some pilots began to feel very fatigued (scores below 8) after 7 h of flight, i.e., 17 h after getting up in the morning. Similar results were found for the eastward flight between ATL and DUS. At the beginning of flight duty, those pilots who could not sleep during the afternoon before departure (local midnight), were awake for 16 h. Fatigue started to increase already after 3 h of flight, when time since last sleep was 19 h. A second factor influencing fatigue is responsible for the change in fatigue scores during the two night flights. The normal course of circadian functions decreases during early hours of night, promoting higher levels of fatigue, and increases during morning hours, with beneficial effects on fatigue. The two different influences of circadian changes affected fatigue mainly in the second part of the LAX-HAM flight.

Results from subjective fatigue ratings may be considered as evidence not sufficient for discussing flight time limitations and rest requirements in view of flight safety. Therefore, findings from objective measurements are necessary to arrive at final conclusions. However, because in several aviation related investigations about fatigue (Ref 23 - Ref 25), the impact of changes in subjective alertness and vigilance on performance was established, the results of this study cannot be neglected when discussing regulations on flight and rest times.

Additional information about subjective and physiological crew fatigue under further operational conditions can be expected from currently conducted investigations (see table 2).

## 4. CONCLUSIONS

The proposed European regulations concerning flight duty limitations and rest requirements as well as the currently discussed amendments of Japanese regulations regarding maximum flight time on the 2-crew flight deck should be examined under consideration of all results available and obtainable from scientific research.

The main principles for determing flight duty and rest time limits should be: (1) Prevent excessive hours of duty and inadequate rest periods both of which can lead to short term and cumulative crew fatigue. (2) Preserve adequate sleep patterns taking into account irregular hours of work and time zone changes.

Considering these principles, the proposed provisions need to be modified. A normal flight duty of a single crew of two should not exceed 10 h. Extensions from this normal duty length should be an exception taking into account the amount of additional duty hours, time of day of landing and number of occurances per week. In particular, duty periods including night work enhance the probability of reduced vigilance and performance as consequence of sleep deficits and circadian influences. They may lead to impairments of performance which may become especially relevant for 2-crew long-haul operations.

References


1. Graeber, R. C., "Crew Fatigue and Circadian Rhythmicity", in Wiener, E. L. and Nagel, D. C., (Eds.), "Human Factors in Aviation", Academic Press, San Diego, 1988, pp. 305-344.
2. Caesar, H., "Long-term Statistics and its Impact on Safety Management and Operational Procedures", in "Proceedings of the 39th Annual International Safety Seminar", Flight Safety Foundation, Arlington, VA, October 1986, pp 11-23.
3. Joint Aviation Authorities, "Flight and Duty Time Limitations and Rest Requirements Proposals: Sub-Part Q", Document 19, JAA Headquarters, Hoofddorp, The Netherlands.
4. Williams, R., "JAA/European Community Flight Time Limitations", Flight Safety Digest, *11*, 7, July 1992, pp 42-46.
5. Graeber, R.C., (Ed.), "Sleep and Wakefulness in International Aircrews", Aviat. Space Environ. Med., *57*, 12, Section II, December 1986.
6. Samel, A. and Wegmann, H. M. "Desynchronization and Internal Dissociation in Aircrew", Ergonomics, *30*, 1987, pp 1395-1404.
7. Gander, P. H., Myhre, G., Graeber, R. C., Andersen, H. T. and Lauber, J. K., "Adjustment of Sleep and the Circadian Temperature Rhythm after Flights across Nine Time Zones", Aviat. Space Environ. Med., *60*, 1989, pp 733-743.
8. Samel, A. and Wegmann, H.M., "Sleep and Circadian Rhythms of an Airline Pilot Operating on the Polar Route: A Case Study", Aviat. Space Environ. Med., *59*, 1988, pp 443-447.
9. Buck, A., Tobler, I., and Borbély, A. A., "Wrist Activity Monitoring in Aircrew Members: A Method for Analyzing Sleep Quality Following Transmeridian and North-South Flights", J. Biol. Rhythms, *4*, 1, 1989, pp 93-105.
10. Spencer, M. B., Stone, B. M., Rogers, A. S. and Nicholson, A. N., "Circadian Rhythmicity and Sleep of Aircrew during Polar Schedules", Aviat. Space Environ. Med., *62*, 1991, pp 3-13.
11. Samel, A., Wegmann, H. M., Summa, W. and Naumann, M., "Sleep Patterns in Aircrew Operating on the Polar Route between Germany and East Asia", Aviat. Space Environ. Med., *62*, 1991, pp 661-669.
12. Gander, P. H., Graeber, R. C., Connell, L. J. and Gregory, K. B., "Crew Factors in Flight Operations: VIII. Factors Influencing Sleep Timing and Subjective Sleep Quality in Commercial Long-Haul Flight Crews", NASA- Technical Memorandum 103852, December 1991.
13. Wegmann, H. M. and Klein, K. E., "Jet-Lag and Aircrew Scheduling", in Folkard, S. and Monk, T. H., (Eds.), "Hours of Work", Wiley and Sons, Chichester, 1985, pp. 263-276.
14. Rosekind, M. R., Gander, P. H., Miller, D. L., Gregory, K. B., McNally, K. L., Smith, R. M. and Lebacqz, J. V., "NASA- Ames Fatigue Countermeasures Program", FAA Aviation Safety Journal, (in press).
15. Rosekind, M. R., Gander, P. H.and Dinges, D. F., "Alertness Management in Flight Operations: Strategic Napping", SAE Technical Paper Series, September 1991, No. 912138.
16. Rosekind, M. R., Graeber, R. C., Dinges, D. F., Connell, L. J., Rountree, M. S., Spinweber, C. L. and Gillen, K. A., "Crew Factors in Flight Operations: IX. Effects of Preplanned Cockpit Rest on Crew Performance and Alertness in Long-Haul Operations", NASA-Technical Memorandum 103884, 1992.
17. Simons, M., "Review of Human Factors Problems Related to Long Distance and Long Endurance Operation of Aircraft", this volume.
18. Flight Standard Division, Japan Civil Aviation Bureau, "Study on Flight Time Limitation for Flight Crew Engaged in Long-Range International Flight Operations", Committee Proposal, February 1993.
19. 2. Durchführungsverordnung zur Betriebsordnung für Luftfahrtgerät (2.DVO LuftBO), Bundesanstalt für Flugsicherung, Frankfurt, Dezember 1981.
20. Wegmann, H. M., Gundel, A., Naumann, M., Samel, A., Schwartz, E. and Vejvoda, M., "Sleep, Sleepiness, and Circadian Rhythmicity in Aircrews Operating on Transatlantic Routes", Aviat. Space Environ. Med. *57*, 12 (Suppl.), 1986, pp. B53-B64.
21. Wegmann, H. M., Conrad, B. and Klein, K. E., "Flight, Flight Duty, and Rest Times: A Comparison between the Regulations of Different Countries", Aviat. Space Environ. Med. *54*, 1983, pp. 524-527.
22. Gundel, A., Nalishiti, V., Reucher, E., Vejvoda, M., Zulley J., "Sleep and Circadian Rhythms During a Short Space Mission", Clinical Investigator, 1993 (in press).
23. Samn, S. W., Pirelli, L. P., "Estimating Aircrew Fatigue: A Technique with Application to Airlift Operations", Brooks AFB, TX, USAF School of Aerospace Medicine, Technical Report SAM-TR-82-21, 1982.
24. Samel, A., Wegmann, H. M., "Circadian Rhythm, Sleep, and Fatigue in Aircrews Operating on Long-Haul Routes", in Jensen, R. S., (Ed.), "Aviation Psychology", Gower Technical, 1989, pp. 404-422.
25. Storm, W. F., Merrifield, J. T., "Fatigue and Workload in Four-Man C-5a Cockpit Crews (Volant Galaxy)", Brooks AFB, TX, USAF School of Aerospace Medicine, Technical Report SAM-TR-80-23, 1980.
26. Samel, A., Gander, P. H., (Eds.) "Light as Chronobiological Countermeasure for Long-Duration Space Operations", NASA-Technical Memorandum 103874, 1991.
27. Roscoe, A. H., "In-Flight Assessment of Workload Using Pilot Ratings and Heart Rate", in Roscoe, A. H., (Ed.), "The Practical Assessment of Pilot Workload", AGARDograph No. 282, Neuilly-sur-Seine, 1987, pp. 78-82.
28. Hart, S. G., Staveland, L. E., "Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research", in Hancock, P. A., Meshkati, N., (Eds.), "Human Mental Workload", North-Holland, 1988, pp. 139-183.

Table 1: Provisions of proposed JAA-regulations (Document 19)

| Provision | Limitation |
|---|---|
| Maximum Flying Hours | 100 h/calender month or 100 h/consecutive 28 days<br>900 h/calender year |
| Maximum Duty Hours | 60 h/7 consecutive days<br>100 h/14 consecutive days<br>1800 h/calendar year |
| Maximum Flight Duty Hours | |
| Single Pilot | 10 h/day |
| Two or more Pilots | 14 h/day |
| Extension by commander's discretion | max. 2 h (3 h with augmented crew) |
| Minimum Rest | As long as preceeding duty or 11 h minimum, whichever is the greater<br>If more than 4 time zones crossed, minimum rest is in h the factor 4 times number of time zones crossed, when time away from home base was shorter than 60 h, or is in h the factor 8 times number of time zones crossed, when time away from home base was longer than 60 h. |
| Night Duty | Limits duties in a time interval between 0100 and 0659 local time. If 3 or more duties within this time interval were performed within 7 days, 36 h rest must be increased by 12 h within 7 days. |
| Split Duty | 3 to 10:59 h split can extend duty by half of the split |
| Days Off | 36 h rest within any 7 consecutive days or 60 h within 10 consecutive days<br>7 calendar days within any calendar month and 24 calender days within any calendar quarter year with at least 50% being taken at home base |

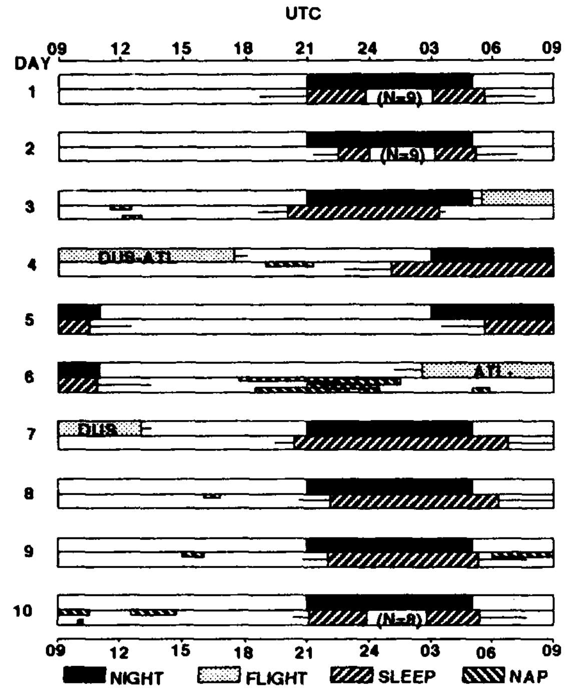
Table 2: Overview of schedules under DLR-investigation (times in GMT and local time LT)

| Route | Flight Leg | Departure | | | Arrival | | | Blocktime | |
|---|---|---|---|---|---|---|---|---|---|
| | | Date | GMT | LT | Date | GMT | LT | | |
| DUS-ATL | DUS-ATL | Mo | 06:15 | 08:15 | Mo | 16:05 | 12:05 | 09:50 | Dayflight |
| | ATL-DUS | Th | 04:05 | 00:05 | Th | 12:55 | 14:55 | 08:50 | Nightflight |
| HAM-LAX | HAM-LAX | Fr | 11:30 | 13:30 | Fr | 23:15 | 16:15 | 11:45 | Dayflight |
| | LAX-HAM | Sa/Fr | 01:00 | 18:00 | Sa | 12:00 | 14:00 | 11:00 | Nightflight |
| FRA-LAX | FRA-LAX | Th | 07:10 | 09:10 | Th | 19:00 | 12:00 | 11:50 | Dayflight |
| | SFO-FRA | Mo | 20:50 | 13:50 | Tu | 07:55 | 09:55 | 11:05 | Nightflight |
| FRA-SEZ | FRA-SEZ | Sa | 20:45 | 21:45 | Su | 06:10 | 09:10 | 09:25 | Nightflight |
| | SEZ-FRA | Su | 19:30 | 22:30 | Mo | 06:00 | 07:00 | 10:30 | Nightflight |

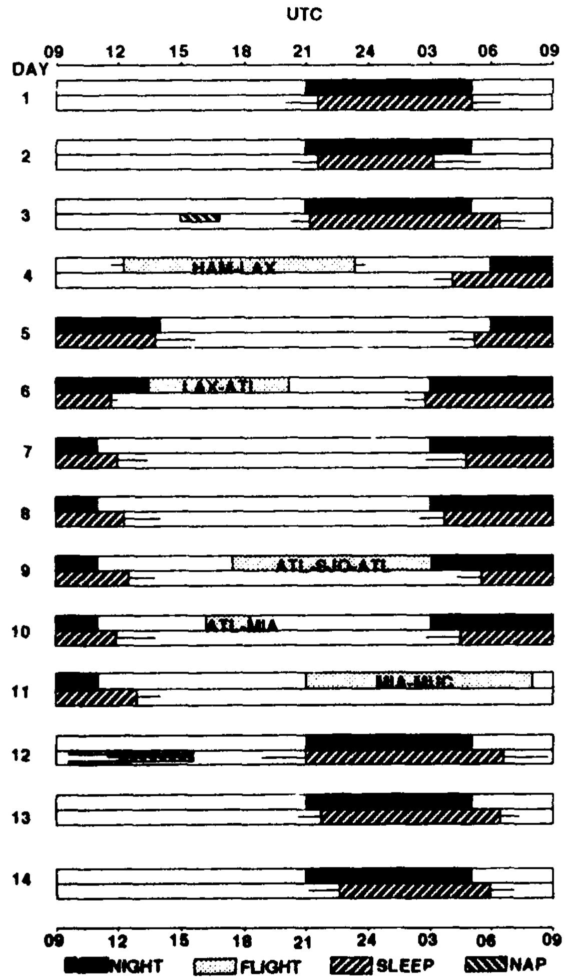
*Figure 1:* **Overview of sleep periods and flight times of the ATL-rotation (N=10). Time axis extends from 0900 to 0900 UTC. Local nights are indicated for the interval between 2300 h and 0700 h local time.**

**Figure 2: Overview of HAM-LAX rotation. (For explanation see figure 1).**

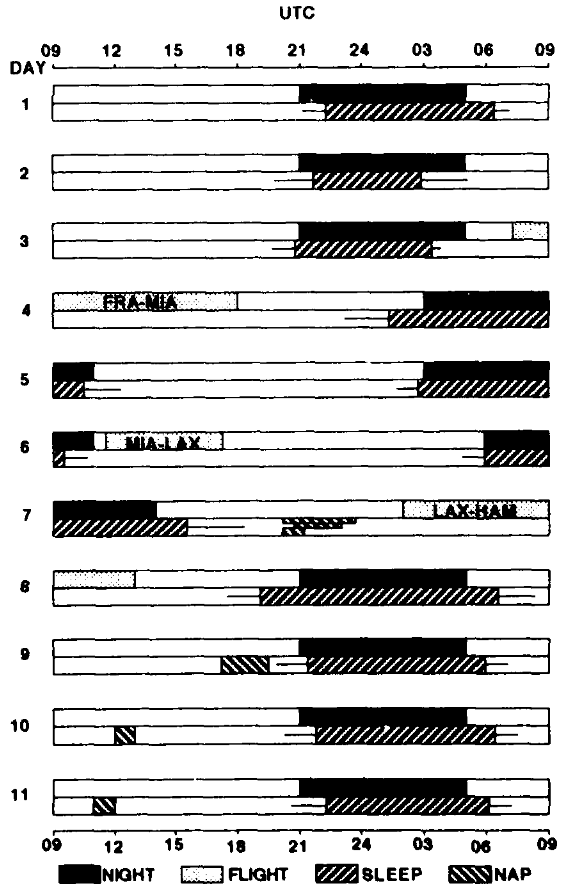
**Figure 3: Overview of LAX-HAM rotation. (For explanation see figure 1).**



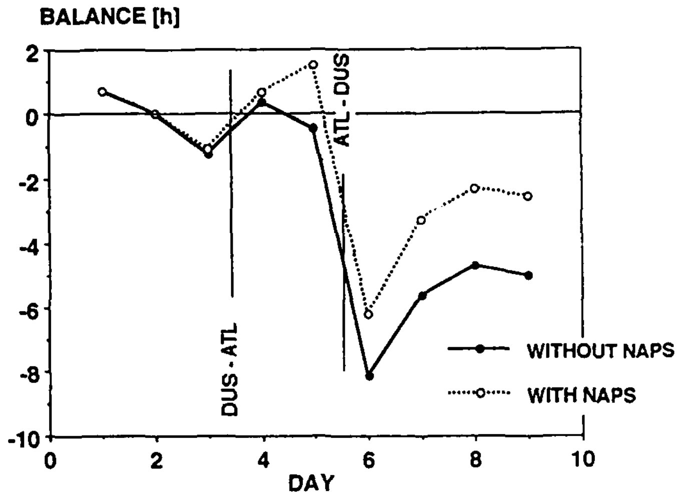

**ATL - ROTATION (n=10): Asleep and wakeup (MEAN ± SD)**

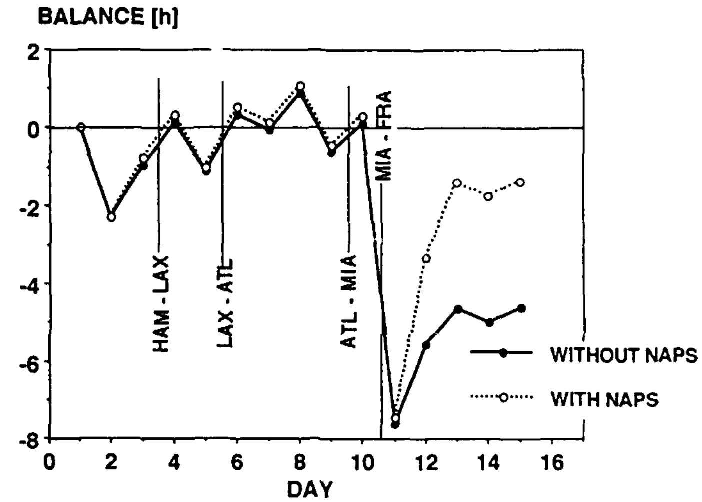



**HAM-LAX ROTATION (n=10): Asleep and wakeup (MEAN ± SD)**




**LAX-HAM ROTATION (n=10): Asleep and wakeup (MEAN ± SI**



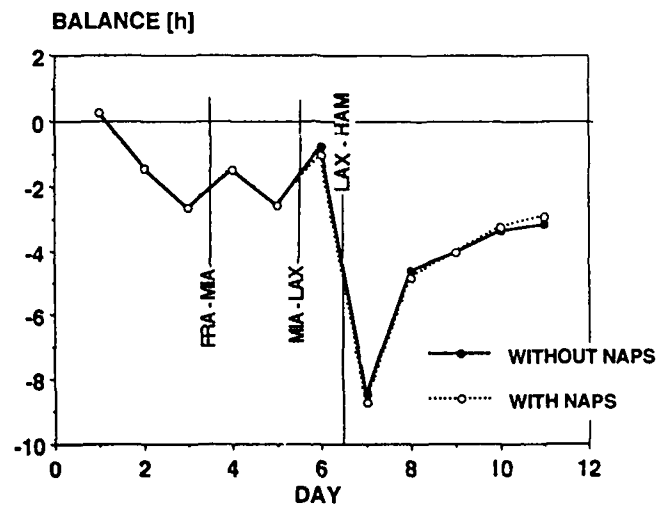




**Figure 4 to Figure 6: Sleep Balance: accumulated deviations of subjectively rated sleep periods from baseline values.**
**Figure 4 (Top): DUS-ATL rotation (N=12)**
**Figure 5 (Centre): HAM-LAX rotation (N=10)**
**Figure 6 (Bottom): LAX-HAM rotation (N=10)**

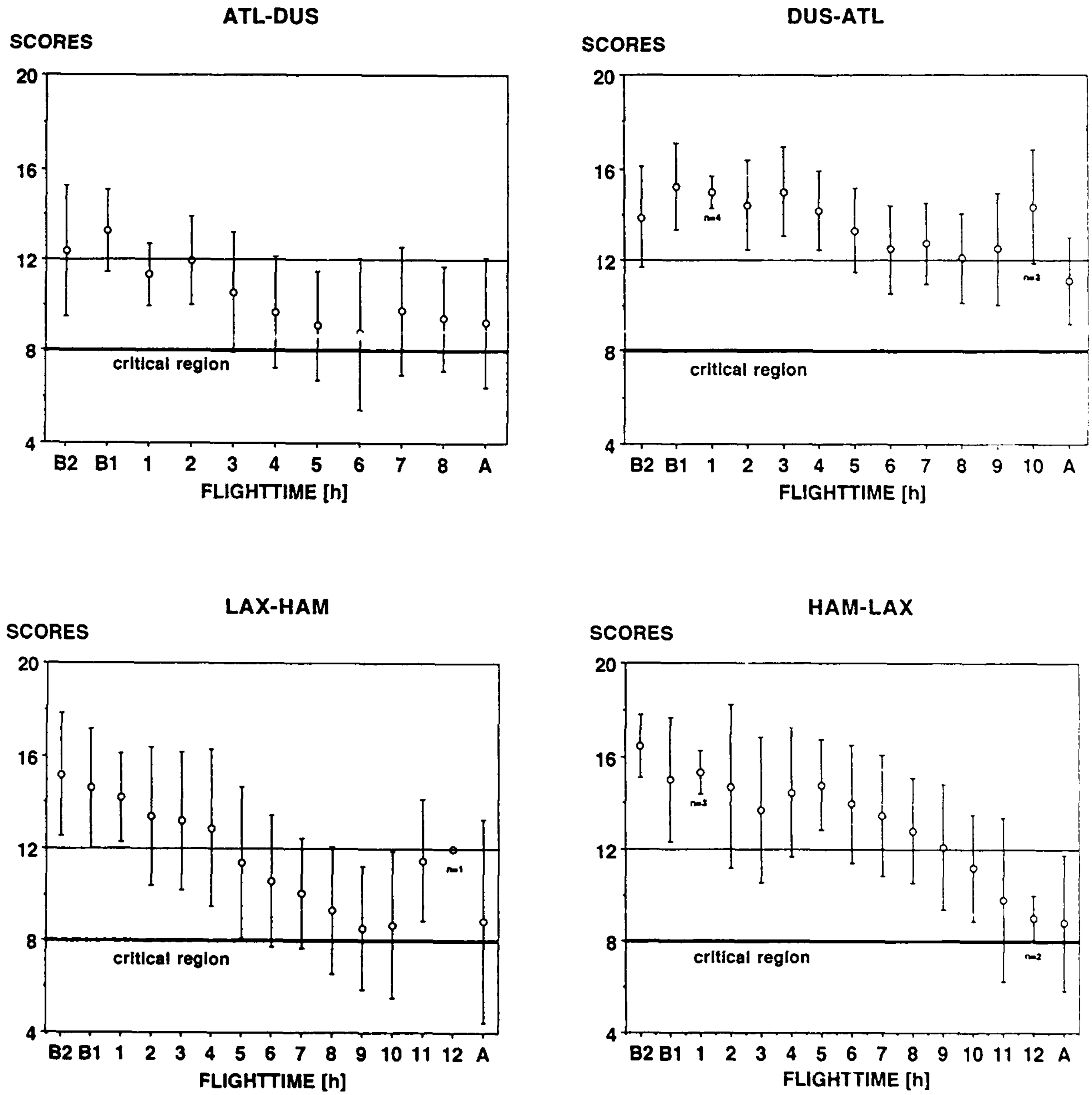



**Figure 7 to Figure 10: Mean fatigue scores (±SD) during flight duty periods. B1 and B2 indicate pre-flight ratings. A indicates postflight ratings. Black bar illustrates critical limit.**

# DETERMINANTS OF SUBJECTIVE FATIGUE FOR C-141 CREWS DURING OPERATION DESERT STORM.

Jonathan French
Kelly J. Neville
William F. Storm
Roger U. Bisson
Patricia Boll

Sustained Operations Branch
Armstrong Laboratory / CFTO
2504 D Drive STE 1
Brooks AFB, TX USA 78235-5104

## SUMMARY

As aircraft flight endurance capabilities increase, the importance of attenuating fatigue during long duration missions increases. Profile of Mood States (POMS) data were used to document cumulative fatigue and to explore the relationships between mission characteristics and changes in mood of C-141 aircrew members during Operation Desert Storm. In particular, this research assessed the effects of increasing the limit of 30-day cumulative flight for long duration transport crews from 125 to 150 hours. POMS data were collected at the beginning of the legal for alert (LFA) and crew rest (CR) intervals. Correlational analyses were used to compare POMS dimensions (anger, depression, confusion, fatigue, vigor, tension) with 13 flight and sleep schedule variables. During both LFA and CR intervals, 30-day cumulative flight hours were not related to subjective mood dimensions. However, when 30-day cumulative flight hours exceeded 125 hours, POMS vigor was decreased by recent (1-2 days) flight and sleep hours. Therefore, attending to recent sleep and flight history may predict decrements in vigor when operational pressures require exceeding the normal cumulative flight hours per month. A first attempt to construct a crew rest equation is proposed that accounts for these factors. This equation is based on a stepwise multiple regression procedure which revealed that vigor and fatigue were best predicted by cumulative 24-hour sleep and 48-hour flight time. In addition to improved crew rest schedules, dedicated crew rest facilities and sleep hygiene instruction are recommended before flying long duration missions.

## 1 INTRODUCTION

Increased efficiency in aircraft design and inflight refueling have resulted in unprecedented flight endurance characteristics for modern aircraft. Human factors issues related to these developments have not progressed as quickly, particularly for long range transport aircraft (1). As assigned mission lengths increase, crew fatigue issues become more important. However, fatigue management techniques and resources are not typically provided to crews. Only very recently have US commercial crews been allowed naps during long flights, although aircraft sleep facilities remain less than optimal (2). Little is known about the factors which most influence fatigue in long duration aircrew. The Gulf war with Iraq

*Presented at an AGARD Meeting on 'Recent Advances in Long Range and Long Endurance Operation of Aircraft', May 1993.*

provided an opportunity to investigate these factors.

The greatest military airlift in history was initiated during the Gulf war by the USAF Military Airlift Command (MAC), now reorganized into Air Materiels Command (AMC). This effort tested the endurance of both the airframes and transport crews. Furthermore, the effort required extending the maximum crew flight limits of 125 cumulative flight hours to 150 cumulative flight hours per 30-days. MAC was concerned with the impact of continuous, long duration missions on flight safety. There were multiple stressors associated with the accelerated pace of MAC flights during Desert Storm. Previous research has suggested that irregular rest and activity cycles associated with long duration missions can lead to deteriorated performance in aircrew members (3,4). As well, continuous, long endurance flights are known to have severe physiological consequences (5,6). Finally, eastward flight, which MAC crews routinely flew, disrupts mission sleep more than westward trips (7). The Sustained Operations Branch of Armstrong Laboratory (CFTO) has experience in evaluating mission-induced fatigue. Accordingly, MAC headquarters requested that investigators from CFTO evaluate the effects of 150 flight hours in a 30-day period coupled with minimum allowable crew rest (12 hours) during the final days of Operation Desert Storm. The data obtained from this study were used to determine the factors which have the greatest impact on air transport crew fatigue.

MAC used a system to limit excessive cumulative flight hours during Desert Storm that depended on the number of flight hours in the most recent 30-day interval. When cumulative flight time reached the limit of 125 hours, crewmembers were occasionally not allowed to fly until their cumulative flight time decreased. For example, if a crewmember had 122 hours in a 30-day interval, they would not be able to fly on a mission over 3 hours until their 30 day interval advanced. The effectiveness of this system in attenuating fatigue has not been evaluated. Further, it occasionally prevented well-rested crews from flying. This study documented fatigue in long duration aircrew flying more than 125 hours per 30 days, investigated factors which may be most responsible for fatigue and explored an alternative system of managing flight hours.

## 2 METHODS

Five C-141B crews were selected by MAC to participate in the study during the final week of Desert Storm and three weeks beyond (16 March-14 April, 1991). The crews were selected from the 437th Military Airlift Wing, Charleston AFB, SC and were authorized for extended cumulative flight of 150 hours per 30-day period and minimum allowable crew rest periods of 12 hours per day for the duration of the 30-day exercise. One investigator from the Sustained Operations Branch of Armstrong Laboratory accompanied each of the crews throughout the data collection period. Crewmembers completed an activity log of events selected from a list of pertinent activities (landings, sleep, meals, etc) as well as oral temperature and fatigue ratings, location, and quality of sleep. These procedures are described more thorougly in other papers presented at a recent AGARD symposium attend to the impact of fatigue on performance, sleep and nutrition (8,9,10). This report describes the Profile Of Mood States (POMS) results that were used to evaluate aircrew subjective states during the 30- day field study. POMS were completed each time the crews became Legal For Alert (LFA) (i.e., at the end of their crew rest) and before Crew Rest (CR) (i.e., at the end of their duty day). The LFA interval began as soon as the CR interval ended and extended until either four hours had passed or a mission had been assigned, whichever occurred first. The majority of the missions were assigned within the 4-hour window. However, at the end of the 4-hour window, the CR interval was usually started again.

POMS is a convenient method of identifying and assessing mood state changes (11). It measures six mood dimensions: tension-anxiety, depression-dejection, anger-hostility, vigor-activity, fatigue-inertia, and confusion-bewilderment (11). POMS consists of 65 adjectives which are rated on a 5-point scale that ranges from 'not at all' to 'extremely'. The raw POMS data were normalized using college student samples, as is the typical procedure for non-psychiatric populations.

The activity log and POMS data were entered into a large data base that resided on a VAX 11-780 computer and were amenable to statistical manipulation. Thirteen sleep and flight schedule variables were derived from the activity logs. Cumulative 30-day flight time was total monthly accumulated flight time for each day in the 30-day exercise. Four other flight schedule variables were cumulative flight hours in one, two, three and five days. An additional four variables were cumulative hours of sleep in one, two, three and five consecutive days. The final four variables were the number of times each subject went to sleep in one, two, three and five days of the study. Data analyses focused on pilots only (aircraft commander and co-pilot) since they slept less during flight than other crewmembers. Other crewmembers were able to either sleep in shifts (engineers) or sleep throughout most of the flight (loadmasters).

After each flight in the study, the Digital Flight Data Recorder (DFDR) information was obtained on magnetic recording tape for later playback and analysis. This technique was designed to provide an objective measure of piloting performance that might be linked to subjective state and with cumulative flight hours (8,13).

## 3 RESULTS

Cumulative flight hours in a 30-day period were organized into blocks: 0-75 hrs, 76-100 hrs, 101-125 hrs and 126-150 hrs. Analysis of variance (ANOVA) comparisons revealed cumulative 30-day flight hour blocks had no significant effect on subjective mood at LFA or CR. In general, POMS scores at LFA were improved ($p < 0.01$) over those obtained at CR for fatigue, vigor and confusion but not for anger, tension or depression. The largest improvements were in fatigue and vigor scores. Vigor and fatigue scores obtained at CR and LFA are shown in Figures 1 and 2, respectively. These figures also show that vigor and fatigue scores were better at the beginning of the study (less than 75 hours) and tended to decline as cumulative 30-day flight hours increase.

The six POMS dimensions were signifi-

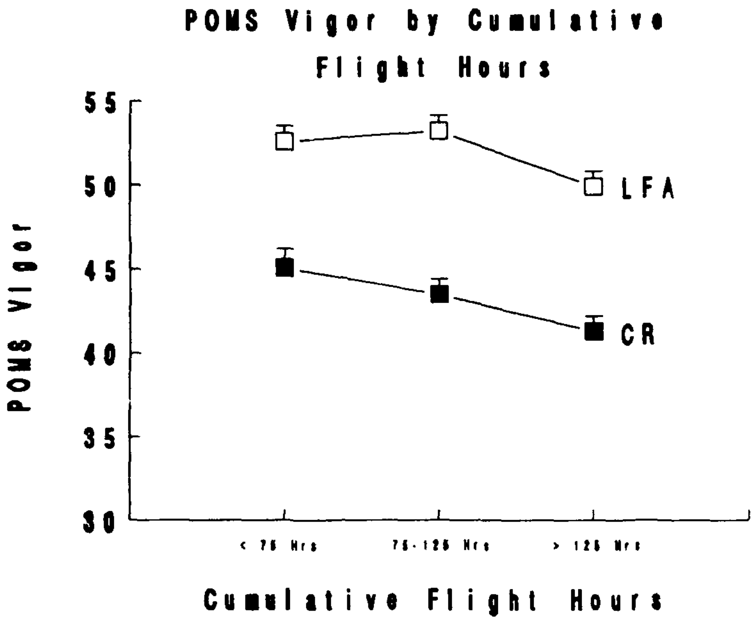



**Figure 1**. POMS Vigor Scores when Legal for Alert (LFA) and during Crew Rest (CR). Average scores and Standard Error of the Means (SEM) are shown.

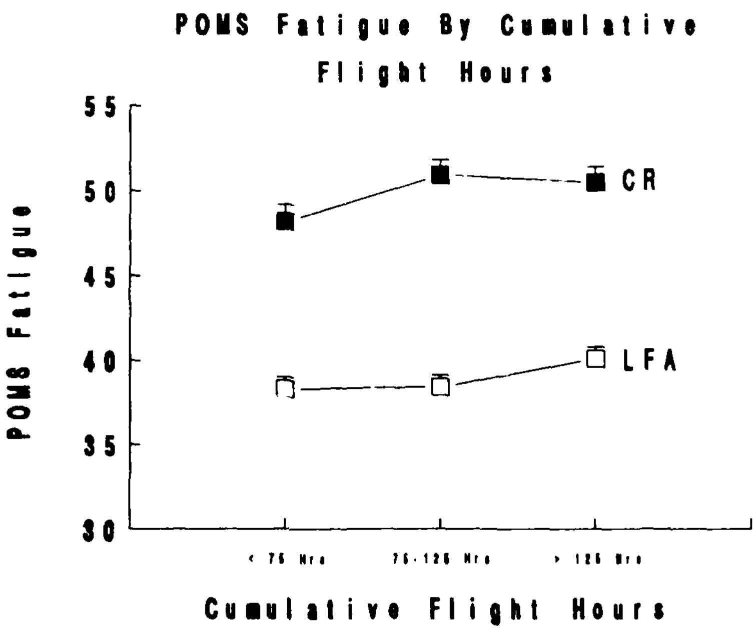



**Figure 2**. POMS Fatigue Scores when LFA and during CR. Average Scores and SEM are shown.

Table 1. Correlation coefficients for POMS dimensions for LFA (SHADED) and for CR over the 30 day study.

| | ANGER | FATIGUE | VIGOR | TENSION | DEPRESSION | CONFUSION |
|---|---|---|---|---|---|---|
| ANGER | — | 0.20 | -0.29 | 0.40 | 0.58 | 0.37 |
| FATIGUE | 0.31 | — | -0.57 | 0.28 | 0.34 | 0.59 |
| VIGOR | -0.29 | -0.68 | – | -0.18 | -0.27 | -0.59 |
| TENSION | 0.73 | 0.32 | -0.30 | – | 0.82 | 0.48 |
| DEPRESSION | 0.81 | 0.36 | -0.36 | 0.64 | – | 0.53 |
| CONFUSION | 0.60 | 0.63 | 0.57 | 0.59 | 0.66 | – |

Table 2. Of the six POMS dimensions, those shown were affected by cumulative flight hours only if recent flight and sleep hours were considered. The Vigor dimension is the most sensitive to cumulative flight hours in a 30 day period and flight or sleep within the prior 24-48 hours.

| | CUMULATIVE FLIGHT HOURS IN A 30 DAY INTERVAL | | |
|---|---|---|---|
| | ≤ 75 hours | 100-125 hours | ≥ 125 hours |
| Legal For Alert | | | |
| Flight in 48 hours | Depression | Tension | — |
| Sleep in 48 hours | — | — | Vigor |
| Crew Rest | | | |
| Flight in 24 hours | — | — | Vigor |
| Sleep in 48 hours | — | — | Vigor |

cantly ($p < 0.05$) intercorrelated as shown in Table 1. The shaded area in Table 1 shows the inter-correlations for POMS scores during the LFA interval. The non-shaded area shows the scores during the CR interval. These data suggest that subjective mood dimensions tended to be similarly affected by the demands of long duration missions.

Evaluation of the POMS data next centered on recent flight and sleep history variables. ANOVA comparisons revealed effects of these variables on three of the POMS dimensions within cumulative 30-day flight hour blocks (see Table 2). Specifically, during LFA, increases in depression and tension were related to increases in 48-hour flight when cumulative 30-day flight hours were less than 75 hours and 100-125 hours, respectively. As well, during LFA, when cumulative flight hours exceeded 125 hours, decreases in vigor dimension were related to decreases in the amount of sleep in the past 48 hours for the LFA and the

CR intervals. During CR, decreases in vigor also were related to increases in 24-hour flight times, as shown in Table 2.

Averages of flight and activity log variables associated with the maximum POMS fatigue scores are shown in Table 3. Scores for the average maximum fatigue value found during the LFA and the CR are shown in Column 1 and 2 of Table 3 (labelled Average (LFA) and Average (CR), respectively). The average maximum POMS fatigue score across the entire 30-day exercise (both LFA and CR) and the associated flight and activity log variables are in the Average (Overall) column. For example, the average time of day (ZULU) in which the greatest POMS scores were recorded occurred at about 11:00 zulu time. This would correspond to about 05:00 local time at Charleston Air Force Base, the home base for these crews. Finding a maximum in subjective fatigue at this time in the morning may be due to circadian rhythmicity of the normally diurnally active pilots. In addition, the maximum POMS fatigue scores occurred early in the 30-day study, prior to the pilot's accumulating more than 94.1 cumulative 30-day flight hours. Table 3 also shows the number of flight and sleep hours the crews experienced in the 24 and 48 hours immediately prior to recording their maximum POMS fatigue scores.

Figure 3 demonstrates changes in cumulative 48 hours of sleep across 30-day flight time blocks. This figure shows that crewmembers slept the least before they had accrued 75 cumulative 30-day flight hours. This figure also shows that the amount of sleep obtained was highest in the 125-150 cumulative 30-day flight hour range.

Analyses of digital flight data revealed that during Instrument Landing System (ILS) approaches, increases in airspeed and heading deviations tended to correspond to increases in subjective fatigue. The maximum deviations in airspeed and heading shown in Figure 4 did not achieve statistical significance when compared across cumulative 30-day flight hours.

Finally, a stepwise linear regression procedure was used to investigate which variables could predict subjective vigor and fatigue values. All 13 variables used in the procedure are listed in Table 4 but only those which significantly improved the predictions were paired with equation estimates in Table 4.

The prediction data shown in Table 4 for fatigue are used in an example in Table 5. The information presents a means to determine how fatigued a crewmember is and a means for determining who is in need of a longer crew rest. The scores are anchored in subjective fatigue and vigor scores. Conceivably, the length of sleep necessary to reduce the scores to acceptable levels can also be determined empirically.

## 4 DISCUSSION

As greater distance capabilities are designed into aircraft the issue of crew fatigue becomes more important. Comfortable crew rest and hygiene facilities should be an integral part of long endurance aircraft design. Long duration missions require careful management of the crew rest periods on the ground as well as in the air.

The study found that pilots can safely fly

Table 3. The average variables corresponding to maximum fatigue scores for each subject during the Legal For Alert (LFA) and Crew Rest (CR) and combined intervals (Overall) are shown.

| | AVERAGE (LFA) | AVERAGE (CR) | AVERAGE (Overall) |
|---|---|---|---|
| Temperature | 97.5 | 97.6 | 97.7 |
| Time (Zulu) | 10:15 | 10:50 | 11:36 |
| Flight In 48 hr | 11.2 | 14.7 | 12.5 |
| Flight in 24 hr | 5.2 | 8.4 | 8.1 |
| Sleep In 48 hr | 12.3 | 11.7 | 14.0 |
| Sleep in 24 hr | 6.4 | 6.8 | 7.8 |
| Cumulative 30-day Hours of flight | 62.9 | 88.9 | 94.1 |
| POMS Fatigue score | 57.0 | 61.3 | 45.3 |

N = 11 pilots

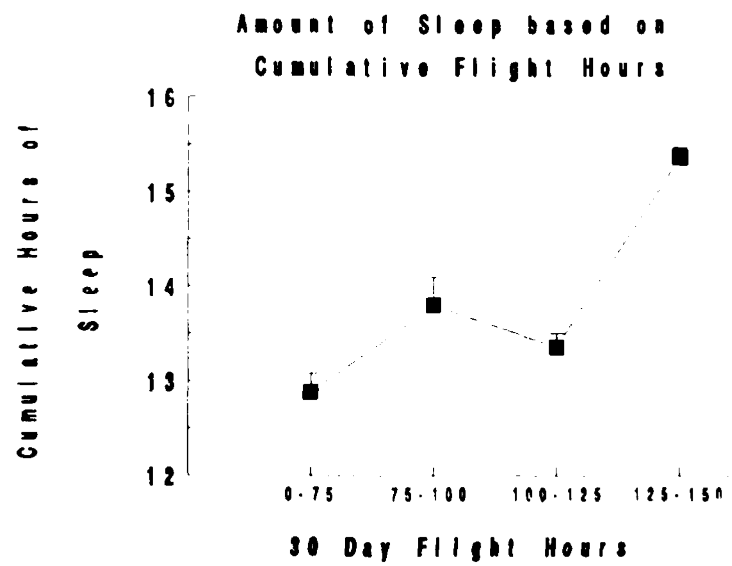



**Figure 3**. Sleep in past 48 hours across cumulative 30-day flight hour blocks. Mean + SEM are shown.

Table 4. Stepwise linear regression estimates of POMS vigor and fatigue. Degrees of Freedom (Total DF), the probability associated with the F ratio (Prob>F), and the overall $R^2$ are shown for vigor and fatigue. The variables which contributed significantly ($p<0.15$) to model the partial $R^2$ value (R**2) for each variable, and the associated probability for each (Prob>F) are also shown.

| | Total DF | Prob>F | Overall R**2 |
|---|---|---|---|
| VIGOR | 267 | 0.0001 | 0.081 |

| Variable | Estimate | R**2 | Prob>F |
|---|---|---|---|
| Intercept | 49.96 | | 0.0001 |
| Flight in 48 hrs | -0.43 | 0.072 | 0.0001 |
| Sleep in 24 hrs | 0.262 | 0.081 | 0.1286 |

| | Total DF | Prob>F | Overall R**2 |
|---|---|---|---|
| FATIGUE | 267 | 0.0001 | 0.147 |

| Variable | Estimate | R**2 | Prob>F |
|---|---|---|---|
| Intercept | 53.2 | | 0.0001 |
| Flight in 48 hrs | 0.38 | 0.07 | 0.0001 |
| Cumulative 30 day hrs | -0.04 | 0.12 | 0.036 |
| Sleep in 24 hrs | -0.57 | 0.14 | 0.008 |

Other variables considered for the model:

Flight hours in 5 days; 3 days; 2 days; 1 day
Sleep hours in 5 days; 3 days; 2 days; 1 day
Sleep attempts in 5 days; 3 days; 2 days 1 day
Cumulative flight hours in 30 days

Table 5. An example of the application of the crew rest interval equation in determining which of 2 crews needs the longer crew rest interval. For illustrative purposes, crew Vigor should be over a value of 45 to be considered mission safe.

Pilot A has 12.5 hours of flight in the last 48 hours and 8 hours of sleep in the past 24 hours.

$$\text{Vigor} = (49.95) + (0.43 * 12.5\text{ hrs}) + (0.26 * 8.0\text{ hrs}) = 46.65$$

Pilot B has 15.5 hours of flight in the last 48 hours and 10 hours of sleep in the past 24 hours.

$$\text{Vigor} = (49.95) + (0.43 * 15.5\text{ hrs}) + (0.26 * 10\text{ hrs}) = 45.88$$

Pilot B: gets the longer crew rest because she/he has less vigor. (If a cut-off score of 45 is used to minimize fatigue, then both pilots would be safe to fly.)

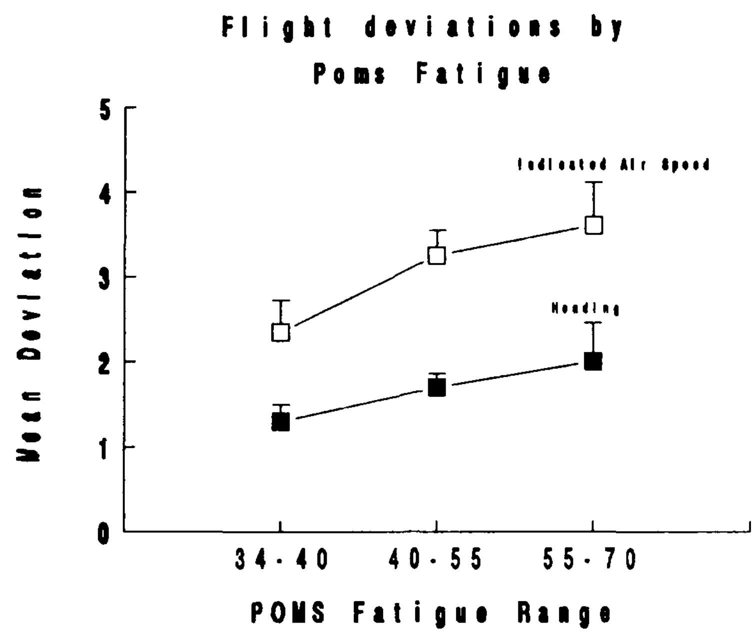



**Figure 4**. Average deviations in heading and airspeed as a function of POMS fatigue. Mean and SEM are shown.

long duration missions in excess of 150 cumulative 30-day flight hours with no greater increase in fatigue than for fewer cumulative flight hours. The differences between LFA and CR intervals in particular for fatigue and vigor, indicated that crew rest was restorative. Cumulative flight hour blocks alone do not account for significant effects on mood. However, combining cumulative flight hours per month with decreasing hours of recent sleep decreased the POMS vigor dimension during LFA and CR intervals only when cumulative flight hours exceeded 125 hours per 30-day period. Vigor was the most sensitive of the POMS dimensions to cumulative flight hours in excess of 125 hours per month when recent sleep (past 24 hours) is considered. Vigor was also affected when flight hours in the past 24 hours are considered with cumulative 30-day flight time.

The finding that the maximum fatigue levels occurred early in the study as shown in Table 3, suggests that the crews were adjusting to the demands of the missions. This suggestion may be supported by data presented in Figure 3 which indicate that crews were getting more sleep as cumulative flight hours increased across missions. There were no serious accidents for transport aircrew that could be related to fatigue during Operation Desert Storm. Still, it was possible to demonstrate that subjective fatigue can be associated with impaired performance as shown in Figure 4. The data in Figure 4 suggests a range of fatigue scores that might be acceptable for mission standards. A goal of the paper was to determine which of the variables under consideration were best correlated with mission-induced fatigue and to construct an empirical formula for quantifying fatigue. The formula is a first attempt to quantify fatigue for use in the field and needs to be empirically verified. Considering recent crew history in determining how much crew rest to assign crews may provide an advantage to managers because more crews should be available than by using the current 30-day cumulative flight hour restriction. It is not difficult for crews to keep track of recent sleep and flight hours since they currently do this for cumulative flight hours. Presumably, the actual amount of sleep necessary to reduce fatigue to acceptable limits could be determined from the further refinement of the equation.

A fatigue management system is needed to plan for long duration missions. The system should include circadian issues, sleep hygiene issues, crew rest schedules, flight schedules, nutrition, exercise, dedicated crew rest facilities, onboard napping facilities and schedules. Physical accommodations could be improved onboard the aircraft. For example, the radio aid known as cell call for military aircraft would prevent the fatigue associated with monitoring long hours of radio static over the ocean. The seats onboard could be more comfortable and more attuned to back support for long duration missions. Humidity control, workable sinks and toilets, better bunk facilities are all means to help reduce the stress and improve the endurance of the crew. Morale of crews would be improved if workable ovens to heat foods were made available. Healthier foods could be made available at flight kitchens and vending machines. Extending the hours at other food facilities for long duration aircraft is highly recommended. Crewmembers should be encouraged to avoid saturated fats and high sugar products. Naps onboard the aircraft should be encouraged. Gyms should be left open 24 hours a day for crews experiencing long duration missions. Consideration also should be given to sleep promoting compounds to increase the restfulness of naps, particularly during unusual crew rest times. Lastly, consideration should be given to stimulants to be used in emergencies during critical periods of flight. These recommendations should extend to ground personnel who support the crews in the air as well. Long duration missions depend on the community that support it and includes the mechanics as well as Air Traffic Controllers.

Since the vast majority of flights crossed multiple time zones travelling in either an eastward or westward direction, no attempt was made to control for direction of flight. It was hoped that these influences would not contribute undue variability to the results since there were just as many eastward as westward flights
An evaluation of subjective data collected from long duration transport crews during the Gulf war found that recent sleep and flight hours were better predictors of fatigue than was cumulative 30-day flight time. Linear regression procedures were used to construct a formula that objectively predicts fatigue and vigor scores. Crew rest onboard the aircraft is currently left to the aircraft commander. The formula described here represents a rational means to determine who gets sleep on the aircraft in flight. Alternative strategies for crew rest inflight would be to have rotating crews whose biological rhythms are 12 hours out of phase. One crew would be rested and ready for flight at take-off while a second team would be ready for rest during the flight and fresh at landing. (14). Attending to recent

sleep and flight histories as well as cumulative flight history may improve vigor and mood when operational pressures require exceeding 125 flight hours per month.

## 5 REFERENCES

1. Simons, M. Environmental factors influencing flight crew performance. NASA Report No.: ETN-91-98698, 14 p, 1990.

2. Pilot fatigue and circadian desynchronosis, National Aeronautics and Space Administration, Moffett Field, CA Ames Research Center. Report No.: NASA-TM-81275; A-8528, 19 p, Apr 1981.

3. Hartman, B.O., Field Study of Transport Aircrew Workload and Rest. Aerospace Med., 42, 8, 817-821, 1971.

4. Sleep and Wakefulness: Handbook for Flight Medical Officers, 2nd Edition (Nicholson, A.N. and Stone, B.M. (Eds). Advisory Group for Aerospace Research and Development, Neuilly-sur-Seine (France). Report No.: AGARD-AG-270(F), 1987.

5. Meyer, L.G. and DeJohn, C.A., Sustained Flight Operations in Navy P-3 Aircraft Naval Aerospace Medical Research Lab., Pensacola, FL. Report No.: NAMRL-1355; XN-NMRDC, Apr 1990

6. Perelli, L.P., Fatigue Stressors in Simulated Long-Duration Flight; Effects on Performance, Information Processing, Subjective Fatigue, and Physiological Cost. Report No.: SAM-TR-80-49, Dec, 1980.

7. Crew Factors in Flight Operations. Part 4. Sleep and Wakefulness in International Aircrews. Graeber, RC (Ed), National Aeronautics and Space Administration, Ames Research Center. Report No.: NAS 1.15:88231; A-86182; NASA-TM-88231, Feb, 1986.

8. Bisson, R.U., Neville, K.J., Boll, P.A., French, J., Ercoline, W.E., McDaniel, R.L., and Storm, W.F., Digital Flight Data as a Measure of Pilot Performance Associated with Fatigue from Continuous Operations During the Persian Gulf Conflict, NATO-AGARD-CP533, Nutrition: Metabolic Disorders and Lifestyle of Aircrew, p29.1- 29.11, 1993.

9. Boll, P.A., Storm, W.F., French, J., Bisson, R.U., Armstrong, S.H., Slater, T., Ercoline, W.E., and McDaniel, R.L., C-141 Aircrew Sleep and Fatigue During the Persian Gulf Conflict, NATO-AGARD-CP 533, Nutrition: Metabolic Disorders and Lifestyle of Aircrew, p 26.1-26.13, 1993.

10. French, J. and Cook T., Nutrition for a Typical MAC Crew during Desert Storm, NATO-AGARD-CP533, Nutrition: Metabolic Disorders and Lifestyle of Aircrew, p 5.1-5.6, 1993.

11. Nowlis, V. and Green, R.F., The experimental analysis of mood. Paper read at the International Congress of Psychology, Brussels, July, 1957.

12. McNair, D.M., Lorr, M. and Droppleman, L.F., EITS Manual for the Profile of Mood States, Educational and Industrial Testing Service. p 3-27, 1971.

13. Neville, K.J., Bisson, R.U., French, J., Boll, P.A. and Storm, W.F. Subjective fatigue of C-141 crew during Operation Desert Storm. Human Factors, In preparation 1993.

14. Storm, W.F. Air crew fatigue during extended transport, tactical, and command post operations. In J. Ernsting (Ed), Proceedings of the NATO Advisory Group for Aerospace Research and Development. Sustained, intensive air operations: physiological and performance aspects. (Report NO AGARD-CP-338) pp 21.1-21.16, 1983.

# QUELQUES SOLUTIONS POUR REDUIRE LES EFFETS SUR L'HOMME DES OPERATIONS DE LONGUE DUREE

(Some solutions to reduce the human effects of extended operation times)

**D. LAGARDE**
**D. BATEJAT**

Centre d'Etudes et de Recherches de Médecine Aérospatiale (C.E.R.M.A.) du Service de Santé des Armées.
BP 73 - 91223 BRETIGNY SUR ORGE CEDEX - FRANCE

## SUMMARY

Mostly, in aeronautical environment, the extended operation times assume the continued operations aspect with long duration flights, sometimes transmeridian. In this operations setting, the fast and repeated passing of several time zones is attended with the classical symptomatology of "Jet-lag", intensified by the own conditions of the mission. The appearance and the extent of "Jet-lag" are variable according to the flight and the involved subject characteristics ; nevertheless, the psychomotor performances decrease is a constant factor of these disorders. In order to investigate with a greater accuracy this aspect in laboratory, the authors present a study model represented by the STRES battery, an ensemble of seven psychomotor tests, recommended by the working group n° 12 of the AGARD/NATO, that allows the evaluation of the whole psychomotor register of a subject situated in stress environmental conditions, in a broad meaning. Two applying examples of these tests to sleep deprivation states are introduced so as to illustrate the sensibility and the interest of implementing this tests battery. In view of the disorders penalizing effect, several authors have postulated for solutions in order to suppress or at least to reduce the duration and importance of such symptoms. Thus, some accurate instructions have been recommended relating to the maximum workload condition that can not be exceeded and to the dual aircrew. Others have enjoined to be synchronise with the new time table before departure or to strengthen the social "zeitgeber" at arrival. Phototherapy, naps, dietetic measures and physical exercice are also a part of the suggested steps. The pharmacological approach with the use of caffeine, hypnotics and more recently of melatonin, have a new lease of interest especially with the appearance of new awakening drugs, as powerful as amphetamines but without their secondary effects. Thus, after the justification of the stimulating drugs use in the setting of wake sleep rhythms desynchronisation, the authors present concisely the modafinil, main representative of this new molecule category. Then, from examples of the laboratory, on occasion of psychomotor performance evaluation with the STRES battery on subjects under sleep deprivation, or on field, they present some results obtained after dispensation of this drug. At the end of this review and of the experimental results, it appears that the extended operation times induce wake-sleep rhythm and psychomotor performances disorders.
Numerous possibilities, complementary, exist in order to reduce the observed disorders ; none of them appears alone sufficient. Nevertheless, the new awakening drugs appearance, on account of their great efficiency and their whole inocuity, should constitute a major element in biological rhythms resynchronisation in the future.

## RESUME

Les opérations soutenues revêtent le plus souvent en milieu aéronautique l'aspect d'opérations continues comportant des vols de longue durée, parfois transméridiens. Dans le cadre de ces opérations, le franchissement rapide et répété de plusieurs fuseaux horaires s'accompagne de la symptomatologie classique du "jet-lag" aggravée par les conditions propres à la mission. L'apparition et l'importance du "jet-lag" sont variables en fonction de la nature du vol et du sujet qui l'accomplit, cependant un facteur constant de ces perturbations est la diminution des performances psychomotrices. Afin d'approcher plus précisemment cet aspect en laboratoire, les auteurs présentent un modèle représenté par la STRES battery, ensemble de sept tests psychomoteurs recommandé par le groupe de travail n° 12 de l'AGARD/NATO, qui permet d'évaluer l'ensemble du registre psychomoteur d'un sujet placé dans un environnement stressant, au sens large du terme. Deux exemples d'application de ces tests à des situations de privations de sommeil sont donnés afin d'illuster la sensibilité et l'intérêt de la mise en oeuvre de cette batterie de tests. Devant l'effet pénélisant de ces perturbations de nombreux auteurs ont proposé des solutions pour sinon supprimer du moins réduire la durée et l'importance de ces symptômes. C'est ainsi que des consignes précises ont été préconisées concernant la charge maximale de travail à ne pas dépasser et le fonctionnement en équipage double. D'autres ont recommandé de se synchroniser au nouvel horaire avant le départ ou de renforcer les synchroniseurs sociaux une fois arrivé. La photothérapie, les petits sommes (ou naps), des mesures diététiques et l'exercice physique font aussi partie de la panoplie des mesures proposées. L'approche pharmacologique avec l'utilisation de la caféine, des hypnotiques et plus récemment de la mélatonine, connaît un regain d'intérêt notamment avec l'apparition de nouvelles molécules éveillantes aussi puissantes que les amphétamines mais sans leurs effets secondaires. C'est ainsi qu'après avoir justifié l'utilisation de substances stimulantes dans le cadre d'une désynchronisation des rythmes veille-sommeil, les auteurs présentent succintement le modafinil, principal représentant de cette

*Presented at an AGARD Meeting on 'Recent Advances in Long Range and Long Endurance Operation of Aircraft', May 1993.*

nouvelle classe de molécules. Puis à partir d'exemples pris en laboratoire, à l'occasion de l'évaluation de la performance psychomotrice avec la STRES Battery chez des sujets soumis à des privations de sommeil, ou sur le terrain, ils donnent quelques exemples de résultats obtenus après administration de cette substance. A l'issue de cette revue et des résultats expérimentaux obtenus, il apparaît que les opérations de longue durée provoquent des perturbations du rythme veille-sommeil et des performances psychomotrices. De nombreuses possibilités, complémentaires, existent pour tenter de réduire les dégradations observées, aucune ne semble être suffisante à elle seule, cependant l'apparition de nouvelles substances éveillantes, en raison de leur grande efficacité et de leur totale innocuité, pourraît constituer dans l'avenir un élément majeur dans la resynchronisation des rythmes biologiques.

## INTRODUCTION

Les opérations aériennes à longue distance et de longue durée ne sont pas sans poser de nombreux problèmes dans le domaine dit du facteur humain. Parmi les problèmes rencontrés, celui de la perturbation du rythme veille-sommeil est essentiel. En effet, les vols transméridiens, en raison du franchissement rapide et répété de plusieurs fuseaux horaires, vont modifier les rythmes circadiens de l'organisme, dont le rythme veille-sommeil. De plus, en milieu militaire, pour des raisons de discrétion et des raisons opérationnelles, les décollages s'effectuent la nuit après toute une journée de préparation de la mission n'ayant pas permis dans la plupart des cas, la prise d'un repos compensateur. C'est ainsi qu'à l'effet propre du décalage horaire, appelé "jet-lag" vont s'ajouter d'une part une privation plus ou moins importante de sommeil et d'autre part un dépassement de la charge de travail, habituelle, dans un contexte opérationel et peut-être de conflit. Les conséquences d'une telle perturbation sont multiples, mais l'une d entre elles peut être particulièrement pénalisante pour la conduite de la mission ; il s'agit de la dégradation des performances psychomotrices. De nombreux chercheurs se sont penchés sur ce problème et un nombre assez élevé de solutions ont été proposées pour tenter de réduire les effets observés. Afin de faire le point sur la question, nous commencerons ce travail en rappelant brièvement les principales altérations du rythme veille-sommeil lors des vols transméridiens, puis nous donnerons un exemple d'étude de la performance psychomotrice en laboratoire à partir de la mise en oeuvre de la STRES Battery (Standardized Tests for Research in an Environmental Stressors). Dans une troisième partie nous donnerons une liste, non exhaustive, des solutions habituellement préconisées pour lutter contre les effets du "jet-lag". Seront aussi envisagées des solutions ergonomiques, physiologiques et pharmacologiques. Enfin, dans la dernière partie, nous aborderons la possibilité de prolonger l'éveil à partir d'une molécule éveillante originale en donnant quelques résultats expérimentaux obtenus lors d'expérimentations de privations de sommeil

Il est illusoire de vouloir répertorier l'ensemble des symptômes ou effets dûs aux perturbations du rythme veille-sommeil, tant ceux-ci sont variables dans leur intensité et divers dans leur expression. En effet, plusieurs paramètres interviennent dans la variation des effets observés et devront être pris en compte dans l'appréciation générale du phénomène. Par ailleurs, l'étiologie de ces phénomènes est encore peu ou mal connue.

## 1) PRINCIPALES ALTERATIONS DU RYTHME VEILLE - SOMMEIL LORS DES VOLS DE LONGUE DUREE

### 1. 1. Synthèse des effets observés

Le rythme veille-sommeil comme beaucoup d'autres rythmes biologiques est dit circadien en raison de sa périodicité voisine de 24 heures (1). Toute interruption ou modification de ce rythme est souvent à l'origine d'un ensemble de symptômes appelés par les anglo-saxons le "jet-lag".

Cependant pour apparaître, cette symptomatologie nécessite, en ce qui concerne le pilote d'aéronef ou des troupes aéroportées, le franchissement rapide de quatre à cinq fuseaux horaires et persiste quatre à cinq jours avant qu'un équilibre soit retrouvé ; le sujet reprenant un rythme physiologique de base (2). En réalité, il a été montré que, si apparemment l'ensemble des désordres fonctionnels rentrait dans l'ordre, certains rythmes fondamentaux comme celui de la température ou de certaines sécrétions hormonales ne se remettaient en phase avec le nouveau rythme imposé que beaucoup plus lentement (deux à trois mois selon le cas) (3).

Les principaux troubles observés sont ceux affectant le sommeil et l'appareil digestif. Les troubles du sommeil consécutifs au décalage existent dans 78 % des cas (2). Il s'agit de difficultés à l'endormissement, d'insomnie nocturne, de réveils précoces et de somnolence diurne. Les troubles digestifs observés, parfois aggravés par le changement de régime alimentaire, sont essentiellemement dûs aux variations incessantes de l'horaire des repas. Mais cette symptomatologie n'est pas la seule manifestation d'une altération du rythme veille-sommeil.

Les perturbations des autres rythmes biologiques comme celui de la température ou des sécrétions hormonales concomitants physiologiques du rythme veille-sommeil, sont peut-être à l'origine d'altérations plus ou moins profondes du fonctionnement général de notre organisme et de son métabolisme de base. Une équipe de chercheurs militaires des Pays-Bas a ainsi distingué des effets aïgus apparaissant rapidement lors de franchissement limités dans le temps des fuseaux horaires et des effets chroniques observés surtout chez le personnel navigant et dûs à des modifications répétées du rythme veille-sommeil (4) (cf Tableau n°1).

L'ensemble de cette symptomatologie, qu'il s'agisse d'effets aïgus ou d'effets chroniques, est retrouvée de façon systématique et à des degrés divers dans les travaux évaluant la quantité et la qualité du sommeil du personnel navigant (5, 6, 7, 8, 9, 10, 11, 12). Il est à remarquer que dans la liste des effets observés, celui de la dégradation des performances, tient une place majeure (13, 14, 12).

1. 2. Facteurs de variations

Les facteurs de variation des effets des privations de sommeil sont essentiellement au nombre de quatre : les facteurs individuels, les facteurs d'environnement, le sens du déplacement pour le "jet-lag" et l'association éventuelle avec les facteurs propres à la mission.

En dehors des états pathologiques, l'âge du sujet semble jouer un rôle relativement mineur dans le cadre des facteurs individuels. Cependant dans certains travaux (15) les sujets inclus dans la fourchette d'âge 40-60 ans semblent plus vulnérables aux privations de sommeil que les sujets plus jeunes. En raison de l'apparition tardive des maxima et des minima du cycle circadien, le décalage du rythme "vers la droite" (nécessaire après un vol vers l'ouest) est plus facile pour la "personne du soir" que pour la "personne du matin".

Les facteurs d'environnement semblent jouer un rôle beaucoup plus important. En effet, à côté du franchissement des fuseaux horaires et du travail posté, facteurs très influents de l'environnement sur le sommeil, le bruit, la température, l'altitude, le confort interviennent pour une bonne part dans la qualité et la quantité de sommeil. En ce qui concerne le bruit, il apparaît que ce qui importe au niveau de la perturbation du sommeil est la différence entre le fond sonore habituel avec lequel vit et dort le sujet et le niveau maximum de bruit observé : plus grande sera la différence, plus grande sera la modification du sommeil. Cependant, les changements obtenus dans la qualité du sommeil peuvent diminuer lors d'expositions répétées aux bruits mais le mécanisme physiologique reste inconnu (14, 16). Les relations sommeil et ambiance thermique ont surtout été étudiées par Muzet (17) à Strasbourg et par Buguet (18) à Lyon ; il semble qu'un sommeil normal soit compatible avec des températures comprises entre 22 et 25° ; au-delà mais surtout en deçà la privation de sommeil en résultant est liée à une diminution de la qualité des performances mentales. Les quelques études réalisées en altitude indiquent un accroissement de la latence d'endormissement mais une augmentation de la durée totale du sommeil (19). Enfin, le confort au sens large du terme est souligné par tous les sujets. La qualité du couchage et de l'environnement psychosocial influent sur la motivation ; l'expérience de la situation vécue par le sujet ou par son entourage semble jour un rôle important sur la qualité subjective du sommeil.

Concernant le transport aéroporté des troupes, le sens dans lequel s'effectue la rotation joue un rôle certain. Les vols vers l'Ouest paraissent mieux supportés que les vols vers l'Est (20, 21, 22, 23). Enfin l'association éventuelle de tous ces facteurs avec ceux inhérents à la mission confiée : difficulté particulière ou dangerosité élevée de la mission, départ en mission de nuit, ou plus prosaïquement conditions météorologiques défavorables, problèmes personnels, éloignement de la famille représentent tout un contexte susceptible de perturber le rythme veille-sommeil d'un combattant engagé dans un conflit.

En résumé, les perturbations du rythme veille-sommeil, et notamment le franchissement rapide de plusieurs fuseaux horaires, provoquent des altérations physiologiques et subjectives du sommeil se traduisant par une baisse des performances et une moins bonne efficacité opérationnelle. (cf Tableau n° 2)

1. 3. Etiologie du "Jet-Lag"

La connaissance exacte de l'étiologie du "Jet-lag" est encore imparfaite, cependant il est possible de distinguer trois facteurs essentiels qui semblent être à l'origine de cette symptomatologie.

- *La fatigue liée au voyage.* Elle n'est pas propre au franchissement des fuseaux horaires puiqu'on la rencontre aussi lors des vols Nord-Sud. Elle peut avoir de nombreuses origines comme les préparatifs du voyage ou de la mission, le maintien prolongé d'une position (même assise), les vibrations mécaniques dûes au moyen de transport, l'ambiance sonore inhabituelle, la fatigue psychique dûe à l'excitation circonstancielle, etc ... (19).
- *La privation de sommeil.* Elle n'est pas non plus spécifique aux vols transméridiens. Cependant, elle est souvent présente avant même le départ, en raison du temps passé à la préparation de la mission. Les perturbations du rythme veille-sommeil dûes aux modifications des rythmes biologiques, au confinement, aux activités nécessaires lors des escales techniques, etc ... (24) s'accompagnent de façon presque systématique d'une dette plus ou moins importante de sommeil.
- *La lenteur et l'irrégularité de l'ajustement des rythmes endogènes au nouveau fuseau horaire.* En effet, même si, en l'absence de toute information externe, lors des expériences d'isolation "hors du temps", les rythmes biologiques persistent avec une période légèrement différente de 24 heures, la lumière et les facteurs sociaux sont les synchroniseurs les plus importants. Cependant, tous les rythmes ne s'adaptent pas avec la même vitesse au nouvel horaire. Et si subjectivement quatre à cinq jours suffisent pour "récupérer" une activité normale, le rythme de la température peut rester perturbé plusieurs semaines. (7, 3)

## 2) UN EXEMPLE D'ETUDE DE LA PERFORMANCE PSYCHOMOTRICE AU LABORATOIRE

2.1. Présentation de la STRES Battery

La batterie de tests S.T.R.E.S. (Standardised Tests for Research with Environmental Stressors) a été élaborée par le groupe de travail n°12 de la Commission de Médecine Aérospatiale de l'AGARD (25) pour permettre la standardisation de l'évaluation des effets de tout facteur de stress sur la performance. Cette batterie est intégrée à l'ensemble des moyens d'évaluation de la vigilance chez l'homme utilisé dans notre laboratoire, et comprenant également des mesures. électrophysiologiques, une surveillance médicale et biologique et le recueil de questionnaires (26). Elle est

implantée sur micro-ordinateurs compatibles IBM PC et comprend sept tests :
- une tâche de temps de réaction qui permet l'évaluation des cinq étapes de traitement suivantes : traitement de la stimulation ou codage, choix de la réponse, programmation de la réponse motrice, activation motrice et enfin exécution de la réponse. Les chiffres "2 - 3 - 4 - 5" sont utilisés comme stimulations, le sujet est invité à répondre le plus rapidement possible sans faire d'erreurs. La réponse dépend de la nature et de la position sur l'écran, droite ou gauche, du chiffre présenté. Suivant les conditions expérimentales les chiffres apparaissent sous une forme normale ou dégradée, l'intervalle inter-stimulus est variable, ou bien la réponse est inversée ou consiste à appuyer sur trois touches successivement au lieu d'une. Le temps de réponse est pris en compte ainsi que le nombre d'erreurs. En cas d'absence de réponse dans un délai de 2 sec., la stimulation suivante apparait après un "bip" sonore ; les non-réponses sont également comptabilisées.
- une tâche de traitement mathématique qui permet l'évaluation des ressources des processus centraux primaires associés à la mémoire de travail. Le sujet doit indiquer si le résultat total d'une série de trois opérations à un seul chiffre (addition et/ou soustraction), présentées sur l'écran, est supérieur ou inférieur à 5, en appuyant le plus rapidement possible sans faire d'erreurs, sur une touche "réponse". Le temps de réponse et le nombre d'erreurs sont pris en compte. En cas d'absence de réponse dans un délai de 15 sec., la stimulation suivante apparait après un "bip" sonore ; les non-réponses sont également comptabilisées.
- une tâche de recherche en mémoire qui comprend les étapes suivants : détection et reconnaissance du stimulus cible, recherche en mémoire et comparaison, sélection de la réponse. Basé sur le paradigme décrit par Sternberg (27), ce test consiste à mémoriser deux ou quatre lettres, puis à dire si chaque lettre cible apparaissant au centre de l'écran fait partie de celles qui ont été mémorisées, en appuyant le plus rapidement possible et sans faire d'erreurs sur la touche "réponse" correspondante. Le temps de réponse et le nombre d'erreurs sont pris en compte. En cas d'absence de réponse dans un délai de 5 sec., la stimulation suivante apparait après un "bip" sonore ; les non-réponses sont également comptabilisées.
- une tâche de traitement spatial qui correspond à une mesure des capacités de la mémoire visuelle à court terme. A chaque essai, le sujet doit comparer un histogramme "référence" de quatre barres (appelé 1), présenté horizontalement, et un histogramme "test" (appelé 2), ayant subi une rotation de 90 ou 270 degrés apparaissant successivement au centre de l'écran et dire s'ils sont identiques ou non, sans tenir compte de l'orientation. Le temps de réponse et le nombre d'erreurs sont pris en compte. En cas d'absence de réponse dans un délais de 15 secondes, la stimulation suivante apparait après un "bip" sonore ; les non-réponses sont également comptabilisées.
- une tâche de poursuite destinée à mesurer les ressources utilisées dans l'exécution d'une tâche de contrôle manuel continu. Le sujet doit à l'aide d'un "joy-stick" maintenir un curseur au centre d'une cible fixe et éviter autant que possible que le curseur dépasse les limites, gauche et droite, de la cible ce qui est qualifié de perte de contrôle. Un indice de déviation du curseur par rapport au centre de la cible est calculé (il s'agit de la racine carrée de la moyenne des écarts mesurés toute les secondes) et le nombre de perte de contrôle est comptabilisé.
- une tâche de raisonnement grammatical qui mesure l'habileté à manipuler des informations grammaticales en utilisant la mémoire de travail. Trois phrases superposées sont affichées au centre de l'écran. Les deux premières phrases décrivent chacune l'ordre de deux symboles. L'un de ces symboles est commun aux deux expressions alors que les deux autres symboles sont différents d'une phrase à l'autre. Le sujet doit vérifier la véracité de ces deux phrases par rapport à l'ordre dans lequel ces trois symboles sont présentés sur la troisième ligne. Deux réponses sont attendues : soit les deux phrases sont identiques, vraies ou fausses toutes les deux, soit elles sont différentes, l'une vraie l'autre fausse. Le temps de réponse et le nombre d'erreurs sont pris en compte. En cas d'absence de réponse dans un délai de 15 sec., la stimulation suivante apparait après un "bip" sonore ; les non-réponses sont également comptabilisées.
- une double-tâche, combinant l'exécution stimultanée de la tâche de poursuite et de la tâche de recherche en mémoire, qui permet la mesure des capacités d'attention divisées. Les données recueillies sont l'indice de déviation du curseur par rapport au centre de la cible et le nombre de perte de contrôle pour la poursuite, le temps de réponse, le nombre d'erreurs et de non-réponses pour la tâche de recherche en mémoire.

L'utilisation de la "STRES battery" ne pose pas de problèmes majeurs. Elle comporte néanmoins un certain nombre de contraintes liées à la nécessité de standardisation. Le matériel utilisé doit répondre à des spécifications techniques précises concernant l'écran (définition de l'image), le clavier (position des touches réponse) et le joy-stick (taille déterminée). Le déroulement des tests doit se faire dans des conditions bien définies ; distance et hauteur du sujet par rapport à l'écran, position des doigts sur les touches, et surtout dans un environnement stable et contrôlé, du point de vue de l'ambiance lumineuse et sonore. Le temps de passage de l'ensemble des sept tests est de l'ordre de 50 minutes, et dans la mesure où du matériel identique est disponible, et où les locaux le permettent, plusieurs sujets peuvent être testés dans une même séance. Enfin, tout enregistrement expérimental doit être précédé d'une phase de démonstration et d'apprentissage indispensable pour obtenir un niveau de performance stable.

### 2.2. Application à deux protocoles expérimentaux de privation de sommeil

La "STRES Battery" a ainsi été mise en oeuvre notamment dans deux études destinées à évaluer les effets de perturbations du rythme veille-sommeil sur la performance.

#### 2.2.1. Privation de sommeil de 60 heures

Cette étude a été réalisée pour étudier les effets d'une privation de sommeil de longue durée sur le niveau de performance. Huit sujets volontaires, de sexe

masculin, âgés de 22 à 31 ans, ont participé à l'expérience. Tous ont été soumis à un examen clinique complet avant dêtre sélectionnés. Ils ont donné leur consentement éclairé selon la convention d'Helsinki.
Le protocole expérimental est le suivant :
Après l'apprentissage des tests, les sujets ont effectué une série d'enregistrements témoins à 3 heures, 9 heures et 17 heures sans privation de sommeil.

Les sujets sont pris en charge le lundi en fin de journée. La privation de sommeil commence le mardi matin après une nuit normale (lever à 7 heures). Pendant toute la durée de la privation de sommeil les sujets sont soumis périodiquement à l'ensemble des mesures (MSLT, questionnaires, examens cliniques et tests psychomoteurs). Entre temps ils sont maintenus éveillés par les expérimentateurs et occupés à des activités diverses. La première session d'enregistrement des tests psychomoteurs à lieu le mardi à 17 heures, c'est-à-dire à la fin d'une journée normale d'éveil. Les enregistrements des tests ont ensuite lieu selon le calendrier suivant :

| | | durée de privation de sommeil |
|---|---|---|
| mercredi | 3 heures | 20 heures |
| | 9 heures | 26 heures |
| | 17 heures | 34 heures |
| jeudi | 3 heures | 44 heures |
| | 9 heures | 50 heures |
| | 17 heures | 58 heures |
| vendredi | 17 heures après une nuit de récupération | |

Tous les résultats ont été traités par analyse de variance avec mesures répétées (ANOVA).

Globalement, on observe une dégradation de la performance en fonction de la durée de la privation de sommeil. Cependant cette évolution n'est pas la même pour toutes les tâches. La dégradation peut être plus ou moins importante et apparaître plus ou moins tôt au cours de l'expérience (28). La tâche de temps de réaction est peu sensible alors que les tâches de poursuite, de traitement mathématique et spatial, et de raisonnement grammatical sont très perturbées par la privation de sommeil. Dans le raisonnement grammatical, l'évolution de la dégradation est régulière au cours de la privation de sommeil dès la première nuit sans sommeil. Alors que dans le traitement spatial cette dégradation n'apparait qu'à partir de 26 heures de privation de sommeil et se traduit par un allongement des temps de réponse combiné à une augmentation des taux d'erreurs et présente de plus une évolution cyclique (13). Enfin, dans la double-tâche, poursuite et recherche en mémoire sont également perturbées dès la première session de 03 heures.

Les tâches de poursuite, traitement mathématique et recherche en mémoire (quatre lettres) représentent des exemples caractéristiques de l'évolution des performances observée durant les soixante heures de privation de sommeil. Dans le test de poursuite, la performance se dégrade dès la première séance de 03 heures (figure 1), l'écart à la cible augmente rapidement et s'accompagne d'un nombre important de pertes de contrôle, indices de l'apparition de "micro-sommeils" (29), après 44 heures de privation de sommeil.

La dégradation apparait un peu plus tard, soit après 26 heures de privation de sommeil pour la tâche de traitement mathématique (figure 2) qui présente un allongement régulier des temps de réponse sans augmentation du nombre d'erreurs.

La recherche en mémoire est également affectée par une privation de sommeil de 26 heures, particulièrement dans le cas de la mémorisation de quatre lettres (figure 3), ceci se traduit surtout par une augmentation importante du nombre d'erreurs.

2.2.2. Perturbations du rythme veille-sommeil avec privation limitée de sommeil (2 fois 27 heures), intérêt de la prise d'un "NAP"

Les résultats obtenus dans l'expérimentation présentée précédemment ont mis en évidence les effets néfastes d'une privation de sommeil de longue durée sur la performance psychomotrice. Mais ces conditions représentent un cas extrème que l'on ne rencontre que de façon exceptionnelle en aéronautique. L'expérimentation suivante a donc été réalisée, dans le cadre d'une coopération Franco-Américaine, pour étudier l'évolution de la performance psychomotrice dans des conditions simulant une situation opérationnelle comportant la prise d'un "nap" diurne.

La situation choisie correspond à la préparation de missions aériennes classiques d'attaque à longue distance. Ce protocole a été mis au point par le laboratoire de l'US Navy (NAMRL de Pensacola) pour évaluer les moyens à mettre en oeuvre pour maintenir les pilotes dans un état de performance optimum. L'expérimentation se déroule sur trois jours et deux nuits. Elle consiste en deux périodes de 27 heures de privation de sommeil séparées par une phase de sommeil diurne de 6 heures. Durant les phases "opérationnelles" de 27 heures les sujets sont maintenus éveillés et soumis à différents examens : cliniques, électrophysiologiques et questionnaires.

Huit sujets volontaires sains ont participé à l'expérimentation. Ils sont âgés de 28 à 47 ans. Tous ont été soumis à un examen clinique complet avant d'être sélectionnés et ont donné leur consentement éclairé selon la convention d'Helsinki.

Le protocole est le suivant :
Après la phase d'apprentissage, l'enregistrement des tests s'est déroulé de la façon suivante :

- nuit normale témoin (de lundi soir à mardi matin 6 heures)
- préparation du plan de vol n° 1 : durée 9 heures
  * mardi 8 heures : tests psychomoteurs
  * mardi 13 heures : tests psychomoteurs
- repos sans sommeil de 15 heures à 19 heures (activités diverses)
- réalisation de la 1ère mission : durée 14 heures
  * mardi 21 heures : tests psychomoteurs
- sommeil de 9 heures à 15 heures
- préparation du plan de vol n°2 : durée 9 heures
  * mercredi 17 heures : tests psychomoteurs
  * mercredi 22 heures : tests psychomoteurs
- repos sans sommeil de 24 heures à 4 heures du matin (activités diverses)
- réalisation de la 2ème mission : durée 14 heures
  * jeudi 6 heures : tests psychomoteurs
  * jeudi 12 heures : tests psychomoteurs

- nuit de récupération (de jeudi 19 heures à vendredi 6 heures)

  * vendredi 8 heures : tests psychomoteurs

Les résultats ont été traités par analyse de variance avec mesures répétées (ANOVA).

Cette expérimentation a permis d'évaluer les effets d'une privation de sommeil limitée sur la performance psychomotrice. Les tests ne sont pas tous aussi sensibles à ces conditions. Les résultats obtenus pendant les premières 27 heures d'éveil sont comparables à ceux de l'expérimentation précédente pour les mêmes durées de privation. Par contre, pendant la deuxième phase de l'expérimentation, c'est-à-dire après la période de sommeil diurne, l'évolution de la performance n'a plus du tout la même allure. Ceci est surtout visible pour les tâches les plus sensibles à la privation de sommeil telles que le traitement mathématique, la poursuite instable, le traitement spatial, la recherche en mémoire et la double tâche. Pour la poursuite par exemple (figure 4) on observe une augmentation importante de l'indice de déviation aux séances de mercredi 4 heures et jeudi 12 heures qui se situent à la fin des deux périodes d'éveil de 27 heures. Cette détérioration du niveau de l'ajustement visuo-moteur s'accompagne également d'une augmentation du nombre moyen de pertes de contrôle. Après la période de sommeil diurne, la performance retrouve un niveau proche de celui du début de l'expérimentation avec, en particulier, la disparition des pertes de contrôle. Cette amélioration après la période de sommeil est identique pour l'ensemble des tâches perturbées par la privation de sommeil.

Ainsi, en dépit de la place défavorable qu'il occupe dans le nycthémère l'intérêt du "NAP" est loin d'être négligeable puisqu'il permet la récupération des performances dégradées.

### 2.3 En résumé

L'utilisation de la batterie de tests STRES s'inscrit dans une démarche destinée à caractériser de façon plus précise les effets de différents facteurs de stress sur la performance. En effet, l'analyse de nombreuses études a montré que la prise en compte d'une seule tâche, malgré les différents mesures effectuées (temps de réponse, nombre d'erreurs, non-réponses), constitue une approche limitée ne permettant pas de décrire le fonctionnement du système de traitement de l'information humaine dans les différentes conditions testées. La prise en compte de plusieurs tâches standardisées fournit par contre un ensemble d'indicateurs qui reflètent de façon plus précise la nature des changements survenus dans le système et facilite les comparaisons.

Les résultats obtenus au laboratoire dans la simulation de différents contextes opérationnels confirment sa fiabilité et sa validité ainsi que la sensibilité spécifique de chacun des tests qui la composent. De plus sa souplesse d'utilisation fait de cette batterie un instrument performant d'évaluation des modifications de l'état mental du sujet, dont les résultats pourront bientôt être consultés par plusieurs laboratoires grâce à la constitution d'une banque de données.

## 3) SOLUTIONS HABITUELLEMENT PRECONISEES POUR REDUIRE LES EFFETS DU "JET-LAG"

De nombreuses recommandations concernant à la fois les aspects ergonomiques, physiologiques ou pharmacologiques ont été formulées, voici une liste non exhaustive de certaines d'entre elles parmi les plus souvent retrouvées dans la littérature.

### 3. 1. Définition d'une charge de travail maximale

Plusieurs travaux, notamment ceux de NICHOLSON (11) ont préconisé la détermination d'une charge de travail compatible avec un rythme de sommeil acceptable au cours d'opérations aériennes à long terme. C'est ainsi que les temps de service compatibles avec un modèle de sommeil acceptable devraient être liés de façon logarithmique avec le nombre de jours de travail (cf figure 5).

Dans ce même travail, il est précisé que la moyenne du temps de sommeil par 24 heures pour les trois jours précédant un vol ne doit pas être inférieure à 6 heures 15 minutes pour le premier pilote et 5 heures 53 minutes pour le second.

En réalité, lors de conflits réels, cette charge de travail est toujours dépassée et le nombre d'heures de sommeil jamais atteint (exemple de la Guerre de l'Atlantique Sud en avril 1982) (30).).

### 3. 2. Le double équipage

Lors de vols de longue durée, la mise en place d'un équipage doublé, en permettant des périodes de sommeil suffisantes en vol, autorise la réalisation de missions de deux jours dans des conditions optimales (31).

### 3. 3. Synchronisation avant le vol

Une modification progressive des heures de sommeil dans les jours précédant la mission est recommandée par certains auteurs (32). Ils proposent de changer l'horaire habituel d'une heure par jour en avançant l'heure du coucher et du lever si le voyage doit se faire vers l'Est, ou en retardant ces horaires si le voyage prévu se fait vers l'Ouest. Mais cette stratégie présente deux inconvénients majeurs. D'une part, elle nécessite autant de jours que de fuseaux traversés, donc de commencer plusieurs jours avant le départ, ce qui est généralement incompatible avec la vie sociale et professionnelle du sujet. D'autre part elle risque d'induire le "jet-lag" avant même le début du voyage, ce qui n'est pas le but recherché.

### 3. 4. Renforcement des synchroniseurs sociaux

A côté de la synchronisation des différents rythmes endogènes, de l'organisme par les synchroniseurs externes, comme l'alternance lumière-obscurité, les facteurs sociaux joueraient également un rôle très important. C'est à partir de cette constatation que certains auteurs (33) ont préconisé de mettre rapidement sa montre à l'heure d'arrivée afin de se synchroniser le plus vite possible après le décollage. La période des repas et celle du sommeil devant être calquée sur celle du lieu de destination.

Par ailleurs, KLEIN et WEGMAN (34) ayant constaté que les sujets qui restent confinés dans leurs hôtels s'adaptent plus lentement que ceux qui s'aventurent au dehors, ces auteurs encouragent les voyageurs à s'exposer à l'environnement social et au cycle jour/nuit de leur lieu de destination dès leur arrivée.

3. 5. La photothérapie

Les relations existant d'une part entre certaines pathologies psychiatriques, comme le syndrome maniaco-dépressif, et la privation de sommeil ou l'éclairement contrôlé, et d'autre part entre périodes d'éclairement et sécrétion de mélatonine (voir plus loin) ont conduit à s'intéresser à la photothérapie pour réduire les effets du jet-lag. Il apparaît ainsi que l'exposition relativement prolongée (5 heures) à une lumière vive (> 2000 lux) peut aider à resynchroniser les rythmes biologiques, température et rythme veille-sommeil notamment (35, 36).

3. 6. La prise de petits sommes (ou naps)

Si les circonstances (opérationnelles ou autres) le permettent, la prise d'un petit somme d'une durée minimum de 10 à 20 minutes peut représenter une stratégie précieuse pour récupérer et améliorer son niveau de vigilance pour un temps donné (21, 34, 37). GRAEBER et al. (ref. 38) recommande la prise de sommes à bord, en montrant que des sommes répétés de 20 minutes favorisent la récupération des performances et le comportement psychologique.

En revanche, il faut également savoir qu'il existe à l'issue de la phase de petit somme une période dite inertielle post-sommeil d'une durée approximative de dix minutes, pendant laquelle les performances sont dégradées. (39). De plus, les sommes réalisées dès l'arrivée peuvent, notamment s'ils sont trop longs, conduire à une exagération des difficultés d'endormissement le soir et peuvent interférer avec la continuité du sommeil. (32).

3. 7. La diététique

Certains programmes de "lutte contre le jet-lag" comptent de multiples facteurs de synchronisation dont la diététique. La composante principale de cette stratégie consiste à programmer des journées alternées avec régime riche puis pauvre en calories, les petits-déjeûners et déjeûners étant riches en protéines et les repas du soir riches en hydrates de carbone. Les repas riches en protéines, étant sensés augmenter la vigilance en stimulant les systèmes adrénergiques et les repas riches en hydrates de carbone devant au contraire faciliter le sommeil. (40).

Les résultats n'ont cependant pas été retrouvés lors d'expérimentations réalisées au laboratoire par d'autres équipes. (41).

3. 8. L'exercice physique

Quelques études réalisées d'abord chez l'animal (42) puis chez l'homme (43) amenaient à penser que des exercices physiques de type aérobic faciliteraient la resynchronisation des rythmes biologiques.

Cependant l'intrication de plusieurs paramètres comme l'exposition à la lumière, l'heure à laquelle est réalisé cet exercice et l'enthousiasme suscité pour cette méthode, font qu'il est difficile de connaître l'effet réel de l'exercice physique sur les effets du "jet-lag".

3. 9. Divers

A titre anecdotique, une technique de manipulation des rythmes circadiens, difficilement applicable tant pour le touriste que pour le militaire en opération, mais intéressant sur le plan de la recherche, consiste à provequer un changement de période endogène du rythme circadien de la température corporelle de rats en faisant varier le facteur gravité. Cette variation est obtenue par des accélérations quotidiennes d'une heure, des rats, en centrifugeuse. (44).

3. 10. Approche pharmacologique : la caféine

En raison de sa consommation très importante dans le monde, le café, habitude alimentaire, peut aussi être administré comme stimulant de la vigilance et à ce titre avoir un rôle dans la lutte contre le jet-lag. En effet, à côté des possibles effets de tolérance dûs à une prise chronique de café, la caféine augmente la vigilance auditive et visuelle et peut permettre lors d'une administration tardive de retarder l'endormissement, mais son effet sur la resynchronisation des rythmes reste limité. (45, 46, 47).

Par ailleurs, il faut garder à l'esprit qu'à côté des effets principaux de la prise de caféine que sont la stimulation de la vigilance, la réduction de la sensation de fatigue et l'impression de favoriser les activités cognitives, il existe de nombreux effets secondaires dont l'intensité est fonction de la dose ingérée et du sujet qui la reçoit. Il s'agit d'arythmies cardiaques, d'une augmentation de la diurèse, de l'apparition de tremblements, d'hyperesthésies, de troubles de la perception, de nausées, de vomissements et de troubles convulsifs à doses toxiques.

3.11. Approche pharmacologique : les Benzodiazépines

Les hypnotiques et plus particulièrement les benzodiazépines tiennent une place importante essentiellement pour deux raisons. D'une part, ils présentent un nombre de spécialités pharmaceutiques élevé et sont, du moins en France, les médicaments les plus consommés. D'autre part, ils sont les premiers à faire partie de la stratégie pharmacologique d'induction de sommeil en situation opérationnelle. L'utilisation d'hypnotiques de type benzodiazépine pour faciliter le sommeil lors de périodes de repos choisies a trouvé une application lors du conflit de l'Atlantique Sud en avril 1982 (30) pendant lequel des pilotes d'Hercule prenaient

20 mg de Témazépam (NORMISON$^{R}$) pour provoquer un sommeil à l'occasion des périodes de repos de 8 heures séparant deux missions de vols de longue durée (25 heures). En dépit de quelques résultats intéressants, les benzodiazépines induisent le sommeil mais ne resynchronisent pas forcément les rythmes circadiens. (48, 49, 50, 51, 52, 53, 54).

Il est donc possible d'utiliser les benzodiazépines lors de situations opérationnelles mais le sommeil induit présente un accroissement du sommeil lent léger (S1 et S2) ainsi qu'une réduction du sommeil lent profond (S3 et S4) et du sommeil paradoxal. Par ailleurs, la présence toujours possible d'effets secondaires comme l'apparition de lassitude, une augmentation du temps de réaction, une incoordination motrice, un état de confusion ou d'excitation paradoxale, des céphalées, des vertiges, des nausées et d'une amnésie antérograde, pénalisent lourdement une administration de type chronique. L'apparition sur le marché de nouvelles molécules hypnotiques non benzodiazépiniques, pourrait avantageusement remplacer les benzodiazépines. (52).

3. 12. Approche pharmacologique : la mélatonine

La tentation d'utiliser cette substance indolique, dérivé méthoxylé et N-acétylé de la sérotonine, sécrétée par la glande pinéale en fonction de l'alternance lumière obscurité, est grande en raison de son intrication dans la rythmicité circadienne. (55).

Au niveau des problèmes de chronobiologie en milieu aéronautique, l'administration de mélatonine a été tentée dans le but de réduire ou supprimer les effets de la désynchronisation engendrés par le franchissement rapide et répété de plusieurs fuseaux horaires. Il est ainsi apparu que la mélatonine accélère le réajustement de l'horloge biologique (56, 57, 58). Les symptômes du "jet-lag" semblent subjectivement mieux supportés lors de la prise de 5 mg de mélatonine au coucher. Cependant, en dépit de ces résultats intéressants, soit en situation réelle de vols transméridiens à partir de questionnaires, soit en laboratoire lors de simulations, quelques résultats moins convainquant subsistent, comme l'effet placebo aussi efficace que le traitement dans 40 % des cas (59) ou chez 1 sujet sur 8 l'obtention par le traitement d'un effet opposé, c'est-à-dire un ralentissement de la vitesse de resynchronisation des paramètres mesurés (température, sécrétions hormonales, ...) (60).

Cette approche pharmacologique reste cependant intéressante et de nombreuses études sont poursuivies tant au niveau des doses de mélatonine administrées que du moment de l'ingestion.

## 4) UNE AUTRE HYPOTHESE AVEC UNE NOUVELLE SUBSTANCE

4. 1. Approche pharmacologique : l'hypothèse

En l' absence de toute information externe, lors des expériences d'isolement temporels, les rythmes biologiques persistent avec une période légèrement différente de 24 heures. On a ainsi démontré l'existence d'un système actif de synchronisation interne, qui exclut que les rythmes biologiques ne soient que des réponses passives à des stimuli externes comme l'alternance lumière-obscurité.

L'horloge interne de l'homme a une périodicité habituellement supérieure à 24 heures, mais restant de l'ordre circadien. L'horloge interne peut s'ajuster chaque jour, en fonction de stimuli venant de l'environnement, mais seulement dans certaines limites. De plus, cette adaptation est asymétrique. Il est en effet plus facile de retarder le cycle veille-sommeil, en restant éveillé plus longtemps et en dormant plus tard (comme lors d'un voyage vers l'ouest), que de l'avancer, comme lors d'un voyage vers l'Est. Cette asymétrie est probablement dûe à la lenteur relative de l'horloge interne, dont la périodicité est légèrement supérieure à 24 heures. (33, 21). Jusqu'à présent le maintien d'un éveil de bonne qualité n'étant possible qu'en utilisant des substances amphétaminiques aux effets secondaires très pénalisants.

En effet si les amphétamines accroissent le tonus général de la vigilance et les performances psychomotrices, avec un état d'euphorie (61), elles peuvent également provoquer de l'anxiété, une tendance à l'isolement social, une exacerbation des signes paranoïdes, des conduites stéréotypées, des troubles de la perception visuelle, une anorexie, un éréthisme cardiaque et l'apparition d'un phénomène de tolérance. (62).

L'utilisation d'un autre type de stimulants aussi puissant que les amphétamines mais dépourvu d'effets secondaires s'avère donc indispensable si on veut utiliser cette hypothèse pour s'adapter plus vite au nouvel horaire.

4. 2. Pourquoi le modafinil ?

Devant les effets pénalisants des substances amphétaminiques, il fallait trouver une autre molécule présentant une totale inocuité mais ayant une puissance d'action comparable aux amphétamines. Le modafinil (ou MODIODAL$^{R}$ ) semble présenter ce profil. En effet, molécule de synthèse, le modafinil présente une activité éveillante assez originale, mise en évidence d'abord chez l'animal, puis confirmée chez l'homme sain et le sujet pathologique atteint d'hypersomnie idiopathique ou de syndrome de Gélineau. (63, 64, 65, 66). Le mécanisme d'action, encore incompris, de cette substance dite eugregorique (eu : bon, gregor : éveil) présente une composante adrénergique agissant au niveau post-synaptique central des récepteurs alpha 1 adrénergiques (67, 62, 65). Des études se poursuivent actuellement tant en France qu'à l'étranger pour approfondir nos connaissances sur les propriétés pharmacologiques de cette substance et sur les différents composants du mécanisme d'action. Dans le cadre aéronautique un certain nombre de travaux ont déjà été menés, il s'agit de quelques exemples de résultats obtenus lors des deux protocoles expérimentaux de privation de sommeil présentés précédemment.

4. 3. Exemples d'application

L'administration de modafinil au cours des deux protocoles de privation de sommeil décrits plus haut a permis le maintien des performances psychomotrices des sujets à un niveau très constant, proche de celui obtenu sans privation de sommeil.

Dans le cas de la privation de sommeil de soixante heures les niveaux de performance, comparables en début d'expérimentation avec ou sans modafinil, quelle que soit la tâche considérée, se différencient plus ou moins rapidement, et plus ou moins largement, mais de façon significative, au cours de la privation de sommeil. D'autre part, l'évolution cyclique de la performance renforcée par la privation de sommeil, persiste lors de la prise de modafinil. La tâche de poursuite et la tâche de recherche en mémoire quatre lettres (figure 6, 7) sont présentées pour illustrer ces résultats. Il faut noter en particulier la disparition presque totale des pertes de contrôle dans la tâche de poursuite avec la prise de modafinil.

Les effets d'une privation de sommeil modérée (27 heures) sur la performance sont moins marqués, néanmoins la prise de modafinil améliore la performance dans tous les cas où celle-ci est dégradée. D'autre part, on observe un effet bénéfique de l'action combinée "nap" + modafinil. Ces résultats apparaissent très clairement dans l'évolution de la performance dans la tâche de poursuite (figure 8).

Il ressort des nombreuses études menées sur les effets de la privation de sommeil que le stockage en mémoire à court terme comme l'accès aux informations acquises récemment nécessitent une quantité de sommeil "suffisante" pour être réalisés dans de bonnes conditions. Dans les tâches composant la STRES battery certains processus mis en jeu font intervenir la mémoire de travail ou mémoire à court terme. C'est le cas en particulier du module d'inversion dans la tâche de temps de réaction où la compatibilité stimulus-réponse est insuffisamment mémorisée, de la tâche de traitement mathématique, de la tâche de traitement spatial et évidemment de la tâche de recherche en mémoire. Ces tâches sont effectivement dégradées par la privation de sommeil. Les résultats obtenus avec le modafinil permettent de penser que son action se situerait sur deux plans, il permet effectivement le maintien d'un niveau d'activation général du système nerveux correspondant à un état d'éveil efficient mais il semble également agir plus particulièrement sur les mécanismes neurophysiologiques qui sous-tendent la mémoire à court terme.

L'ensemble de ces résultats nous conduisent donc à envisager une application opérationnelle qui pourrait ainsi être orientée en aéronautique dans la réduction des effets dûs au "jet-lag".

4. 4. Avantages de l'utilisation des eugrégoriques en situation opérationnelle

L'utilisation du modafinil ou d'une substance de type eugrégorique présente de nombreux avantages extrêmement précieux en situation aéronautique opérationnelle.

En effet, la prise du produit est facile par voie orale. Les effets ont une durée limitée mais le sommeil est possible avant la fin de la durée d'action, si l'environnement est favorable. Il s'agit d'une substance éveillante mais non anti-sommeil. En cas de nécessité absolue, il est possible d'antagoniser les effets de ce produit par l'administration de chlorpromazine. Les effets des eugrégoriques sont puissants mais modulables en fonction de la dose. Enfin, il n'existe pas d'effets secondaires pénalisants aux doses actives.

## CONCLUSION

Les perturbations du rythme veille-sommeil représentent donc un effet pénalisant dans la conduite d'une mission, en raison essentiellement des désynchronisations des rythmes circadiens dont le rythme veille-sommeil, dont la symptomatologie (ou jet-lag) basée sur les troubles du sommeil et les troubles digestifs s'accompagne également d'une dégradation des performances psychomotrices. Ces dernières peuvent être évaluées au laboratoire à partir d'un ensemble de sept tests psychomoteurs réunis au sein de la STRES battery, recommandée par un goupe de travail de l'OTAN. Il s'agit d'un test de temps de réaction, de traitement mathématique, de raisonnement grammatical, de recherche en mémoire, de reconnaissance spatiale, de poursuite visuelle et une double tâche couplant recherche en mémoire et poursuite visuelle. La mise en oeuvre de cette batterie de tests à l'occasion de deux protocoles expérimentaux de privations de sommeil, a permis de mettre en évidence la sensibilité, la fiabilité et la reproductibilité de ces tests. La recherche de solutions permettant de réduire les effets du "jet-lag" a donné lieu à un ensemble de travaux ayant abouti à de nombreuses recommandations et consignes, parfois peu efficaces. L'approche pharmacologique apparait en revanche plus rigoureuse et relativement prometteuse notamment lors de l'utilisation des hypnotiques et surtout de la mélatonine. De plus l'apparition récente d'une nouvelle famille de substances d'éveil dont le chef de file est le modafinil, aussi puissantes que les amphétamines mais sans effet secondaire, permet de reconsidérer cette approche et d'envisager chaque fois que cela sera possible un prolongement de l'état d'éveil qui devrait être un éveil efficient. Les premiers résultats obtenus lors de situation de privation de sommeil ont déjà montré l'intérêt de ce type de substance pour maintenir un haut niveau de performance pendant 48 heures. Il convient de poursuivre les recherches dans cette voie afin d'explorer la capacité éventuelle de resynchronisation des rythmes biologiques du modafinil, dont les mécanismes d'action, vraisemblablement multiples et la totalité des propriétés pharmaceutiques ne sont pas encore complètement élucidés. Les effets sur l'homme des opérations aériennes de longue durée, essentiellement ceux perturbant le rythme veille-sommeil font ainsi l'objet de nombreuses études. Pour l'instant aucune "solution miracle" n'existe, mais le développement important des recherches notamment sur le plan pharmacologique devrait permettre de disposer dans les prochaines années d'un ensemble de possibilités efficaces à utiliser en fonction de la situation et des conditions environnementales.

REFERENCES :


1 - HALBERG F. RENBERG A. Rythmes circadiens et rythmes de basse fréquence en physiologie humaine - J. Phsyiologie, 1967, 59, 117-200

2 - MARTINOT M.S., ANGIBOUST R. Les problèmes liés aux décalages horaires chez le personnel navigant. Méd. Aér. Spat., 1984, 23, 90, 190-198

3 - BENOIT O. Le rythme circadien veille sommeil - In : Physiologie du Sommeil, Masson éd., paris, 1984, 63-84

4 - HEYSTER W.H. Human implications of modern warface round the clock operations and sleep management - Doc. n° GW 89.05, March 1989. Directorate of Personnel, Behavioural Sciences Depertement. The Hague, Netherland

5 - SAMEL A. and WEGMANN H.M. Sleep and circadian rhythms of an Airline pilot operating on the Polar Route. A case study. Aviat. Space Environ. Med., 59, 1988, 443-447.

6 - WEGMANN H.M., GUNDEL A., NAUMANN M, SAMEL A., SCHWARTZ E. and VEJVODA M. Sleep, sleepiness and circadian rhythmicity in aircrews operating on transatlantic routes. Aviat. Space Environ. Med, 57, 1986, B53-64.

7 - KLEIN K.E., WEGMANN H.M. and HUNT B.I. Desynchronization of body temperature and performance circadian rhythm as a result of outgoing and homegoing transmeridian flights. Aerospace Med., 43, 1972, 119-132.

8 - DELUZ P. et CHARETTEUR M.P. Les vols longue durée sans escale. Conséquences physiologiques pour le personnel naviguant commercial. Med. Aero. et Spat., 123, 1992, 211-215.

9 - LAGARDE D.P., CHALON S. et CIZEAU J. Vols de longue durée et perturbations du rythme veille-sommeil. SSA TRAV. SCIENT., 12, 1991, 217-218.

10 - BOLL P.A., STORM W.F., FRENCH J., BISSON R.U., ARMSTRONG S.D., SLATER T., ERGOLINE W.R. and Mc DANIEL R.L. - C-141 Aircrew sleep and fatigue during the Persian Golf conflict - AGARD conference OSLO NORWAY.
Oct. 1992.

11 - NICHOLSON A.N. Duty hours and sleep patterns in aircrew operating world-wide routes. Aerospace Med. 43, 1972, 138-141.

12 - AKERSTEDT T. Jet-lag. A review. Medecine Aéronautique et Spatiale, 123, 1992, 201-210.

13 - BATEJAT D. and LAGARDE D. Circadian rhythm and sleep deprivation : effects on psychomotor performance. Med. Sci. Res., 20, 1992, 167-168.

14 - JOHNSON L.C. Sleep disturbance in humans. AGARD. Lecture series 105, 1979, 4-1/4-8.

15 - WEBB W.B. Experiments on extended performance : repetition, age and limited sleep periods. Behavior Research Methods, Instruments and Computers. 1985, 17, 27-36.

16. GRIEFAHN B. Sleep in noisy environments. Effects limits preventiva measures. 10th Congress of the European Sleep Research Society, Strasbourg, 1990, 12.

17 - LIBERT J.P., DINISI J., MUZET A., FUKUDA H., EHRHART J. Sleep stage changes in men exposed to chronic heart - 5th International Congress of Sleep Research, Copenhague, Denmark, 1987, 216

18 - BUGUET A., ROUSSEL B., FOURCADE J., MAUVISSEAU M., PIANTCHEBKO C. Sommeil de l'homme en ambiances et dans des situations agressives. Rapport CRSSA n° 51/PH.

19 - JOERN A.T., SHURLEY J.T., BROOKS R.E., GUENTER C.A., PIERCE C.M. Short-term changes in sleep patterns on arrival at the South Polar Plateau. Arch. Int. Med., 1970, 125, 649-654.

20 - DEMENT W.C., SEIDEL N.F., COHEN S.A. Jet-lag : recommendations for coping and treatment. 5th International Congress of Sleep Research. Copenhagen, Denmark, 1987, pp 335.

21 - GRAEBER R.C., DEMENT W.C., NICHOLSON A.N., SASAKI M. and WEGMANN H.M. International cooperative study of aircrew layover sleep : operational summary. Aviat. Space Environ. Med., 57, 1986, B10-13

22 - NICHOLSON A.N. Sleep patterns of an Airline pilot operating World-Wide East-West Routes. Aerospace Med. 41, 1970, 626-632.

23 - JOUVET M. et DEBILLY G. Rythme activité/repos du personnel navigant aérien rapport DRET n°86/065 Ministère de la Défense - France - 1992

24 - LAGARDE D.P. Evolution des états de veille et de sommeil au cours et à l'issue d'un confinement prolongé. SSA TRAV SCIENT., 11, 1990, 197-198.

25 - Human Performance Assessment methods, AGARDograph n° 308, AMP Working Group 12 AGARD Lecture Series 163, May 1989.

26 - LAGARDE D., BATEJAT D., CIZEAU J. et al. Evaluation des états de vigilance chez le sujet humain. Médecine Aéronautique et Spatiale, 1991, 30, 111-120.

27 - STERNBERG S. Two operations in character recognition : some evidence from reaction time measurements. Perception and Psychophysics, 1967, 2, 45-53.

28 - LAGARDE D., BATEJAT D., PRADELLA S., FELIN J.F. Evolution des performances psychomotrices lors d'une privation de sommeil de soixante heures. Intérêt d'un apport pharmacologique, "Opération Dauphin". Rapport CERMA 91-20, Juillet 1991.

29 - WILLIAMS H.L., LUBIN A. and GOODNOW J.L. Impaired performance with acute sleep loss. Psychological monograph, 73, 1-26.

30 - BAIRD J.A., COLES P.K.L. and NICHOLSON A.N. Human factors and air operations in the South Atlantic Campaign : discussion paper. Journal of the Royal Society of Medicine, 76, 1983, 1-5.

31 - ATKINSON D.W., BORLAND R.G. and NICHOLSON A.N. Double crew continuous flying operations : a study of aircrew sleep patterns. Aerospace Med., 41, 1970, 1121-1126.

32 - MONK T. Coping with the stress of Jet-Lag. Work Stress, 1987, 1, 163-166

33 - MOLINE M.L. et ZENDELL S.M. Le jet-lag, syndrome de décalage des transports aériens intercontinentaux. Aspects actuels. Bulletin Veille-Sommeil, 5, 1991, 12-19.

34 - KLEIN K. WEGMANN H. The resynchronization of human circadian rhythms after transmeridian flights as a result of flight direction and mode of activity. In Saheving L.E., HALBERG F., PAULY J. (Eds). Chronobiology IGAKU SHOIN - Tokyo 1974.

35 - CZEISLER C., KRONAUER R., ALLAN J., DUFFY J., JEWERR M. Bright light induction of strong ressetting of the human circadian pacemaker. Science, 1989, 244, 1328-1333.

36 - DAAN S. and LEVY A. Scheduled exposure to daylight : a potential strategy to reduce jet-lag following transmeridian flight. Psychopharmacol. Bull. 1984. 20, 566-568.

37 - TATTI M., BESSET A. et BILLIARD M. Conditions extrêmes et régimes ultra-courts du cycle veille-sommeil. Bulletin Veille-Sommeil, 1991, 7, 12-15.

38 - GRAEBER R.C., ROSEKIND M.R., CONNELL L.J. and DINGES D.F. Somme en poste de pilotage. Journal de l'OACI., 1990, 6-10.

39 - NAITOH P., KELLY T. and BABKOFF H. Sleep inertia : is there a worst time to wake up ? Naval Health Research Center, 1991, Report 91-45. SAN DIEGO - CALIFORNIA.

40 - EHRET C. and SCANLON L. Overcoming jet-lag. Berkeley Publishing Corporation, New-York, 1983.

41 - MOLINE M., POLLAK C., WAGNER D., ZENDELL S., LESTER L. Effects of the "jet-lag diet" on the adjustement to a phase advance. Proceedings of the Second Meeting of the Society for the study of Biological Rhythms. May 1990.

42 - WINFREE A. Hamsters without jet-lag Nature, 1987, 330, 311-312

43 - MROSOUSKY N. and SALMON P. A behavioural method for accelerating re-entrainment of rhythms to new light-dark Nature, 1987, 330, 372-373

44 - FULLER C.A., MURAKAMI D.M. and DEMARIA-PESCE V.H. Entrainment of circadian rhythms in the rat by daily one hour G pulses. The Physiologist (US), 35, 1992, S63-S64.

45 - LIEBERMAN H.R., FINE B.J., KOBRIECK J.L. and GABRIELI J.D. Effects of caffeine on mental performance and mood : implication for aircrew members. Conférence AGARD - OSLO NORWAY - Oct. 1992.

46 - EVANS S.M. and GRIFFITHS R.R. Caffeine tolerance and choice in humans. Psychopharmacology, 108, 1992, 51-59.

47 - EHRET C., POTTER V. and DOBRA K. Chronotypic action of theophylin and of pentobarbital as circadien zeitgebers in the rat. Science, 1975, 188, 1212-1215.

48 - PENATAR D.M., BELENKY G., GARRIGAN J.J. and REDMOND D.P. Triazolam impairs learning and fails to improve sleep in a long-range aerial deployment. Aviat. Space Environ. Med., 60, 1989, 594-598.

49 - NICHOLSON A.N. Hypnotics and air operations. AGARDograph CP-338, 1983, 15-1/15-7.

50 - LAVIE P. Effects of midazolam on sleep disturbances associated with Westward and Eastward flights : evidence for directional effects. Psychopharmacology, 101, 1990, 250-254.

51 - VAN REETH O. and TUREK F.W. Adaptation of circadian rhythmicity to shift in light-dark cycle accelerated by a benzodiazepine. Am. J. Physiol. 253, 1987, R204 R207.

52 - JEANNEAU A., LAGARDE D. Utilisation des hypnotiques en milieu aéronautique. Med. Aéro. et pat., 1990, 29, 114, 46-56.

53 - TUREK F.W. and VAN REETH O. Use of benzodiazepines to manipulate the circadian clock regulating behavioral and endocrine rhythms. Horm. Res., 31, 1989, 59-65.

54 - MISTLBERGER R., HOUPT T. and MOORE-EDE M. The Benzodiazepine phase-shifts circadian activity rhythms in a diurnal primate, the squirrel monkey (Saimiri Sciureus) Neuroscience Letters, 1991, 124, 27-30.

55 - NOZAKI M., TSUSHIMA M. and MORI Y. Diurnal changes in serum melatonin concentrations under Indoor and Outdoor Environments and light suppression of nightime melatonin secretion in the femal Japanese monkey. Journal of Pineal Research, 1990, 9, 221-230

56 - SACK R. and LEWY A.J. Phase-shifting and sleep-promoting effects of melatonin. J. Sleep Res., S1, 1992, 203.

57 - ARENDT J., DEVESON S., TOTTERDELL P., FOLKARD S. Use of melatonin in sleep disorder associated with adaptation to forced phase shift. J. Sleep Res., S1, 1992, 12.

58 - PETRIE K., CONAGLEN J., THOMPSON L., CHAMBERLAIN K. Effect of melatomin on jet-lag after long haul flights. Br. Med. J., 1989, 298, 705-707

59 - ARENDT J., ALDHOUS M., ENGLISH J., MARKS V. and ARENDT J.H. Some effects of jet-lag and their alleviation by melatonin. Ergonomics, 30, 1987, 1379-1393.

60. SAMEL A., WEGMANN H.M. and VEJVODA M. Circadian adaptation after simulated time shifts. The effect of melatonin. J. Sleep Res., S1, 1992, 205.

61 - BABKOFF H. and KRUEGER G.P. Use of stimulants to ameliorate the effects to sleep loss during sustained performance. Military Psychology, 4, 1992, 191-205.

62 - LAGARDE D. Les stimulants de la vigilance. NEURO-PSY, 1993, 2, 71-78.

63 - MILHAUD C.L. and LAGARDE D.P. Présentation d'un nouveau stimulant : le CRL 40476. AGARDograph - cp - 415 - NATO NEUILLY/SEINE FRANCE- 1987 - 5-1/5-7.

64 - KLEIN M. and MILHAUD C. Etude de l'action anti-sommeil des substances psychotropes chez le primate. Perspectives d'application en milieu militaire. AGARD Conference Proceedings n° 338 - Sustained Intensive Air Operations : Physiological and Performance Aspects. 1983, 14-1/14-12.

65 - LYONS T. and FRENCH J. Modafinil : the unique properties of a new stimulant Aviat. Space Environ. Med. 1991, 62, 432-435

66 - BASTUJI H. and JOUVET M. Traitement des hypersomnies par le Modafinil Presse Méd., 1986, 15, 1330

67 - DUTEIL J., RAMBERT F., PESSONNIER J., HERMANT J.F., GOMBERT R. and ASSOUS E. Central alpha 1 adrenergic stimulation in relation to the awakening activity of modafinil : behavioural studies in laboratory animals. European Journal of Pharmacology, 1990, 180, 49-58

Table 1

## MAIN JET - LAG SYMPTOMS

| Acute effects | Chronic effects |
|---|---|
| - Sleep disorders : | |
| Sleepiness difficulties, insomnia, untimely waking up interrupted sleep rhythm, sleep duration and quality decrease in a subjective way | - gastric ulcers<br>- intestinal disorders |
| - Performances decrease | - chronic tiredness and insomnia |
| - Attention decrease | |
| - Disorder of digestive functions | - prostation |
| - global sensation of discomfort | - intolerance |
| - Irritability | |

Table 2

## VARIATION FACTORS

| Individual factors | Environmental factors |
|---|---|
| - age | - direction time zones passing |
| - "big" and "small" sleeper | - sonorous and thermic level |
| - morningness, and vespertiness | - conflict intensity |
| - deprivation sensibility | - bedding |
| - environment perception | - psychosocial environment |

Figure 1

Changes in performance at the Unstable Tracking task under 60 hours sleep déprivation versus control trials

deviation index: sleep deprivation ———— control trials ⋇
control losses: sleep deprivation ■

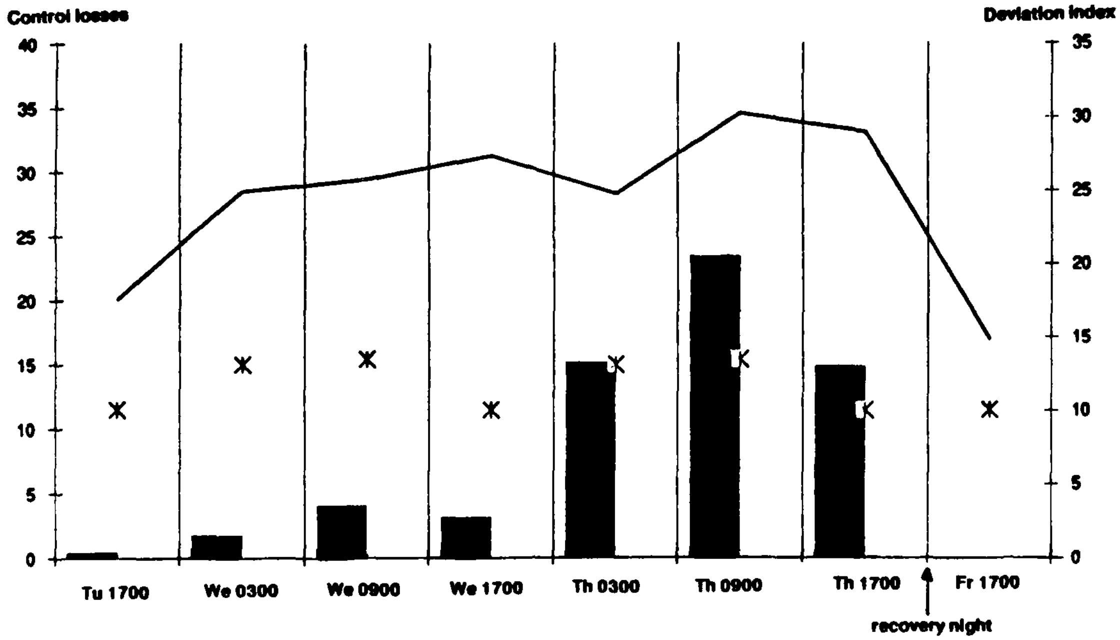



Figure 2

Changes in performance at the Mathematical Processing task under 60 hours sleep déprivation versus control trials

reaction time: sleep deprivation ———— control trials ⋇
errors: sleep deprivation ■ control trials □

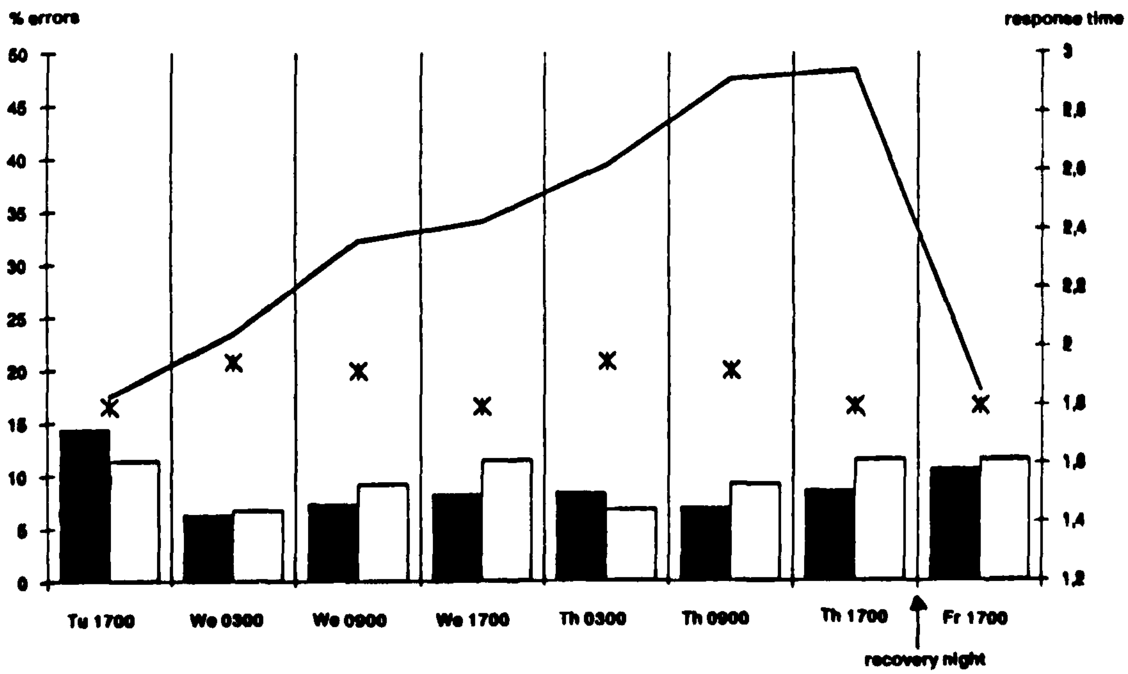


Figure 3

Changes in performance at the Memory Search task under 60 hours sleep déprivation versus control trials

reaction time: sleep deprivation ——— control trials ⋇
errors: sleep deprivation ■ control trials □

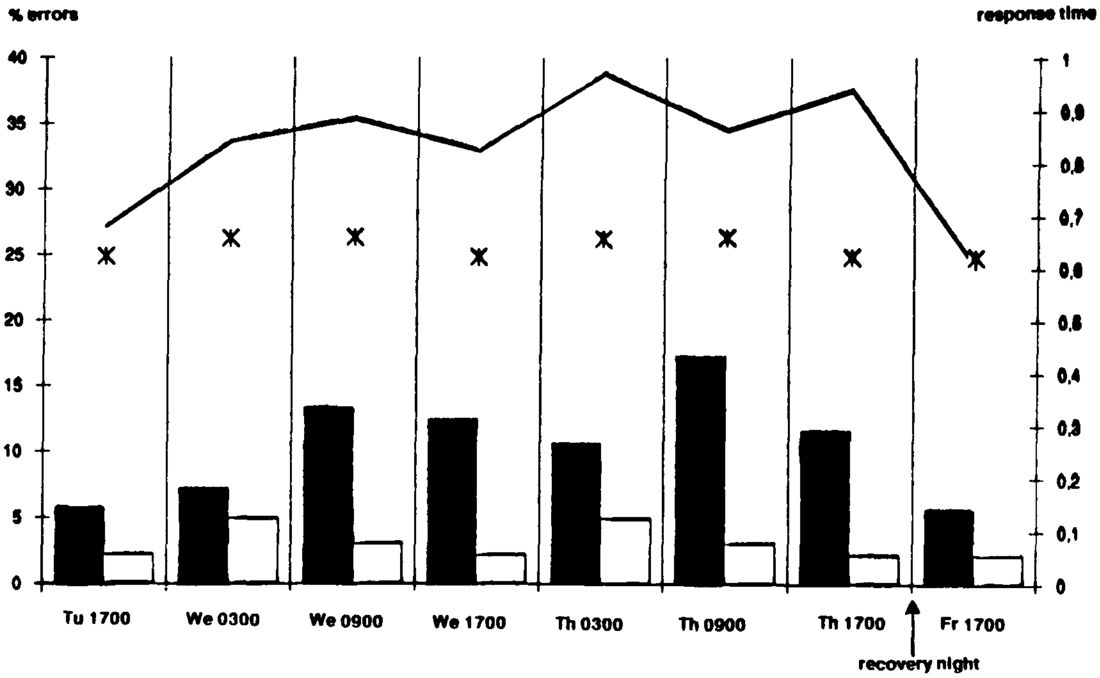



Figure 4

Unstable Tracking task performance under 27 hours sleep deprivation before and after a NAP

deviation index: ———
control losses: □

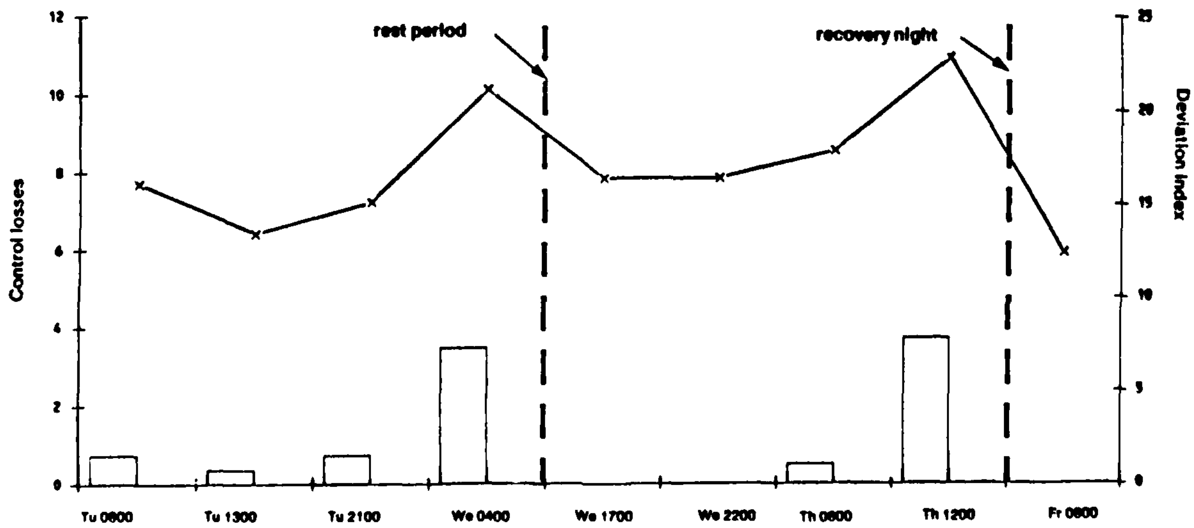
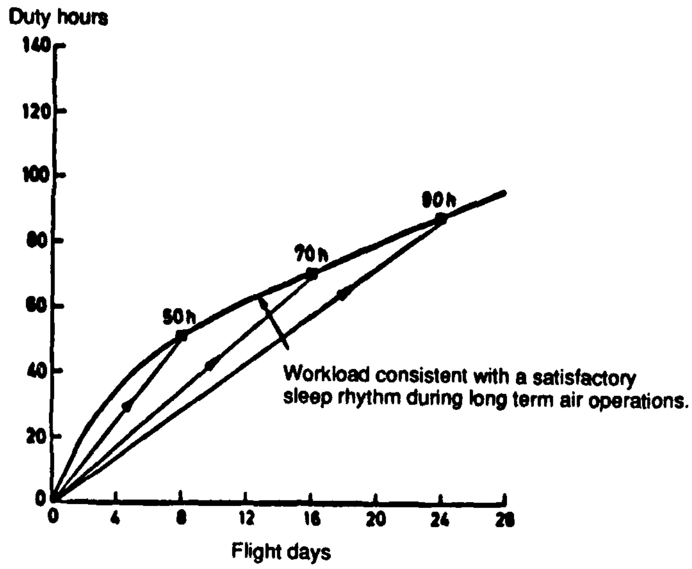
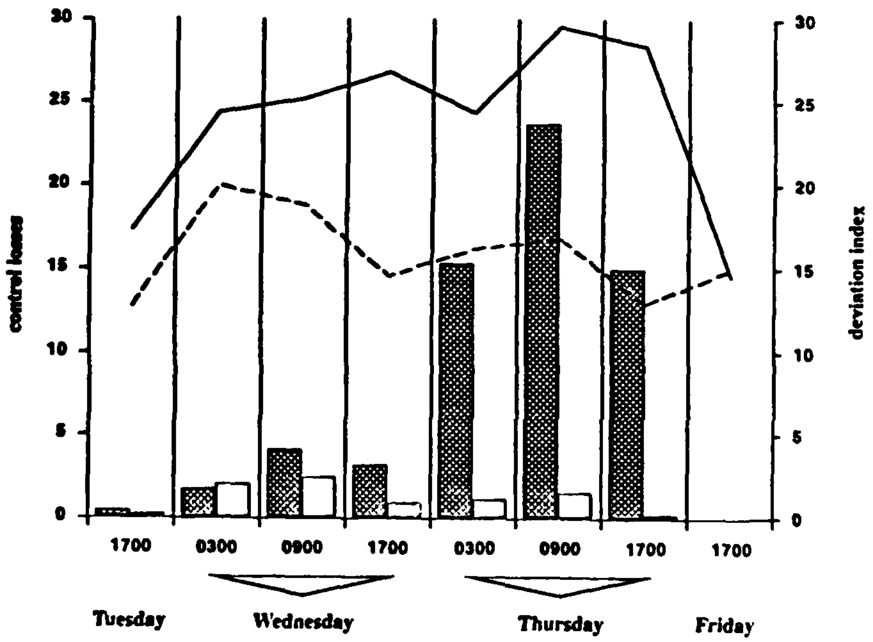


Figure 5




Service duration according to flight time considered consistent with satisfactory sleep rhythm.

Figure 6

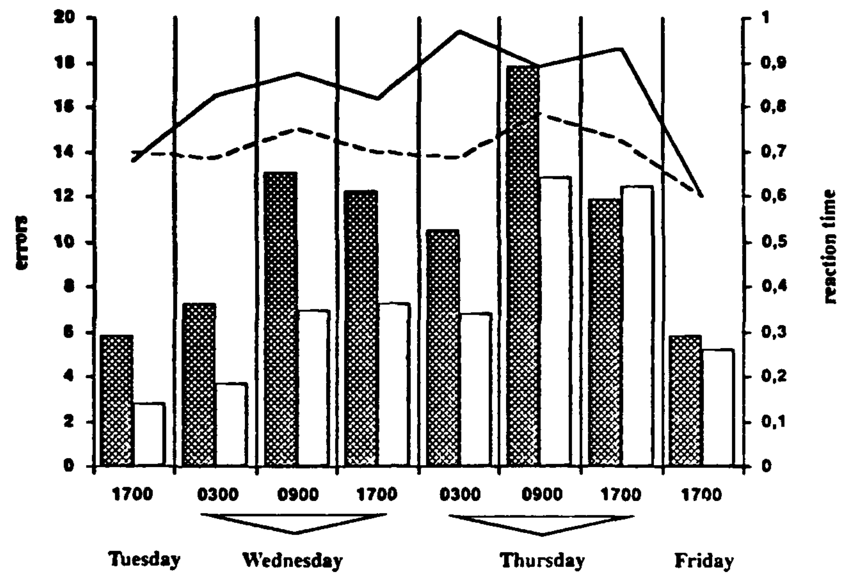



Comparative changes in performance at the Tracking task under placebo and modafinil

deviation index: placebo —— modafinil ------

control losses: placebo ▆ modafinil ☐

Figure 7



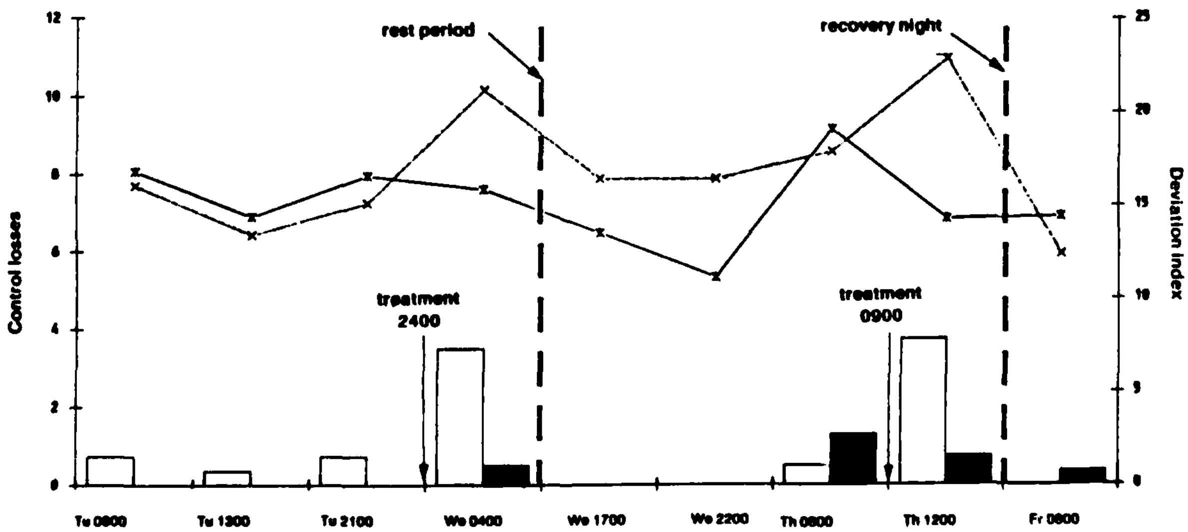

Comparative changes in performance at the Memory Search task (4 letters) under placebo and modafinil

reaction time: placebo —— modafinil - - - - - -
% errors: placebo ▩ modafinil □

Figure 8

Unstable Tracking task performance under 27 hours sleep deprivation before and after a NAP, with and without modafinil administration

deviation index: placebo ———— modafinil - - - - - - - - -
control losses: placebo □ modafinil ■



# FLIGHT TEST CERTIFICATION OF A 480 GALLON COMPOSITE FUEL TANK ON CF-18

written by
Major Mario B.J. Lagrange
Aerospace Engineering Test Establishment
Canadian Forces Base Cold Lake
Medley, Alberta, T0A 2M0, Canada

presented by
Captain Bradley J. McKeage
Aerospace Engineering Test Establishment
Canadian Forces Base Cold Lake
Medley, Alberta, T0A 2M0, Canada

## ABSTRACT

The Aerospace Engineering Test Establishment (AETE), as the Canadian Forces (CF) flight test authority, has recently completed flight tests and analysis of a major store certification program to establish an operational flight envelope for the carriage and jettison of a newly designed 480 gallon external fuel tank (EFT) for the CF-18 aircraft. The certification process involved a progressive series of analysis, wind tunnel tests, qualification tests, ground tests and flight test activities. Most of the pre-flight activities were performed by the designer, McDonnell Aircraft Company (McAir), while all flight testing was the responsibility of AETE with engineering support from McAir. The progression of events from the qualification testing to the final fight testing recommendations are summarized herein. The primary focus of this paper is on the flying activities such as flutter, loads, stability and control, separation/jettison and performance. Special instrumentation, flight test techniques and test concept philosophy are also discussed. This paper highlights various technical problems encountered, such as the near flutter onset condition observed with tanks 50 percent full, the premature failure of the inboard wing spar pylon receptacle discovered after the last manoeuvring loads flight and the localized pitch-up phenomena observed during stability and control (S&C) testing. A glance at the increased range and payload capabilities is also included. Overall, the 480 gallon EFT was determined to be a viable option for the CF-18 aircraft.

## INTRODUCTION

Background. To increase the war stock of external fuel tanks for the CF-18 aircraft, the Government of Canada established a follow-on fuel tank acquisition program. The options considered included buying more of the currently used 330 US gallon EFTs or supporting the development of a new composite material 480 EFT on the CF-18 aircraft. This option was selected because of the technological benefits which could be accrued from transferring filament wound composite technology to Canadian industry and for the potential of providing increased range performance and payload capacity. Hence, AETE was tasked by the National Defence Head Quarters (NDHQ) to support McAir and Canadian industry in the flight test certification of the 480 gallon EFT on the CF-18 aircraft.

Objectives. The 480 gallon EFT certification program was divided into two distinct phases. Phase I consisted of conducting a proof of concept demonstration so that a war time clearance could be issued for the carriage of the 480 gallon EFT on the CF-18 aircraft. This category I flight testing was conducted in concert with the designer, McAir, who was responsible for the qualification tests, pre-flight analyses, proposed test matrix, and post-flight data analyses. This phase included fight test activities such as flutter, carriage and stores ejection loads, S&C, tank separation/jettison (Sep/Jett), performance and limited electromagnetic interference/compatibility (EMI/EMC) ground tests. In addition, a Royal Australian Air Force (RAAF) requirement to certify the 480 gallon EFT for carriage on the centreline station was originally incorporated into this test program. However, the withdrawal of the RAAF from the joint venture resulted in the cancellation of any further centreline carriage test effort. Phase II testing, currently under completion will establish a full clearance envelope for the employment of various weapons in the presence of the 480 gallon EFT. This category II testing will involve engineering support from Canadair Incorporated.

Test Item Description. The 480 gallon EFT is a lightweight, survivable structure fabricated from two graphite filament wound shells with a foam filled honeycomb core between them. Glass cloth laminate core inserts are used to provide frames for attaching a graphite strongback box, three large access doors and all the required aircraft interface hardware. The tank does not contain baffles, and has been optimized for low manufacturing cost and ease of maintenance. Figure 1 depicts the physical characteristics of the 480 gallon EFT and compares them with the 330 gallon EFT. The extended length of the 480 gallon EFT does not permit jettisoning the tank with the trailing edge flaps (TEF) fully deflected without collision between the tank and the TEF. Also, centreline carriage requires a five inch extension/adapter (figure 2) between the 480 gallon EFTs

*Presented at an AGARD Meeting on 'Recent Advances in Long Range and Long Endurance Operation of Aircraft', May 1993.*

and the aircraft to allow for landing gear extension without interference. The adapter is fastened to the tank through extended suspension lugs and remains with the tank during jettison. The production 480 gallon EFT are fitted with a more reliable modular fuel valve assembly and, as a result of shortcomings identified during this test program, a low pass filter and a metal based wrap layer for better EMI protection.

## PRE-FLIGHT TEST ACTIVITIES

Stores Clearance Process. AETE was assigned the overall responsibility of recommending a clearance envelope for the 480 gallon EFT on the CF-18 aircraft to the NDHQ stores clearance office. McAir was also contracted by NDHQ to provide engineering support to AETE. Thus, the stores clearance plan used for this test program was very similar to that used for the F-15 and F/A-18 full scale development programs. The plan consisted of a logical progression of qualification tests, laboratory tests, engineering analysis, ground tests and flight tests. A block diagram of the 480 gallon EFT store clearance process is shown in Figure 3. As the primary contractor, McAir carried out, under NDHQ contract, several engineering analyses and laboratory tests. Throughout the early phases of this process, the CF, including AETE personnel, continuously reviewed McAir progression to ensure that CF vested interests in the program were met. AETE active participation in this store clearance process started with an EMI/EMC safety of flight test (SOFT). All flight test activities were carried out at Cold Lake using AETE's instrumented CF-18 and personnel. The flight test matrices were recommended by McAir and approved by AETE. The test team consisted of an AETE Project Officer (PO) who was essentially the team leader, AETE test pilots and several engineers from McAir and AETE. McAir was responsible for all data analysis which was subsequently reviewed by AETE's engineers. Again, the decision to proceed to the next test point was made by an AETE test controller (often the PO himself) based on concurrent recommendations from McAir and AETE engineers. The procedure used in this test program was safe, efficient and worked well either in the Flight Test Control Room (FTCR) or in the briefing room preparing for the following mission. AETE is most likely to use a similar procedure for the Category II flight trials.

Qualification Tests. A series of laboratory tests were carried out by the supplier, Brunswick Corporation of Lincoln, Nebraska, to ensure that the 480 gallon EFT met the procurement specifications established by McAir. The qualification test program consisted of several tests including maintainability, lightning, slosh and vibration, ejection, fragment impact, flame engulfment, environmental and explosion containment. The qualification tests identified several shortcomings with the 480 gallon EFT. The most significant was the inability of the tank to withstand a lightning strike without internal arcing. The original tank design resulted in internal arcs on five different locations within the tank. Fixing this shortcoming would have required several months. To remain within the planned test program schedule, it was decided to complete the flight testing using tanks that were not shielded for lightning and EMI protection. A flight test restriction prohibiting flight through precipitation static conditions was imposed for all sorties. Also an EMI Safety of Flight Test (SOFT) was required prior to the start of flight testing. In this case, the flexibility given to the program office and the early involvement of the flight test agency, AETE, allowed for a compromise which helped expedite the completion of this certification program.

Similarly, delays in the design and production of the modular fuel valve assembly required the initial flight testing to be carried out using the existing 330 gallon EFT fuel valve system. The flight test certification of the modular fuel valve assembly was the subject of a separate test program which identified only one problem area involving the valve manual precheck assembly which will be rectified on the production 480 gallon EFT.

Wind Tunnel Tests. A series of wind tunnel tests were conducted by McAir, under NDHQ contract, to gather aerodynamic coefficients and derivatives required for the subsequent engineering analysis. The wind tunnel tests were grouped into five different sessions using various facilities. The Calspan eight foot wind tunnel was used to obtain S&C data as well as transonic performance data on a six percent scale model. The McAir Low Speed Wind Tunnel (LSWT) provided S&C characteristics for low speed and power approach with and without flap configurations using a 12 percent scale model. The same McAir LSWT was used to gather flutter data using a 17.5 percent scale flutter model. Trials conducted on a six percent scale model in the McAir Polysonic Wind Tunnel in 1984 provided the necessary information to derive the aerodynamic loads predictions. Last but not least, the Naval Ship Research and Development Center (NSRDC) wind tunnel was used to investigate the Separation and Jettison (Sep/Jett) characteristics of the 480 gallon EFT and of various other stores in the presence of the tank. The data obtained during these wind tunnel tests were used in various engineering analyses to determine the most critical configurations for flight testing and to establish the initial flight test envelopes. A list of flight test configurations is reproduced in figure 4.

Ground Fit and Function Tests. Several ground tests were required prior to the start of the flight test program.

The ground fit and function test, carried out on a production aircraft off the McAir assembly line in St. Louis, showed that the 480 gallon EFT was compatible with the CF-18 and successful fuel transfer was demonstrated. This test also revealed that clearances from the centreline 480 gallon EFT to the nose wheel hold back bar and to the launch bar actuator were less than minimum distances specified in MIL-STD-1289A (Referenced 1). Similarly, ground clearance for the centreline 480 gallon EFT was only 2.8 inches with soft tires and deserviced struts. This is less than the minimum requirements listed in reference 1. Because these deviations were only observed with either deserviced struts or the nose wheel rotated 30 degrees, and because no physical contact was observed, it was agreed to proceed with the test program as is. Again, AETE participation in this ground fit and function test helped in reaching a quick compromise with the contractor, McAir.

Ground Vibration Tests. Four different ground vibration tests (GVTs) were carried out in support of this certification program. The cantilevered pylon GVT, the full aircraft GVT and the structural mode interaction (SMI) GVT were performed at McAir, with CF participation, using a production aircraft. A rigging check GVT was carried out at AETE, with McAir involvement, for each configuration to be flutter tested, using the test aircraft. The cantilevered pylon GVT was performed to determine the liquid fuel correction factors as a function of the tank fuel level. The test set-up consisted of a 480 gallon EFT loaded on a CF-18 wing pylon attached to a rigid test fixture. Five fuel levels were tested from empty to full. A dynamic model of the 480 gallon EFT and wing pylon was developed based on the correction factors. This model was then used to help identify three critical configurations to be tested in the full aircraft GVT. Subsequently, this dynamic model was modified to improve its correlation with the full aircraft GVT results. This refined model was then used for all flutter prediction analysis.

As previously mentioned, three configurations were tested during the full aircraft GVT (Figure 4). The aircraft, a production single-seat CF-18, was supported by soft jacks designed to dynamically uncouple the aircraft from the ground which allowed the measurement of aircraft rigid body modes at frequencies less than two Hz. The tests were performed with the landing gear retracted, canopy closed and all access panels secured. Selecting the "RIG" mode on the flight control system (FCS) ensured that all control surfaces were in the neutral position. The pylons and stores were rigged to minimize freeplay such that maximum mechanical energy was transmitted through all interfaces. The dynamic symmetry of the store rigging was verified by comparing the store resonant frequencies on both sides of the aircraft during dwell excitation. Where required, adjustments were made to obtain acceptable dynamic symmetry. Symmetric and antisymmetric frequency response surveys were conducted to obtain transfer function plots using a sine sweep excitation at constant force provided by two electrodynamic exciters. Modal frequencies were obtained from these plots while damping coefficients were derived using the log-decrement method on single mode decay time histories. The mode shapes were then mapped using the multi-node sinusoidal excitation technique.

The vibration data obtained from this test were used to verify the McAir analytical aircraft/480 gallon EFT dynamic model used to perform flutter analysis. The GVT data also served as a baseline for comparison with vibration mode frequencies and damping coefficients measured during flutter flight testing. Overall, the frequency and mode shape results showed good correlation between the analysis, the full aircraft GVT and the rigging check GVT. Figure 5 tabulates the results for one of the configurations tested.

The Structural Mode Interaction (SMI) GVT check was required to verify that low frequency tank modes do not couple with the aircraft FCS to produce an unacceptable dynamic response. The two configurations tested are also depicted in figure 4. These tests were performed during the full aircraft GVT using exciters attached at the stick position and the FCS feedback accelerometer package. The tests consisted of a series of sinusoidal sweeps through the tank mode frequency ranges using maximum force lateral excitation on the tanks, followed by a dwell at the antisymmetric roll frequency. The SMI was investigated with the control stick in each of the four stick position quadrants and for all flap deflections. The results of this GVT showed no instabilities, sustained oscillations, or unacceptable dynamic responses of the FCS.

Prior to commencing flutter testing, a rigging check GVT was carried out on the two most critical flutter configurations to ensure proper installation of stores on the test aircraft. Freeplay was minimized to achieve dynamic similarity on both sides of the test aircraft Although the test procedure was similar to that used for the full aircraft GVT, this rigging check GVT was performed with the landing gear extended using the soft tire suspension technique. Transfer function plots were gathered at selected locations on the test aircraft. The modes of interest were partially mapped by manually recording response amplitude and phase relative to a reference location on the structure. The results correlated relatively well with the modal frequencies obtained during the full aircraft GVT (Figure 5). One discrepancy was found during one rigging check GVT which identified an antisymmetric mode at 7.46 Hz. This mode, which resembled the wing first antisymmetric bending mode but with reverse relative phasing between tank pitch and fuselage lateral motion, was not found by the analysis nor during the full aircraft GVT. This phenomena was believed to be the result of modal interferences of the aircraft structure elastic modes with the soft tire suspension system.

Electromagnetic Compatibility Ground Tests. The electromagnetic compatibility (EMC) of the 480 gallon EFT with the CF-18 avionic/electrical systems was partially evaluated through several contractor ground tests. Owing to the lack of an EMC control plan, AETE was required to conduct an extensive analysis of potential electromagnetic interference (EMI) and EMC concerns based on contractor lightning and fuel probe radio frequency (RF) susceptibility test results. With composite walls, RF radiation is capable of passing through the 480 gallon EFT with more ease than a conventional metal tank. Such radiations could be coupled to the internal aircraft electrical/avionic system degrading its performance. Also, a potential exists for ignition of fuel vapour by RF radiation. Static charge build-up, because of friction, can occur from fuel flowing within the tank plumbing, from fuel sloshing within the tank, or from flying through moisture or dust (precipitation static). Static build-up may also affect the aircraft electric/avionic systems as well as ignite fuel vapour. This analysis categorized the EMI problems as either flight or mission critical. Those which were flight critical were addressed and ground tested, if proper resources were available at AETE, prior to flight testing. The EMI/EMC tests carried out at AETE prior to flight testing included a thorough inspection for design specification compliance; measurement of bonding, limited conducted emissions, and static potential build-ups; and CF-18 critical system functional checks with limited potential source interference for a Safety of Flight Test (SOFT). Several observations that indicated deficiencies with the tank design were made throughout the EMI/EMC ground testing. However, none of these were severe enough to halt flight testing with the 480 gallon EFT. As a precautionary measure, a restriction not to fly through visible moisture or any precipitation static potential environment was imposed on the pre-production 480 gallon EFT until a conductive coating/wrapping is applied to the tank. Similarly, flight in high electromagnetic environment areas was not recommended for the 480 gallon EFT without fuel probe line EMI protection (low pass filter).

## FLIGHT TESTING

This section of the paper will provide the reader with an overview of the aircraft instrumentation and AETE installations used in support of this certification program. Then each of the flight test activities such as flutter, manoeuvring loads, store ejection dynamic loads, stability and control, separation/jettison and performance will be discussed.

Aircraft Instrumentation. Both of AETE's instrumented CF-18 aircraft, used throughout this certification program, have identical data acquisition systems capable of selecting data from the avionics multiplex (mux) buses and from various other sources. The current system provides a 64 channel analogue data acquisition capability. Data from the analogue signal conditioners along with selected data from direct analogue and digital inputs, mux buses, time code generator and the Flutter Exciter Control Unit (FECU) are encoded into a pulse code modulation (PCM) format and stored on the onboard MARS-2000 tape recorder. Pilot voice and selected direct analogue signals can also be recorded on dedicated FM channels. All PCM data are telemetered to the Flight Test Control Room (FTCR) for real time monitoring. Wing strain gauges were also installed during production assembly as part of the basic instrumentation package. These gauges, located at three different spanwise locations, are sensitive to either bending or torsion and allow identification of the wing overall motion during flutter testing. The additional instrumentation required for specific flight activities are discussed later in each of the flight test sub-sections.

For reasons of flight safety, the FTCR was used for most flight test missions. This facility permits real-time monitoring of selected parameters from the telemetered PCM data. Several monitoring devices are available, from simple strip chart recorders to large television screens, which can be used to display either raw telemetered data or near real-time processed data in engineering units. The FTCR is also equipped with a flutter analysis workstation comprising a fast Fourier analyzer for near real-time spectral analysis, four lissajous scopes, and a display for monitoring the test aircraft FECU parameters. The FTCR set-up can be adapted to the user requirements. The communication system in the FTCR provides each operator with the capability to transmit/receive through UHF radio. During this test program, while everyone could receive pilot transmission, only the test controller (an AETE personnel) and in an abort situation, the lead engineer (normally a McAir personnel) were allowed to transmit to the test aircraft. Later in the test program, a hot mike capability was installed in one of the test aircraft which allowed all intercoms within the test vehicle to be telemetered to the FTCR. This feature enhanced the safety of flight and reduced pilot workload.

All test sorties were flown over Cold Lake Air Weapons Range (CLAWR) which also includes the AETE's Primrose Lake Evaluation Range (PLER). PLER is located on the southern boundary of CLAWR and approx 25 miles north of the airfield. This range is exclusively used by AETE for test and evaluation purpose. PLER facilities used in support to this test program included telemetry rebroadcast and tracking radars for all sorties while phototheodolites and meteorological data were required only for the Sep/Jett trials.

Structural Mode Interaction (SMI) Testing. SMI testing consisting of two high speed taxi runs and several flight test points integrated within the flutter flight test matrix. Since configuration 1 (Figure 4) was identified as the most critical SMI configuration, it was decided to fly this configuration first during the flutter flight testing. The first taxi run was carried out on a smooth runway while the second run used a rougher runway in an attempt to induce structural mode coupling with the FCS. Both tests were performed with full 480 gallon EFTs and half flap selected. During these taxi runs the control stick was firmly held in the aft right and forward left quadrants for about 10 seconds to see if an oscillation build-up would result. The SMI flight testing consisted of exciting the aircraft structure with lateral and longitudinal stick raps while monitoring the aircraft FCS response. This exercise was performed at various flight regimes including take-off and climb-out. The SMI taxi and flight testing confirmed the expectation, based on previous flight test experience with a similar store configuration, that no FCS coupling with aircraft vibration modes will occur for the CF-18 while carrying the 480 gallon EFT.

Flutter Flight Testing. These tests were carried out to verify that the allowable carriage envelope of the CF-18 configured with 480 gallon EFT is flutter free up to 1.15 times limit speed. The testing consisted of monitoring modal damping trends and frequency coalescence of the different modes involved in the flutter mechanism, previously identified during the pre-flight flutter analysis and supported by the full aircraft GVT results. The left digital display indicator, on test aircraft CF-188907, was replaced by a flutter exciter control unit (FECU), shown in figure 6, which provides aileron displacement signals to the FCS. Three modes of aileron excitation are available through the FECU; sinusoidal sweep (from one frequency to another), dwell (at one frequency for a given time) and random (random noise within a selected frequency band). The FECU has built-in safety features which automatically shut down aileron excitation whenever roll rate or normal acceleration exceed a certain value or whenever the pilot depress the paddle switch. The FECU can hold up to 15 pre-programmed set ups which can be activated at the touch of one button. The FECU control display is also reproduced via telemetry on a monitor in the FTCR.

Flutter flight testing consisted of sinusoidal sweeps and single frequency dwells conducted over a range of altitudes and airspeeds. The test points were divided into distinct dynamic pressure groups with each group representing a higher dynamic pressure zone. The FECU was the primary mode of inputting in-flight aileron excitation while stick raps had to be used when testing was carried out beyond the normal acceleration limits of the FECU. Functional check of the FECU, including the built-in safety features, was carried out by the pilot on each flight prior to commencing flutter testing. Upon clearance from the flight test controller in the FTCR, the pilot proceeded with the mission. Symmetric or antisymmetric excitations were used at different fuel states and aircraft attitudes to excite the mode of interest which was a function of the configuration and the flutter mechanism involved. Sweeps were used to determine resonant frequencies while dwells provided the damping characteristics at and near these frequencies. Engineers in the FTCR constantly monitored key parameters using strip chart recorders and lissajous displays. Review of near real-time transmissibility plots (T-plots) was performed as sine sweeps were completed and review of decay trace was carried out during dwell excitations. The flutter speed was determined through extrapolation of the flight est data using the Zimmerman flutter margin method and through correlation with the various flutter analyses. When it became too difficult to follow both damping modes with the Zimmerman method, testing continued by tracking only the lesser damped mode. Both McAir and AETE flutter engineers analyzed and reviewed the processed data after each flight and test points from the subsequent higher dynamic pressure zone were selected for the next test sortie. The last test points consisted of a series of dives performed at maximum velocities from 30,000 to 5,000 feet mean sea level (MSL) with one second dwell excitations at selected altitudes. This was performed to demonstrated flutter free operations of the configuration tested.

The pre-flight flutter analysis predicted that the full 480 gallon EFT was the critical tank fuel level for flutter testing regardless of the configuration flown. Flutter testing of configuration 1 confirmed this prediction. The flight test projected antisymmetric flutter speed for configuration 1 correlated well with the analytical prediction, and allowed flight to the full CF-18 tank envelope. The stability of configuration 1 was also verified by low level flight to maximum velocity and demonstration dives out to the allowable flight limits, with acceptable modal damping being exhibited in all cases. However, flutter testing of configuration 2(Figure 4) showed that the half full 480 gallon EFT has the lowest projected flutter speed. A near flutter onset condition was observed during a dwell excitation at maximum velocity and low altitude. Real-time monitoring of wing gauge outputs (Figure 7) indicated a significant reduction in damping resulting in the test point being aborted. Previous testing with full 480 gallon EFTs was successfully completed at similar test conditions. The flutter mechanism involved wing first bending and fuselage first lateral bending modes, as predicted by analysis. This lower flight est projected flutter speed will result in a carriage speed restriction for that particular configuration. The demonstration dives for configuration 2, carried out at various fuel states, were successfully completed to expand the higher altitude envelope out to the specified Mach number. The remaining flutter flight testing proceeded quickly and without incident. The use of aerial refuelling helped expedite the flutter test program specially for the test points involving high drag configurations where a minimum of 5000lb internal fuel was required.

Active Oscillation Control (AOC) Testing. When configured with heavy stores on the outboard pylon and wing tip missiles on, the CF-18 encounters a 5.6 Hz limit cycle oscillation (LCO). Unlike flutter, LCO is not divergent in nature but creates unacceptable lateral oscillation levels in the cockpit which affect pilot performance. This phenomena, characterized by wing first bending and torsional motion which couples with the fuselage to produce lateral fuselage bending, is caused by a structural/aerodynamic interaction which excites the antisymmetric outboard store pitch mode. This oscillation is suppressed by the AOC system which is implemented in the CF-18 FCS. The AOC system is automatically activated when the aircraft is flying below 9,000 ft MSL or above 0.82 Mach and for heavy outboard stores configuration with wing tip missiles on. The AOC system is essentially a feedback loop integrated into the FCS which senses the forward lateral accelerations, passes the signal through a passive bandpass filter, then through a phase shifter and output to the aileron to suppress the oscillation. The oscillation is aggravated slightly by an inboard fuel tank and since it is not predicted analytically, the certification of a 480 gallon EFT required flight testing to verify that the current AOC system adequately controls the oscillation with the larger fuel tanks installed. The configuration used for AOC testing is depicted in figure 4. Flight testing was also conducted with the AOC system deactivated under similar flight regimes so that a system effectiveness assessment could be made. A slight modification to the flight control computer wiring was required to disable the AOC system in-flight. The test approach consisted of flying symmetric manoeuvres under increasing normal acceleration and Mach number while simultaneously exciting the structure with lateral stick raps. The pilot seat lateral accelerations were monitored by engineers in the FTCR using strip charts recorders. A soft limit of 0.15g lateral acceleration was defined as the abort criteria. Simulated weapon delivery manoeuvres using 20 to 35 degree dive angle and maximum velocity dives were performed to demonstrate the AOC system effectiveness. For most flights the AOC system was effective in reducing the 5.6 Hz LCo to within acceptable levels (Figure 8). However, relatively high 5.6 Hz oscillation levels remained with half full 480 gallon EFT at high speed and low altitude. Flight restrictions will be required to maintain the oscillation levels within acceptable limits.

Manoeuvring Loads Testing. Extensive loads testing was required to demonstrate the safe manoeuvring envelope of the 480 gallon EFT since it is heavier and larger than any other stores flown on the CF-18. The manoeuvring loads testing was divided into two separate parts. The centreline carriage loads testing was carried out on aircraft CF-188701 while the wing carriage loads testing was done using aircraft CF-188907. Each aircraft had different specific instrumentation added to its basic systems to support these tests. For flight safety reasons centreline loads testing was combined with stability and control (S&C) testing to form a carriage test matrix. This was necessary as some of the loads test points required aircraft attitudes and flight regimes which were considered critical for aircraft departure and similarly some S&C test points were loads critical. Hence, it was common to have loads and S&C test point intermixed in one test card. However, the S&C issues will be reported in a separate section of this paper. The configurations selected for centreline and wing carriage loads testing are depicted in figure 4. The testing consisted of a build-up approach based on both progression in dynamic pressure and criticality of the manoeuvre performed including the amplitude of the control input. Once stabilized at a flight condition, the pilot performed certain manoeuvres known, from previous flight test programs, to induce large loading at the pylon/aircraft interface. These included steady state pull-ups, wind-up turns (WUT), steady state push downs, 1 g 360 degree rolls, -1 g 180 degree rolls, rudder kicks, and rolling pull-outs (RPO). After a test point, the data was reviewed by McAir and AETE engineers in the FTCR and the test controller cleared the pilot to the next test point.

Centreline Carriage Loads. Aircraft CF-188701 was specially instrumented with an aircraft centre of gravity accelerometer and approximately 30 strain gauges for in-flight strain monitoring at designated critical locations in the centreline pylon, pylon adapter and at the aft attachment fuse. The gauges in the centreline pylon adapter were installed in an attempt to provide real-time measurements of load data through gauge calibrations.

This method of measuring centreline loads had the advantage of being quick and allowing for immediate clearance to the next test point. However, the confidence in using this method was relatively low because of the limited instrumentation used in the calibration process. The second method used to obtain centreline loads values was the trajectory analysis. This method uses measured aircraft flight path with previously derived wind tunnel data to compute inertial and aerodynamic forces, and ultimately to calculate the pylon/aircraft interface loads. This technique requires a considerable amount of post-flight data because of the large number of time slices within one manoeuvre. All centreline loads testing was carried out using a three fuel tanks configuration with the centreline fuel quantity ranging from full to empty while the wing tanks remained empty.

A total of nine test sorties were required to complete the centreline loads test matrix. The first flight indicated that the centreline adapter strain outputs were only producing 10 percent of their expected values. Owing to time constraints it was then decided to proceed with the testing using the trajectory analysis method to derive the loads data. In the mean time, AETE found that the strain value range supplied by McAir were erroneous by a factor of 10. Corrections were made to the instrumentation gains but these gauges still only provided limited data because they were installed in an area too far away from the main load path. Hence, the trajectory analysis was the only reliable method to obtain centreline loads values.

The first two flights were carried out with the centreline tank filled up with 2600 lb of fuel (400 US gallons). Post-flight data analysis revealed that the centreline pylon aft attachment bolt had reached 108 percent its design load limit during a 360 degree, full aileron roll. On the same manoeuvre, the centerline pylon strain gauges, located at a critical fillet radii, was estimated to be over twice the maximum strain value predicted by McAir pre-flight analysis. Some of the strains recorded were well beyond the yield point of the material. The pylon was removed and inspected using non-destructive techniques (NDT) and no defect was found. However, in view of the inconsistency between the predicted attachment strain values and those measured in flight testing, the centreline loads test matrix was completed with an empty centreline tank. A usable flight envelope was determined using the trajectory analysis method and analytically included fuel to predict attachment loads for a full 480 gallon EFT. It should be pointed out that even with an empty 480 gallon EFT, the centreline pylon strains at the critical fillet radii were near the maximum allowable level predicted by McAir. One of the reasons for poor correlation between predicted and flight test strain values is the lower two-dimensional stress concentration factor used by McAir in their analysis applied to a critical region featuring double curvature (three-dimensional). Also it is quite possible that the centreline loads model is erroneous by itself. Nevertheless, previous flight testing conducted at AETE has revealed that this problem was not unique to the 480 gallon EFT but also applied to the 330 gallon EFT currently used by the CF. A structural loads monitoring program has been established and the impact of these high strain manoeuvres on the fatigue life of the CF-18 is being investigated.

Wing Carriage Loads. In support of these trials, test aircraft CF-188907 was configured with two specially instrumented wing pylons. Each pylon was modified with several strain gauges at McAir. These calibrated gauges enabled real-time measurement in the FTCR of load data at the pylon hook, pylon post roll moment, pylon post pre-load, aft attachment vertical and side loads, and aft tie fuse load. Later in the test program, aircraft CF-188907 was also fitted with five strain gauges in the critical radius of the wing pylon receptacle to verify that pylon measured loads were within the maximum permissible strains of the wing pylon receptacle. As per the centreline loads testing, symmetric and unsymmetric manoeuvres that were not considered to be departure critical were carried out first while the remaining test points were performed after the S&C flight testing was successfully completed for that configuration/manoeuvre. The wing carriage loads test matrix and manoeuvres performed were similar to those of the centreline testing. Because real time monitoring of the pylon/wing interface loads was available and the confidence level of the instrumentation used was much higher than that of the centreline pylon, a more practical build-up approach was used to expand the 480 gallon EFT wing carriage envelope during flight testing. Upon review of the data by both AETE and McAir engineers in the FTCR, the test controller cleared the pilot to proceed with a more critical test point. Generally, envelope expansion was carried out in build-up increments of 0.5g for symmetric manoeuvres keeping the entry conditions constant. Unsymmetric manoeuvres used similar build-up increments but also performed the manoeuvres using half control inputs first followed by full control inputs. This was continued until either a limit value was exceeded or if the next test point was likely to have overshot any limits.

The wing carriage loads testing was uneventful until a premature failure in the port inboard wing pylon receptacle was discovered after the test aircraft had safely landed from its last manoeuvring loads mission. This failure was transparent to the engineers manning the FTCR as well as to the test pilot. The crack was discovered during the post-flight routine check as fuel was found leaking from the pylon receptacle area. Since the cracked receptacle (Figure 9) is an integral part of the number three wing spar, the entire inner wing had to be removed and shipped to McAir for repair. A new port inner wing was installed and testing was resumed after a three month delay. Part of this delay was due to the installation of strain gauges on the inboard starboard wing pylon receptacle to monitor and correlate receptacle strain levels with pylon hook loads. Also the replacement inner wing was a production non-instrumented item which had no provision for installation of test instrumentation. However, the existing instrumentation in the starboard wing was similar to that in the original port wing and, after a re-calibration of the instrumented pylon on the starboard side, testing was resumed using the starboard wing vice the port wing to collect flight test data. A pylon receptacle strain survey was carried out using full 330 gallon EFT. Symmetric WUTs and unsymmetric RPOs were performed at various load factors and the receptacle strains were plotted as a function of pylon loads (Figure 10). This survey provided data which permitted to be correlation, by extrapolation of pylon loads flight test data from previously flown missions to receptacle strain levels. This exercise showed that even the maximum pylon hook load values previously recorded were well within the allowable yield strain level of the receptacle and that it should have not failed from the 480 gallon EFT loads alone.

McAir conducted an extensive investigation as to the cause of this premature failure (Reference 2). Several failure causes were investigated including stress corrosion cracking, low cycle fatigue and static overstress, although the design loads for the wing spar receptacle had never been exceeded during any part of this test program. During disassembly of the wing pylon receptacle, the beryllium - copper wear plate that attaches to the lower flange (the sill which the pylon hook bears on) was installed incorrectly. The wear plate is installed correctly when its thin edge is located inboard as shown in figure 11 (the wear plate angle is exaggerated for better visualization). The localized wear surfaces and crack observed on the wear plates is reproduced in figure 12. Further investigation by the CF revealed that other CF-18 aircraft also had incorrectly installed wear plates. Upon further review of historical data by McAir it was discovered that a USN F/A-18 had suffered a port wing failure in virtually the same location as CF-188907. Fractographic inspection of the failure indicated that both failures were identical; however, it could not be ascertained if the wear plate on the USN aircraft was installed incorrectly. The findings of the McAir investigation concluded that no material discrepancies were found and that there was no evidence of stress corrosion cracking or fatigue. The investigation report conclusion states that the pylon receptacle failure on CF-188907 was owing to static overload and was precipitated by a reversed wear plate. The expected fatigue life of the CF-18 inboard pylon receptacles, with the wear plate installed correctly, was determined to be well beyond the life expectancy of the aircraft.

<u>Store Ejection Dynamic Loads</u>. Previous testing and analysis indicated the need for store ejection dynamic loads flight testing because of the load increment caused by the dynamic response of the structure during store ejection. Hence, these tests were carried out to obtain flight test data to establish release load factor limits of selected CF-18 outboard wing pylon stores while retaining 480 gallon EFTs on the inboard wing pylon. Although the tests were performed using full 480 gallon EFTs, allowable limits were analytically derived for full, partially full and empty 480 gallon EFTs. These tests were carried out on CF-188907 after the wing pylon receptacle failure. Therefore, not only pylon hook loads were monitored but also the receptacle strain levels. In addition, accelerometers were installed on the starboard wing tip, wing fold, outboard pylon, and on the nose of the starboard 480 gallon EFT. The FTCR was used to monitor all store ejection dynamic loads sorties with the critical parameters being pylon hook load, pylon aft attachment vertical and side loads, and pylon receptacle strains.

The ejection of a store produces a transient response on the aircraft structure and retained stores/pylons which can be separated into steady-state and dynamic components. The steady state component consists of inertia and aerodynamic loads occurring just before the store release. The dynamic component results from the ejector piston force, the sudden weight released from the wing, and the application of the unbalanced airloads as lift exceeds the inertia load immediately after the stores are released. As a result it was necessary to use a build-up approach increasing normal acceleration at release. Two critical configurations (Figure 4) were identified for testing; the release of two MK-84s in salvo and the ripple salvo release of four MK-83s with a 200 millisecond release interval. Pre-flight analysis indicated that the release interval was an important factor in the severity of the resulting dynamic loads. The analysis dictated that 200 millisecond was the most critical release interval for that particular MK-83 configuration, even more so than the MK-84 salvo release at the same load factor. All releases were carried out at the same flight conditions except for load factor which was progressively increased based on the results of the previous drop. The store ejection dynamic loads testing was completed quickly without major unserviceabilities. The flight test data showed, as expected, that the pylon hook loads and aft attach vertical loads were the most critical components. The maximum inboard pylon hook loads measured in flight were considerably less than predicted values and contrary to the pre-flight analysis the salvo release of two MK-84s bombs was indeed more severe than the ripple salvo release of four MK-83 bombs with the most critical release interval setting as shown by figure 13. The inboard pylon vertical aft attach limit load was exceeded by four percent during the last MK-84 release sortie. This limit was driven by the pylon structure and not the wing interface, both inboard pylons were checked and no irregularities were found. The final normal accelerations recommended for store release in the presence of the 480 gallon EFTs are limited by the pylon aft attachment which is definitely not in the pylon primary load path. This stresses the importance of harmonized aircraft design in that a secondary structure should not restrict the employment of the primary structure to its full potential.

Stability and Control Testing. The larger size and fuel weight of the 480 gallon EFT dictated that the effects of this new tank on CF-18 stability and control (S&C) characteristics be evaluated. As previously mentioned, S&C testing was integrated into the manoeuvring loads tests to form a safe carriage test matrix. The specific objectives of these flight trials were to determine and demonstrate a departure free envelope for the CF-18 loaded with 480 gallon EFT configurations as well as to evaluate CF-18 flying qualities with such configurations. Both CF-188701 and CF-188907 were used for these trials. Special instrumentation included a flight test nose boom with pitot head, total temperature probe, AOA and angle of sideslip vanes. Testing consisted of evaluating the flying qualities and departure resistance of the selected 480 gallon EFT configurations using a build-up approach in a series of standard test manoeuvres. These manoeuvres included level accelerations/decelerations, control doublets, steady heading sideslips, WUT, rudder rolls, lateral stick rolls, coordinated rolls, cross control and several operational mission tasks. All these were performed at various flight regimes and flap/gear configurations. The production aircraft yaw rate tone threshold was used as a soft flight test limit for yaw rate. After review of preliminary flight test results, the sideslip angle test limit, initially defined, was slowly increased by 50 percent using one degree increments because the original limit was reached with less than full rudder pedal deflection early in the S&C testing.

The three empty 480 gallon EFTs S&C configuration (Figure 4) was determined to be the worst case for lateral-directional stability and henceforth was flight tested on both single-seat and dual-seat aircraft. Provision was made to replace the centreline 480 gallon EFT with a 330 gallon EFT if a loads or S&C limit was encountered, since the centreline 480 gallon EFT was a RAAF configuration only. When the RAAF withdrew from this program, all subsequent testing was carried out with a 330 gallon EFT on the centreline. Baseline flights with three 330 gallon EFTs were performed as a benchmark for the qualitative evaluation of aircraft flying qualities with 480 gallon EFT. Because of the reduced directional stability of the dual-seat aircraft, and unavailability of wind tunnel data for the three tank configuration, two flights were flown with only two 480 gallon EFTs on the wing stations as a build-up for departure resistance. All end points of the test matrix were flown with 3000 lb total fuel or less to verify the departure free envelope at the aft CG conditions. The interdiction S&C configuration, which includes three 480 gallon EFTs and four MK-83 bombs (Figure 4), represented the worst case for longitudinal stability at low fuel state (aft CG) and was only tested on the dual-seat CF-188907.

The S&C testing was completed without aircraft departures and a departure free envelope for the CF-18 configured with 480 gallon EFT was determined. Overall the flying qualities of the CF-18 configured with 480 gallon EFTs were similar to that of comparable 330 gallon EFT configurations. Apparent lateral directional stability was positive on both the single and dual aircraft at all AOA and for all configurations tested. Regions of negative airframe lateral-directional stability were observed in mid to high AOA because of the large adverse yawing moment of the aircraft rolling surfaces. In all occurrences the FCS was successful in turning these instability regions transparent to the pilot. One coordinated input 360 degree roll performed in the high subsonic, mid AOA region resulted in a 30 degrees/second yaw rate build-up. Post-flight data analysis revealed that the very large proverse contribution of the rudder, commanded by the full rudder pedal input, was fundamentally responsible for the overall high level of yawing moment and yaw rate observed. Although the aircraft remained quite controllable throughout this manoeuvre, it was decided nevertheless to include a note in the AOI advising the pilot of these potentially high yaw rate flight regimes and manoeuvres.

Pitch response and damping were satisfactory on the single and dual aircraft for all 480 gallon EFT configurations at most flight conditions tested. Pitch response became quite sensitive above 0.8 Mach and high AOA with AOA soft limits often overshot. However, the aircraft never departed and the pilot always regained precise pitch control. Review of the flight test data revealed several regions of negative airframe stability mostly above 20 degrees AOA and high subsonic Mach number. One of the most interesting phenomena observed during this test program was a longitudinal stick reversal experienced by CF-188701 with three 480 gallon EFT during a WUT at 0.8 Mach/35,000 ft. Post-flight data analysis confirmed this negative apparent longitudinal stability (Figure 14). Further review of the data indicated that this pitch up phenomena was partially caused by the quickness of the manoeuvre relative to the large time constant of the filtered AOA to the trailing edge flap (TEF) controller. Review of the TEF position relative to the AOA showed deflections much greater than the scheduled position as the manoeuvre progress (Figure 15) which significantly increased the nose up pitch moment. The control laws of the CF-18 are based on a commanded load factor system which in theory should provide the precise load factor at all times such that stick reversal should not happen. However, as the aircraft enters the region of airframe instability, the trim stabilator requirement changes from trailing edge up to trailing edge down. This momentary imbalance, aggravated by the previously mentioned TEF lag, results in a pitch-up, although the pilot holds a nearly constant longitudinal stick input. The natural reaction of the pilot is then to introduce forward stick to augment the control laws. McAir is confident that, given enough time and oscillations, the control laws should eventually seek out the commanded load factor. Although the pilots have found these localized pitch-up phenomena bothersome, they were not considered hazardous. An AOI note advising the pilot about the pitch-up tendency of the CF-18 configured with 480 gallon EFT in certain flight regimes will be recommended. Basically the departure free envelope for the CF-18 with 480 gallon EFT is practically identical to that of the CF-18 with 330 gallon EFT.

Lift-off speeds using military power and maximum power were recorded for several aircraft configurations throughout this test program. In general, carriage of full 480 gallon EFT resulted in normalized take-off speeds comparable to that of the 330 gallon EFT. A consistent trend depicted in the analysis of the take-off data indicates that the aircraft operating instructions (AOI) are in average 6 knots lower than the normalized flight test data. It is recognized that take off testing intrinsically produces large variances; however, three test pilots were involved in this testing and all were briefed to use 12 degree nose-up stabilator initial trim with full aft stick deflection during take off roll, yet hardly none of the test points recorded had a take-off speed less than that published in the AOI. Further testing to spot check the validity of AOI take-off data will be recommended.

Separation/Jettison Testing. The separation/jettison (Sep/Jett) testing was performed to demonstrate safe jettison of the 480 gallon EFT from the CF-18 aircraft and to compare the tank flight separation results with those predicted using the wind tunnel database and McAir's six degrees of freedom (SDF) computer code. The pre-flight analysis conducted by McAir identified a total of seven jettison trials for flight testing; five from the wing stations and two from the centreline station. The later were deleted from the Sep/Jett text matrix as a result of the RAAF withdrawal from this program. All Sep/Jett testing was carried on CF-188701 equipped with a flight test nose boom. In addition, three photosonic 1PL high speed cine cameras were installed on the starboard wing tip missile launcher while a fourth camera was located at the keel position. The tip cameras were calibrated so that their film could be used to provide SDF trajectories through photometric data reduction. Each of the 480 gallon EFTs dropped during these trials were prepared with numbered decals to aid in the photometric data reduction. All jettisons were done with empty and purged tanks since this was the predicted worst case fuel level. The FTCR was used to monitor the trials.

The overall test approach used a build-up procedure increasing Mach and airspeed independently by varying the release altitude and finishing with an end point demonstration. A total of four ejected and one auxiliary release (non-ejected) of 480 gallon EFT were successfully demonstrated during this test program. The auxiliary jettison of an empty 480 gallon EFT from the CF-18 wing station was carried out once good correlation was established between flight test data and McAir's SDF computer program predicted separation trajectories. The last jettison trial was conducted with two MK-83 low drag bombs on a vertical ejector rack (VER) mounted on the outboard wing station adjacent to the jettisoned 480 gallon EFT. To distribute the aerodynamic asymmetry between take-off and landing, an empty 330 gallon EFT was loaded on the port inboard wing station of the test aircraft and retained throughout the flight. All releases were carried out with flaps and landing gear up. At the highest dynamic pressure release, the tank aft end projected several inches above the plane of the wing pylon lower surface. Although this area is used by the TEF when fully deflected, at such high dynamic pressure the TEF are not deflected enough to be in the area of concern. However, the jettison of the 480 gallon EFT with the TEF fully deflected may be hazardous and an AOI warning to that effect is warranted. Overall, the 480 gallon EFT separation photometric data adequately matched the separation trajectories predicted by McAir's SDF computer program with some variations in pitch rate and yawing tendency of the 480 gallon EFT. The larger predicted angular motion may be attributed to the tank deforming under the ejector area thereby absorbing some of the ejection force. But most probably, the variance in angular motion may be from the different magnitude of the full scale aerodynamic characteristics from the predicted values since wind tunnel data was only available up to 35 degree pitch attitude. Nevertheless, the ejected and auxiliary jettison envelopes of the 480 gallon EFT on the CF-18 were successfully demonstrated to the desired limits.

Performance Testing. Limited performance testing was conducted to verify the wind tunnel predicted drag indices for various 480 gallon EFT configurations. At a typical cruise condition, the predicted drag increment for the 480 gallon EFT from wind tunnel testing was reported (Reference 3) to be three counts higher for centreline carriage and 13 counts more for two wing carriage than a similar configuration using 330 gallon EFT. All performance sorties were flown on CF-188701 configured with a flight test noseboom. Apart from this flight test noseboom, which had a drag index (DI) of 1.3, the test aircraft was representative of a fleet aircraft. Performance data was gathered during five flights using level accelerated flight and stabilized level flight using the constant weight to pressure ratio (W/ ) technique. Owing to the limited number of flights available; the several configurations to be tested; measuring devices on AETE's instrumentated aircraft; and the non-residency of a CF-18 trust deck at AETE; data reduction was rather archaic. It consisted of extrapolating drag indices from the AOI based on a measured Mach number and calculated fuel flown from fuel quantity variations over a two minute time period. A sensitivity analysis was performed and the flight test derived drag indices were estimated to be within seven counts of the true value at 0.8 Mach.

The clean aircraft, configured with only wing tip missiles, was first tested to verify the baseline drag index. The result showed that the baseline aircraft had an average DI of 25. This was approximately 15 drag indices higher than the expected value, accounting for aircraft modifications, fuseland launchers and flight test noseboom. The difference in the DI was attributed to normal inservice degradation of the aircraft performance. Similar results were obtained during a subsequent performance test program carried out to evaluate the CF-18 performance at low altitudes for various configurations including the 480 gallon EFT. Thus, a basic aircraft DI was recommended for insertion in the performance part of the AOI. Contrary to the AOI which considers the DI to be independent of Mach number, the test results showed that the variation of actual DI with Mach will affect some of the range and combat radius predictions from these AOI. However, test data indicate that this assumption may be considered valid for the flight regime anywhere between 0.7 and 0.92 Mach. Essentially the flight test data showed that, allowing for the baseline offset and at a typical cruise condition, the actual DI for the 480 gallon EFT configurations closely matches the McAir predicted values. The flight test performance results also confirmed the predictions that a CF-18 configured with two 480 gallon EFTs was essentially the same DI as a three 330 gallon EFT configuration. Since these two configurations carry similar amounts of fuel, the utilization of two 480 gallon EFTs has the advantage of freeing up one additional weapon station for an increased payload capability. Overall, the limited performance data gathered during this test program have indicated that the carriage of 480 gallon EFT instead of 330 gallon EFT substantially increases the range and endurance of the CF-18 aircraft.

## SUMMARY

This flight test program was successful in demonstrating safe carriage and jettison of a composite 480 gallon EFT for the CF-18 aircraft. A recommendation will be forwarded to NDHQ so that a certification clearance can be issued. A total of 98 test sorties were flown on CF-188701 and CF-188907 in support of these trials, 34 for flutter, AOC and SMI, 28 for S&C, 18 for manoeuvring loads, six for dynamic loads, five for Sep/Jett, five for performance, and two for the wing receptacle strain survey. Except for performance testing, most of these flights required a safety/photo chase aircraft.

The minor deficiencies identified throughout this test program on the prototype 480 gallon EFT have been corrected on the production model. The EMI/EMC concerns with this composite material tank were addressed by incorporating an EMI low pass filter on the fuel quantity probe and including a metal based wrapping near the tank surface. Most EMI/EMC testing was repeated with this improved design with the final test currently being carried out at AETE.

Data gathered from all analysis, ground and flight tests have indicated that the 480 gallon EFT is a viable option for the CF-18 aircraft. As predicted analytically, no SMI will occur from the carriage of this tank. Minor speed limitations will be required for certain configurations based on the flutter and AOC test results. The higher than predicted strain values from the centreline loads testing may result in additional flight restrictions if centreline carriage is reconsidered, but as previously mentioned centreline carriage was not a Canadian driven requirement. The wing inboard pylon receptacle failure will not restrict the wing carriage of the 480 gallon EFT since this failure was attributed to an incorrectly installed wear plate. Based on the dynamic loads flight test results, the wing pylon aft attachment load limits will somewhat restrict the permissible normal acceleration for outboard store releases in the presence of a 480 gallon EFTs. Safe separation and jettison of the tank was demonstrated to the desired limits and performance testing has shown that the use of 480 gallon EFT increases the range and capability of the CF-18 aircraft. The follow-on test program, currently under planning, will establish a full clearance for employment of various stores adjacent to the 480 gallon EFT. Overall, this test program provided AETE personnel with valuable experience which will most likely be reflected in future store certification programs.

## REFERENCES

(1) MIL-STD-1289A, Military Standard Ground Fit and Compatibility Tests of Airborne Stores, 11 November 1976

(2) McAir Letter M47-330-19537, Results of Canadian Aircraft CFB7 Inboard Pylon Receptacle Failure Investigation, 11 August 1989

(3) McAir Report MDC B0024, Stability and Control/Drag test on a Six-percent Scale F/A-18 Model With External 480 Gallon Fuel Tank in the Calspan Eight-foot Transonic Wind Tunnel, 15 March 1987

| PHYSICAL COMPARISONS EFT'S | | |
| --- | --- | --- |
| 330 | VS | 480 |
| ALL METAL/SURVIVABLE | WRAPPED | COMPOSITES |
| 188-4/189 IN | LENGTH | 215 IN |
| 28-2/28-6 IN | DIAMETER | 31-9 IN |
| 220/290 LBS | DRY WEIGHT | 310 LBS |
| 330 GALS<br>2,244 LBS | USABLE FUEL | 480 GALS<br>3,264 LBS |

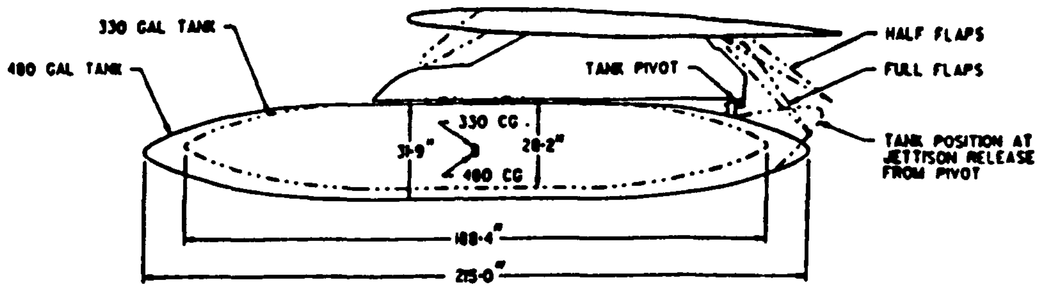



FIGURE 1 – COMPARISON OF EXTERNAL FUEL TANKS PHYSICAL CHARACTERISTICS

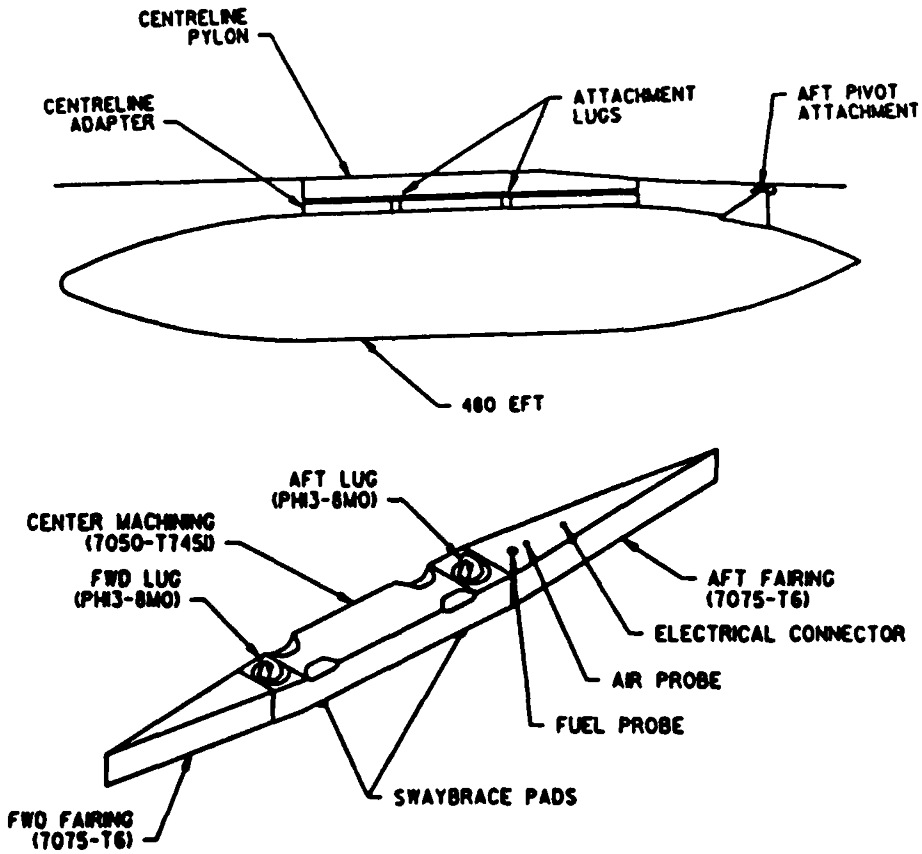



FIGURE 2 – CENTRELINE ADAPTOR FOR 480 GALLON EFT

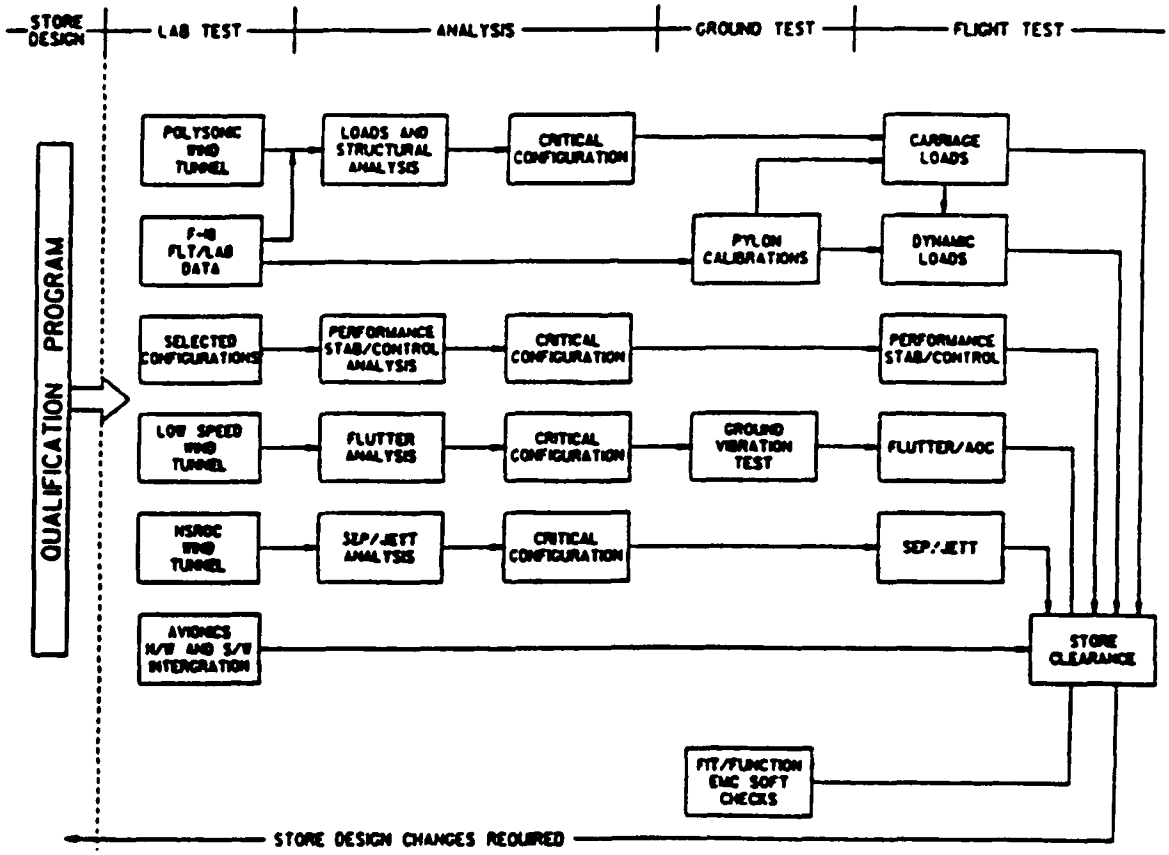
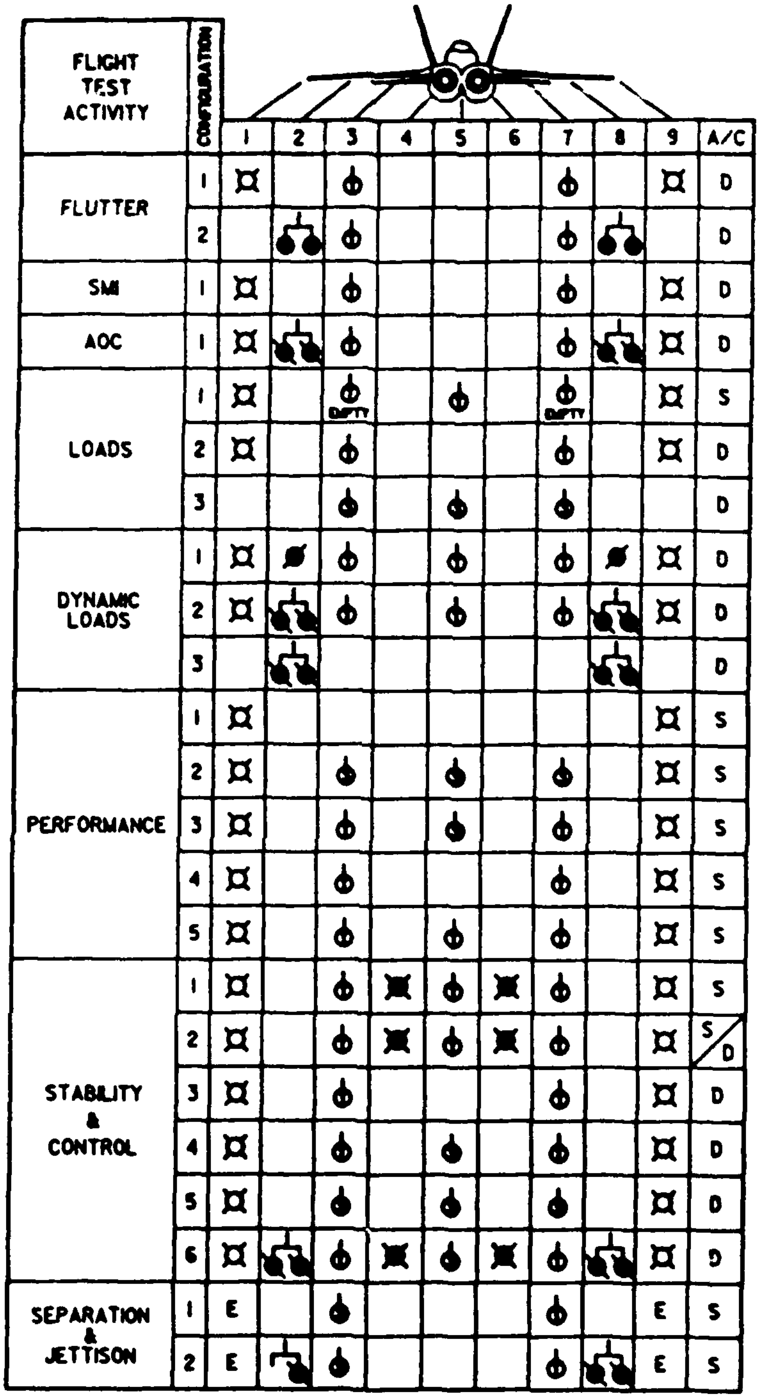


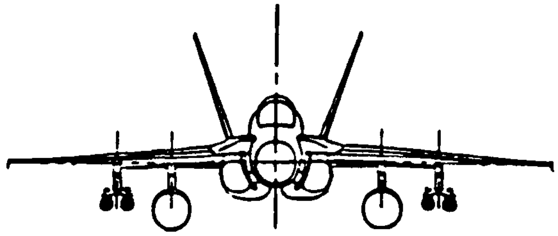

FIGURE 3 – 480 GALLON EFT STORES CLEARANCE PROCESS




- 480 FUEL TANK
- AIM-9L/M MISSILE
- MK 82
- E - EXTERNAL CAMERAS
- 330 FUEL TANK
- MK 83
- MK 84
- AIM-7
- D - DUAL SEAT AC 907
- S - SINGLE SEAT AC 701

FIGURE 4 – CONFIGURATIONS FLIGHT TESTED

**TIP MISSILES OFF, 2 MK-82 OUTBOARD, 100% 480 EFT INBOARD**



| ANALYTIC MODE DESCRIPTION | SYMMETRIC | | | ANTI-SYMMETRIC | | |
|---|---|---|---|---|---|---|
| | ANALYSIS HZ | GVT HZ | RIG HZ | ANALYSIS HZ | GVT HZ | RIG HZ |
| TANK ROLL | 2.45 | 2.51 | *NM | 3.05 | 3.14 | NM |
| TANK PITCH | 6.00 | 6.17 | 6.19 | 5.75 | 5.72 | 5.89 |
| TANK YAW | 5.92 | 6.04 | NM | 5.93 | 6.42 | NM |
| OUTBOARD STORE ROLL | 4.05 | 4.41 | 4.45 | 4.63 | 4.73 | 4.45 |
| OUTBOARD STORE PITCH | 7.88 | 8.14 | 8.43 | 7.60 | 8.60 | 8.77 |
| OUTBOARD STORE YAW | 12.49 | 13.49 | 13.19 | 12.53 | 13.36 | 13.37 |
| WING 1ST BENDING | 5.53 | 5.91 | 5.77 | 8.31 | 8.08 | 8.12 |
| WING 1ST TORSION | 17.50 | 17.36 | 16.42 | 17.47 | 17.19 | 16.96 |
| WING 2ND BENDING | 11.90 | 12.60 | NM | 14.78 | NM | NM |
| FUSELAGE 1ST BENDING | 9.42 | 10.33 | NM | 8.80 | 9.74 | 9.31 |

*NM - NOT MEASURED

FIGURE 5 – SUMMARY OF TYPICAL 480 GALLON EFT GVT RESULTS

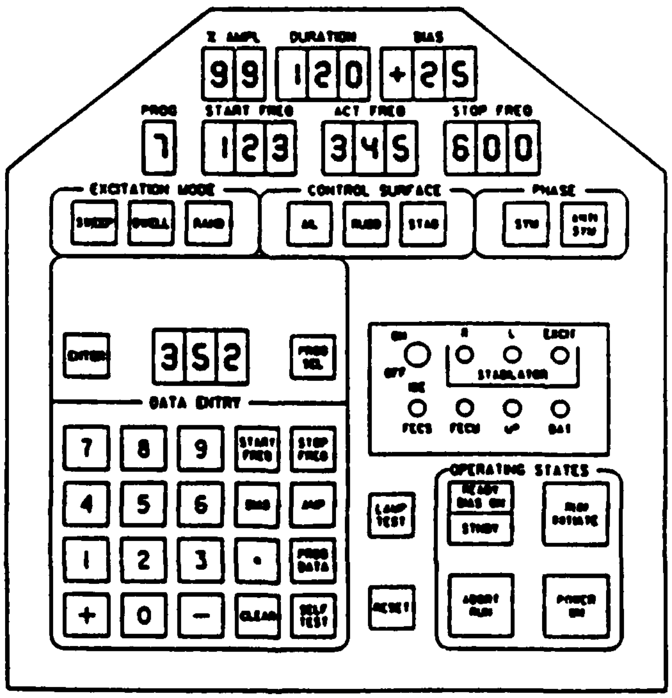



FIGURE 6 – FLUTTER EXCITER CONTROL UNIT

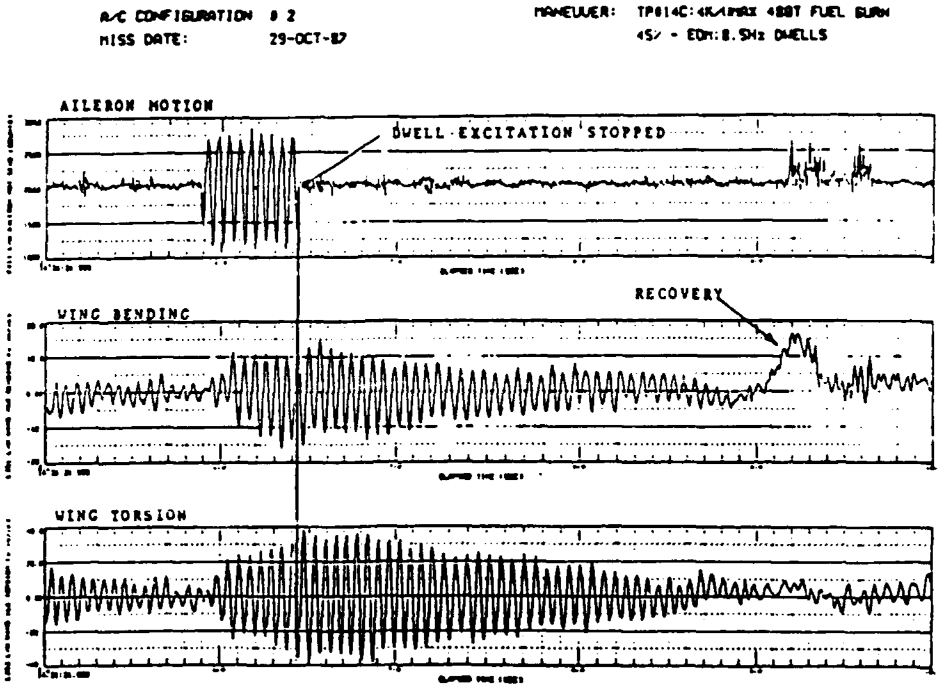



FIGURE 7 – RESPONSE OF WING STRAIN GAUGES AT LOW DAMPING

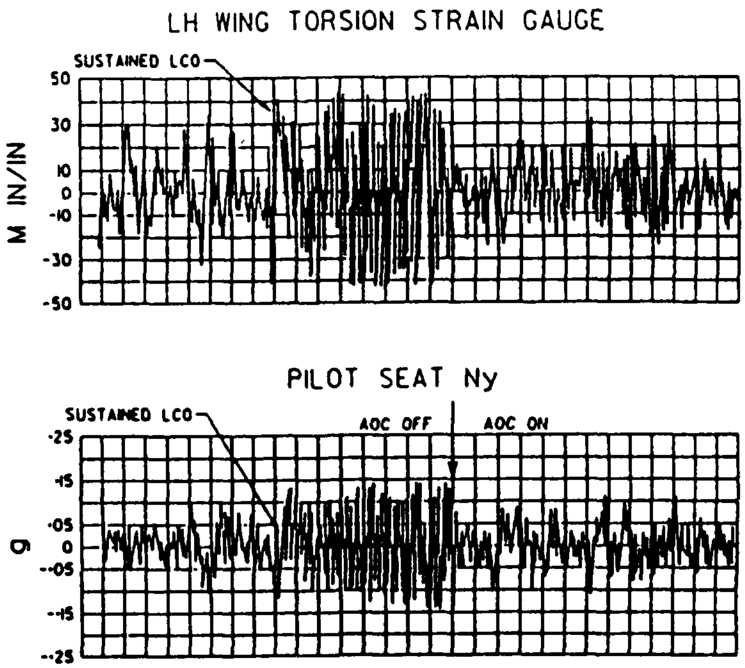



FIGURE 8 – AOC SYSTEM EFFECTIVENESS

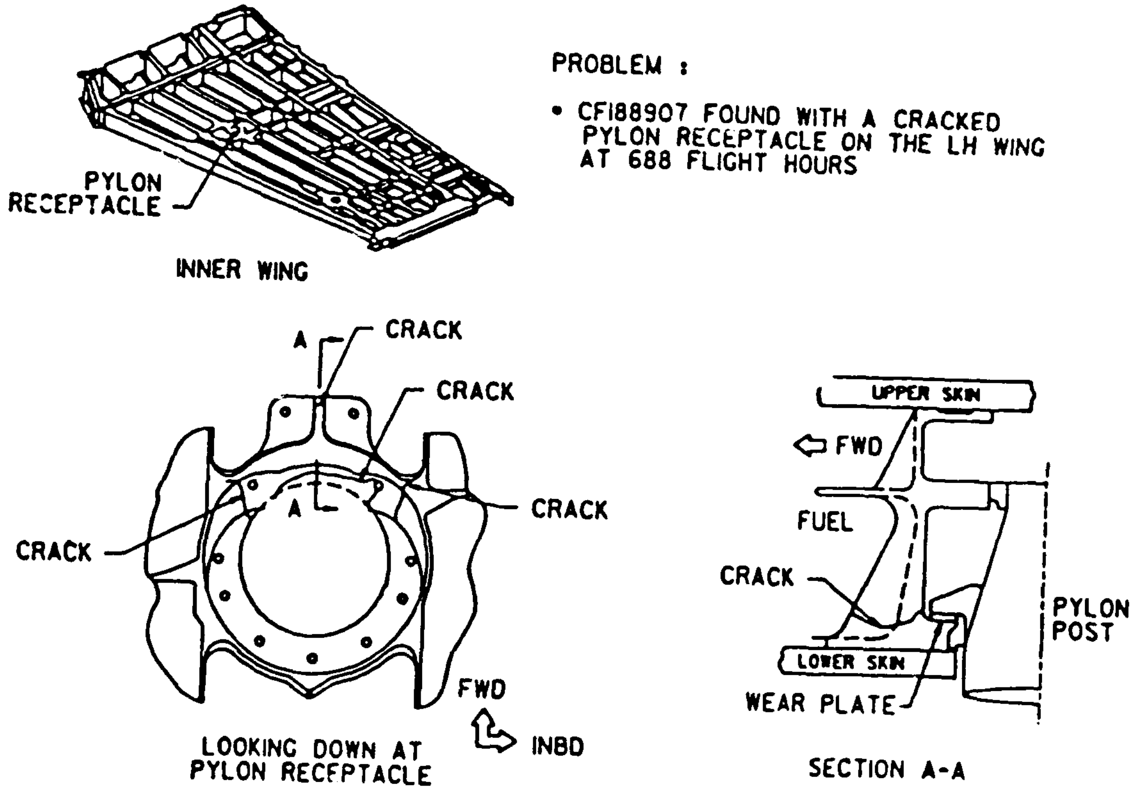



FIGURE 9 – INBOARD WING PYLON RECEPTACLE CRACK

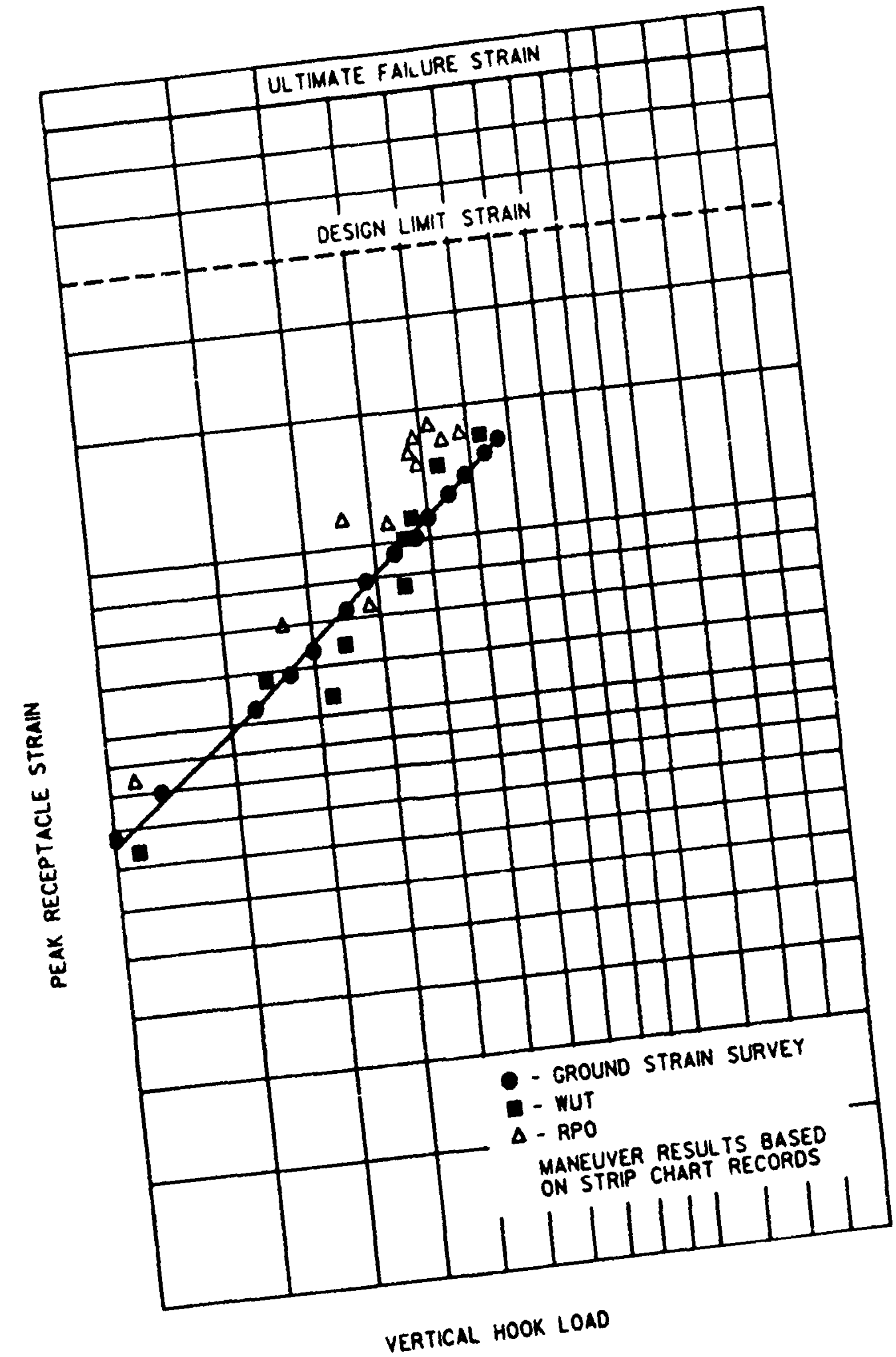



FIGURE 10 – INBOARD WING PYLON RECEPTACLE STRAIN/LOADS SURVEY

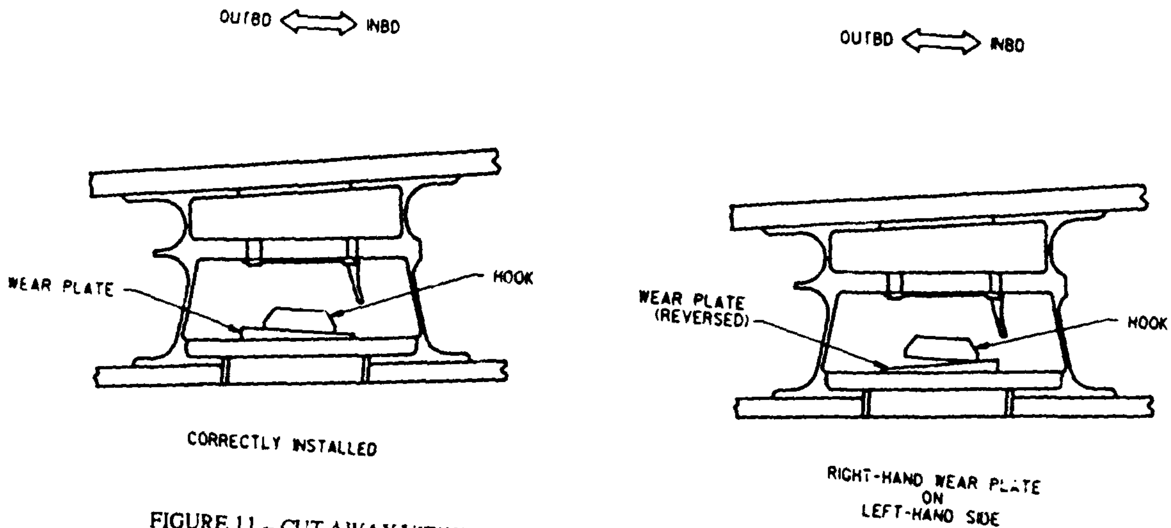



FIGURE 11 - CUT AWAY VIEWS OF WING PYLON RECEPTACLE & PYLON HOOK

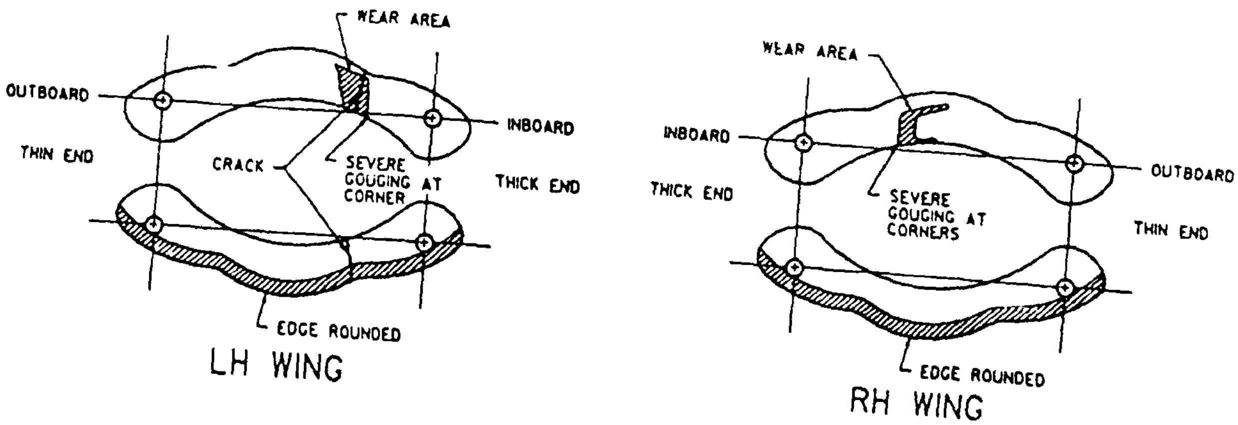



FIGURE 12 - WING PYLON RECEPTACLE WEAR PLATES FROM CF-188907

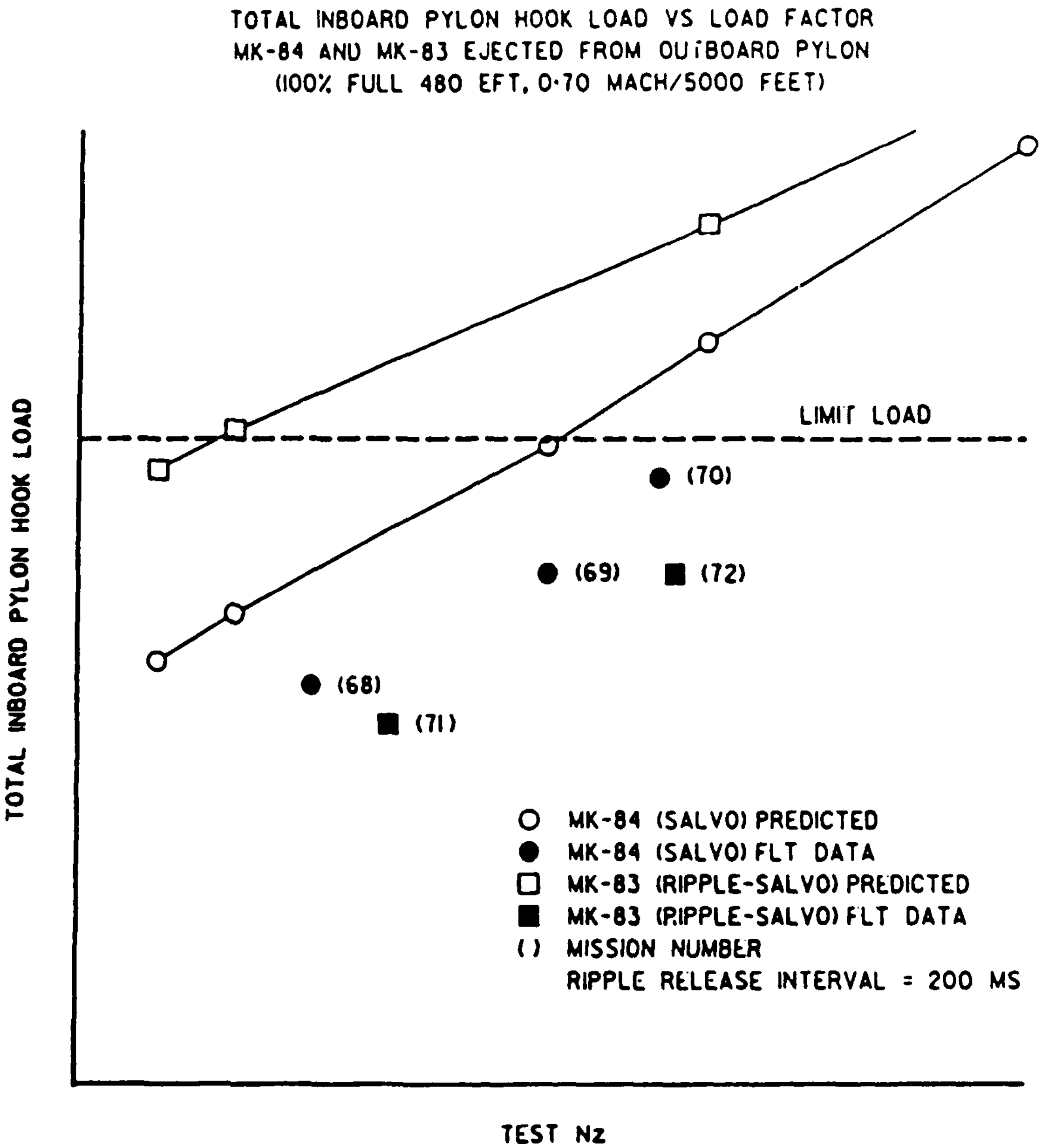



FIGURE 13 – PYLON HOOK LOADS FROM STORE EJECTION DYNAMIC LOADS TESTING

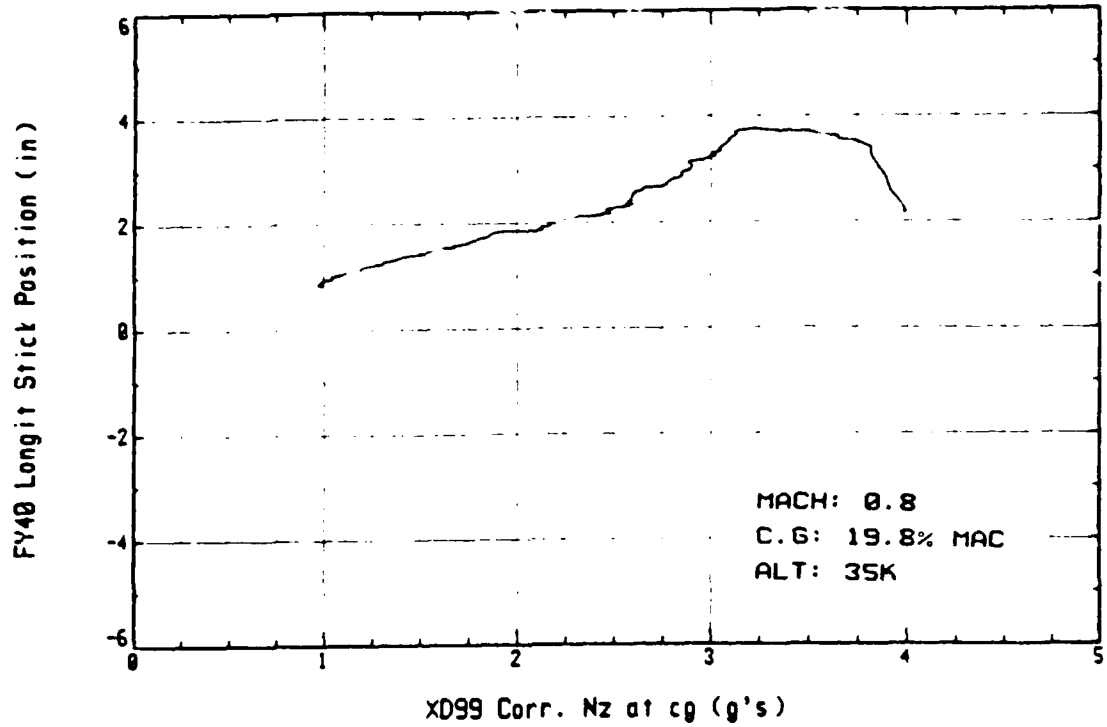



FIGURE 14 - LONGITUDINAL APPARENT STABILITY DURING WIND-UP TURN (3 x 480 EFT)

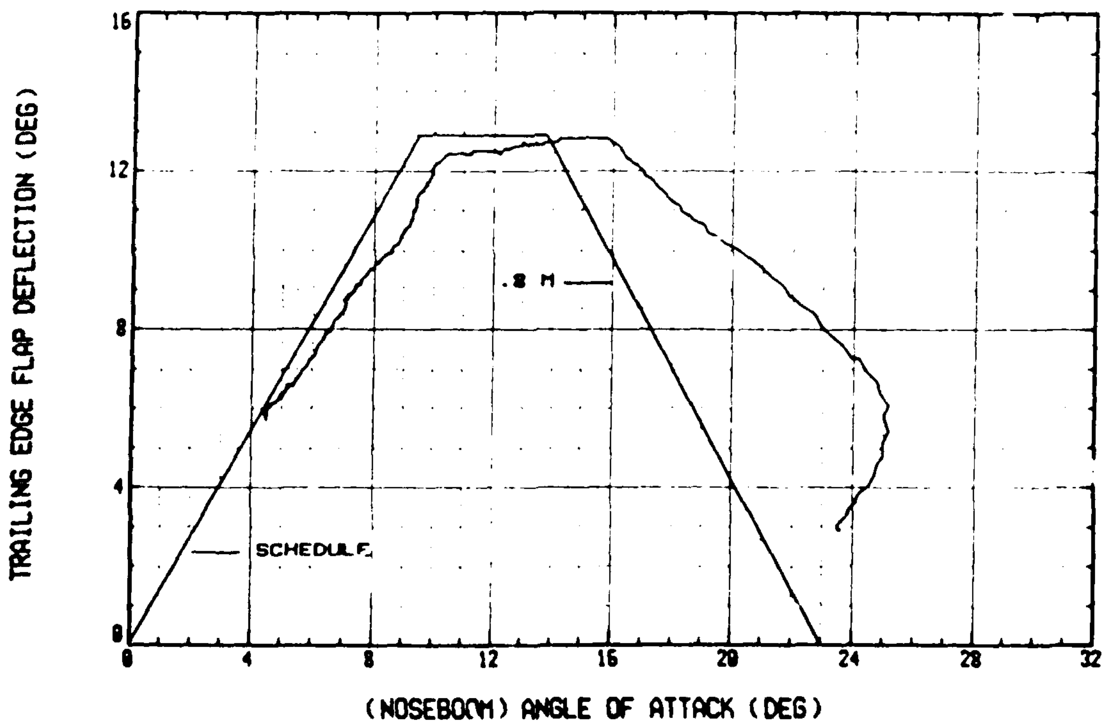



FIGURE 15 - TRAILING EDGE FLAP POSITION VERSUS SCHEDULE DURING WIND-UP TURN

# RAVITAILLEMENT EN VOL
# L'EXPERIENCE DE DASSAULT-AVIATION APPLIQUEE AU RAFALE

par

**Charles Defreville**
Dassault-Aviation
Direction Générale Technique
78 quai Marcel Dassault
92214 Saint-Cloud
France

## 0 RESUME

Le Rafale, dernier avion de combat de Dassault Aviation, est pourvu d'un circuit de ravitaillement en vol à base d'une perche fixe. Le but de l'article est de retracer les principaux faits marquants qui ont jalonné sa conception et qui témoignent de la variété des disciplines sollicitées : structure, aérodynamique, systèmes, etc ...

Dans un deuxième temps sont décrits les essais réalisés tant au sol qu'en vol, qui ont permis de vérifier les performances du système et les qualités de vol de l'appareil.

## 1 INTRODUCTION

### 1.1 Rappel de l'importance du sujet

Le nombre d'avions dans les Forces Françaises pour assurer la défense du territoire diminue au fil du temps, allant de pair avec l'accroissement de leur potentiel. La durée moyenne des missons, leur domaine de surveillance et d'intervention ont sensiblement augmenté.

Parallèlement,et sans parler de contexte géopolitique, les évènements de ces dernières années ont prouvé que les interventions militaires sont disséminées en de nombreux endroits du globe. Ces interventions requièrent souvent l'utilisation des forces aériennes, et fréquemment des avions de combat : ils doivent d'adord se rendre sur le lieu, et ils se voient ensuite confier des missions variées de type surveillance avec temps d'attente ou raid loin de la base.

Ces missions des temps actuels requièrent pour les avions de combat une capacité d'autonomie en vol ou d'action à longue distance très importante.

Il y a plusieurs réponses possibles pour répondre à ces besoins : capacité interne de carburant, utilisation de réservoirs externes, diminution de la consommation spécifique des moteurs, etc ...

Le bon compromis fait la réussite d'un bon avion, sur ce sujet, comme sur les nombreux autres.

Le ravitaillement en vol a l'avantage d'apporter peu de contrainte dans la définition de l'avion. Cette fonction nécessite cependant des moyens logistiques assez lourds, les avions ravitailleurs. Mais l'avantage opérationnel est tel, qu'au cours des années, de plus en plus de pays ont décidé de s'en doter.

Finalement, et à force d'allonger l'autonomie en vol, on peut imaginer qu'un jour, sa limite ne sera pas imposée comme souvent par la consommation en carburant, mais pourquoi pas pour la consommation en huile des réacteurs !

### 1.2 Expérience des avions de combat de Dassault-Aviation

Les performances demandées pour le ravitaillement sont devenues de plus en plus précises et exigeantes au cours du temps. Cette évolution se retrouve au travers des générations successives des avions de combat multimissions de Dassault.

- Le Mirage III, avion des années 60, ne comporte pas de système de ravitaillement dans sa version de base. Lors des rénovations des Mirage III export, réalisées par notre société ou des concurrentes, le rétrofit de ce circuit est souvent proposé.

- Le Mirage F1, avion des années 70, n'était pas doté d'un circuit de ravitaillement dans ses spécifications techniques initiales. Le premier avion de série en était certes équipé, mais le circuit a été moins optimisé en terme de performances, vu son introduction tardive en début de mise en série.

- Le Mirage 2000, avion des années 80-90, a été conçu dès le départ avec un circuit de ravitaillement comportant une perche fixe amovible. Cette perche est montée en permanence, pour la plupart des versions.

Un bon nombre d'avions Dassault ont aussi été conçus pour des profils de mission plus spécifiques. Ils comportent de base un circuit de ravitaillement en vol : Mirage IV, Jaguar, Etendard et Super-Etendard, entre autres. Ce dernier est même avion ravitailleur, grâce à l'emploi d'un pod spécifique monté sous fuselage ; certaines versions de Mirage F1 export ont aussi cette capacité.

Sur le Rafale, futur avion de combat polyvalent de Dassault, le niveau de performances du circuit de ravitaillement a été fixé très haut, en regard de ses différentes versions ainsi que des missions variées qu'il aura à effectuer.

L'objet de cet article est de montrer, au travers du cheminement qui a amené sur cet avion à la solution retenue pour le circuit, quels sont les aspects les plus marquants, en particulier ceux dont le savoir-faire de l'avionneur est intervenu dans les choix effectués.

*Presented at an AGARD Meeting on 'Recent Advances in Long Range and Long Endurance Operation of Aircraft', May 1993.*

# 2. LE PROGRAMME RAFALE

## 2.1 Grandes lignes du programme

En France, à l'horizon 2000 et au-delà, les besoins de renouvellement des flottes recouvrent des avions de combat très différents et aux missions très variées :

- dans l'Armée de l'Air française :
    - MIRAGE IIIE et Jaguar (attaque au sol)
    - mirage F1C (défense aérienne)
- dans l'Aéronautique Navale Française :
    - Crusader (défense de la flotte)
    - Etendard IVP (reconnaissance)

Les versions export de ces avions ainsi que leur concurrent ont été prises en compte dans l'analyse prospective.

L'Etat Français a décidé de lancer un avion polyvalent capable de subvenir à ces différents besoins : le Rafale. Les principales caractéristiques opérationnelles de cet avion biréacteur de la classe des 9 tonnes (masse à vide) sont :

- 3 versions principales ayant un haut degré de communauté de système et de cellule : biplace air, monoplace mer, monoplace air.
- une manoeuvrabilité et un rayon d'action très importants
- un radar aux fonctions air/air et air/sol simultanées, un système d'autoprotection très intégré
- des armements de la dernière génération : le Mica (air/air) et l'Apache (Air/sol).

4 avions ont été commandés en 1988 au titre du développement

- le monoplace air C01 affecté au développement des systèmes de base et du moteur : il totalise actuellement plus de 200 vols.
- le monoplace mer M01 chargé des essais de compatibilité sur porte-avions.
- le biplace B01 et monoplace mer M02, outre leur spécificité permettront d'asurer la mise au point en vol du système d'armes.

3 défis caractérisent ce programme :

- Le défi technique : 3 versions simultanées, un système d'armes entièrement nouveau.
- Le défi calendaire : les besoins de l'Aéronavale sont incontournables pour la succession des Crusader.
- Le défi financier : En ces temps économiquement perturbés, le respect des coûts est le garant de la poursuite du programme.

La phase d'industrialisation du programme a été lancée en janvier 1993, le premier vol du premier avion de série est prévu en octobre 1996.

## 2.2 Ravitaillement en vol: objectifs, missions envisagées

L'Armée de l'Air a demandé que l'avion soit muni d'un système de ravitaillement en vol comportant un perche fixe amovible.

Cette spécification est conforme au concept d'un avion polyvalent, elle permet d'adapter l'avion au profil de sa mission, qui ne requiert pas systématiquement le besoin de ravitaillement en vol.

Elle permet aussi de définir une perche simple.

Les profils type de missions type exprimées par l' Etat-Major ont pour la plupart une caractéristique commune : un rayon d'action très important pour les missions air-sol, des temps d'attente très importants pour les missions air-air. Les spécifications des missions de convoyage sont devenues plus formalisées qu'auparavant, suite à l'évolution du contexte international.

Une démonstration de vol de convoyage de France jusqu'à Kourou (Guyane Française) a été récemment effectuée par 3 MIRAGE 2000 accompagnés par un avion ravitailleur KC135.

Pour l'Aéronavale, la système de ravitaillement est indissociable d'un avion embarqué. Pour des raisons de sécurité, les cycles de pontée et de recueil sont toujours réalisées en présence d'un avion ravitailleur, pour parer toute éventualité.

## 2.3 Avions ravitailleurs en service dans les Armées françaises

Le principal avion ravitailleur d'avions de combat en service dans l'AAF est le Boeing KC135-FR. Il est équipé à l'intrados du fuselage d'un kit de ravitaillement, dérivé du système de base de type réceptacle (boom receptacle) monté sur les KC 135 américains. Ce kit permet le ravitaillement des avions munis d'une perche équipée en extrêmité du matériel au standard US/MS 24356-1 type MA-2, conforme au STANAG 3447 annexe B (drogue/probe).

L'adaptation consiste en la mise en place à l'extrémité de la partie rétractable d'une tuyauterie souple relativement courte munie d'un coupling (type MS24355-1), partie femelle de l'extrêmité de perche. Ce coupling est entouré d'une partie conique dont les deux bases formés d'une armature en aluminium sont reliées par des bandes de caoutchouc:le panier. Ce système permet :

- de stabiliser la tuyauterie souple et le coupling pendant le vol

- de faciliter l'approche et le contact lors du ravitaillement. Cette approche est essentiellement contrôlée par le pilote du ravitaillé.

La tuyauterie souple absorbe les mouvements relatifs entre le ravitailleur et le ravitaillé accouplé. A ce moment, la pointe de l'avion ravitaillé est à environ 20 mètres de l'articulation du mât du ravitailleur.

Le KC135 F est théoriquement capable de débiter 2260 litres de carburant sous une pression de 3,5 bars conformément à la norme US MIL-F-38363-B.

A partir de 1993, certains KC-135FR vont être rétrofités de pods Flight Refuelling MK 32B, installés en extrêmité de chaque voilure, rendant ainsi ces avions capables de ravitailler 3 avions à la fois ou de pouvoir ravitailler les boeings AWACS en rééquipant le dispositif sous fuselage du système standard (boom).

Ce pod déroule environ 15 mètres de tuyauterie souple pour ravitailler. Les performances attendues sont de l'ordre de 750 l/mn sous 3,5 bars de pression.

Les Super-Etendards ravitailleurs de l'Aéronavale sont équipés d'une nacelle de ravitaillement en vol de type Douglas D827-B, fabriquée sous licence par la société Intertechnique. Ils effectuent l'ensemble des missions de ravitaillement sur les porte-avions actuels. La nacelle est pourvue d'une tuyauterie souple déroulable d'environ 15 mètres de long. Les caractéristiques des couplings en extremité sont aussi conformes au STANAG 3447 annexe B, ce qui préserve une interopérabilité entre les Armées.

Les performances en débit sont de l'ordre de 750/mn sous une pression moyenne de 3,5 bars.

Le domaine de ravitaillement du KC135 FR s'étend de 200 kt à 325 kt à des hautes altitudes; celui du Super-Etendard est limité à 280 kt maxi (par la nacelle) mais n'a pas de contrainte en altitude.

## CONCEPTION DE LA PLATE-FORME

### 3.1 Généralités

Une conception réussie d'un circuit de ce type repose aujourd' hui sur deux facteurs:

- la rigueur de définition, l' examen des réglementations françaises, STANAG, ou américaines; en l' occurence,la standardisation des matériels utilisés pour le ravitaillement est basée sur les normes américaines.

- le retour d' expérience, qu'on peut aussi nommer savoir-faire, ou comment apprécier la limitation des règles. Avec l' évolution des technologies, la sophistication des moyens de calcul, et corrélativement les demandes de performances de plus en plus exigeantes, les règles sont souvent poussées à leur limite; elles sont d'ailleurs les premières à le reconnaitre, leur dernière édition ressemble plutôt à des recommandations. Il importe alors au concepteur de justifier les solutions qu' il a prises devant ses spécificateurs.

La conception du système de ravitaillement en vol sur RAFALE a respecté cette démarche que les exemples qui suivent vont essayer d'illustrer.

### 3.2 Perche de ravitaillement : critères d'implantation

#### 3.2.1 De quel côté ?

Sur les avions de combat français, le ravitaillement en vol est effectué au moyen d'une perche externe .

L'implantation de cette dernière vérifie les contraintes d'encombrement du panier de ravitaillement spécifiées dans le STANAG 3447.

Sur le démonstrateur Rafale A, l'expérience a montré que les dérogations n'étaient pas admises: une sonde de pression d'essais a été arrachée 2 fois lors de la première campagne en vol, car son installation ne respectait pas le gabarit recommandé.

Le choix du coté de la perche ne fait par contre l'objet d'aucune contrainte incontournable. Les avions Dassault, prototypes ou de série, ont la perche implantée à droite, gauche, parfois même au centre, ce qui simplifie le débat !

Le Rafale était initialement doté d'une perche à gauche, tradition propre à un biréacteur selon Dassault. En effet, une explication possible s'appuie sur le fait que l'approche, puis la tenue de la position de l'avion ravitaillé est contrôlée en vitesse par le régime moteur ; le pilote maitrise plus facilement l'avion avec la manette des gaz du moteur droit plus accessible ; le moteur gauche à une position de régime intermédiaire fixe est moins susceptible à une ingestion accidentelle de carburant lors des phases de connexion/déconnexion.

Pour une perche fixe, la position droite est préférée ; elle permet de dégager la visibilité du pilote en approche terrain lors du dernier virage qui a lieu le plus souvent sur la gauche.

Sur Rafale, la manette des gaz est unique pour les 2 moteurs ; d'autre part, le temps de réponse et la fourchette de variation de poussée de ces derniers sont tels que les principes de pilotage anciens sont à réviser.

Par contre, les pilotes de l'AAF, entrainés à former "la bouche à droite" derrière le Boeing KC135 sur les avions en service tels que les Mirage F1 ou Mirage 2000 ont demandé à revenir à une perche implantée à droite sur Rafale, une des premières modifications adoptées lors du développement du programme.

#### 3.2.2 Perche fixe ou rétractable ?

Sur Rafale C, la perche est fixe et amovible ; elle peut être installée suivant mission, au même titre que pylônes ou emports .

Pour la version Rafale M, le besoin est différent : la perche est un élément indispensable pour toutes les missions de l'avion évoluant à partir du Porte-avions .

Conformément à ce besoin différent, et sans pénaliser a priori l'avion vis à vis d'autres critères, la perche du Rafale M était initialement rétractable et implantée dans la partie avant droite du baquet pilote, communément appelée "bajoue". La rétraction était commandée par un vérin hydraulique relié à l'un des 2 circuits hydrauliques de l'avion. La sortie pouvait être effectuée en secours sur le 2ème circuit.

A la suite des premiers maquettages ayant pour but de présenter l'architecture interne des avions aux Services Officiels, une analyse de la valeur a été lancée à la demande de l'Aéronavale dans un souci de rapprocher la définition des cellules et par là de réduire les coûts. Cette analyse a permis l' adoption de la perche fixe sur Rafale M, qui a même été installée en rattrapage sur le premier avion de développement, Rafale M01, en cours de fabrication à l'époque.

Le couple d'évaluation coût/performance a été déterminant ; les paramètres les plus importants ont été : masse, aménagement, traînée, fiabilité et maintenance, sécurité, utilisation opérationnelle, discrétion.

Ces aspects de définition qui n'avaient pas été abordés finement dans la phase initiale de développement ont été examinés et optimisés dans le cadre de cette étude.

### 3.2.3 Critères de positionnement de la perche

Outre le côté, le critère de positionnement de la perche et de son extrêmité est un souci qui intervient dans la définition initiale de la cabine. Il fait beaucoup appel à l'expérience des utilisateurs et du constructeur.

Le positionnement de l'extrémité de perche est primordial surtout dans le cas d'une perche fixe, il doit satisfaire 2 exigences apparemment contradictoires :

- être bien visible lors de la phase de ravitaillement,
- se faire "oublier" pendant les autres phases du vol. il est préférable que, vu du pilote, le gland soit situé sous l'horizon pendant les vols stabilisés,

Sur Rafale, la perche et son mât ont été placés de telle façon qu'ils se retrouvent masqués par le montant du viseur tête haute. Cette position permet d'éviter un trouble binoculaire en bordure de la glace du viseur holographique où sont présentées des symbologies collimatées à l'infini.

**On ne peut définir la position de l' extrêmité de la perche sans vérifier qu' elle est compatible de l'emploi du phare de ravitaillement interne, dont l' installation est très contraignante.**

En effet, lors du ravitaillement derrière KC135, l'Opérateur Ravitailleur en Vol, qui se trouve dans le ravitailleur, a un rôle primordial car il contrôle la manoeuvre d'approche et la sécurité du transfert. De nuit, cette opération est rendue encore plus délicate et il lui faut la meilleure visibilité possible sans être pour autant aveuglé.

De son côté, le pilote doit pouvoir observer le panier éclairé pendant la phase d'approche terminale ainsi que l'extrêmité de la perche, sans subir aucun désagrément provenant d'un reflet de lumière parasite en cabine ou d'un éclairage indiscret.

Sur Rafale, le phare de ravitaillement est installé en "bajoue" droite au niveau du pilote ; il est rétractable sous l'action d'un vérin électrique. Son allumage est commandé par le pilote au moyen d'une commande située sur la manette des gaz.

## 3.3 Technologie, structure

### 3.3.1 Dimensionnement de la perche

Le dimensionnement de la perche fixe et de son attache sur le fuselage est déterminé par 2 principaux critères

- La tenue à l'enveloppe des efforts lors du ravitaillement.
- La tenue à l'engagement dans la barrière d'arrêt détresse.

1/ La détermination des efforts engendrés par le panier lors du ravitaillement repose sur les valeurs preconisées pour l'utilisation derrière Boeing KC 135.

Les valeurs ont néanmoins été périodiquement réévaluées à chaque génération nouvelle d'avion suite à des campagnes d'essais en vol et à des relevés et expertises d'incidents recueillis chez les utilisateurs.

Les 2 cas majorants en effort sont rencontrés :

- à l'accrochage du panier, correspondant à un choc longitudinal pur.
- au découplage en fin de transfert, où l'effort longitudinal plus faible est combiné à un choc radial provoqué par la déconnexion.

Le dimensionnement du fusible, situé à la liaison entre le gland en extremité et la perche est le point sensible, car le dimensionnement du reste de la structure du mât et du fuselage s'en déduit par l'empilage des coefficients de marge adéquats.

2/ Par rapport à la forme et en fonction de la proéminence de la perche, le nombre de brins ramassés par celle-ci lors d'un arrêt détresse et la décélération attendue permettent de déterminer quelle doit être l' effort que doit endurer le pied de perche..

### 3.3.2 Matériau

La perche du Rafale était conçue initialement en acier 15CDV6, comme celles des avions Dassault précédents. Plusieurs raisons ont été déterminantes pour retenir finalement le titane TA6V pour le Rafale:

- l'expérience sur les avions précédents a montré que les tubes de perche ont rencontré des problèmes de fatigue dus à des utilisations plus fréquentes qu'estimées initialement, fatigue causée par les chocs répétés du panier. L'utilisation systématique de la perche sur la version Marine a conduit à remettre en cause l'acier comme matériau de base initial.

- les progrès techniques des fondeurs qui ont permis d' obtenir des ébauches coulées en TA6V avec des caractéristiques mécaniques très bonnes et homogènes; outre les contraintes admissibles maintenant comparables entre acier et titane, le titane présente une résilience aux basses températures meilleure que l'acier, c'est à dire une caractéristique de comportement au choc plus élevée. Ce gain de santé métallurgique permettra de résoudre une bonne partie des phénomènes de fatigue thermique rencontrés avec le matériau précédent.

- Le gain de masse est de l'ordre de 30% sur la masse totale de la perche , bien que plus chère en fabrication, la perche en technologie TA6V a beaucoup d'avantages : le surcoût est compensé par la réduction très importante de cycle en fabrication, liée au procédé utilisé.

La seule incertitude qui restait à vérifier en vol concernait la souplesse plus grande attendue de cette perche, dûe à l'allongement relatif plus fort du titane sous une même contrainte; des calculs de comportement aéroélastique ont été effectués au moyen d' ELFINI, logiciel de calcul structure développé par Dassault, afin de mettre en évidence d'éventuelles interactions entre les modes propres de la perche et ceux du fuselage ( flutter) . Aucun phénomène rédhibitoire n'a été décelé.

Lors des essais en vol, un buffeting transversal de la perche a été observé pour des vitesses transsoniques, basse altitude et fort facteur de charge. Suite à cette constatation, des accéléromètres ont été implantés le long du mât de perche pour rechercher ces modes de couplage et les comparer à ceux issus du calcul.

Après dépouillement des essais, les conditions d' ancrage en partie inférieure ont été incriminées. Les renforcements locaux côté structure appliqués sur les avions suivants devraient résoudre le problème ; le phénomène n'offre pas de risque de divergence de type explosif, mais il est jugé gênant, car vraiment trop visible par le pilote !

### 3.3.3 Description - fabrication

La perche est une pièce monobloc composée de la partie externe, mât et pièce d'accrochage du gland en extremité, et d'une partie interne qui s' encastre dans la structure du fuselage au moyen d'une chape et d'un doigt de centrage; ce principe d'accrochage simple est conçu pour faciliter les opérations de pose-dépose.

Dans sa définition actuelle, la perche est monobloc et composée de 3 éléments, ébauches coulées et creuses, réusinés localement avant d'être soudés entre eux (procédé TIG : Tungsten Inert Gas).

L'apport de CATIA, logiciel de CFAO utilisé chez Dassault Aviation, a été déterminant pour la réalisation des ébauches coulées. Le procédé de cire perdue utilisé a permis, en exploitant directement les modèles pour la commande numérique, de respecter des tolérances de géométrie et d'interchangeabilité jamais obtenues auparavant pour une telle pièce .

Pour l'exemple, les effets de retrait prévisibles en fabrication, dûs aux déformations thermiques subies par le matériau lors de la coulée (effet d'homothétie), ont été corrigés dès l' usinage des moules, à partir du modèle de conception initiale.

## 3.4 Aérodynamique

### 3.4.1 Hypothèse de travail

Les formes de la perche de ravitaillement ont été déterminées à l' issue d' une phase de définition qui a mis en oeuvre des moyens d'étude théoriques et expérimentaux.

Cette approche mixte est assez représentative de la façon de Dassault-Aviation d' aborder ces problèmes typiques de conception.

Dans le cadre de contraintes géométriques nombreuses :

- position et forme du gland d'extremité

- gabarit d' encombrement du panier

- point d' ancrage sur la structure

- section minimale du mât ( pour limiter les pertes de charge lors du transfert ),

les études aérodynamiques avaient pour objectif de réduire les perturbations de l' écoulement d'air introduites par la perche à un niveau acceptable tout en gardant une géométrie simple pour la fabrication.

Les perturbations aérodynamiques principalement étudiées concernent la traînée supplémentaire dûe à la perche et les interactions avec l' écoulement à l' entrée d' air moteur.

L' expérience de Dassault de ce type de perche, ainsi que des essais en soufflerie préliminaires, ont montré que les limites de fonctionnement de l' entrée d' air en supersonique (limites dûes au phénomène de "buzz" ) sont sensibles à l'installation d' une perche de ravitaillement. Dans le cas d'emport d' un réservoir ventral, des interactions néfastes entre perche et réservoir dégradaient ces limites.

### 3.4.2 Déroulement des études

Compte tenu des contraintes géométriques imposées pour le mât de perche, les paramètres disponibles pour réaliser le bon compromis sont la loi de vrillage et le profil.

Les outils numériques ont permis d' établir les lois de vrillage adaptées aux conditions de vol critiques pour l' entrée d' air. Ces outils théoriques ont également permis d' évaluer la traînée des différentes formes de perche définies en associant les lois de vrillage et les différentes formes de profil.

Les principaux codes utilisés, développés par la Direction des Etudes Avancées, ont été :

- le code AURORE en supersonique, utilisant la méthode des singularités; il a servi en début d' étude à l' identification des principaux effets, puis ultérieurement à des balayages des solutions potentielles sur différent cas de vol (Mach, incidence , dérapage)
- le code EULER , qui s'appuie sur la résolution des équations tridimensionnelle d' Euler en fluide parfait ; il a permis de mener les analyses fines.

Les essais d' entrée d' air en soufflerie ont utilisé une maquette à l' échelle 1/4 , équipée de prises de pression instationnaires ; ils se sont déroulés dans l soufflerie de S2 Modane de l' ONERA.

Ces essais ont donné les limites de " buzz" et les critères de compatibilité entrée d' air / moteur pour l' ensemble du domaine de vol supersonique. Les différentes configurations d' emports externes ont été étudiées :

- perche + réservoir sous fuselage
- perche + MICA , etc...

Les résultats d' essais ont permis de tirer les lois de vrillage et les formes de profil les plus efficaces vis à vis de ces critères : la forme de perche retenue rejette les limites de " buzz " hors du domaine de vol, objectif pour toutes des configurations envisagées en supersonique.

### 3.4.3 Bilan

Les études aérodynamiques utilisant les outils théoriques et les essais en soufflerie ont permis de définir une forme de perche de ravitaillement qui :

- respecte les contraintes géométriques imposées par l' architecture avion et le transfert de carburant,
- représente un supplément de traînée qui a été jugée acceptable ( 1.5 % de la traînée avion lisse en palier supersonique )
- n' introduit pas de limitation du domaine de vol par rapport à celui de l' avion sans perche
- reste de géométrie simple ( section de profil biconvexe, vrillage de mât linéaire ).

Aujourd' hui, le comportement constaté en vol sur Rafale n' a pas remis en cause le choix effectué

### 3.5 Discrétion

La forme de la perche fixe saillante peut contraster avec les formes relativement adoucies du Rafale qui font partie des mesures immédiatement visibles réalisées pour limiter la signature électromagnétique de l'avion.

Sur ce point, il est nécessaire de mentionner l'objectif du Rafale en vulnérabilité : dans un souci de cohérence lié à la polyvalence de ses missions futures, le Rafale est un avion de combat discret mais non furtif.

L' influence de la perche sur la signature de l'avion a été analysée et traitée comme l'est, par exemple, celle des points d'emports. Après traitement, le niveau relatif de la perche sur le bilan total a été mesuré et jugé acceptable par rapport aux objectifs globaux.

Pour l'anecdote, l'extrémité métallique du gland de perche est de forme hémisphérique ; elle peut constituer une bonne référence pour l'étalonnage des moyens de mesure de signature !

## 4. CONCEPTION DU CIRCUIT CARBURANT

### 4.1 Architecture des réservoirs

La capacité interne du Rafale lui confère déjà une autonomie propre importante.

Les réservoirs internes du Rafale sont subdivisés en 2 sous-ensembles gauche et droit, de capacité sensiblement identique et affectés respectivement aux réacteurs gauche et droit.

On distingue pour chaque sous-ensemble :

- un réservoir avant centré à l'avant du fuselage,
- un réservoir structural de voilure constitué par le caisson central,
- un réservoir "nourrice" en fuselage, situé en amont de la tuyauterie d'alimentation réacteur.

Le caisson de dérive forme aussi un réservoir de carburant ; il se déverse simultanément dans les 2 nourrices.

La quantité de carburant interne est supérieure à 6000 l. L'avion est capable de 5 réservoirs externes largables :

- un réservoir sous fuselage de 2000 l de capacité,
- deux réservoirs par demi-voilure, de 2000 l de capacité au point 1 d'emport de charge, de 1250 l au point 2.

La capacité maximale d'emports en carburant du Rafale est supérieure à 14500 l, ce qui est relativement important pour un avion de cette classe.

### 4.2 Circuit de transfert-remplissage

#### 4.2.1 Description résumée

Le transfert des réservoirs est effectué principalement par pression d'air généré par un circuit situé en dérivation du circuit de conditionnement d'air.

Le remplissage au sol s'effectue par un coupleur unique conforme au STANAG 3105, situé à gauche de l'avion.

En aval, les tuyauteries du circuit de remplissage vont distribuer tous les réservoirs de l'avion. Pour les réservoirs externes, de voilure et de dérive, ces tuyauteries sont parfois communes avec celles de transfert, dans un souci de simplification et de gain de masse.

La tuyauterie de ravitaillement en vol en aval de la perche vient se brancher sur la ligne principale du circuit de remplissage sol.

Le dimensionnement du circuit en pression est conforme aux normes US en vigueur, avec quelques adaptations pour être compatible des normes de dimensionnement françaises appliquées sur l'avion.

Le circuit de remplissage en vol est dimensionné pour une pression nominale de 3.5 bar.

Les phénomènes de surpression sont traités avec soin: ils peuvent dépasser de plusieurs fois la pression nominale, cas qui engagent la sécurité de l'avion ; ils se produisent en particulier lors de la fermeture et l'ouverture du circuit, opération parfois normale ou d'autres fois aléatoires comme un décrochage accidentel du panier lors du transfert.

Les marges de dimensionnement sont respectées et les essais d'ancrage des tuyauteries sont réalisés avec rigueur

#### 4.2.2 Critères importants

La fonction ravitaillement en vol doit satisfaire en priorité:

- La sécurité :

  Le transfert et le remplissage ne nécessitent aucune intervention d'un calculateur ni du pilote. En particulier, le centrage est peu sensible à ces opérations.

  La sécurisation des fonctions est d'un ordre supérieur à 2 pour les pannes dites catastrophiques pour l'avion.

- Les performances :

  Le remplissage du carburant s'effectue simultanément dans les différents réservoirs.

  Les performances en temps de remplissage sont tributaires des perte de charges dans les lignes; ces pertes de charge partielles doivent évidemment être les plus faibles, mais elles doivent aussi être cohérentes entre elles, afin que les fins de remplissage intermédiaires ne génèrent pas de déséquilibre.

### 4.3 Commandes et contrôles pilote

La mise en configuration des réservoirs pour le remplissage en vol, quand le pilote bascule l'interrupteur de commande situé en banquette, se limite à l'ouverture des vannes de remplissage des groupes. Pendant le remplissage, seul le transfert des réservoirs externes sur la ligne commune est arrêté, il n'est pas perturbé vers les nourrices ni les moteurs.

Lors du basculement de l'interrupteur ravitaillement sur manche, la VTL droite présente automatiquement la page CARBURANT :

Celle-ci présente les informations:

- du niveau des réservoirs internes ou externes jaugés,
- de la quantité de carburant délivrée, dont la croissance pendant le plein peut etre surveillée.

Le bon déroulement du ravitaillement est vérifié par les informations de jaugeage. En fin de ravitaillement, le pilote met à jour la quantité carburant restante, soit en la recalant sur la quantité jaugée, soit en renseignant et validant la quantité délivrée, information transmise par le ravitailleur.

### 4.4 Performances : objectifs, essais réalisés

Les essais de performances de transfert en vol ont été réalisés derrière Boeing KC135FR, Rafale en configuration lisse uniquement.

Pendant ces essais, la pression de ravitaillement fournie par le KC135 avec 2 ou 4 pompes est restée inférieure à la pression nominale de 3,5 bar. Au fur et à mesure de la diminution de la perméabilité du circuit (fermeture successive des diverses vannes), la pression de ravitaillement augmente. A la fin du remplissage, pour un débit nul, la pression maxi a atteint environ 6 bar. Même après recalage des pressions initiales, les valeurs restent inférieures à la pression d'épreuve de 12,5 bar.

Après correction des pressions initiales, les valeurs de débit moyen sont largement au-dessus des exigences de la norme MIL-F-38363B. En partant de 10% de carburant interne restant, et pour des conditions nominales, la durée de remplissage en vol de l' avion en configuration lisse est inférieure à 4 minutes.

# 5. ESSAIS EN VOL

## 5.1 Système de commandes de vol

Le ravitaillement en vol est un rendez-vous essentiel des Essais en Vol car il permet de constater la pilotabilité de l'appareil et la validité des premiers réglages de commandes de vol. Le système de Commandes de Vol est un système complexe dont la réussite conditionne souvent celle de tout le programme de l' avion.

Le Rafale est, dans la lignée progressive des Dassault, un avion Delta-canard dont rapport poussée/poids de l'ordre de 1,2 à la masse de combat, lui confère une très grande manoeuvrabilité, un des éléments clés des fiches programme des Etats-majors.

Son équilibre est assuré au moyen de 11 gouvernes, dont le pilotage est effectué par les commandes de vol numériques. Certains modes utilisent les réacteurs comme 2 gouvernes supplémentaires.

L'architecture du système de Commandes de Vol du Rafale est basée sur :

- un mode principal assuré par 3 calculateurs numériques agissant sur l'ensemble des gouvernes de l'avion,
- un mode secours analogique qui agit sur les gouvernes principales de l'avion (élevons et drapeau).

Comme tout système complexe, il se reconfigure automatiquement, après apparition de panne double dans divers modes dégradés. Le mode secours analogique, peut se déclencher automatiquement dans les cas critiques, ou par sélection du pilote.

Les modes dégradés interessant la pilotabilité en ravitaillement correspondent à :

- la double panne d'anénométrie établie (gains forfaitaires)
- la double panne de numérique (pilotage en secours analogique)

Pour assurer la fonction ravitaillement avec un bon taux de réussite, il importe de réaliser des essais en vol avec des procédures spécifiques afin de :

- régler et mettre au point les lois de pilotage dans la configuration nominale, et ses différents états possibles,
- vérifier et régler les modes dégradés en les forçant pendant les essais.

Cette brève description de l'architecture des CDVE du Rafale montre qu'il faut étudier et pouvoir évaluer en vol un nombre important de configurations afin de valider toute fonction l'impliquant fortement.

## 5.2 Concepts nouveaux sur Rafale

Dans de nombreux domaines, le Rafale a franchi des étapes technologiques importantes par rapport au Mirage 2000, dernier avion de combat en utilisation opérationnelle de Dassault; dans celui des commandes de vol et du pilotage en particulier, certains concepts, tout en s' inscrivant dans la continuité qui font la réputation de Dassault, sont très novateurs:

- Le concept des commandes de vol numériques déjà évoqué a pour but d'assurer un niveau de sécurité en vol élevé. Il fallait vérifier, dans toutes les reconfigurations possibles des commandes de vol, l'aptitude de l'avion au ravitaillement.
- L'anémobaroclinométrie est un capteur essentiel pour les commandes de vol; celui-ci repose sur Rafale sur un système à base de 4 sondes multifonctions implantées dans la partie inférieure du fuselage avant. Leur sensibilité éventuelle aux effets de turbulence, de sillage était un point majeur à vérifier en vol.
- Le pilotage numérique des moteurs (calculateurs FADEC), est radicalement nouveau ; couplé à un temps de réponse extrêmement rapide , ces deux effets devaient etre évalués dans ce cas de pilotage fin, demandant souvent de jouer sur les gaz.
- Le concept de pilotage par manche et manette implantés latéralement apporte un confort unaninement apprécié par les pilotes. Le débattement du manche de faible amplitude était *un point important à valider.*

## 5.3 Réalisation des essais

### 5.3.1 Déroulement des essais

Les premiers essais de ravitaillement ont eu lieu dès le début du programme. En effet, cette vérification du comportement de l'avion est un des rendez-vous majeurs dans la mise au point de la plate forme. Il a été un des sujets principaux de la première campagne d'évaluation officielle du Rafale C01.

Le Rafale C01 a effectué son premier vol le 19 mai 1991 à la base d' essais d' Istres; son role dans le développement du programme est :

- d'identifier en vol la plateforme ; aérodynamique, performances, qualités de vol
- de mettre au point les systèmes de base : moteur, systèmes de servitude, l' ergonomie du poste de pilotage.

Les commentaires sur l'évaluation sont issus principalement de cette campagne effectuée par de nombreux pilotes , dont les opérationnels.

Ils incorporent aussi quelques analyses effectuées lors d'une campagne d'esssais similaire réalisée en 1989 sur le démonstrateur Rafale A. Cet avion démonstrateur a permis, en avance sur le programme Rafale, de valider certains concepts nouveaux relatifs au pilotage et développés depuis le Mirage 2000, dernier avion de combat en utilisation opérationnelle.

D' autres essais en vol ponctuels ont lieu par la suite, permettant de valider les améliorations successives.

### 5.3.2 Diverses configurations testées

Dans le mode principal, divers réglages des lois d' ordre de pilotage fonction du débattement du manche ont été testés , en profondeur et en gauchissement. Toutefois, c' est surtout en profondeur , sensible pour la précision de l'approche qu' ont été testées diverses lois adoucissant les effets autour de la position neutre du manche ( dites lois d' amédée ).

Ces réglages ont subi un passage préalable sur le Banc de Simulation Globale, simulateur de pilotage temps réel, mais leur mise au point ne pouvait être testée que sur avion , pour vérifier ce type de comportement en vol relatif entre 2 avions ayant des caractéristiques dynamiques en vol très différentes.

Sur avion, les lois de pilotage sont modifiables en vol grâce à un dispositif d' installation d' essais commandable en cabine, ce qui a parmis de comparer différents types de réglage pour des conditions de vol identiques et avec le même pilote.

Bien entendu, les modes dégradés ont été testés, afin de vérifier leur pilotabilité et d' y effectuer les réglages de mise au point pour la fonction ravitaillement.

### 5.3.3 Influence du type des avions ravitailleurs

Les principes d'approche et de tenue de l'avion sont très différents suivant les types d'avion ravitailleurs.

Le Super-Etendard dispose d'un dispositif de ravitaillement avec nacelle Douglas composée d'un long tuyau déroulable et d'un panier souple. L'ensemble est très sensible au champ aérodynamique de l'avion ravitaillé en rapprochement, ce qui provoque des mouvements nuisibles du panier.

En plus de son effet sur le panier, le souffle du moteur du Super-Etendard peut aussi perturber dissymétriquement le ravitaillé en approche finale.

Par contre, une fois le contact réalisé, le pilote n'a pas à tenir sa place avec une grande précision, le tuyau rétractable permettant un certain mouvement relatif entre les deux avions.

Le KC-135, au contraire est muni d'un mât rigide raccordé à un petit tuyau souple au bout duquel le panier n'a pas une grande liberté de mouvement.

La mise en contact s'en trouve facilitée mais ce dispositif ne tolère pas de variations d'écartement entre les deux avions. La technique qui consiste à faire décrire une boucle au tuyau souple permet une petite tolérance avec mouvements relatifs. La phase de ravitaillement proprement dite nécessite donc un pilotage plus fin derrière un KC 135 que derrière un Super-Etendard ; contrairement à la mise en contact, qui est facilitée par un dispositif rigide moins sensible au champ aérodynamique.

Cette tolérance de mouvement relative est assez limitée et les zones conseillées ont été définies et par le constructeur de la nacelle du KC135 et par les utilisateurs suite à leur expérience sur les avions précédents.

### 5.3.4 Résultats - techniques de pilotage utilisées

9 pilotes ont effectué des essais de ravitaillement en vol sur Rafale A ou sur Rafale C01 au cours des campagnes.

Suivant leur origine, Armée de l'Air ou Aéronavale, les techniques utilisées par les pilotes ont été parfois très différentes, ce qui démontre que le type d' avion ravitailleur est prépondérant. Les enseignements les plus caractéristiques sont résumés ci-après :

- en approche, la technique qui consiste à piloter l'avion par rapport au panier et non par rapport à une référence prise sur l'avion ravitailleur n' est pas la plus appropriée. En phase finale, le pilote devient souvent trop fébrile sur le manche.

- une approche au panier à vitesse relative trop faible n'est pas bonne, car elle laisse au panier le temps de tourner (surtout derrière le Super-Etendard),

- en approche, il faut rechercher le contact dans la partie inférieure du panier car le choc déstabilise moins aérodynamiquement l'ensemble flexible + panier.

- le palonnier a été très peu utilisé par les pilotes, et s'il l'a été, son apport n'a pas été très significatif.

- Les excellents temps de réponse moteur ont surpris plus d'un pilote dans les premiers temps; après une rapide acclimatation, ils furent un atout essentiel dans les phases d'engagement, permettant de doser précisément l'écartement par rapport au ravitailleur. Les réserves initiales quant à la maîtrise correcte et simultanée de la poussée des 2 moteurs ont été levés grâce à la facilité de contrôle de la poussée par la manette. Sur les avions de la génération précédente, les pilotes adoptaient une conduite des moteurs beaucoup plus prédictive. Sur Rafale, les pilotes envisagent de se servir systématiquement des moteurs pour la tenue de vitesse et pour la phase de séparation du panier, de préférence à la fonction aérofreins.

### 5.3.5 Bilan des essais réalisés

Le confort d'utilisation a été apprécié et le ravitaillement en mode normal des commandes de vol a été jugé très sain.

Suite aux balayages des différents réglages, l' optimisation de celui de la loi d' ordre manche a pu être effectuée; elle sera intégrée complètement lors des futures étapes de développement du système de commandes de vol.

Coté capteurs, le fonctionnement de l'anémométrie n'a causé aucun souci. Les mouvements du panier à l'approche perturbent brièvement le fonctionnement de quelques sondes, mais sans conséquence durable. Aucun effet de sillage dû au ravitailleur n'a été ressenti durablement.

Le ravitaillement dens l'ensemble des modes dégradés testés a été jugé faisable, plus fatigant derrière KC135. En particulier, le pilotage en secours analogique s'est avéré correct, un peu plus fatigant derrière KC 135.

En résumé, pour tous les pilotes et en y incluant leur phase d' apprentissage du pilotage sur Rafale ainsi que tous les réglages qui ont pu être testés, les taux de réussite à l' engagement et à la tenue du ravitaillement ont dépassé largement 80 % dans le mode normal et ses sous configurations.Dans les modes dégradés, ce taux de réussite est quasiment aussi élevé.

Au stade initial du développement, ces résultats ont été jugés excellents, une telle probabilité de succès n' ayant jamais été atteinte aussi tôt sur les programmes précédents.

## 6. CONCLUSION

Les essais de ravitaillement sur Rafale C01 qui ont eu lieu en configuration lisse ont permis de vérifier la conformité de l'appareil à ses spécifications :pilotage, fonctions, systèmes, performances, et d'identifier les points perfectibles.

Outre le parcours d' optimisation prévu, pour le ravitaillement en vol, il reste encore diverses configurations à vérifier en essais sur avions, au sol et en vol .

Les étapes suivantes sont prévues dans le calendrier général des essais:

- ravitaillement en vol avion avec réservoirs externes

- ravitaillement de nuit

La version Rafale M est capable de la fonction ravitailleur. Cette fonction n' est pas prévue dans le premier standard opérationnel livré à l'Aéronavale en 1997 sur les porte-avions actuels. Elle sera intégrée après la mise en service du Porte-Avions Charles de Gaulle, prévue pour 1998.

# FUTURE TANKER CONSIDERATIONS AND REQUIREMENTS

by

**Lavon Jordan**
Frontier Technology, Inc.
4141 Colonel Glenn Highway, Suite 140
Beavercreek, Ohio 45431 USA

**Michael Krimmer, Major U.S. Air Force**
ASC/SDCA Building 16
Wright-Patterson AFB, Ohio 45433-6503 USA

## BACKGROUND

Starting seven years ago, the USAF Aeronautical Systems Center began analyzing future tanker system requirements and developing plans for satisfying these requirements. As shown in Figure 1, Frontier Technology, Inc. (FTI) supported the USAF in four of the efforts. Boeing and Douglas did the other two studies. The first FTI contract identified future requirements, developed and evaluated solutions and wrote a strawman master plan for USAF review. The second study evaluated five commercial derivative tanker concepts and modifications to the KC-10 and KC-135 in six mission areas.

- USAF AERIAL REFUELING MASTER PLAN (FRONTIER) 1986-87
- USAF AERIAL REFUELING SYSTEM DEV. PLAN (FRONTIER) 1988-89
- USAF MULTI-POINT AIR REFUELING ANALYSIS (FRONTIER) 1990-91
- USAF KC-10 LOW ALTITUDE OPERATION (DOUGLAS) 1989-90
- USAF TANKER SURVIVABILITY EVALUATION (BOEING) 1991-92
- USAF KC-135R MPRS ALTERNATIVES (FRONTIER) 1993

FIGURE 1. AERONAUTICAL SYSTEMS CENTER SPONSORED AERIAL REFUELING ANALYSES

Frontier has completed one KC-135 multi-point analysis and is currently doing a second one. The completed effort determined: (1) the pros and cons of hose-drogue refueling and (2) the best fuel pumping rate for the KC-135 using two, wing air refueling pods. The current job involves a more in-depth, overall assessment of operational needs, concepts of operation and alternative wing pods. It emphasizes compatibility with Allied and U.S. Navy aircraft receivers.

Frontier Technology is presenting two related papers at this AGARD symposium (see Figure 2). This paper (#21) covers the rationale and requirements for multi-point refueling. It covers trends and future employment of aerial refueling tankers, as well as the increasing importance of interoperability.

In Frontier's second paper (#24), Mr. Copeland provides more details on KC-135 multi-point refueling, emphasizing performance and effectiveness improvements when refueling Allied and USN aircraft. This analysis focused on individual strike packages of varying size and overall theater results.

21. FUTURE TANKER CONSIDERATIONS AND REQUIREMENTS
    (1) DISCUSS TRENDS RELATED TO FUTURE USES OF TANKERS
    (2) EXPLAIN IMPORTANCE OF INTEROPERABILITY

24. BOOM-RECEPTACLE VERSUS HOSE-DROGUE METHODS
    (1) PRESENT ANALYSIS OF MULTI-POINT REFUELING
        - INDIVIDUAL STRIKE PACKAGES
        - OVERALL THEATER RESULTS
    (2) DISCUSS METHODOLOGY AND MEASURES OF MERIT

FIGURE 2. OVERVIEW
FRONTIER'S PRESENTATIONS IN SESSION IV

Throughout this paper, the term "multi-point refueling" is used. Figure 3 defines singlepoint and multi-point refueling. Currently the KC-135 is configured as a single point tanker.

*Presented at an AGARD Meeting on 'Recent Advances in Long Range and Long Endurance Operation of Aircraft', May 1993.*

Either the boom or boom-drogue adapter (BDA) kit is used. In the basic boom configuration, the KC-135 can refuel all USAF aircraft, a small fraction of international aircraft and no USN/USMC aircraft. Most allied and most USN/USMC aircraft are probe-equipped, and therefore are incompatible with the KC-135 boom. KC-135 tankers can be made compatible with probe-equipped aircraft by the installation of the boom-drogue adapter (BDA) kit on the tankers. BDA kits, however, have operational and safety concerns.

- SINGLE-POINT REFUELING
  TANKER WITH A SINGLE BOOM
  RECONFIGURATION ON THE
  GROUND WITH A SHORT HOSE AND DROGUE, CALLED A "BOOM DROGUE ADAPTER" (BDA) KIT

- MULTI-POINT REFUELING
  TANKER WITH A SINGLE BOOM

  +

  2 WING MOUNTED HOSE-DROGUE PODS

  +

  REFUELING RECEPTACLE ON RECEIVER

FIGURE 3. DEFINITIONS OF KEY TERMS FOR KC-135s

Multi-point refueling does not use the BDA kit. It is compatible with both probe-equipped and receptacle-equipped receivers. This is accomplished by adding two hose-drogue pods to either wing. The boom still can be used to refuel Allied and USAF aircraft as is currently done.

## TANKER USE IN DESERT SHIELD AND DESERT STORM

Figure 4 depicts the scope of tanker work performed by Frontier in air refueling. However, This paper focuses on only the areas enclosed in boxes. We emphasize KC-135 tanker use in Desert Shield/Desert Sorm, reviewing lessons learned and pointing out limitations for future consideration.

| THEATERS | TYPES OF RECEIVERS |
|---|---|
| • STRATEGIC-<br>- AIRLIFT<br>- NUCLEAR<br>• TACTICAL<br>- MID-EAST<br>- WESTERN PACIFIC<br>- CENTRAL EUROPE | • USAF<br>• USN & USMC<br>• ALLIED |
| **NEW U.S. TANKERS** | **KC-135 TANKER** |
| • SMALL (757-200)<br>• MEDIUM (767-200, LR, ER & L1011)<br>• LARGE (MD-11)<br>• JUMBO (747-400) | • KC-10, KC 130<br>• KC-135A, E, & R MODS<br>• TANKER-TO-TANKER REFUELING<br>• MULTI-POINT (BOOM & DROGUE) |

FIGURE 4. FRONTIER HAS EVALUATED A BROAD RANGE OF OPTIONS

Figure 5 presents the geographic layout of the primary elements in the Desert Storm scenario. Shown here are those elements relevant to the analysis of air refueling operations. These include air bases for the tactical aircraft and tanker aircraft, USN aircraft carrier locations in both the Red Sea and the Persian Gulf, and typical refueling tracks and orbits employed in Desert Storm. Also shown are representative target areas throughout Iraq and Kuwait. Actual deployments were somewhat different.

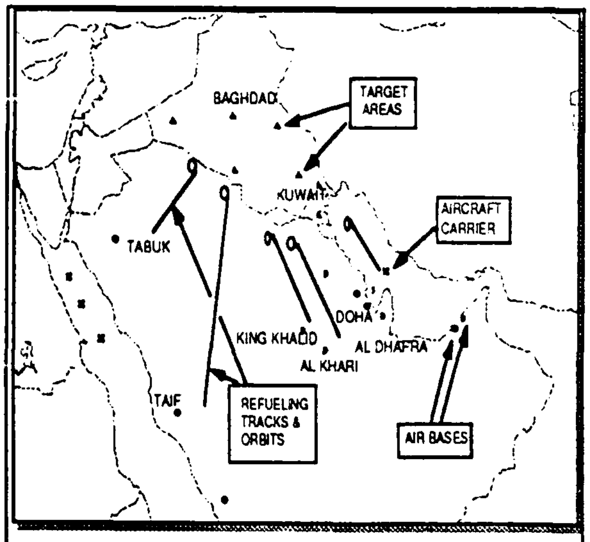



FIGURE 5. REGIONAL MAP FOR ANALYTICAL PURPOSES ONLY

As seen in Figure 6, airlift and tanker aircraft and crews were busy in Desert Shield/Desert Storm. If the U.S. had more airlift capability it would have been used. The Civil Reserve Air Fleet was activated for the first time. It played a crucial role. Gen. Fogelman, Chief of the Air Mobility Command, feels we will have even more dependency on CRAF in the future and is planning for it.

- DEPLOYMENT (KC-10 & KC-135)
  - 16,000 AIRLIFT MISSIONS
  - 500,000 METRIC TONS OF CARGO
  - 500,000 PASSENGERS
- EMPLOYMENT (MOSTLY KC-135)
  - 38,000 REFUELINGS
  - 270,000 METRIC TONS OF FUEL OFF LOADED

FIGURE 6. TANKER SUPPORT IN DESERT SHIELD/ DESERT STORM

In the deployment phase, primarily KC-10s refueled the airlifters. KC-135s refueled KC-10s. As we'll see on the next figure, KC-135s did 85% of the refuelings during the employment phase.

Figure 7 provides a breakout of the USAF's air refueling operations in support of Desert Storm (17 Jan to 28 Feb 1991). Also included are over 6,000 refuelings performed by KC-135E model tankers operated by the Air Force Reserve and Air National Guard. The pie chart on the left shows the distribution of refueling transactions by tanker type. The chart on the right shows the distribution of refuelings by receiver type. As can be seen, almost three quarters of the refuelings were in support of the Tactical Air Command, divided almost evenly among F-15, F-16, and other aircraft. The majority of the SAC refuelings were to support B-52 aircraft.

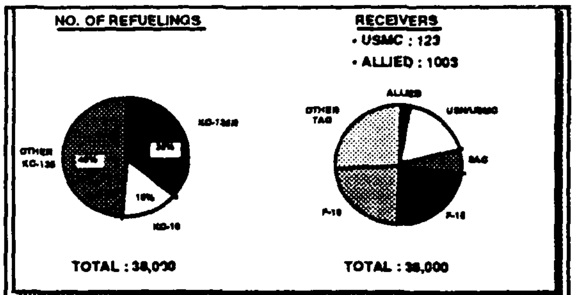



FIGURE 7. USAF REFUELING IN DESERT STORM

Note the comparatively low level of support provided to the USN/USMC and Allied air forces. Most USN/USMC and Allied aircraft are probe equipped, and therefore incompatible with KC-135 boom tankers. The USMC was very reluctant to use BDA equipped tankers, resulting in only 123 total refuelings provided to the USMC by the USAF. Many of the USN refuelings shown here were transfers of fuel from USAF tankers to USN KA-6 aircraft, which then transferred the fuel to USN strike aircraft. Allied and USMC aircraft were mostly supported with drogue equipped Allied tankers. It is unclear if additional Allied and/or USN/USMC strike sorties would have been flown had the USAF had more drogue equipped tankers.

## REFUELING OBSERVATIONS

The next three figures illustrate important factors which have been analyzed thoroughly and were substantiated by Desert Storm experience. Figure 8 shows that refueling requirements varies dramatically with time. During the employment phase, attacks are usually planned to occur in waves. Just prior to an attack, multiple strike packages require refueling to maximize their range and payload capabilities. By "topping-off" their fuel tanks, their flight profile can be planned to maximize weapon effectiveness and survivability (e.g., low altitude penetration). Timing is critical to ensure simultaneous penetration. This effect causes the highest peaks on the graph. As receivers return they sometimes need fuel to safely reach their bases. This effect causes the lower peaks.

(NOSEBOOM) ANGLE OF ATTACK (DEG)

FIGURE 15 - TRAILING EDGE FLAP POSITION VERSUS SCHEDULE DURING WIND-UP TURN



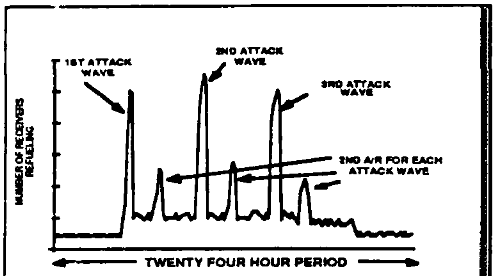



FIGURE 8. RECEIVER REFUELING ACTIVITY VARIES GREATLY WITH TIME

Offensive planners preferring to mass strike aircraft into large attack waves increases strike aircraft survivability by saturating the enemy air defenses (Fig 9). It also allows strike aircraft to provide mutual support to each other, such as fighter escort, electronic countermeasures, and defense suppression. Supporting large attack waves, however, stresses the air refueling capability. Wave attacks require numerous refuelings over a relatively short period of time. Since fighter aircraft require relatively small quantities of fuel per refueling, the problem confronting air refuelers is generally not in providing a sufficient quantity of fuel, but in providing sufficient offload points to allow all refuelings to be completed within the time constraints. Additionally, the large numbers of aircraft involved can present an airspace deconfliction problem. Even when enough tanker aircraft are available, it is often difficult to schedule them in the available airspace.

Therefore, we see that supporting wave attacks requires highly efficient tanker operations. In this case efficiency can be defined as "how many receivers each tanker can support in a given length of time." Increasing efficiency will allow more strike aircraft to be supported by the tanker force, within the available airspace.

- WAVE ATTACKS ARE PREFERRED BY PLANNERS
  - SATURATES DEFENSES
  - MUTUAL SUPPORT
- WAVE ATTACKS STRESS AERIAL REFUELING
  - MANY REFUELINGS, SMALL AMOUNT OF FUEL
  - SHORT TIME SPAN
  - STRICT AIRSPACE CONTROL
- TANKER EFFICIENCY DEPENDS ON:
  - COMPATIBILITY WITH RECEIVERS
  - REFUELING (RATE QUEING TIMES & TRANSFER TIMES/# RECEIVERS)
  - NOT ON TOTAL FUEL CAPACITY OF TANKER

FIGURE 9. TANKER EFFICIENCY DRIVES ATTACK EFFECTIVENESS

In order for tanker operations to be efficient, tankers have to be compatible with all types of receivers. This avoids the need to dedicate a portion of the tanker fleet to certain receivers, and improves utilization of tankers in the air. Additionally, efficiency can be improved by increasing the refueling rate. The refueling rate for a group of receivers is the sum of the queuing times and the fuel transfer times, divided by the number of receivers. Queuing time is defined as the time between when one receiver disconnects from the tanker until the next receiver begins to receive fuel. Fuel transfer time depends on the transfer rate and the quantity of fuel being transfered. Transfer rate is limited by either the rate at which the tanker can offload fuel, or the rate at which the receivers can accept fuel, whichever is lower. For fighter operations, queuing time is often as significant as transfer time. Improving either of these times will increase tanker efficiency. Increasing the total fuel capacity of the tanker will not, in general, increase the efficiency of tanker operations in support of wave attacks.

Several lessons were learned in Desert Storm. For example, tankers are valuable assets. For striking deep targets, they are essential. For continuous air patrol they are a force multiplier. While tankers contributed heavily to the success of the Allied air campaign, together we faced the challenge of future joint operations.

In the Mid-East war, the enemy waited five months, allowing the "good guys" to transport the needed personnel and cargo. This may not always be the case. Gen. Colin Powell believes we should plan for simultaneous conflicts which would strain our airlift and tanker assets even more (Figure 10).

- MULTIPLE, SIMULTANEOUS CONFLICTS
  - LONG RANGE, LONG ENDURANCE OPERATIONS
  - JOINT OPERATION WITH ALLIES, USN AND USMC
  - FEWER USAF TANKERS
  - LESS INFRASTRUCTURE THAN DESERT STORM
- INTEROPERABILITY
  - RELIABLE, SAFE REFUELING WITH INTERNATIONAL CREWS
  - TANKERS WHICH ARE COMPATIBLE WITH ALL TYPES OF RECEIVERS
- THESE TRENDS POINT TOWARD:
  - MULTIPLE FUEL OFFLOAD POINTS ON EACH TANKER

FIGURE 10. MAJOR TRENDS AFFECTING AERIAL REFUELING

To provide the interoperability for large, multi-national and joint campaigns, USAF tankers must (1) be compatible with all types of receivers and (2) provide multiple fuel offload points.

## INTEROPERABILITY CONSIDERATIONS

Of the 1000 total tankers in the Free World, three-quarters are boom-equipped. Of the 14,500 receivers less than 50% are compatible with booms. Figure 11 illustrates the problem in conducting combined operations using boom-equipped KC-135s. None of the USN aircraft can be supported, while only 14% of NATO aircraft and 29% of the international aircraft can be supported.

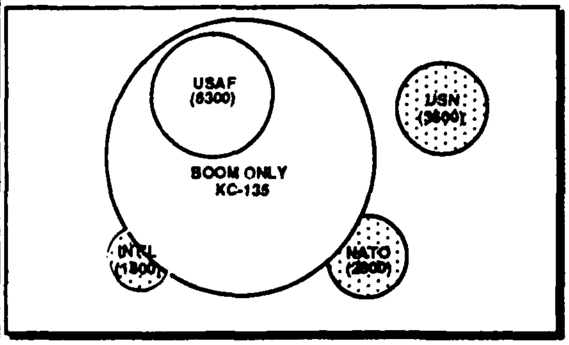



FIGURE 11. BOOM TANKER INTEROPERABILITY LIMITATIONS

Figure 12 shows the aircraft that can be refueled using the KC-135's boom-drogue adapter kit. The gray area outside the circle shows the large number of aircraft that cannot be refueled while the boom-drogue adapter kit is installed on the tankers boom.

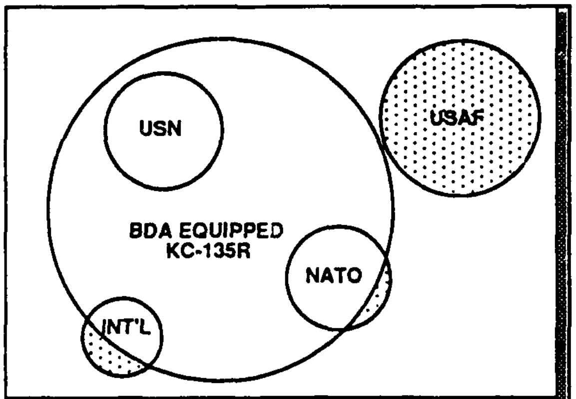
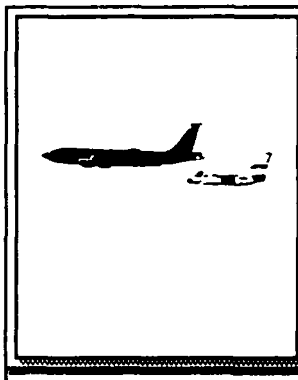



FIGURE 12. BDA INTEROPERABILITY LIMITATIONS

Figure 13 indicates that in addition to requiring that a fraction of the KC-135 tanker force be pre-dedicated to refueling either receptacle or probe equipped aircraft, there are other concerns related to BDA kits. Operational flexibility is obviously reduced. Scheduling is more difficult. The number of sorties supported is less. The USN and USMC pilots have indicated safety, reliability and other major concerns with BDA use. Additionally, the kits cause an increase in drag since the hose- drogue is deployed at all times.



- CAN REFUEL ONLY PROBE EQUIPPED AIRCRAFT
- REDUCES FLEXIBILITY-SCHEDULING & IN-AIR OPERATIONS
- CAUSES SAFETY CONCERNS
- LOWERS RELIABILITY
- INCREASES DRAG

FIGURE 13. LIMITATIONS WITH BDA

As discussed earlier, it is imperative in future conflicts to maximize the compatibility of KC-135 tankers with the 7000 Allied and USN receivers that are not boom-compatible. The Multi-Point Refueling System (MPRS) for the KC-135R is a significant step in this direction. (See Figure 14).

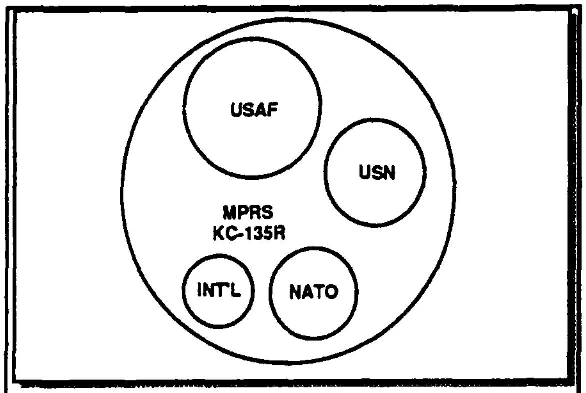



FIGURE 14. KC-135R MULTI-POINT INTEROPERABILITY LIMITATIONS

## SUMMARY

Frontier's analysis indicates that modifying a fraction of the KC-135R tankers to include the wing pods is the best way for the USAF to improve compatibility with Allied and US Navy aircraft. It is affordable, effective, reliable, safe and versatile. The problems with BDA kits were discussed earlier. New USAF tankers are not realistic for the near term.

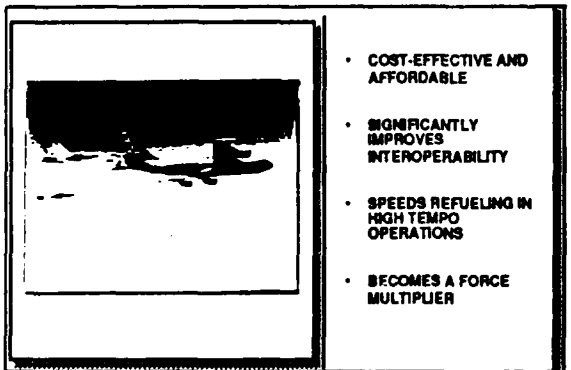



FIGURE 15. BENEFITS OF ADDING MULTI-POINT REFUELING

Figure 15 illustrates Multi-Point operations. In addition to being very cost-effective, there are several operational advantages.

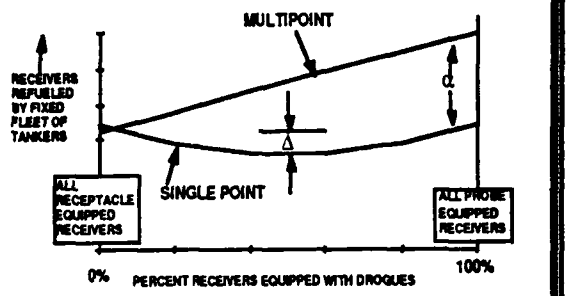
(1) Interoperability. The USN, USMC, and most potential Allied aircraft employ probe/drogue refueling. Multi-Point KC-135Rs allow the USAF to support the air refueling needs of joint service/Allied operations.

(2) High tempo operations. Multi-Point provides a significant improvement in the performance of a tanker fleet when air refueling operation are time constrained.

(3) Force multiplier. The benefit is derived primarily from the versatility of a modified KC-135R.

(4) Operability flexibility. The inclusion of refueling pods receptacle on KC-135's increases the potential range of operations, and the number of acceptable basing sites.

Figure 16 contrasts the efficiency of multi-point and single point refueling using a fixed number of tanker aircraft. This is a notional chart based on the relationships we have seen in on our theater analyses. The left axis represents the number of receiver aircraft refuelings. The horizontal axis is the percent of receivers equipped with probes, that is, the number of aircraft which can refuel from the multi-point refueling pods. The multi-point work Frontier has done shows that as the percent of probe equipped receivers increase there is an increase in number of receivers that can be refueled by the fixed size tanker fleet (Top Curve). The size of this increase ($\alpha$) varies from scenario to scenario, and is dependent on several factors including the percentage of strike sorties involved in wave attacks, the time allowed for refueling each attack wave, and the mission distances the aircraft have to fly. Our experience indicates that this increase in efficiency typically ranges from 25% to 50 % for the multi-point tanker fleet. Note that when all receivers are receptacle equipped (0% equipped with drogues) multi-point tankers are slightly less efficient than single point tankers. This is because the maximum fuel load that a multipoint tanker can carry must be reduced due to the additional weight of the pods, plus the additional drag due to the pods.




Δ : KC-135 AIRCRAFT CANNOT REFUEL BOTH TYPES OF RECEIVERS, VALUE IS SCENARIO DEPENDENT

α : MULTIPOINT TYPICALLY 25-50 % GREATER, DEPENDING ON SCENARIO FACTORS SUCH AS WAVE TIME DURATIONS

FIGURE 16. MULTIPOINT REFUELING MORE EFFICIENT FOR THEATER OPERATIONS

The numbers of receivers that the single point KC-135 tanker fleet can refuel typically decreases when the receiver fleet is a mix of receptacle and probe equipped aircraft. This is because dedicated tankers are needed for each type receiver, and frequently a duplication of tanker assets in the air is required to support both types of receivers. Again, the size of this reduction in performance is scenario dependent. This reduction in performance will not show up for single point tanker aircraft which do not need to land to service the two types of receivers. An example is the KC-10A which has a single refueling hose-drogue and a single boom which are both mounted near the centerline of the aircraft. This tanker can use only the boom or the hose-drogue at one time, not both simultancously.

Figure 17 summarizes the major requirements for tankers which must support all types of receiver aircraft in future conflicts where the infrastructure varies widely. The need for interoperability will probably increase; not decrease. Shorter refueling cycles are needed to improve refueling effieciency and subsequently strike effectiveness. Multi-point refueling helps satisfy the interoperability and efficiency requirements by (1) refueling both receptacle- and probe-equipped receivers and (2) simultaneously refueling two receivers.

Tankers will be used as airlifters, when available, to offset the deficiency we have in airlift capacity. For example between 100 and 200 KC-135s may be modified to make loading/unloading of cargo more straight-forward. This is done by installing rollers. Our analysis indicates that there is a payoff for KC-135 tanker-to-tanker refueling as well. It not only supports long range operations, but it permits the returning, lighter tanker to land at most modern airfields.

- INTEROPERABILITY
  - SAFELY REFUEL ALLIED, USN & USAF RECEIVERS
  - REFUEL RECEPTACLE AND DROGUE RECEIVERS
  - REDUNDANT DELIVERY DEVICES
- *IMPROVED REFUELING EFFICIENCY - SHORTER CYCLES*
- DUAL USE - HAUL FUEL OR CARGO/PASSENGERS
- TANKER-TO-TANKER REFUELING - SUPPORT LONG RANGE OPERATIONS AND GREATLY INCREASE THE NUMBER OF ACCEPTABLE BASES

FIGURE 17. FUTURE TANKER SYSTEM REQUIREMENTS

# AERIAL REFUELING INTEROPERABILITY FROM A RECEIVER FLYING QUALITIES PERSPECTIVE

D.J. Ludwig
FW331, Flight Test and Engineering Group
Naval Air Warfare Center Aircraft Division
Patuxent River, Maryland 20670, USA

**SUMMARY**

Over the past decade, there has been increased emphasis on inter-service and international operability with respect to aerial refueling (AR). One area concerning interoperability that needs to be considered in light of the increased trend towards large multi-point tankers is receiver flying qualities during AR. This paper stresses the importance of conducting receiver proximity trials to optimize refueling position behind the tanker and providing the pilot with the best receiver flying qualities for AR that can be attained. Receiver flying qualities behind the tanker can be seriously degraded if proper steps to optimize receiver refueling positions are not taken prior to final design. Poor receiver flying qualities in the refueling positions can reduce engagement success rate, increase the amount of training required, increase mishaps, increase refueling cycle time and seriously degrade mission effectiveness of the tanker. There are, of course, many other considerations regarding tanker/receiver compatibility such as airspeed/altitude compatibility, fuel system compatibility, communications, night lighting, etc. But this paper primarily addresses receiver flying qualities and the importance of refueling position behind the tanker as it pertains to flying qualities. Specific programs discussed are Navy trials with the Air Force KC-10 and KC-135 tankers and Navy programs to bring a wing pod tanker capability to the P-3 airplane. Additionally, efforts underway to enhance tanker mission effectiveness of the KC-130 with a variable geometry drogue are discussed and their ramifications explored.

## INTRODUCTION

The U.S. Navy has embarked on several joint aerial refueling (AR) programs designed to improve interoperability between the Navy and Air Force, improve the AR efficiency of land based tankers and improve the selection of tanker assets available to the military planners. Currently, the primary Navy tankers operate from aircraft carriers and include the A-6 and S-3 configured with self contained AR stores (buddy stores). The Marine Corps uses land based KC-130 tankers. By memorandum of understanding, the Air Force provides large land based tanker support to the Navy. This support is provided by KC-10 and KC-135 tankers.

The KC-10 was developed with a probe/drogue refueling system in the fuselage in addition to the boom/receptacle system to provide true interoperability between Air Force tankers and Navy receivers. The efficiency, however, of that tanker is limited by the fact that only one receiver can be refueled at a time. A program was started to retrofit wing AR pods on the KC-10 to provide a multiplane refueling capability.

The KC-135 tanker is primarily a boom/receptacle type tanker for refueling Air Force airplanes incorporating a universal air refueling receptacle installation (UARRSI). In the mid 1960s, a boom drogue adapter (BDA) was developed as an interim measure to allow the boom system to refuel probe equipped receiver airplanes. The BDA is a 9 ft hose section with paradrogue which attaches to the end of the boom. The BDA system has disadvantages in that it is difficult to refuel from, it limits the KC-135 to probe/drogue refueling, only, when installed, and can refuel only one receiver at a time. Following the KC-10 wing pod program, the Air Force has embarked on a wing AR pod program for the KC-135 as well.

The Navy is looking at the P-3 anti-submarine warfare airplane to fulfill a roll as a medium land based tanker to support carrier battle group operations as well as filling an international role. This is partially due to the current reduced submarine threat and the presence of increasing numbers of surplus P-3 airframes. The P-3 tanker includes wing pod mounted hose/reel AR systems and is in the conceptual stage at this time.

The Marine Corps KC-130 tankers provide refueling support for fixed wing and rotary wing aircraft. The conversion of the tanker from fixed wing to rotary wing tanking speeds is accomplished by changing paradrogues to provide a constant range of drogue drag to the hose take-up response mechanism. This drogue conversion, however, limits the efficiency of the tanker in that the wing pod can only refuel one type of receiver without a paradrogue change on the ground. The Marine Corps is investigating a variable geometry drogue that maintains constant drag over the wide range of airspeeds necessary to support both fixed and rotary wing aircraft. The variable geometry drogue offers benefits to other aspects of AR, as well, including potential for providing constant drogue trail position regardless of airspeed and better optimization of hose take-up response mechanisms.

The trend toward wing pod tankers raises challenges to the designers, evaluators and operators. Wing pod tankers can be inherently more difficult to refuel from due to asymmetric air flow fields behind the wing pods and tanker/receiver proximity limitations. Receiver refueling position behind wing pod tankers can be much more critical in terms of receiver flying qualities than fuselage mounted tanker systems.

## KC-10 WING AERIAL REFUELING PODS

The Navy has completed receiver qualification tests of the Air Force KC-10 tanker configured with wing pods. Navy involvement began in 1989 with initial trials using S-3 and F/A-18 receivers and a 50 ft (15 m) hose version of the wing pods. The S-3 was chosen because of its non-fly-by-wire irreversible flight control system, large wing span and tall vertical stabilizer, with good basic flying qualities characteristics. The F/A-18 airplane was used because it represents a modern tactical fighter type airplane with digital fly-by-wire flight control system. Severe problems with poor receiver flying qualities in the refueling positions required a closer look at the effects of the tanker flow field on the receiver airplane. Wind tunnel tests to investigate problems with hose extension/retraction characteristics shed light on the nature of the flow field behind the tanker leading to a series of proximity evaluations using S-3, A-7 and F-14 airplanes. The results of these proximity tests eventually led to the installation of longer 74 ft (23 m) refueling hoses to improve basic receiver flying qualities in the refueling positions.

**Short Hose Receiver Flying Qualities**

Receiver pilots tested the flying qualities aspects of refueling from the tanker by first stabilizing at the approach position defined as 20 ft (6 m) behind the paradrogue in trail and flying the airplane vertically and horizontally, 10 ft (3 m) from the centered position to get a feel for the aft flow field. The pilot then flew his airplane to the precontact position defined as 5 ft (2 m) behind the paradrogue in trail and maneuvered vertically and horizontally, 5 ft from the centered position. Following precontact maneuvering, the receiver cleared from behind the paradrogue which then was retracted and the receiver airplane was maneuvered into the simulated refueling positions. These preliminary tests were then followed by refueling engagements using various closure rates up to 10 ft per second (3 m/sec).

*Control Force Requirements*

At the precontact position the receiver had approximately 7 ft (2 m) of step down from the pod when a 2.5 q drogue was used at 250 KEAS. The S-3 pilot felt moderate turbulence on the vertical tail. There was an inboard rolling moment which required 5-7 lbs (22-31 N) of outboard countering lateral stick force and an inboard yawing moment which required 25-30 lbs (111-133 N) of outboard rudder pedal force to counter. During contact with the drogue and moving into the refueling range, the rolling moment increased in the same sense requiring 15-20 lbs (67-89 N) outboard lateral stick force. Yaw moment abruptly reversed in sense requiring 50-60 lbs (222-267 N) of inboard rudder to counter. Maintaining receiver alignment with the tanker resulted in a steady heading sideslip with 5-8 degrees of outboard-wing-down roll attitude. During contacts, as the receiver moved into the refueling range, varying control forces with increasing cross-controls were difficult to anticipate. During contacts if the receiver flew 5 ft (1-2 m) high in relation to the free trail hose position, the S-3 experienced a pitch-up moment that needed to be countered with 4-5 lbs (18-22 N) of forward stick force. These control force requirements to fly the airplane into the refueling range of the short hose pods caused us to have concern about the flow field behind the wing pods. Results of wind tunnel tests conducted by Douglas Aircraft Company collaborated with S-3 control force requirements test results. The pilot's workload flying at the refueling positions were greatly influenced by the nature of the flow field behind the tanker and is discussed in the following paragraphs.

*Flow Visualization*

Review of wind tunnel tests performed by Douglas Aircraft Company showed how the receiver airplane was influenced by the flow field behind the tanker. The dominant flow pattern below the level of the pod contained a strong outboard vector component which caused the hose and drogue to trail outboard 4-6 degrees. Outboard of the wing pod, the flow field vector component was shifted upwards as the airflow rolled up and around the wing tip vortex core. With 10 ft (3 m) of step-down, the S-3 receiver vertical tail was mostly under the influence of the flow field below the plane of the wing which caused the airplane to fly misaligned with the tanker as shown in figure 1.

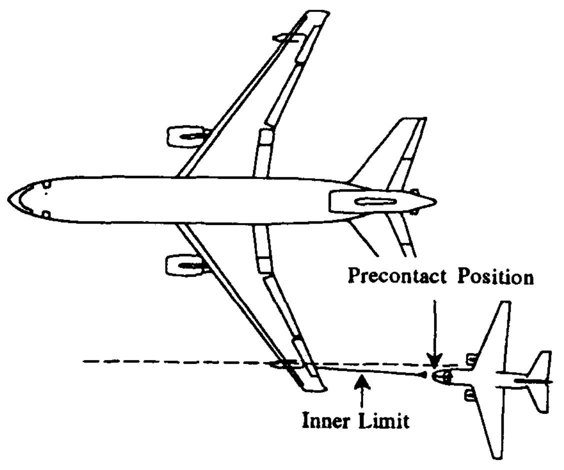



Figure 1
Receiver Misalignment with the Tanker

The effect of the flow field beneath the pod caused a higher angle of attack on the receiver's outboard wing than on the inboard wing which created a roll moment towards the tanker extended centerline. Countering with aileron increased the yaw moment towards the tanker (adverse yaw) requiring outboard rudder to counter the induced sideslip. Above the wing pod, the dominant flow pattern contained a strong inboard vector component. When the receiver moved upward, the vertical stabilizer became increasingly under the influence of the inboard flow pattern which caused an abrupt outboard yaw moment that had to be countered with inboard rudder. Figure 2 illustrates this point.

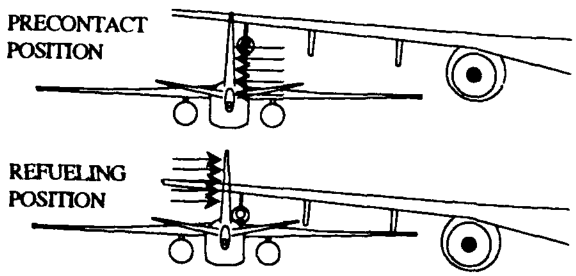



Figure 2
Flow Field Influence on Receiver Vertical Stabilizer

The total effect was described by pilots as "like balancing on top of a ball" or "the airplane doesn't fly like an airplane there". All of these effects were increased in intensity at slower speeds and heavier tanker gross weights (higher angle of attack) although at lower speeds the drogue trails lower which increased the vertical distance between the receiver vertical stabilizer and the influence of the inboard flow vector. The obvious solution to the problems described above was to lower the receiver position by trailing a longer length of hose which not only lowered the receiver position, but increased tanker/receiver separation which is enhancing from a safety aspect.

*Need for Pilot Rating/Workload Assesment*

As a way to quantify the effects of tanker flow field on receiver flying qualities, flying qualities were assessed at stabilized positions around the natural trail position of the hose/drogue using the Cooper-Harper handling qualities rating (HQR) scale as described in reference a. Numerical ratings were grouped into three levels as shown in the figure 3 simplified HQR scale.

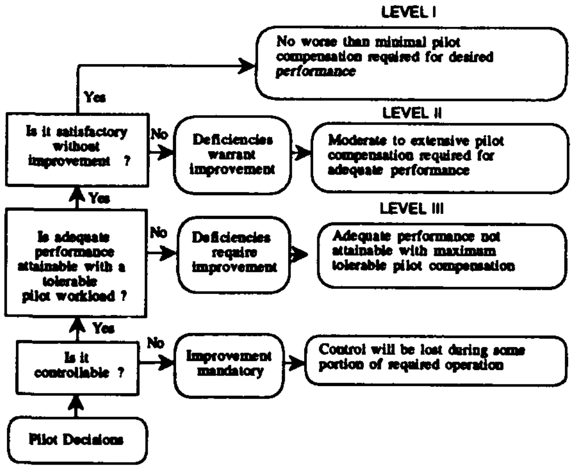



Figure 3
Simplified Cooper-Harper HQR Scale

Because the handling qualities ratings are dependent on proper task selection and their usefulness dependent on proper mission relation, the selected task was a function of the receivers position behind the tanker. For example, the approach position is defined as 20 ft (6 m) behind the paradrogue and is primarily an observation position that the receiver establishes himself in prior to approaches to the drogue. Accurate position keeping is not so critical and additionally, there is no immediate reference to the actual receivers position other than the tanker. Therefore, the task was to maintain a stable position within a rather loose ± 2 ft (< 1 m) for desired performance and ± 3 ft (1 m) for adequate performance. The precontact position is defined as 5 ft (1-2 m) behind the paradrogue and is the position where approaches to drogue contact are initiated. Tolerances are much tighter since ideally the receiver stabilizes behind the drogue within the extended outer perimeter of the paradrogue such that with application of power, the receiver will have a reasonable chance of hitting within the inner cone of the drogue. The tolerance was therefore ±1/4 drogue width (0.2 m) for desired performance and ±1/2 drogue width (0.4 m) for adequate performance. The receiver also stabilized at displaced positions away from the centered position typically ±10 ft (3 m) from the approach position and ±5 ft (1-2 m) from the precontact position using the same lateral and vertical tolerances. This provides data for mapping of the aft flow field behind the tanker which allows assessment of receiver flying qualities at various simulated drogue positions and for operational considerations where the pilots will routinely deviate from the nominal positions. The inner limit position is defined as the position within the refueling range of the hose reel system where fuel transfer is automatically secured and the AR system provides a warning to the receiver that he is close enough (typically a flashing amber light). The position keeping tolerances are somewhat looser than the precontact position since the receiver can maneuver around horizontally and vertically without detriment. The tolerance chosen was ± 2 ft (< 1 m) for desired performance and ± 3 ft (1 m) for adequate performance.

*Results of Pilot Workload*

Initial aerial refueling tests with the 50 ft (15 m) trail length pods revealed high pilot workload while refueling, particularly when the receiver was moving from the contact position into the refueling range towards the inner limit. To better quantify flying qualities in the refueling positions, proximity tests were performed using an S-3A and TA-7C. Results of the flying qualities tests as a function of receiver position behind the tanker are shown in figure 4.

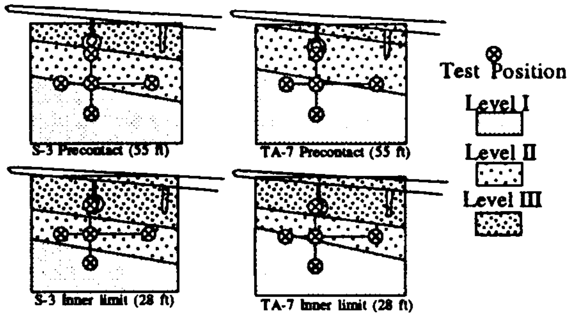



Figure 4
Receiver Flying Qualities as a Function of Position

The S-3 experienced borderline level I/II flying qualities at the precontact position. Flying qualities improved as the receiver moved down or outboard from the tanker fuselage. Movement inboard reduced flying qualities apparently due to the effects of increased engine buffet on the S-3 wing and increased roll moment towards the tanker. Moving to a 5 ft (<2 m) high position resulted in significant degradation in flying qualities with an abrupt outboard yawing moment and increased inboard rolling moment. The combined effect resulted in near level III flying qualities at the high position. Following receiver contact with the drogue, the receiver experienced constantly changing control forces required to maintain the proper vertical and horizontal position behind the refueling pod. Flying qualities proximity tests revealed level II flying qualities at the inner limit of the refueling range defined as 28 ft (8-9 m)behind the pod, which abruptly degraded to level III flying qualities as the receiver moved 2-3 ft (1 m) higher than the normal trail position of the hose. TA-7C test results were similar to the S-3. The level II flying qualities in the refueling range and abrupt degradation in flying qualities if the receiver drifted high in relation to the normal hose trail position were considered unsatisfactory and warranted improvement. Further proximity tests were recommended to evaluate receiver flying qualities at positions behind the tanker simulating wing pods with 74 ft (23 m) hoses.

**Long Hose Receiver Flying Qualities**
*Proximity Tests*

Follow-on receiver proximity tests were conducted using an S-3A and an F-14D. The TA-7C was not used due to unavailability. Results of the long hose proximity flying qualities tests are shown in figure 5.

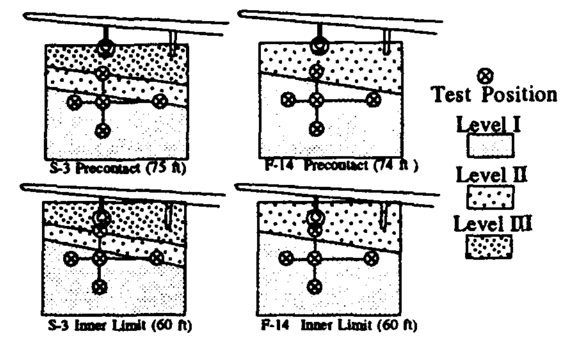



Figure 5
Receiver Flying Qualities as a Function of Position

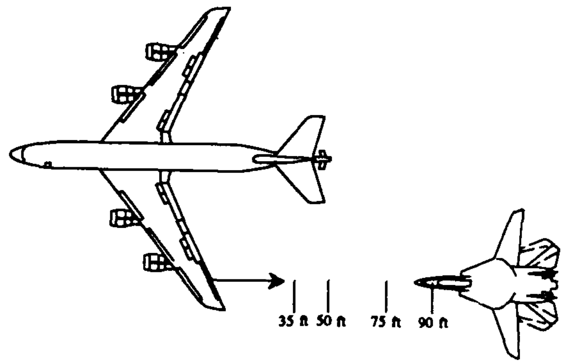



Figure 6
Receiver Proximity Test Positions

There was significant improvement in S-3 flying qualities at the test positions. Particularly, there were level I flying qualities at the nominal vertical/horizontal refueling position all the way to the inner limit. There was still a degradation in flying qualities to level III as the S-3 moved to a high refueling position, but the transition from level I to level II flying qualities was adequate warning and the degradation was not as abrupt as experienced with the short hose positions. F-14 flying qualities at the simulated refueling positions were very good with level I flying qualities at all test positions except at the 5 ft (1-2 m) high position where flying qualities degraded slightly to level II.

*Receiver Qualification*

Receiver qualification tests were conducted to qualify the A-6E, AV-8B, EA-6B, F-14D, F/A-18 and S-3 for refueling operations from the KC-10 wing pods. All receiver pilots reported level I flying qualities at the nominal refueling positions.

## KC-135 WING AERIAL REFUELING PODS

### General

The Air Force and Navy have completed receiver proximity tests of the Air Force KC-135R tanker simulating a wing pod tanker configuration. The KC-135R is a low wing military tanker/cargo airplane using four CFM-56 engines. Navy involvement consisted of proximity evaluations using S-3B and F-14D airplanes. The purpose of this evaluation was to identify optimum receiver aerial refueling positions behind a wing pod configured tanker. As with the KC-10 proximity tests, receiver flight controls inputs were used to map the flow field behind the tanker. Flow field was mapped by having the receiver pilot stabilize at specific positions behind the tanker and note longitudinal, lateral and directional trim and/or stick and pedal force requirements. Thus airframe moments generated by varying tanker flow fields could be better understood, their impact on airplane flying qualities assessed with the intention of identifying optimum drogue trail positions for aerial refueling.

### Proximity Positions

The proximity positions were chosen to simulate hose trail lengths between 50 (15 m) and 75 ft (23 m). Receiver pilots stabilized at 95, 75, 50 and 35 ft (29, 23, 15 and 11 m) behind the simulated wing pod location as illustrated in figure 6.

At each trail position the receiver maneuvered from the initial centered position vertically and horizontally to a displaced position dependent on trail position. At the 50 and 75 ft positions (15 and 23 m), the receiver stabilized at displaced positions 10 ft (3 m) from the centered position using pilot's line-of-sight and at 5 ft (2 m) from the centered position at the 35 ft (11 m) trail position. The 75 and 50 ft positions simulated the initial contact position where receiver flying qualities have a profound effect on the pilot's ability to position the probe horizontally and vertically within the confines of the paradrogue. As with the KC-10 wing pod tests, the receiver pilot's task was to position the airplane horizontally and vertically with a tolerance of ±1/2 drogue width (0.4 m) for adequate performance. This simulated a 30 in (0.8 m) diameter drogue. The 95 ft position simulated an approach or observation position behind a simulated 75 ft hose. The 35 ft position simulated the inner limit position while refueling from tanker system with a 50 ft hose. Receiver centered and 10 ft displaced positions are illustrated in figure 7.

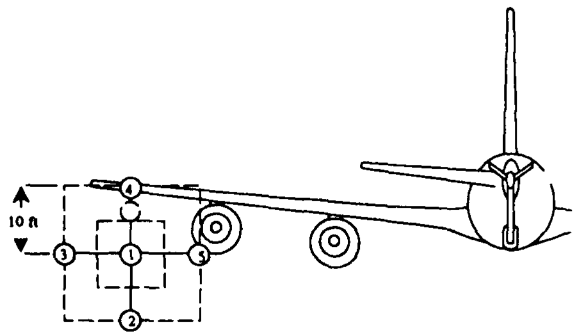



Figure 7
Receiver Test Positions

### Flow Field Mapping

*Control Force Requirements*

At the 75 ft (23 m) centered position (position 1), the S-3 required 5 lbs (22 N) of outboard stick force to counter a roll moment inboard towards the tanker extended centerline. Maintaining a horizontal/vertical position within the defined tolerance required very small, <1/2 in (<1 cm) and continuous lateral and longitudinal control stick movements with no apparent flow field induced yaw moment. Position 2 required 4 lbs (18 N) outboard stick force and position 3 required a slightly less outboard control stick force of 3 lbs (13 N) to counter less flow field induced inboard roll moment. The pilot felt moderate chop on the vertical tail of the airplane when he flew to a position 5 ft (<2 m) above the neutral position without any significant effects on the airplane's yaw axis.

At the 50 ft (15 m) position, the S-3 lateral control force requirements slightly higher than the 75 ft (23 m) position requiring 5-6 lbs (22-27 N) of outboard stick force to stabilize at position 1. Stabilizing at position 3 required 3 lbs (13 N) of outboard lateral stick force to counter the inboard roll moment. It was more difficult to stabilize at the high position (position 4) within ±1/2 drogue width (0.4 m) due to increase in buffet on the vertical tail and required 6-7 lbs (27-31 N) of outboard control stick force and continuous, 3/4-1 in (2.5 cm) lateral control movements and a continuously varying forward control stick pressure of 5 to 10 lbs (27-44 N). At the 35 ft position (simulated inner limit), the pilot experienced continuous light chop at position 1. Maintaining a stable position within ± 1/2 drogue width (0.4 m) required 6-7 lbs (27-31 N) of outboard control stick force and 15 - 20 lbs (67-89 N) of outboard rudder pedal force to counter an apparent inboard yaw moment. Continuous, 1/2 in (1 cm) lateral and longitudinal stick movements were required to stabilized within the desired tolerances. Stabilizing at the outboard position 3 required approximately 4 lbs (18 N) of outboard lateral stick force to counter the reduced inboard roll moment. When moving high to position 4 at 3-5 ft (1-2 m) above the neutral position, there was sufficient difference in the flow field as the S-3 vertical stabilizer was positioned above the tanker wing to cause an abrupt outboard yaw moment at a rate of approximately 5 degrees/sec and an increase inboard roll moment. Additionally, there was a tendency for the airplane to draft towards the tanker wing pod position. Forward control stick pressure was required to counter an apparent increased pitch-up moment.

In general, flying qualities in most areas, except position 4, behind the KC-135 wing were satisfactory for AR. The best receiver flying qualities for the S-3 and F-14 were consistently experienced at position 2 providing level I flying qualities. Flying qualities degraded to borderline level I/II at positions 1, 3 and 5. As the receiver moved up to position 4, abrupt changes in the induced moments about the airplane's pitch and yaw axis required well-timed control inputs by the pilot to compensate. Both the S-3 and F-14 experienced borderline level II/III flying qualities at position 4 with the worst flying qualities experienced at the 35 ft (10 m) trail position where the S-3 approached the limits of controllability. The overriding factor in the reduced flying qualities at position 4 was not the absolute magnitude of control inputs required, but the rate at which the required inputs changed with small position deviations. For optimum refueling conditions, the receiver requires an volume of space around the trail position of the hose where small variations in receiver position of ± 5 ft (2 m) do not require abrupt, well-timed control inputs to compensate for flow field variations. Additionally, the receiver position must be high enough in relation to the tanker to provide adequate visual tanker references for AR. The optimum refueling position for receiver flying qualities is illustrated in figure 8. Visual cues for AR however were degraded at positions 2 inside of 50 ft (15 m) of trail.

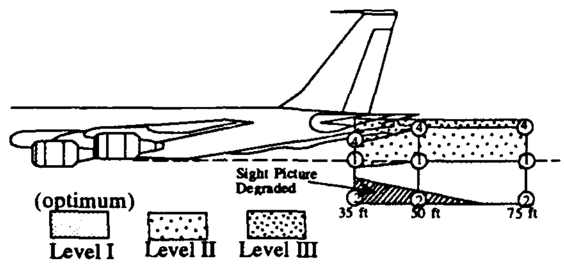



Figure 8
Receiver Flying Qualities and Sight Picture

## P-3 WING POD TANKER

### General

The P-3 Orion is a four-engine, low-wing, land-based airplane designed for antisubmarine warfare and maritime patrol. The P-3 airframe has good potential as a medium give tanker. An aerial refueling configuration that includes a give and receive capability has been studied. As a receiver, the P-3 fuel system needs to receive fuel at a high rate to minimize the amount of time the pilot has to fly the airplane in close formation. This is born from the fact that the P-3's flying qualities are not optimized for precise formation flying and high pilot workload is a limiting factor. Several feasibility test programs have investigated the P-3 flying qualities in the receiver roll using the Air Force Universal Aerial Refueling Receptacle Installation (UARRSI) and the Navy's probe/drogue refueling system. Several tanker configurations have also been studied which include a fuselage installed hose reel system and wing pod mounted hose reel systems for probe/drogue refueling. The inherent advantages of the wing pod mounted hose reel systems includes increased reliability of the tanker system because of redundancy and reduced refueling time for a group of tactical aircraft because of the potential for two airplanes to refuel at once. Thus, discussion will be limited to a test program that investigated the feasibility of the P-3 as a wing pod tanker.

### Feasibility Evaluation

A feasibility evaluation of the P-3 as a wing pod tanker was conducted to verify that adequate receiver airplane flying qualities existed in refueling positions behind the P-3. The evaluation was performed using an S-3 receiver with positioning based upon a simulated wing aerial refueling pod located midway between the outboard engine and wing tip on both wings (existing stations 11 and 16). The simulated pod's hose was 82 ft (25 m) from the pod to the drogue. The pod was estimated to hang below the wing to the approximate level of the tanker fuselage, with hose drop dependent on airspeed but assumed to be approximately 15 ft (5 m) at the full trail position and 10 ft (3 m) at the inner limit of the refueling range. Testing was conducted at a range of airspeeds from 200 to 275 KIAS. An illustration of the tanker configuration with F-14 airplanes engaged is shown in figure 9.

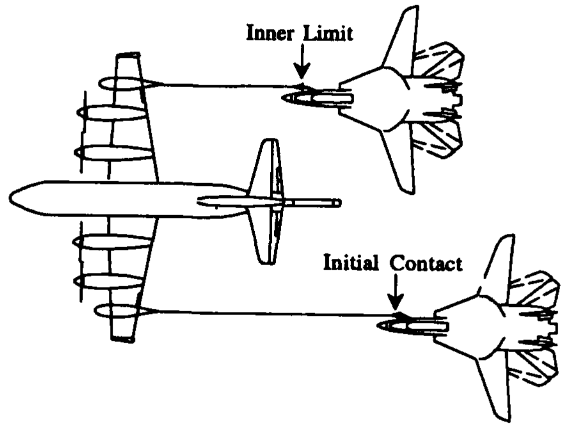



Figure 9
P-3 Wing Pod Tanker with F-14's Engaged

*Approach Position*
At the approach position 100 ft (30 m) behind the simulated drogue position, stabilizing the S-3 airplane required 4 lbs (18 N) of lateral control stick force away from the tanker and 10 to 15 lbs (44-67 N) of rudder pedal force away from the tanker to counter the apparent adverse yaw. Maintaining the approach position within ±3 ft (1 m) was very easy for the pilot, requiring small 1/4 in (0.6 cm) lateral and longitudinal inputs every 2-3 seconds which resulted in level I flying qualities. Moving 10 ft (3 m) above the stabilized position resulted in greater induced roll and yaw moments towards the tanker extended centerline. These moments were easily countered with an additional 10 lbs (44 N) outboard lateral stick force and 15-20 lbs (67-89 N) of outboard rudder pedal force. The high position was preceded by a high frequency airframe buffet. The position inboard 10 ft from the centered position resulted in higher inboard roll and yaw tendency than the centered position but less than the 10 ft high position . When flying to the 10 ft outboard position, there was a less inboard roll tendency than the centered position with no apparent effects from wing tip vortices. The 10 ft low position was similar to the outboard position. Overall, the changing flow field induced airplane moments were gradual as the receiver moved within 10 ft of the centered position and lateral/directional control force requirements were in the same sense (not cross controlled). Both characteristics made flying qualities at the approach position level I.

*Contact and Inner Limit Positions*
Flying qualities at the contact position 82 ft (25 m) behind the simulated pod, were similar to the approach position and were generally level I at all of the positions within 10 ft (3 m) of the centered position. Flying qualities at the inner limit degraded slightly to level II at the centered, high and inboard positions primarily due to the presence of moderate buffet which required continuous 1/4 in (0.6 cm) lateral and longitudinal inputs to stabilize within ±3 ft (1 m). The airplane handling qualities at the approximate refueling positions behind the P-3 are more than adequate for aerial refueling and superior to other wing pod tankers recently tested.

## VARIABLE GEOMETRY DROGUE

**Fixed and Rotary Wing Aerial Refueling**
The US Marine Corps uses KC-130 tankers in a dual role refueling both fixed wing and rotary wing aircraft. Because of the lower refueling speeds for helicopters which range from 100 to 120 KCAS, the KC-130 is configured with a high drag drogue which maintains sufficient tension on the hose for the operating range of the hose take-up response mechanism. Fixed wing refueling typically is conducted between 200 and 265 KCAS so the tanker must be configured with a lower drag drogue to maintain hose load within the operating range of the hose take-up response mechanism. The requirement to change drogues before refueling fixed or rotary wing aircraft severely limits the flexibility of the tanker. The tanker must land and have the drogue changed before providing refueling support for the other type aircraft. A variable geometry drogue with sufficient drag range to accommodate both helicopters and fixed wing airplanes is much needed to improve operational flexibility.

**Standard Drogue Position**
Changes in free trail drogue position can make a significant difference in the way the receiver airplane flies during aerial refueling. Typically the changes in receiver airplane position because of the trail position of the drogue helps define the optimum refueling speeds. Behind large tankers, the high relative trail position of the drogue places the receiver increasingly into increased buffet and/or dramatic changes in air flow patterns behind the wing which can severely degrade airplane handling qualities. At slow speeds, the drogue trails lower to a point where the receiver pilot's visual references are reduced which can be especially disconcerting to the pilot at night. Different trail positions of the drogue due to changes in airspeed require the receiver pilot to adjust his piloting technique to accommodate the changes in airflow field effects and to adjusts his visual references so that proper lineup and closure rate control is maintained. A variable geometry drogue will trail at a relatively standard position so that receiver pilots are not required to make adjustments due to changes in airflow field effects and sight picture. The ultimate goal is to make aerial refueling as routine as possible.

**Hose Response**
Current hose take-up response mechanisms and their operating capabilities are limited by the large changes in drag with airspeed which is inherent in fixed geometry drogues. Two schools of thought for providing hose take-up response during contacts are as follows:

a. Limited airspeed envelope, fixed response rate.
b. Wide airspeed envelope, variable response rate.

Benefits to the two types of response systems are discussed in the following paragraphs.

*Fixed Response Systems*
The fixed response rate systems are simple, reliable and work quite well at optimum speeds. However, as you deviate from optimum speeds, the characteristics of the system become degraded in different ways depending on whether you are slow or fast in airspeed. As speed is decreased, drogue drag becomes less able to overcome the constant tendency for hose to reel in. A speed somewhat higher than the point were drogue drag equals take-up hose tension sets the lower speed limit because the ability of the receiver airplane prob to latch into the reception coupling is degraded without some amount of static load. Also, drogue drag needs to be higher than take-up tension to overcome breakout plus friction in the reel. Otherwise, in range disconnects can occur, which result in the drogue remaining in a position not fully extended. The upper

speed limit of the fixed response/fixed drag system is set by receiver probe strength. For example, assuming a hose take-up tension of 300 lbs (1.33 kN), a 4.0 q drogue at 325 KEAS would result in a static load on the receivers probe of 1,135 lbs (5.05 kN). Coupled with increased load due to impact, refueling probe limit loads can be exceeded. The answer to these limitations is to optimize the static load on the probe for best latching characteristics while providing adequate probe strength margin. A variable geometry drogue would allow optimizing the static load on the probe while expanding the usable airspeed envelope without potential for exceeding probe strength.

*Variable Response Systems*

The variable response rate systems work well over a wide range of speeds but tend to be mechanically limited in speed range and produce varying response characteristics with respect to hose take-up response because of the different hose trail angle characteristics of fixed geometry drogue systems. These systems set hose take-up response as a function of airspeed typically by setting a reference hydraulic pressure based on hose tension. As the receiver makes contact with the drogue, this causes an imbalance in the hydraulic servo valve which then causes the reel motor to reel in the hose until the reel is again supporting the drag of the drogue and balance in the servo valve is achieved. The airspeed range, however, is limited by the mechanical range of the reference boost cylinder which theoretically could be designed to accommodate the much lower speeds of helicopter refueling using the same drogue. The problem is the low trail position of the drogue would require extensive modifications of the drogue level wind mechanism and exit chute area to accommodate the wide range of hose trail angles illustrated in figure 10.

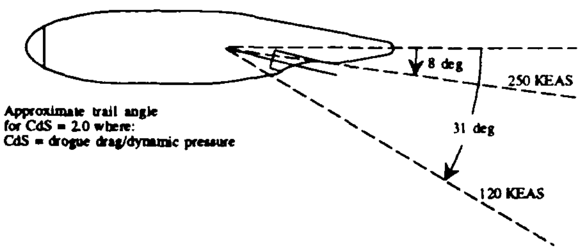



Figure 10
Hose Trail Angle as a Function of Airspeed

A variable geometry drogue designed to provide constant drag over a wide range of airspeeds would result in a constant optimum trail angle for hose carriage mechanisms, pod exit chutes and receiver visual tanker references. Additionally, the complicated variable response mechanism could be discarded altogether reducing the complexity of the hose response system.

## CONCLUSIONS

Receiver flying qualities behind large wing pod tankers are extremely dependent on the receivers position in space while refueling. Large wing pod AR tanker designs require receiver proximity testing before freezing the design to optimize receiver refueling position behind the tanker and give the receiver pilot the best flying conditions possible. The concept of a variable geometry drogue that maintains a relatively constant position in space regardless of airspeed has potential to provide tanker designers flexibility in tailoring the refueling package to provide a drogue position optimized for receiver flying qualities and sight picture.

## FUTURE PROJECTS

Future projects will include receiver compatibility testing with the KC-135 configured with wing aerial refueling pods. We are also in the planning stages of a feasibility program to conduct receiver engagements with a dry hose P-3 wing pod tanker to be followed by prototype development if the feasibility program is successful. Work is underway to get preliminary drag data for a variable geometry drogue concept for application on the U.S. Marine Corps KC-130 tanker. And to improve tanker accessibility to military planners during joint exercises between participating nations, we are pursuing a qualification program to verify and/or improve interoperability between tankers and receivers from various nations.

## REFERENCES

1. Cooper, G. and Harper, R., The use of Pilot Rating in the Evaluation of Aircraft Handling Qualities, NASA TN D-5153, April 1969.

# TANKER SYSTEM AND TECHNOLOGY REQUIREMENTS DEFINITION: A TANKER TECHNOLOGY ROAD MAP

by

**John Koriagin**
Transport Aircraft
McDonnell Douglas Aerospace
Long Beach, California 90846 USA

**Berton B. Rund, Major U.S. Air Force**
ASC/SDCT, Building 16
2275 D Street, Ste. 16
Wright-Patterson AFB, Ohio 45433-7233, USA

**SUMMARY**

This paper presents a process that leads from comprehensive tanker system requirements analysis to the development of a technology "road map." This road map is a matrix listing key technology requirements for future air refueling tanker aircraft capabilities, and the current status of research and development activities in these key areas. Generalized examples from material prepared under a U.S. Air Force Contracted Research and Development (CRAD) study are utilized [(1)]

Multi-mission capabilities (i.e., tanker, and cargo and passenger transport) are often preferred for these new aircraft. This allows the flexibility of use for many purposes besides that of just air refueling: military cargo and passenger deployments, humanitarian relief, medical air evacuation, executive transport, etc. For this reason these tankers are often referred to as "tanker/transports" to emphasize these capabilities. In this paper, the term "tanker" is used to describe what, in all likelihood will be a tanker/transport.

## 1. SYSTEM REQUIREMENTS DEFINITION

In order to validate the need for any new air refueling (AR) tanker system and its performance requirements, a thorough systematic requirements analysis needs to be performed. The intent of this paper is to offer one methodical approach that could be used in developing the design, technology, and operational support requirements for a tanker fleet procurement.

This paper presents a structured sequence of five primary tasks (Figure 1) that can be used to define the functional and performance requirements for any new or derivative tanker aircraft.

(1) Contract No. F33657-90-D-0029, Task Order 0008 "Tanker Technology Trade Studies: Low Altitude Aerial Refueling (LAAR) Operations." Final Report MDC K5550, dated 15 March 1991, prepared for USAF/AFSC Aeronautical Systems Division, Wright-Patterson AFB, Ohio 45433.

This approach starts with the using service (i.e., a NATO Nation Air Force) utilizing their mission scenarios to define major mission needs, including projected enroute threat definitions. System requirements are generated during this phase. Next, candidate airframes available for modification to tankers need to be identified. Once this is done, then the ability of these candidates to perform the tanker missions can be evaluated. If there are significant performance or survivability shortfalls, an Enhancement Analysis can be conducted. Finally, a candidate aircraft can be recommended. Or, if there is no totally satisfactory solution, concepts can be re-evaluated by going through Tasks 3, 4, and 5 again, possibly with new candidate airframes from Task 2.

Each of these five tasks are described in the following sections, in varying levels of detail. The emphasis in this paper is on the first task: Generating a comprehensive needs statement and defining the various measures of effectiveness that can be used to discriminate among candidate airframe solutions.

### 1.1 Mission Needs Statement.

Based on user-provided scenarios, analyses are conducted to generate a Mission Needs Statement. This identifies desired aerial refueling mission capabilities and system needs. Other roles and missions (e.g., cargo, passenger, aero-medical evacuation) desired for the aircraft must also be considered at this point. Measures of effectiveness to be used in later analyses, are defined during this first step in the process.

A functional analysis is also performed as an element of this task. This analysis identifies, through an iterative process, tanker functions required to implement the mission. This leads to the identification of tanker systems and the allocation of requirements to those systems.

#### 1.1.1 *Scenario Definition*

A comprehensive set of scenarios that delineate the potential range of tanker missions needs to be defined by the using National Air Force. If applicable, emphasis may be placed on multi-role Tanker/Transport utilization.

The mission scenarios, if definitive, can also be used to size the force of tankers required and comparatively evaluate candidate tanker force cost effectiveness.

It cannot be emphasized too strongly that the scenarios generated by the using service must be comprehensive, with regard to expected usage of the tanker aircraft, and demanding yet realistic in their expectations of its capabilities. Otherwise, the value of the total requirements development and selection process can be seriously degraded.

Tanker missions can be broken down into the following types, assuming multi-role tasking; primary elements that should be considered in a comprehensive mission definition are also listed:

**MISSIONS**

1. DEPLOYMENTS (LONG RANGE)

   A. Air Force Deployments
      (1) Tasking:
         o Refuel Fighters and Other Transport Aircraft
         o Provide Control and Escort Communication and Navigation Functions, if Required
         o Transport Cargo and Personnel
      (2) Mission Elements:
         o Units: Types, Quantities, Support Equipment and personnel
         o Timing
         o Routes, Bases, Geopolitical Factors
         o Threat Environment

   B. Ground Force Deployments
      (1) Tasking:
         o Refuel Other Transport Aircraft
         o Transport Cargo and Personnel
      (2) Mission Elements:
         o Units: Types & Quantity of Equipment
         o Timing
         o Routes, Bases, Geopolitical Factors
         o Threat Environment

   C. Humanitarian
      (1) Tasking:
         o Transport Cargo and Personnel
         o Refuel other Transport Aircraft
      (2) Mission Elements:
         o Cargo, Passengers
         o Aeromedical Evacuation

   D. Special Air Missions
      (Government Executive Transport)
      Tasking: Transport Personnel and Cargo

2. EMPLOYMENTS (AIR FORCE IN-THEATER)

   A. Tasking:
      o Refuel Fighter/Attack (including Naval Force) Aircraft
      o Refuel Airborne Warning and Control System (AWACS) Platforms
   B. Mission Elements:
      o Units: Types, Quantities (Sortie Force Structure)
      o Fighter/Attack Aircraft External Store Configurations
      o Timing
      o Routes and/or Radii of Action, Basing Structure
      o Tactical Requirements
      o Threat Environment

3. SPECIAL OPERATIONS

   A. Tasking:
      o Refuel Special Mission Aircraft, Including Helicopters
      o Transport Cargo and Personnel
   B. Mission Elements:
      o Unique System Requirements
      o Unique Operational Requirements
      o Unique Tactical Requirements
      o Threat Environment

In each of these missions there may be specific air refueling tasks to be accomplished either as an element of the primary mission or by separate supporting mission tasking. As an example of air refueling as an element of the primary mission task, using Mission 1.A., Air Force Deployments: The tanker is tasked to air refuel deploying fighters, while on this same mission it is also tasked to carry supporting cargo and passengers (a "mission tanker/ transport" role).

In a supporting role, the tanker may be based somewhere along the deployment route, and tasked to air refuel the mission tanker and/or its accompanying fighters enroute. If the supporting tanker is at the departure base, it can be tasked to "top off" the mission tanker and/or fighters so they can fly further on the initial mission leg.

In a similar case, if the tanker is only tasked to carry cargo and/or passengers in Mission 1.B. it may be necessary to have supporting tankers air refuel the mission aircraft or other cargo transports enroute.

### 1.1.2 *Measures of Effectiveness*

Measures of effectiveness related to the performance of tanker and tanker/cargo aircraft missions can be selectively used to measure the capability of competing airframe candidates.

Generally, these measures of effectiveness can be categorized into basic tanker airframe performance capabilities, performance related to the missions supporting specific receiver aircraft, scenario-specific missions, tanker force sizes to support specific scenarios, and the life cycle cost of those forces.

When determining force sizes and costs, the total system must be considered: The aircraft, its supporting logistics system, and flight crew manning. The logistics systems spare parts inventory, maintenance equipment and personnel availability, and flight crew manning levels determine airframe availability in terms of flying hours per day, and can impact ground turn-around service times. In USAF usage, the term "weapon system" is used even for transport aircraft systems to emphasize this total system capability.

Potentially useful measures of effectiveness are tabulated below, and some graphical examples are given in the accompanying illustrations:

### MEASURES OF EFFECTIVENESS

1. BASIC CAPABILITIES

   A. OFFLOAD Vs. RADIUS-OF-ACTION (See Figure 2)
   B. TIME-ON-STATION (ToS) Vs. RADIUS-OF-ACTION (RoA) (See Figure 3)
   C. OFFLOAD Vs. TIME-ON-STATION Vs. RADIUS-OF-ACTION (See Figure 4)
   D. PAYLOAD Vs. RANGE (See Figure 5)
   E. TAKEOFF GROSS WEIGHT Vs. FIELD LENGTH
      Also a Function of Altitude, Temperature, Runway Condition
   F. GROSS WEIGHT Vs. LOAD CLASSIFICATION NUMBER (LCN)

2. RECEIVER SPECIFIC CAPABILITIES

   A. No. RECEIVERS SUPPORTED Vs. TIME-ON-STATION Vs. RADIUS-OF-ACTION (See Figure 6)
   B. No. RECEIVERS SUPPORTED Vs. PAYLOAD Vs. RANGE (See Figure 7)

3. SCENARIO SPECIFIC CAPABILITIES

   A. FIGHTER DEPLOYMENTS
      (With Specific Routes, Route Winds, Abort and Support Bases Available, etc.)
      (1) Number of Fighters Deployed plus Support Cargo and Personnel Carried (Single Tanker Measure of Effectiveness). (See Figure 8 and 9 *)
      (2) Tanker Force Required for Unit Closure (Multiple Tanker Measure of Effectiveness)
   B. GROUND FORCE DEPLOYMENTS
      (With Specific Routes, Route Winds, Bases Available)
      (1) Cargo and/or Passenger Capabilities (Single Transport Measures of Effectiveness)
         a. Number of Pallet Loads
         b. Types of Vehicles Loadable
         c. Number of Passengers
         d. Load Flexibility (Mix of Cargo and Passengers)
         e. Ground Handling & Cargo Loading Equipment Required
         f. On-Board Loader (OBL) Availability
         g. Built-in Cargo Loading Ramp (Note that if a military cargo aircraft, such as the C-130 or C-17, is chosen for modification into a tanker role, the need for an OBL or high-lift loading equipment is eliminated.)
      (2) Force Capability (Multiple Transport Measures of Effectiveness)
         a. Unit Closure
         b. Through-Put (e.g.; Ton-Miles per Day)
   C. FIGHTER/ATTACK AIRCRAFT COMBAT AIR PATROL OR STRIKES
      (1) Radius of Action (Single Tanker Measure of Effectiveness)
      (2) Tanker Force Required (Multiple Tanker Measure of Effectiveness)

4. FORCE SIZE

   A. PARAMETRIC MODELING
      Force Size as a Function of Multiple Generic Variables:
      (1) Operational Variables (Radius to the air refueling track, 24-Hour-a-Day or Periodic Daily Operations, Scheduled or Continuous Operations)
      (2) Tanker Capability (Performance, Weights, Utilization Rates (flight hours per day), Sorties per Day, Ground Turn Around Time)
      (3) Receiver Demands (No. of Receivers in a "Cell," Fuel Onloads per Receiver, Time between Cell Arrivals, Fuel Transfer Rate, Receiver Hookup Time)

---

* Note: This example uses a "real world" training deployment case developed early in the Royal Netherlands Air Force (RNLAF) KDC-10 Program. Extremely conservative assumptions were used for a very demanding mission in order to determine whether there would be any need to consider supplemental lower fuselage fuel tanks. As can be seen from the resulting mission capability of the KDC-10 with only existing wing fuel tanks, supplemental fuel was not required.

B. SCENARIO-DRIVEN MODELS & SIMULATIONS
Force Size or Force Effectiveness in support of specific scenarios, such as those listed under category 3, above.

5. FORCE LIFE CYCLE COSTS
Total weapon system (aircraft system, logistics system, training system) and its operations and support costs:

A. ACQUISITION
Includes research, development, test, and engineering (RDT&E), production/modification, flight test, and support investment.

B. OPERATION & SUPPORT
Operations and support (O&S) costs include unit mission personnel, unit consumption, organic, intermediate and depot level maintenance, sustaining investment, installation support personnel, indirect personnel support, and personnel acquisition and training.

O&S costs will be very dependent on the type of maintenance system chosen, whether a totally using-service-provided organization (USAF standard for large fleets of same-type aircraft operating out of many bases), or a Contractor Logistics Support (CLS) organization (the USAF uses a CLS approach for its moderate sized fleet of about 60 KC-10 operating out of three main *operating bases), or some combination of the* two. For small quantities of unique aircraft, a CLS approach may be the most practical.

1.1.3 *Functional Analysis*

Functional analysis provides a structured way of accounting for all the tanker aircraft's mission-driven system requirements. This will include requirements for all elements of its air refueling-specific systems and functionally related supporting systems (communication, navigation, lighting). Requirements for ancillary mission equipment, such as cargo or passenger provisions, or special equipments to support unique missions such as aeromedical evacuation or executive transport should also be considered in this task. Some major elements of a tanker/transport functional analysis are given below.

**FUNCTIONAL ANALYSIS ELEMENTS**

1 AIR REFUELING REQUIREMENTS

A. Boom (for Receptacle-Equipped Receivers)
   (1) Boom Mounting Location
   (2) Control Station Location
      a. Direct-view in lower fuselage compartment
      b. Remote-view on main deck (Remote Air Refueling Operator (RARO) Station)

B. Hose/Drogue (for Probe-Equipped Receivers)
   (1) Installation Location
      a. Fuselage (Interior, Exterior)
      b. Wing-Mounted
   (2) Control Panel Location

C. Supporting Fuel Systems

D. Supporting Communications, Lighting, and Navigation (Including Rendezvous) Equipment

E. Supplemental Fuel Tanks

F. Air Refuelable Tanker Capabilities (Receptacle, Probe, Boom or Probe Reverse Air Refueling)

2. CARGO HANDLING REQUIREMENTS

A. Bulk Cargo (Palletized or Containers)
B. Vehicles or Other Rolling Stock
C. Self-Loading (OBL)
D. Cargo-Loading Door or Ramp

3 PASSENGER ACCOMMODATIONS

A. Standard Passengers
   (1) Permanent
   (2) Optional/Removable
B. Aeromedical Evacuation
C. Special Air Mission

4. AIRFIELD OPERATIONAL RESTRICTIONS/ CAPABILITIES

A. Short Field Takeoff or Landing
B. *Austere/Unimproved Field Operations*
C. LCN Limitations
D. Self-Support Capabilities
E. Bulk Fuel Offload

### 1.2 Candidate Airframes

In-service airframes which could be candidates for modification to the tanker role, and their relevant performance and mission capabilities, are defined. Once in-service airframes are evaluated (and possibly eliminated as candidates), other military and commercial transports can be identified. The last option is that of designing and developing a new tanker aircraft.

For modified airframes, if the primary receivers are all probe-equipped, then the addition of wing-mounted air refueling hose/drogue pods or a centerline fuselage installation to the tanker is usually less of a problem, than if the receivers have air refueling receptacles. Then the tankers have to be equipped with the boom system and the associated operator control station installations.

1.2.1 *In-Service Transport Conversion*

Cargo or passenger transport, or large bomber airframes that are already in the National Air Force inventory are probably easiest for that service to use for conversion to tankers. Besides size and appropriate propulsion system, issues generally focus on current need in their primary role, airframe condition and remaining useful life, and ease and cost of conversion to the tanker role in the required configuration.

1.2.2 *Other Military Transport Conversion*

Either new or used transports, if available from another National Air Force, could be candidates for tanker modifications. Many nations have converted new or used C-130 cargo aircraft to tankers by adding wing pods, or, in a few cases, a cargo-ramp mounted hose/drogue reel. Many also add suppler ıtal fuel tanks, either wing-mounted pods or main cargo deck installations.

Another example of military sales was the French Air Force acquiring new KC-135A directly off the Boeing production line through US Government Foreign Military Sales (FMS). These were later re-engined with CFM-56 plus other modifications.

When the C-17 enters operational service in the USAF it should also be available for FMS acquisitions. This large, capable cargo airplane could be modified into a "Cargo/Tanker" with significant air refueling capabilities. Studies have already been done for some interested NATO countries (Canada for one) to develop configuration and performance alternatives. If only probe-equipped receivers have to be refueled, preliminary evaluations have concluded that adding the KC-10A's FRL Mk. 32B wing pods to existing C-17 wing hard points would be a relatively straight forward installation. Another modification that may be worthwhile considering is activating the dry center wing bay as a 10,000 U.S. gallon (37,850 liters) fuel tank, which significantly improves tanker offload and range performance.

1.2.3 *Other Civilian Transport Conversion*

An almost traditional route to acquiring tankers has been the modification of commercial passenger jet transports, either first generation narrow-bodied aircraft (e.g., Boeing 707, Douglas DC-8) or second generation wide-bodies (e.g., L heed L-1011, Douglas DC-10). Also, all the survivı , major airframe producers (including those in the former Soviet Union) would be happy to sell any of their new jets to governments interested in modifying them into tankers.

1.2.4 *New Tanker/Transport Aircraft Development*

The last option, because it would be the most expensive, is to design, develop, and produce a wholly new tanker aircraft. If a new cargo transport is to be developed, such as the current European Future Large Aircraft (FLA) program, then air refueling features are included because of the necessity of making any new military airframe capable of multi-role utilization.

### 1.3 Capabilities Analysis

This analysis determines functional and performance strengths and shortfalls of the candidate airframes and interfacing systems relative to the required air refueling capabilities specified in the Mission Needs Statement.

1.3.1 *Candidate Airframe Functional Capabilities*

In this task the suitability of the candidate airframe to accept tanker mission-specific modifications are evaluated. Again, the extent of these modifications are dependent on the receivers to be refueled (probe and/or receptacle equipped), and the need to augment basic performance (such as supplemental fuel tanks, or new, higher performance engines).

1.3.2 *Candidate Airframe Performance Comparison*

Once candidate airframes have been sufficiently defined, then their performance can be assessed against those Measures of Effectiveness that have been selected as most appropriate in Task 1 (Section 1.1.2).

1.3.3 *Candidate Airframe Survivability*

If threat environments are a serious concern, then the capability of the candidate aircraft to survive that environment, using either built-in hardening, counter measure suites, or tactics, is evaluated against the threats defined in Task 1 (Section 1.1.1)

Unlike commercial transports, some military aircraft, such as the new USAF C-17 have been designed from inception to "go in harm's way." The C-17 design incorporated survivability features, including fuel tank inerting (the Onboard Inert Gas Generator System) and component separation, which help harden the aircraft against conventional weapons such as armor piercing and high explosive projectiles. In addition, structural design for low altitude penetration capability reduces aircraft detectability and exposure to hostile fire.

### 1.4 Enhancements Analysis

The Enhancements Analysis addresses significant shortfalls, if any, identified in Task 3, and defines those modifications to the candidate airframes deemed necessary to complete the specific tanker mission flight profiles and operational functions. This includes enhancing tanker survivability.

1.4.1 *Modifications Required*

It may be determined that surviving candidate airframes may need further modifications in one of the following areas to meet mandated design goals:

1. Function Enhancements

Examples of functional enhancements (see Section 1.1.3 and 1.3.1) are improvement in fuel transfer rate, adding multi-point air refueling capability, adding cargo handling equipment (e.g., rollers on the main deck floor or a large cargo door), or provisions for medical evacuation.

2. Performance Enhancements

Examples of these enhancements are anything that improves the candidate airframe's performance when measured against the selected measures of effectiveness of Task 1 (see Section 1.1.2 and 1.3.2)

3. Survivability Enhancements

Given inputs from scenarios, mission profiles, projected threat environment, and the initial susceptibility and vulnerability analyses, it may be necessary to consider further survivability features. One example is the addition of special counter-measure pods or installations.

1.4.2 *Modified Aircraft Capabilities*

If the candidate airframe has been modified, it then must be re-evaluated in each affected area:

1. Functional Capabilities
2. Performance Capabilities
3. Survivability

**1.5 Solution Concepts**

Candidate aircraft that meet, or can be modified to meet, the tanker system requirements are proposed. Performance improvement trade-offs, technical risk, life cycle cost, and effectiveness analyses on those systems and/or design changes are also evaluated during this study phase.

1.5.1 *Candidate Tanker/Transport Systems*

In this step in the process, candidate aircraft should be evaluated in the following major areas to determine the program finalist(s):

1. Performance Capabilities Comparisons
2. Technical Risk Comparisons
3. Life Cycle Cost Comparisons

1.5.2 *Recommended System*

Finally, if the design office has a clearly superior candidate, it will probably have to produce reports for higher levels recommending the candidate airframe and the program for its acquisition and introduction to operational service.

**[or]**

1.5.3 *Re-Evaluate Candidates*

At this point the responsible design office may chose to re-evaluate surviving candidate systems by iterating through Tasks 3, 4, and 5. Maybe even revisiting Task 2 to find more capable (or lest costly) alternatives.

**2. TANKER TECHNOLOGY PLANS DEFINITION**

Technology requirements considerations for future tanker capabilities are shown on Figures 10 and 11. Requirements (the Work Breakdown Structure (WBS) elements) have been collected from U.S. Air Force and DoD agencies, and from discussions at various Aerial Refueling Systems Advisory Group meetings. (ARSAG is a Congressionally chartered organization chaired by Headquarters AMC (Air Mobility Command) to deal with Air Force, DoD inter-service and international aerial refueling technical and operational issues.)

Programs listed in the next column are representative of those that either have, or will require, that particular technology. The programs listed are not complete nor comprehensive, simply best guesses at representative ones.

The 'Technology Status' entries are estimates of whether efforts have been, or are being conducted in one of the four USAF AFMC (Air Force Material Command) budget categories:

1. Research
2. Exploratory Development
3. Advanced Development
4. Engineering and Manufacturing Development

In this example, entries in category 4 may also be for advanced technology elements that are out of development and either in production or operational, but may not be generally available.

At this point in time, the status of technology activities, indicated by a 'X' in one or more of the four categories, are best estimates by a McDonnell Douglas study team in the course of performing the study of Reference 1. These need to be reviewed and updated by the tanker community, or by a tanker program office, if and when a new program is initiated.

The 'Priority' entry field is blank in this example, but could be a numeric rating (for example, from 1 to 10, 1 being highest priority). This could be used by the responsible program office to set overall research and development activity priorities as they apply to the needs of a specific tanker program.

Treated as "living documents," these charts can provide a long range planning tool for defining, setting priorities, funding, contracting and controlling future tanker research and development activities.

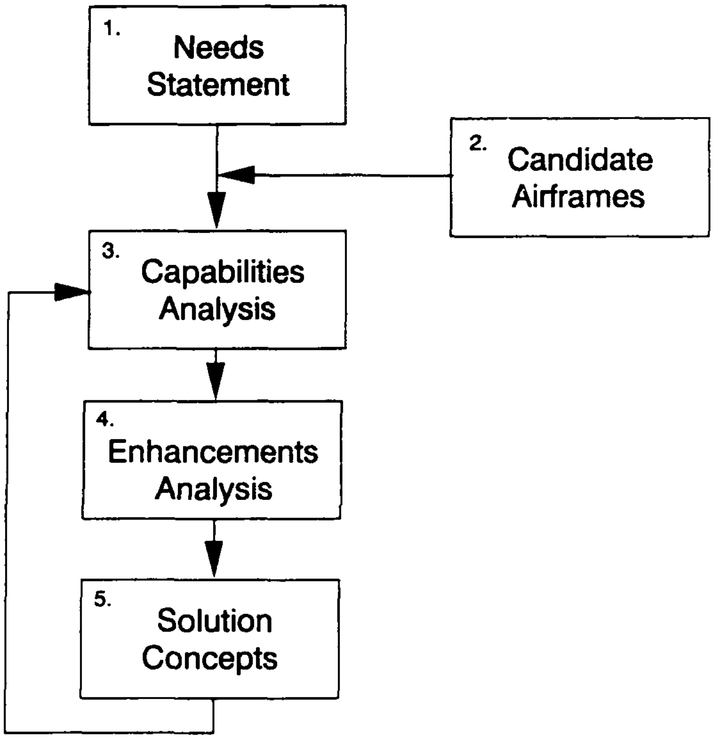



**Figure 1. Tanker System Requirements Development Task Flow**

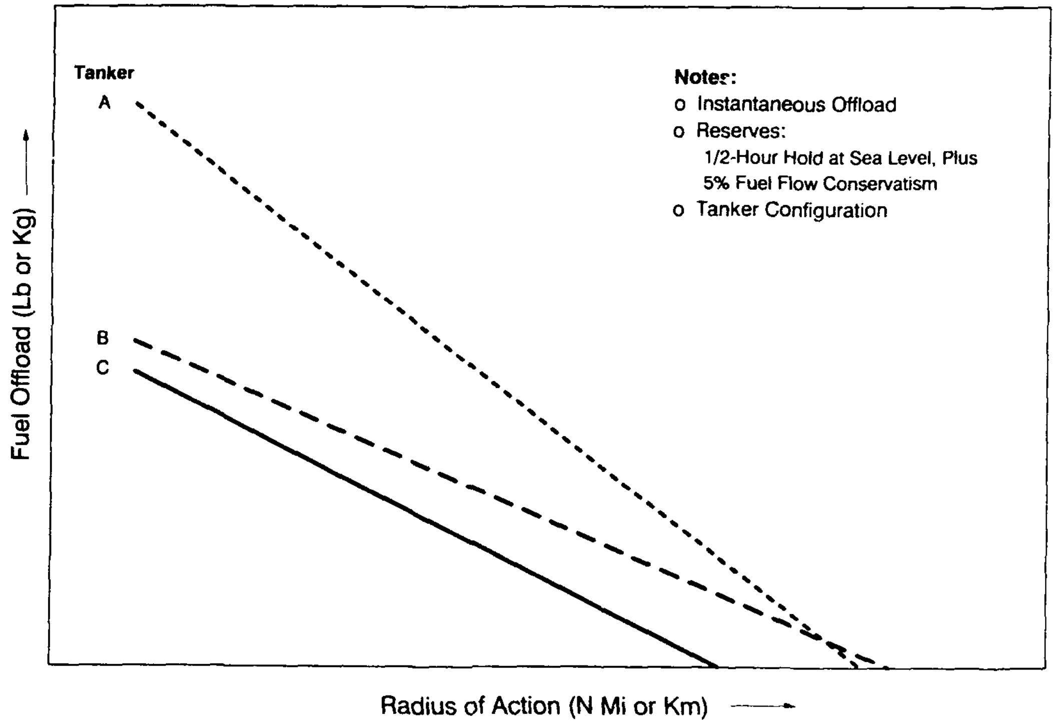



**Figure 2. Offload vs. Radius-of-Action Example**

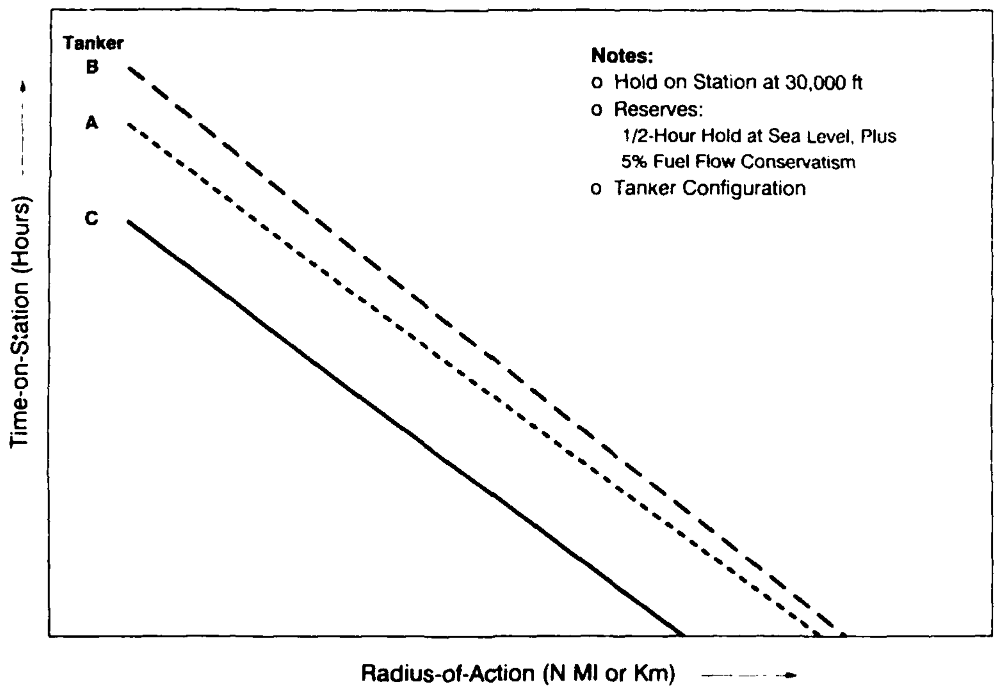



**Figure 3. Time-on-Station vs Radius-of-Action Example**

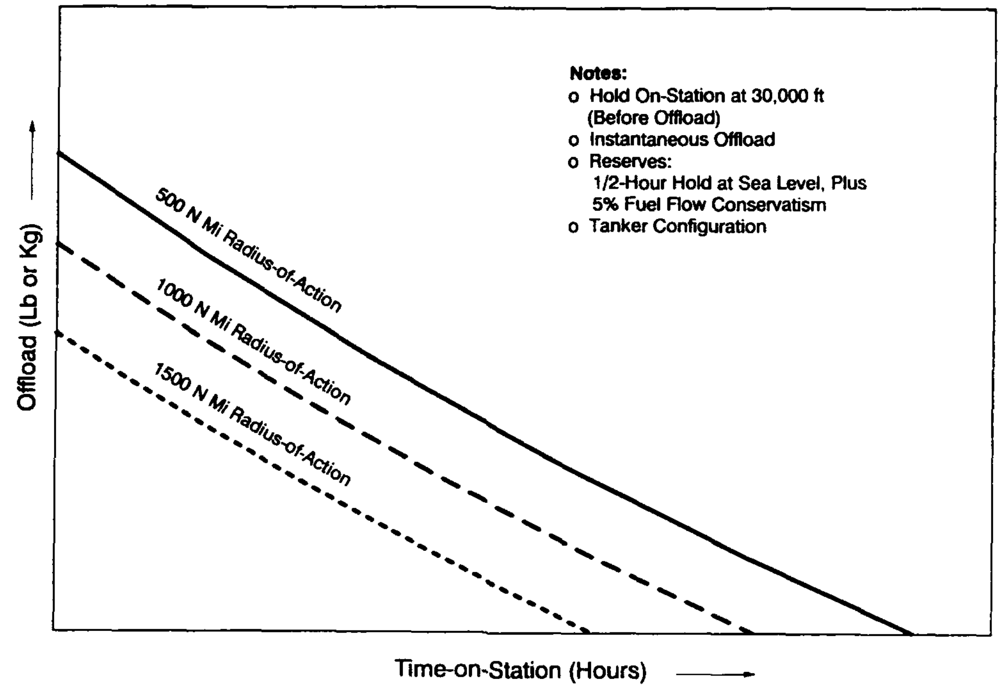



**Figure 4. Offload vs. ToS vs. RoA Example**

A4.DRW 05/01/93

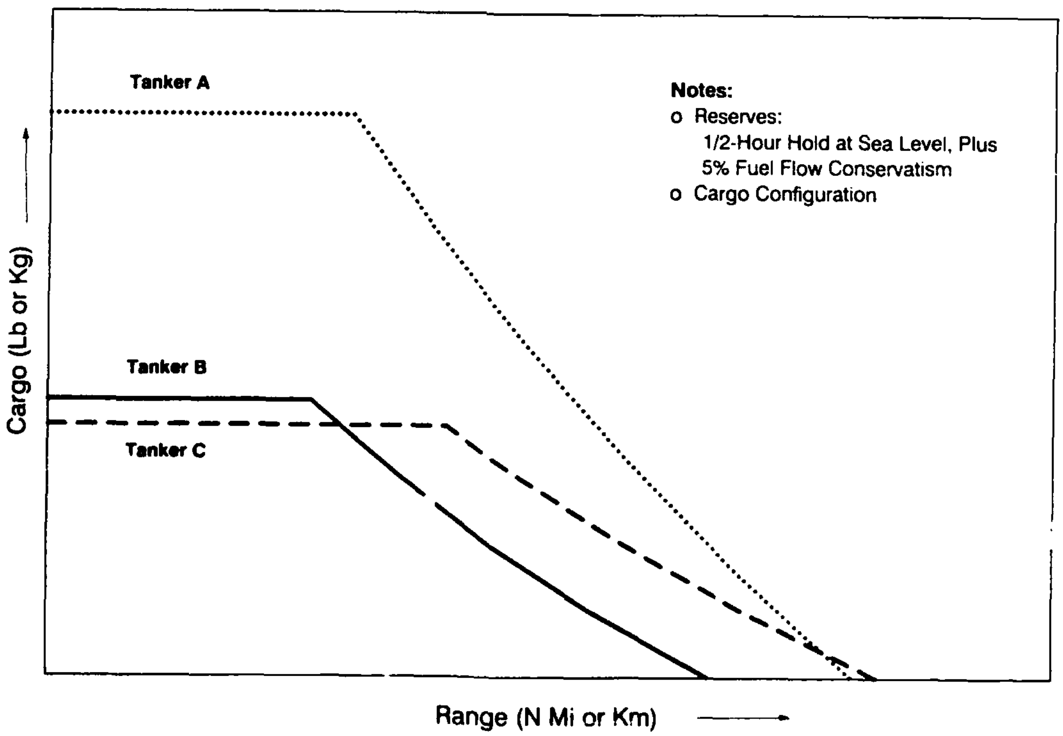



**Figure 5. Payload vs. Range Example**

A5.DRW 05/01/93

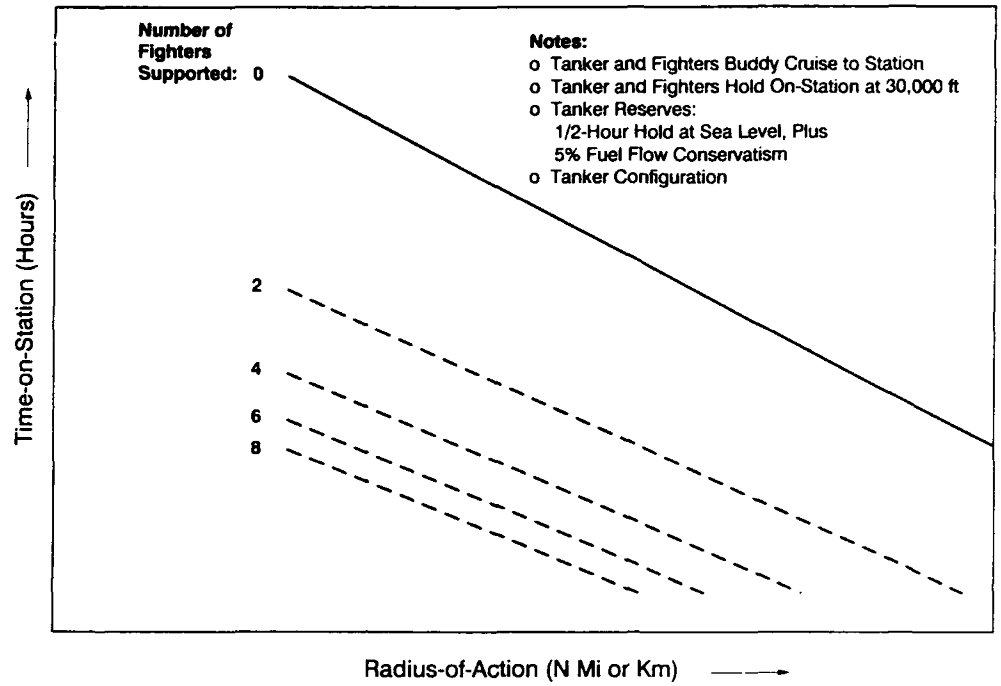



**Figure 6. No. of Receivers Supported vs. ToS vs. RoA Example**

AL DRW 05/01/93

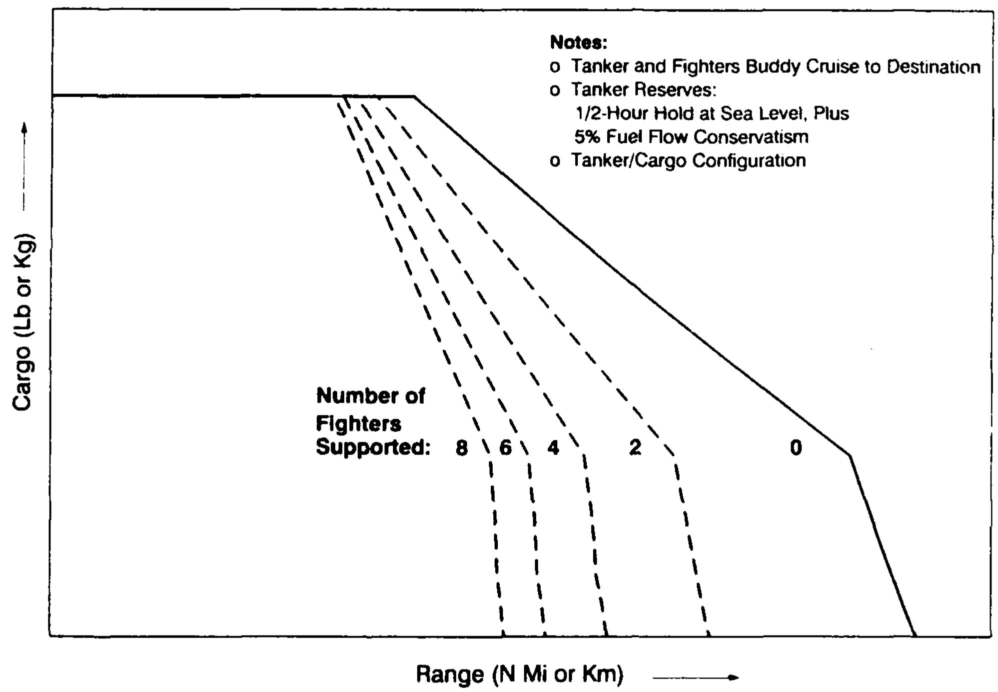



**Figure 7. No. of Receivers Supported vs. Payload vs. Range Example**

A1 DRW 05/01/93

| | TANKER/TRANSPORT KDC-10-30CF | FIGHTER F-16A |
|---|---|---|
| CONFIGURATION | CENTERLINE BOOM<br>CARGO & PASSENGER PROVISIONS<br>NO SUPPLEMENTAL FUEL | (2) AIM-9<br>(2) 370 U.S. GAL. FUEL TANKS |
| WEIGHTS (LB) | | |
| TAKE OFF GROSS WEIGHT | 565,000 | 30,200 |
| OPERATING EMPTY WEIGHT | 250,000 | 18,400 |
| MAX ALLOWABLE CARGO | 151,000 | - |
| MAX FUEL LOAD | 240,000 | 11,800 |
| MISSION PLANNING | MISSION RULES: | |
| RESERVES (LB) | 20,000 LB RESERVES<br>5% FUEL FLOW CONSERVATISM | 2,400<br>0% |
| ENROUTE WINDS | 90% WORST ANNUAL | |
| CRUISE/REFUELING FLIGHT CONDITIONS | | |
| ALTITUDE (FT) | 28,000 | |
| AIRSPEED | MACH 0.82 (487 KTAS) | |
| FUEL TRANSFER RATE (LB/MIN) | 3,000 | |
| FORMATION TIME (MIN/FIGHTER) | 2 | |

**Figure 8. Fighter Deployment Mission Ground Rules and Assumptions Example**

RNLAF F-16 DEPLOYMENT TWENTHE AB TO GOOSE BAY, CANADA

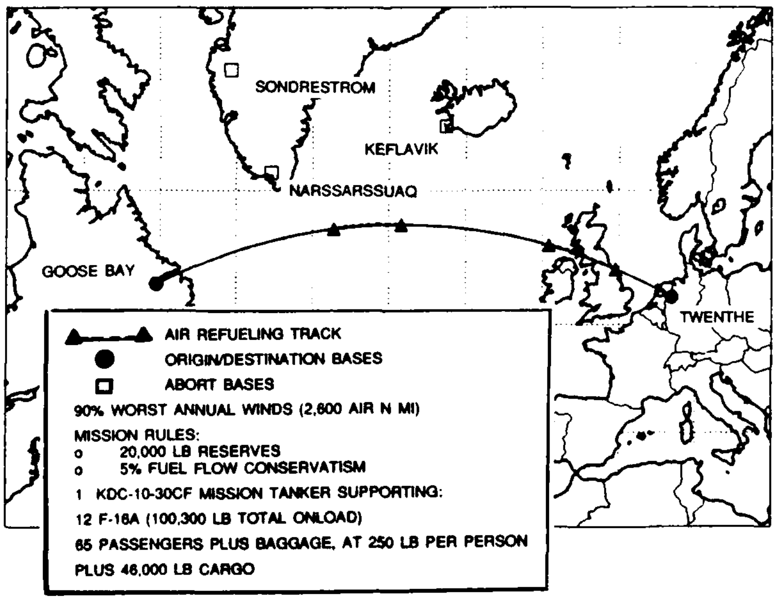



**Figure 9. Fighter Deployment Mission Example**

| Work Breakdown Structure (WBS) Element | Programs | Technology Status | | | | Priority |
|---|---|---|---|---|---|---|
| | | Research | Exploratory Development | Advanced Development | Engineering & Manufacturing Development * | |
| 1000 Advanced Boom Systems | | | | | | |
| 1100 Boom | | | | | | |
| 1110 High Transfer Rates | KC-10 | | | | X | |
| 1120 Fly-by-Wire Control | KC-10 | | | | X | |
| 1200 Boom Control Station | | | | | | |
| 1210 Direct View | | | | | | |
| 1211 Operator Prone | KC-135 | | | | X | |
| 1212 Operator Seated | KC-10 | | | | X | |
| 1220 Remote View (Remote Air Refueling Operator (RARO) Station) | KDC-10 | | | X | | |
| 1300 Refueling Envelope Expansion | KC-10 | | | | X | |
| 1400 Automatic Hookup | | X | | | | |
| 2000 Adv. Hose/Drogue Systems | | | | | | |
| 2100 Installation/Location | | | | | | |
| 2110 Fuselage-Mounted | | | | | | |
| 2111 Interior | RAF L-1011 | | | | X | |
| 2112 Exterior Pods | CIS Tanker | | | | X | |
| 2120 Wing-Mounted Pods | KC-10 | | | | X | |
| 2200 Control Displays | RAF L-1011 | | | | X | |
| 2300 High Transfer Rates | RAF L-1011 | | | | X | |
| 2400 Variable Speed Basket | KC-130 | | | X | | |
| 2500 Self-Stabilizing Basket | | | X | | | |
| 2600 Automatic Hookup (Homing Basket) | | X | | | | |

* Note: Entries in this column may also be operational.

Figure 10. Tanker Technology Requirements Example (1 of 2)

A10.DRW 05/01/93

| Work Breakdown Structure (WBS) Element | Programs | Technology Status | | | | Priority |
|---|---|---|---|---|---|---|
| | | Research | Exploratory Development | Advanced Development | Engineering & Manufacturing Development * | |
| 3000 Multi-Point Refueling | | | | | | |
| 3100 Boom System | | X | | | | |
| 3200 Hose/Drogue Systems | KC-130 | | | | X | |
| 3300 Both Systems (Inflight Selectable) | KC-10 | | | | X | |
| 4000 Supplemental Fuel Tanks | | | | | | |
| 4100 Lower Fuselage | KC-10 | | | | X | |
| 4200 Main Deck | KC-130 | | | | X | |
| 4300 Wing Pods | KC-130 | | | | X | |
| 4400 Automatic Fuel Transfer With CG Control | C-17 | | | | X | |
| 5000 Air Refuelable Tanker | | | | | | |
| 5100 Receptacle System | KC-10 | | | | X | |
| 5200 Probe System | RAF L-1011 | | | | X | |
| 5300 Both Systems | FLA | | X | | | |
| 5400 Reverse Air Refueling | | | | | | |
| 5410 Boom/Receptacle | KC-10 | | | | X | |
| 5420 Hose/Drogue/Probe | | X | | | | |
| 6000 Automatic Rendezvous | | | | | | |
| 6100 Inverse TACAN | KC-10 | | | | X | |
| 6200 Radio Emission Controlled (EMCON) Operations | | X | | | | |
| 7000 Inflight Survivability | | | | | | |
| 7100 Fuel Tank Inerting | C-17 | | | | X | |
| 7200 Aircraft Hardening | C-17 | | | | X | |
| 7300 Countermeasure Suites | USMC KC-130 | | | | X | |
| – etc. – | | | | | | |

* Note: Entries in this column may also be operational.

Figure 11. Tanker Technology Requirements Example (2 of 2)

A11.DRW 05/01/93

VARIABLE GEOMETRY DROGUE
**Fixed and Rotary Wing Aerial Refueling**
The US Marine Corps uses KC-130 tankers in a dual role refueling both fixed wing and rotary wing aircraft. Because

the receiver airplane prob. to latch into the reception coupling is degraded without some amount of static load. Also, drogue drag needs to be higher than take-up tension to overcome breakout plus friction in the reel. Otherwise, in range disconnects can occur, which result in the drogue remaining in a position not fully extended. The upper



# HOSE- DROGUE VS BOOM RECEPTACLE AIR REFUELING


by

**Donald Copeland**
Frontier Technology, Inc.
530 E. Montecito Street, Suite 105
Santa Barbara, California 93103-3245 USA

**Thomas McConnell, Lt. Colonel U.S. Air Force**
ASC/SDCA Building 16
Wright-Patterson AFB, Ohio 45433-6503 USA


## BACKGROUND

The basis of this paper is analyses performed by Frontier Technology, Inc. for the USAF. Frontier has performed evaluations of multiple tanker candidates to supplement and to eventually replace the KC-135 tanker fleet. The analyses included tanker refueling support for six mission areas; (1) theater employment of combat fighter aircraft, (2) intercontinental fighter deployments, (3) extended offshore range of naval carrier operations, (4) intercontinental airlift, (5) North American air defense, and (6) long range nuclear warfare.

The characteristic airborne refueling needs of the six missions are somewhat different. The first mission listed, theater employment of combat fighter aircraft, is characteristically different from the other areas in that it stresses the need to refuel more aircraft over shorter periods of time than the other five mission demands except for some situations in air defense support. In theater employment operations the demands of the larger tanker aircraft are stressed the most when waves of aircraft attack during short periods of time in the attempt to overwhelm enemy defenses. This tanker demand is in contrast to that of the nuclear warfare mission which requires large amounts of fuel for a single receiver (bomber) aircraft on a lengthy mission where the precise refueling time is not critical.

## SELECTED PAST WORK

### "Air Refueling Systems Development Plan" (ARSDP)

Frontier performed this extensive analysis effort for the USAF to examine future tanker requirements, options to supplement the KC-135, identify the best aircraft alternative(s) to replace the KC-135, and examine several technology options for future tankers. This analysis was done across the six mission areas listed above. The analysis focus was towards cost effectiveness. Costs were broken into acquisition, operations, and support costs. Five new candidate tanker aircraft were evaluated in this effort. They consisted of derivatives of commercial aircraft. The commercial aircraft considered were: Boeing's 757-200, 767-200, 747-400, a highly modified 767-200 called the 767-200LR, and Douglas' MD-11. Sensitivity analysis was performed to examine the cost benefits of adding hose-drogue pods to the candidate tankers. This addition became known as the "Multipoint" refueling system.

### "Air Refueling Multipoint Analysis"

This work involved performing a cost effectiveness evaluation of various air refueling pod configurations, which have different pumping rate capabilities. The analysis included modeling wartime scenarios accounting for realistic aircraft timing, receiver aircraft fuel system back pressure, aircraft fuel burn rates for all phases of flight, tanker modification costs, refueling pod acquisition costs, and operations and support costs. The span of refueling pod pumping capabilities evaluated ranged from 1,500 to 3,000 liters per minute (400 to 800 gallons per minute).

### "Tanker Alternatives for Royal Saudi Arabian Air Force"

Frontier performed this work to evaluate the most cost effective tanker for the Royal Saudi Arabian Air Force (RSAF). Considered were existing tanker aircraft, receiver aircraft inventory and planned receiver aircraft buys, local

*Presented at an AGARD Meeting on 'Recent Advances in Long Range and Long Endurance Operation of Aircraft', May 1993.*

geography, unique RSAF cost issues, and other RSAF unique concerns.

## Hose-Drogue versus Boom Receptacle Air Refueling

Among other issues presented by Mr. Lavon Jordan of Frontier Technology, Inc. this morning was the hose-drogue and boom receptacle compatibility issues of receiver aircraft and tankers. Mr. Jordan presented the advantages of a single tanker being able to refuel both types of receiver aircraft on a single refueling mission. Figure 1, "Multipoint KC-135R is Compatible with Allied & USN Receivers" shows that the multipoint tanker has no interoperability limitations for refueling probe equipped receivers of NATO, USN, Freeworld International aircraft and receptacle equipped US Air Force aircraft.

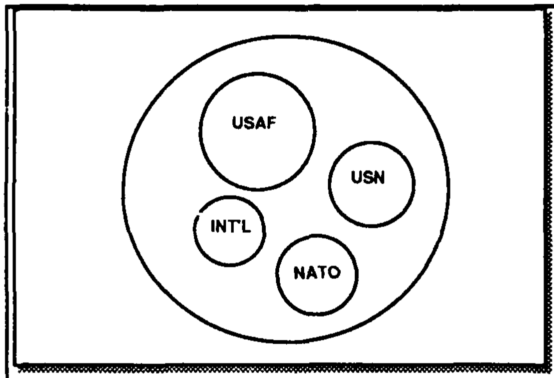



**FIGURE 1. MULTIPOINT KC-135R IS COMPATIBLE WITH ALLIED & USN RECEIVERS**

The purpose of this presentation is to contrast the operational performance of tanker aircraft having two wing mounted hose-drogue pod systems in addition to a refueling boom versus tanker aircraft which are equipped with only a single boom system, Figure 2.

- PREVIOUS PRESENTATION ESTABLISHED:
  MULTIPOINT PROVIDES IMPORTANT INTEROPERABILITY
- QUANTIFICATION OF MULTIPOINT BENEFITS WILL NOW BE PRESENTED
  - EFFICIENCY FOR REFUELING INDIVIDUAL STRIKE PACKAGES
  - EFFICIENCY IN OVERALL THEATER OPERATIONS

**FIGURE 2. PURPOSE**

The boom can be fitted with a short hose drogue while the aircraft is on the ground. In this case the aircraft cannot refuel receiver aircraft which are equipped with a receptacle (for the boom), Figure 3.

- MULTIPOINT: TANKERS WITH 2 WING MOUNTED HOSE-DROGUE POD SYSTEMS + BOOM
- SINGLEPOINT: TANKER WITH A SINGLE BOOM WHICH CAN BE RECONFIGURED ON THE GROUND WITH A SHORT HOSE AND DROGUE, CALLED A "BOOM DROGUE ADAPTER" (BDA) KIT PLUS A RECEPTACLE FOR TANKER TO TANKER REFUELING

**FIGURE 3. DEFINITIONS USED**

These two configurations are applicable to the US Air Force's KC-135 tanker fleet. KC-135 aircraft are currently equipped with a single refueling boom which can be fitted with a short hose-drogue kit. The US Air Force is considering retrofitting a fraction of the aircraft with wing mounted refueling pods. This paper will contrast multipoint vs single point at two levels, Figure 4.

- INTEROPERABILITY - PREVIOUS PAPER BY L. JORDAN
- SHORTER REFUELING CYCLES
  - CAN BE CRITICAL FOR RETURNING AIRCRAFT
  - MORE EFFICIENTLY SUPPORTS ATTACK WAVES
  - INCREASES RANGE OF INDIVIDUAL STRIKE PACKAGES
- MORE RECEIVER SORTIES SERVICED BY EACH TANKER (IN HIGH TEMPO OPERATIONS)
- CAN REDUCE AIRSPACE REQUIREMENTS

**FIGURE 4. BENEFITS OF MULTIPOINT**

The first is for a single strike package of aircraft. The second is an overall theater comparison. Shorter or quicker refueling cycles are a main advantage of multipoint. The reduced time to refuel multiple aircraft is derived from refueling two aircraft at a time. The increased speed at which refueling can be done is especially important to receiver aircraft returning from action low on fuel. These aircraft in flights of multiple aircraft commonly need fuel in a short period of time to prevent diverting to an unplanned air base. A diversion would lengthen the time until the next sortie could be flown by that particular aircraft.

## Comparisons Based on Refueling a Single Strike Package

Figure 5 contrasts time to refuel strike packages of the three sizes indicated. The basis of the calculations include; a queuing time of two minutes between aircraft contacts, a pumping rate of 450 gallons per minutes (1700 liters per minute) for single point and 400 gallons per minute (1500 liters per minute) for each of the multipoint refueling pods, and a fuel transfer of 8,350 lb. (3,788 kilograms). The figure shows that the multipoint tanker can refuel the strike packages in about one half the time of the single point tanker.

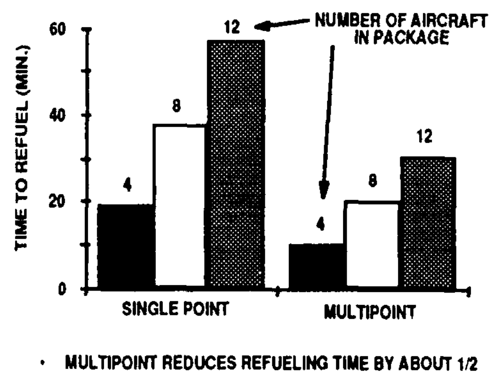



FIGURE 5. MULTIPOINT IMPROVES STRIKE PACKAGE REFUELING TIME

There has been considerable discussion in the US over whether the multipoint queuing process is faster or slower than the single point boom operation. Factors such as pilot proficiency for the technique used and receiver rendezvous techniques are a part of this question. Figure 6 shows that multipoint is less sensitive to queuing time variances than single point. This figure shows results similar to the previous figure using queuing times of 1.5 minutes and 3 minutes. A significant point to be made is that receivers are refueled faster using multipoint than single point, even when a multipoint queuing time is double that of single point (3 minutes vs 1.5 minutes for single point). This is because the fuel pumping rate for multipoint is nearly double that of the single point rate.

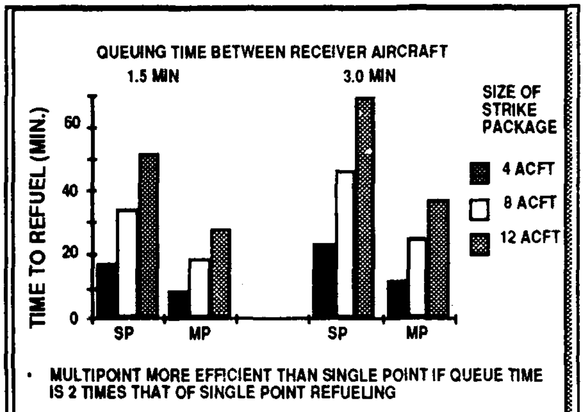



FIGURE 6. MULTIPOINT IMPROVES STRIKE PACKAGE REFUELING TIME

Fighter strike package range is affected by the period of time used waiting for the entire strike package to be refueled. The first aircraft to be refueled has the least quantity of fuel at the end of the refueling process. The entire package is limited in range by the aircraft with the least fuel. The more aircraft in the strike package, the longer the wait and the greater quantity of fuel burned by the first aircraft prior to departing the refueling area. Figure 7 shows the relationship of mission radius, which is on the left, to single and multipoint refueling based on the number of aircraft in the strike package. This figure also shows that multipoint provides a significant decrease in range penalty over that of single point refueling times.

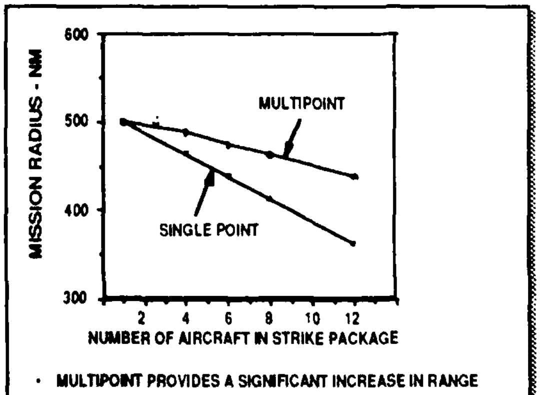



FIGURE 7. FIGHTER RANGE REDUCTION DUE TO REFUELING TIME

Commonly when strike packages are refueled, the first aircraft to be refueled is refueled again, that is after the last aircraft in the package queue. This does provide some increase in range for the entire package. In fact all the aircraft could be refueled again. This could be repeated again. However additional refueling continues to delay the implementation of the offensive portion of the mission. Figure 8 shows the benefit of refueling the first aircraft a second time. The benefit is greatest for the 12 aircraft strike package size. The major point to be made is that the benefit of a second refueling of the first aircraft is insignificant compared to the range benefit of using multipoint.

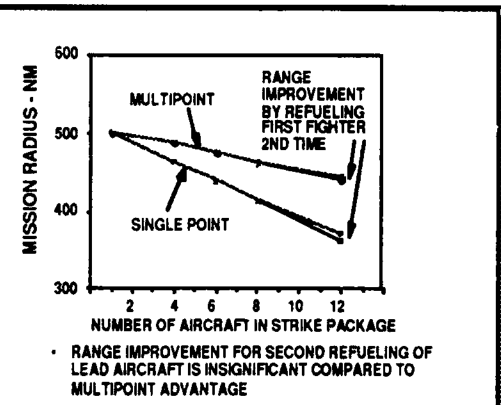



FIGURE 8. FIGHTER RANGE REDUCTION DUE TO REFUELING TIME

## Overall Theater Comparisons

This portion of the presentation discusses the overall differences in capabilities of multipoint and single point refueling operations in a theater scenario, Figure 9.

- INTEROPERABILITY - PREVIOUS PAPER BY L JORDAN
- SHORTER REFUELING CYCLES
  - CAN BE CRITICAL FOR RETURNING AIRCRAFT
  - MORE EFFICIENTLY SUPPORTS ATTACK WAVES
  - INCREASES RANGE OF INDIVIDUAL STRIKE PACKAGES
- MORE RECEIVER SORTIES SERVICED BY EACH TANKER (IN HIGH TEMPO OPERATIONS)
- CAN REDUCE AIRSPACE REQUIREMENTS

FIGURE 9. BENEFITS OF MULTIPOINT

We generate the fuel demand based on a representative theater combat situation, Figure 10. This is based on scenario development and receiver aircraft characteristics. Tanker performance characteristics used in the modeling include takeoff fuel, tanker burn rates, offload pumping rates, refueling equipment reliability, and aircraft ground servicing times. The TacRefueler model is used to determine number of tankers needed by tanker configuration, fuel required by time, tanker sorties required by time, and sorties per day flown by each tanker.

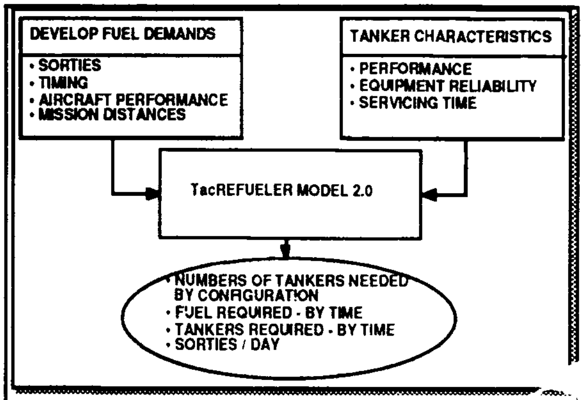



FIGURE 10. APPROACH FOR THEATER EMPLOYMENT OPERATIONS

The scenario development, Figure 11, includes items such as force level composition, types of sorties and the proportion of each type of sortie assigned to each aircraft type. Types of sorties include Interdiction, Close Air Support, Offensive Counter Air, and Defensive Counter Air. Sorties are also allocated for day time and night time because of timing consideration differences.

- DETERMINE FORCE LEVEL/COMPOSITION
  - No. OF AIRCRAFT BY TYPE
  - BASING BY AIRCRAFT TYPE
- DETERMINE No. OF SORTIES FOR EACH A/C TYPE TO BE FLOWN BY:
  - MISSION TYPE (OCA, DCA, CAP, INT, CAS, SEAD, SUPPORT)
  - SERVICE OR COUNTRY (USAF, USN, USMC, ALLIES)
- DEFINE REPRESENTATIVE MISSIONS FOR EACH A/C TYPE:
  - RANGE FROM BASE TO AIR REFUELING AREA TO TARGET AREA
  - FLIGHT PROFILE
- DETERMINE FUEL REQUIREMENTS FOR EACH REPRESENTATIVE MISSION
  - CHECK FOR RANGE FEASIBILITY
  - CHECK FOR POST STRIKE REFUELING NEED
- ALLOCATE SORTIES BY A/C TYPE TO REPRESENTATIVE MISSIONS
- SCHEDULE SORTIES BY:
  - % FLOWN IN DAY VS. NIGHT
  - % FLOWN IN WAVES VS. CONTINUOUS OPERATION BY INDIVIDUAL STRIKE PACKAGES

FIGURE 11. SCENARIO DEVELOPMENT METHODOLOGY

Individual sortie timing is generated as shown in Figure 12. The tall spikes show the narrow timing window in which refueling is conducted in support of attack waves. The smaller spikes represent refuelings for the returning aircraft. The lowest levels of refueling at both ends of the chart show a lower concentration of activity at night for this particular scenario.

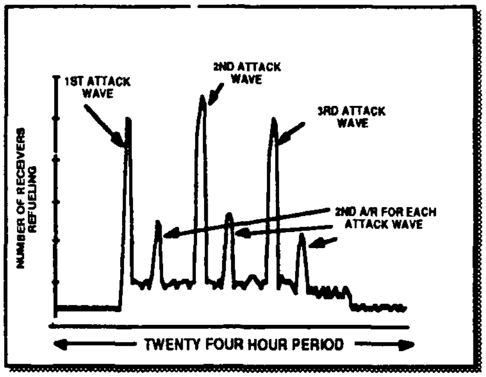



FIGURE 12. RECEIVER REFUELING ACTIVITY VARIES GREATLY WITH TIME

Figure 13 is a typical regional map showing representative locations of major elements of a scenario such as air bases, refueling locations, and target areas. Mission distances from takeoff base are estimated by using target area location and aircraft basing from a map generated for analytical purposes only. A routing factor is added to the straight line mission distances for threat avoidance.

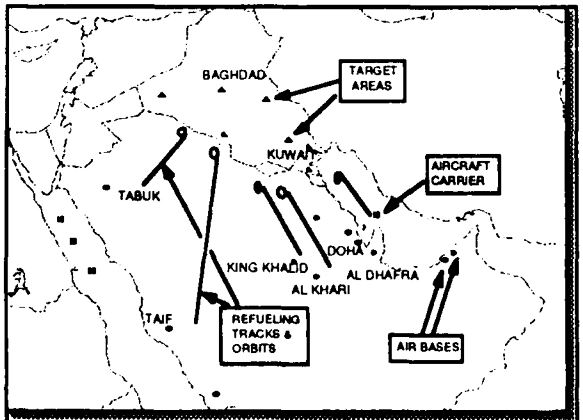



FIGURE 13. REGIONAL MAP FOR ANALYTICAL PURPOSES ONLY

The receiver's fuel burn performance is used for the different phases of flight. These include start engines, takeoff, and climb; high altitude cruise; low altitude ingress; target attack; low altitude egress; high altitude return to base; and reserve fuel required. The fuel demand by time and location is inputted into the TacRefueler model along with the tanker characteristics to determine number of tankers needed to meet the fixed job. Other outputs include fuel required by time, tanker sorties flown by time, tankers in the air at any given time, sorties flown by tanker, and others.

Figure 14 shows an overview of the TacRefueler Model Version 2.0. This version adds the capability to randomize variations in receiver queuing times, aircraft equipment failures, and aborts. It also models the response to these unplanned events based on actual theater situations, such as time to launch a replacement tanker and its time to reach the refueling location. Version 2.0 has provisions to evaluate various tanker and receiver utilization concepts such as refueling using only tracks, only anchors and orbits, or a mix of the two.

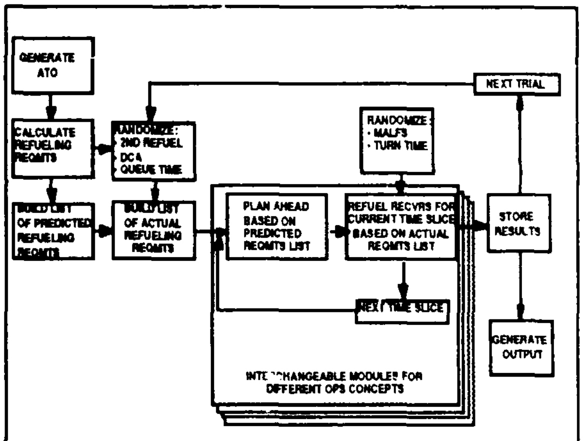



FIGURE 14. FRONTIER's TACREFUELER 2.0 EFFECTIVENESS MODEL

Figure 15 shows the percentage improvement in tanker efficiency in terms of additional strike sorties supported relative to the single point baseline. The improvements shown are for the representative scenario and for attack waves using both one half hour timing and one hour timing. This chart shows that multipoint is more efficient that single point for both attack timings.

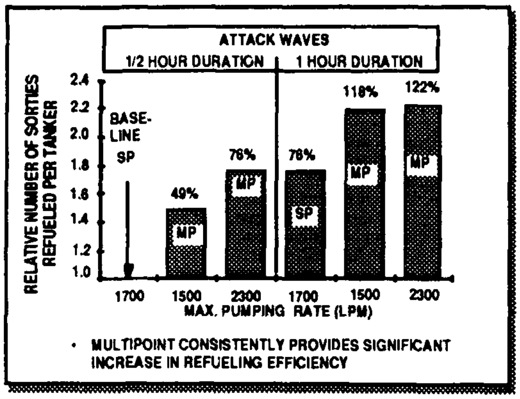



FIGURE 15. SORTIES REFUELED IMPROVEMENT USING MULTIPOINT

Figure 16 contrasts the efficiency of multipoint and singlepoint for a fixed number of tanker aircraft. This is a notional chart which was generated to show the relationships we have seen based on our theater analyses. The left axis represents the number of receiver aircraft refueled. The horizontal axis shows the percent of receivers equipped with probes relative to total receivers. The work Frontier has done, shows that as the percent of probe equipped receivers increases, there is an increase in number of receivers that can be refueled by the fixed tanker fleet size. This increase is dependent on the distances the aircraft have to fly and therefore the individual receivers fuel demand and the fuel the tanker burns. Frontier's experience indicates that this increase in efficiency typically ranges from 25 to 50% greater for the multipoint compared to single point, depending on scenario conditions.

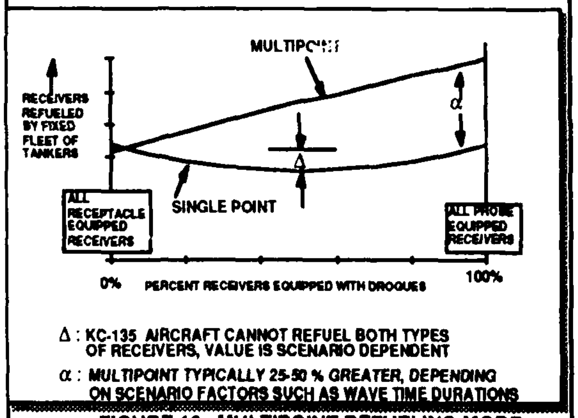



FIGURE 16. MULTIPOINT REFUELING MORE EFFICIENT FOR THEATER OPERATIONS

For the KC-135 equipped with the BDA (single point) the numbers of receivers that can be refueled typically decreases when the receiver fleet is composed of a mix of receptacle and probe equipped aircraft. This is because dedicated tankers are needed for each type receiver. This reduction in performance is not expected for single point tankers which do not need to land to service the two types of receivers. An example is the KC-10A which has a single refueling hose-drogue and a single boom which are both mounted near the centerline of the aircraft. This tanker can use only the boom or the hose-drogue at one time, not both simultaneously.

In summary, Figure 17 shows the benefits that multipoint provides. These include interoperability benefits, shorter refueling cycle times, and more receiver sorties serviced by each tanker in high tempo theater operations. Airspace requirements were not explicitly discussed in this presentation, but by virtue of multipoint's efficiency, airspace can be saved using multipoint because refueling is performed in a more timely manner and larger numbers of receivers can be refueled by the typical tanker using the multipoint concept.

- INTEROPERABILITY - PREVIOUS PAPER BY L. JORDAN
- SHORTER REFUELING CYCLES
  - CAN BE CRITICAL FOR RETURNING AIRCRAFT
  - MORE EFFICIENTLY SUPPORTS ATTACK WAVES
  - INCREASES RANGE OF INDIVIDUAL STRIKE PACKAGES
- MORE RECEIVER SORTIES SERVICED BY EACH TANKER (IN HIGH TEMPO OPERATIONS)
- CAN REDUCE AIRSPACE REQUIREMENTS

FIGURE 17. BENEFITS OF MULTIPOINT

# THE KDC-10 PROGRAMME OF THE ROYAL NETHERLANDS AIR FORCE

by

**Col. Paul R. Brinkgreve**
Training and Transport Aircraft and Helicopter Division
Directorate of Materiel, Royal Netherlands Air Force
P.O. Box 20703
NL-2500 ES
Den Haag
The Netherlands

**Summary**

Replacement of the RNLAF F-27 transport fleet, first mooted in 1984, became a serious option a few years later because of a growing need for AAR capacity. Years of discussion and market research resulted in a requirement for (among others) two DC-10 aircraft to be modified into tanker/transport aircraft. The budget was not sufficient to develop new KMD-11 tanker aircraft, nor did it allow buying existing tanker aircraft. On the basis of earlier programmes from other countries, involving different aircraft, RNLAF decided that it should be possible to modify two DC-10 aircraft into so-called KDC-10 aircraft. With assistance from McDonnell Douglas Aircraft (MDA), four aircraft were selected on the basis of a number of criteria. These aircraft were studied thoroughly. On the basis of condition and price two Martinair DC-10-30 CF aircraft were purchased on 30 June 1992. These will be modified into KDC-10 tanker/transport aircraft.

The RNLAF contracted MDA to study feasibility, timetable and cost of modifying two (Martinair) DC-10-30 CF aircraft into tanker/transport aircraft. The study concluded that the programme was feasible within the proposed time frame, given that USAF would cooperate. Also the total cost estimate could be kept within budget. It was not possible to keep the KC-10 Aerial Refuelling Operator (ARO) station, so a new Remote Aerial Refuelling Operator (RARO) station will have to be developed. The design, however, is not completely new as it has been implemented on other aircraft.

The RNLAF expects the first KDC-10 aircraft to be in service by January 1995, the second to follow approximately three months later. Based on this, the modification of the first aircraft is scheduled to start on 1 July 1994 and of the second in December 1994. Development of the modification programme has already begun. USAF has been requested to assist RNLAF in programme management, contracting and purchasing of certain parts.

**List of abbreviations**

| | | |
|---|---|---|
| ACMI | - | Air Combat Manoeuvring and Instrumentation (Range) |
| ARO | - | Aerial Refuelling Operator (Station) |
| AWACS | - | Airborne Warning and Communication System |
| DAC | - | Douglas Aircraft Company |
| FAA | - | Federal Airworthiness Agency |
| FMS | - | Foreign Military Sales |
| FLA | - | Future Large Aircraft |
| GPS | - | Global Positioning System |
| IFF | - | Identification Friend or Foe |
| KLM | - | Koninklijke Luchtvaart Maatschappij (Royal Dutch Airlines) |
| KSSU | - | (Consortium of) KLM, Swissair, SAS and UTA |
| LOA | - | Letter of Agreement |
| MDA | - | McDonnell Douglas Aircraft |
| NATO | - | North Atlantic Treaty Organisation |
| NLR | - | Nationaal Lucht- en Ruimtevaartlaboratorium (Netherlands Aerospace Laboratory) |
| OR | - | Operations Research |
| RARO | - | Remote Aerial Refuelling Operator (Station) |
| RNLAF | - | Royal Netherlands Air Force |
| TACAN | - | Tactical Air Navigation |
| UHF | - | Ultra High Frequency |
| UN | - | United Nations |
| USAF | - | United States Air Force |
| VTOL | - | Vertical Take-off and Landing |
| WEU | - | Western European Union |

## Historical Overview

1. The RNLAF transport aircraft fleet consists of 12 F-27 Friendship aircraft, i.e. 3 passenger aircraft and 9 troopships, suitable for para drops and/or air transport. The aircraft have been purchased in 1960 as the successor of the famous DC-3 Dakota. Serious discussion on replacement of the F-27 started in 1984 with the announcement thereof in the Defense white paper. A working group was founded to establish the requirements for the new transport aircraft. Among the first candidates taken into consideration were Hercules C-130, Transall

C-160, Fokker F-50, Fokker F-100, Sherpa, Alenia G222 and Casa CN235. These aircraft, with a wide range in payload capacity, could fulfil the transport requirements for fixed wing aircraft. In addition transport helicopters and other VTOL aircraft like the V22 'Osprey' were considered to fulfil the short-range VTOL requirements. However, at that time there was no defined requirement for air refuelling yet. In the discussions establishing the transport requirements, the air refuelling requirement grew gradually, although nobody could really believe the reality of fulfilling this requirement.

2. The ongoing demand for a reduction of aircraft noise around air bases dictated fewer but longer F-16 sorties. As a side effect, this could result in a possibly more cost-effective use of the new Air Combat Manoeuvring and Instrumentation Range (ACMI) to be established over the North Sea. Exporting low-flying activities to less densely populated areas led to an increase in long-distance ferry flights. In addition the United Nations were making more demands on the forces to stage peacekeeping operations. Together these factors emphasize the need for more transportation and air refuelling capability, for which an OR study was considered necessary. The OR study, carried out in cooperation with the National Aerospace Laboratory (NLR), analyzed the requirements mentioned above. As a result of the OR study, four aircraft categories were defined:

a. Category A. Heavy transport aircraft with air refuelling capability and a range of about 4500 km;

b. Category B. Medium-size transport aircraft suitable for operations from improvised airfields and with a range of about 1200 km;

c. Category C. Transport helicopters with a range of about 300 km, and

d. Category D. Aircraft suitable for transport of light cargo and/or a small number of passengers, preferably with a transatlantic capacity.

This presentation will concentrate on the category A heavy transport aircraft with air-refuelling capacity.

3. In a NATO briefing in September 1987 on the mission need for air refuelling capability, the "used aircraft" option was mentioned as one of the possibilities for NATO members to fulfil the air refuelling requirement. And although the tanker capacity required at the time could still be contracted with the USAF, the expected reduction of US Forces in Europe increased the demand for an 'own' tanker capability. However, buying used aircraft was a completely new idea for the Royal Netherlands Air Force, as it probably is for most air forces. Also the size of the tanker aircraft is also much greater than we were used to in our air force.

4. The Mission Need Document of the RNLAF on transport aircraft was accepted by the Ministry of Defense in October 1989 with the authorization to perform a pre-feasibility study based on the transport and air refuelling need of the Netherlands Armed Forces. Primarily this need was based on the deployment of the ACE Mobile Force F-16 Squadron, which resulted in requirements for range and air refuelling. Additional requirements were included for training operations, i.e. low flying in Goose Bay (Canada), air-to-air operations in the ACMI range above the North Sea and, last but not least, for transport of personnel and equipment for (out-of-area) operations under NATO, WEU or UN auspices. In all, the yet-to-be-purchased aircraft are already destined for many missions.

## Pre-Feasibility Study

5. The initial study on the availability of proper aircraft for tanker operations resulted in the following short list:

a. **Boeing KC-135**. The KC-135 is in use with the USAF and other Air Forces but is not in production any more. There were no acceptable KC-135 aircraft available on the market.

b. The **KC-10A** is also in use with the USAF but is also out of production and not available on the used aircraft market. To obtain these aircraft the production line would have to be reopened.

c. **Boeing 707**, a rather old aircraft that did not comply with modern noise and environmental requirements. It was to be expected that modification of this aircraft into an acceptable tanker might become very costly.

d. **Future Large Aircraft (FLA)**, a NATO project for replacement of C-130 Hercules, C-160 Transall and P3 Orion. The availability and cost of the FLA is yet unknown.

e. **Airbus A300B4 and A310**, which could be modified for tanker operations. However, the modification would have to be developed from scratch. This was expected to be a time-consuming and costly affair.

f. **Boeing KE-3**, a tanker derivative of the NATO E-3 AWACS, developed and produced for the Saudi Air Force. To obtain these aircraft the production line would have to be reopened.

g. **KMD-11**, the tanker derivative of the MD-11, was considered to be too expensive for the RNLAF.

h. **DC-10-30**, either as a combi-freighter aircraft (CF) or a passenger aircraft, the latter to be modified into a CF. The DC-10-30CF aircraft could be modified into a tanker by using part of the existing design for the KC-10.

A combination of Fokker F-100 and C-130 Hercules aircraft was also considered but, owing to F-16 air refuelling system and speed requirements, the tanker requirement could not be fulfilled with the proposed combination. In addition the range requirement could not be met with the Fokker F-100.

The pre-feasibility study indicated that used DC-10-30 aircraft, providing they were in excellent technical condition, would be the most cost-effective option for the RNLAF.

## Feasibility Study

6. The RNLAF contracted McDonnell Douglas Aircraft (MDA) to perform a feasibility study on the modification of two DC-10-30CF aircraft into tanker aircraft. The study directive was to provide sufficient information on feasibility, schedule and cost to the RNLAF for parliament approval of the programme.
The approach followed was:

a. Select the baseline aircraft. For study purposes a DC-10-30CF (convertible) aircraft was chosen as the baseline aircraft. This meant that, if a passenger aircraft should be selected, the aircraft would first have to be modified into the convertible configuration.

b. Identify the required changes to modify the baseline aircraft into a tanker aircraft. To a receiving aircraft, the tanker should look like a KC-10A, while leaving as much as possible of the existing aircraft.

c. Conduct a preliminary design of the identified changes, making maximum use of existing KC-10A design.

d. Identify and contact the possible modification centres. The modification centre has to be FAA-certified and approved by MDA.

e. Estimate the time schedule.

f. Estimate the modification costs.

The primary mission of the aircraft should be the aerial refuelling of F-16 and other aircraft with a boom receptacle. Secondary missions will be air transport of cargo and/or passengers.

7. The study concluded that:

a. the programme was feasible;

b. the estimated cost could be kept within the given budget;

c. the desired delivery schedule could be achieved under the following conditions:

(1) Engineering and procurement should start no later than July 1992;

(2) Approval to proceed should come no later than October 1992;

(3) The first DC-10-30CF should be at the modification centre by May 1994;

(4) The booms must be available.

8. The KC-10A has an Aerial Refuelling Operator (ARO) Station in the specially redesigned tail section of the aircraft. The study found that the construction of such a station in the existing DC-10 would be very costly. Therefore it was proposed to develop a remote station near the flight deck.

The feasibility study was approved by parliament on 28 February 1992, after which the procurement phase began.

**Aircraft Selection**

9. Selection of appropriate aircraft was carried out in two stages. The first stage consisted of a market search on the available DC-10-30 aircraft in passenger, convertible or freight configuration and a first selection based upon given selection criteria. In this stage assistance was sought from experienced agencies like Airclaims and the Used Aircraft Division of Douglas Aircraft Company (DAC). The latter was contracted for assistance in the selection of the aircraft.
The second stage dealt with a thorough technical evaluation of the selected aircraft and a comparison of the main criteria and the price. Also in this stage contract negotiations were started with the selected aircraft companies. Due to the inexperience of the RNLAF in buying used aircraft, a specialised lawyer was contracted for assistance in the contract negotiations. The advice to contracting a specialised lawyer was given by different sources and, although it did not seem obvious that - rather expensive - expertise should be hired, it was decided to follow this advice. How important this was we have learned in the meantime, unfortunately.

10. On the basis of the advice of DAC's Used Aircraft Division a number of general first selection criteria were produced. These selection criteria were:

a. The aircraft should preferably have no more than 60,000 flying hours and 20,000 cycles and definitely no more than 75,000 flying hours and 25,000 cycles;

b. The aircraft should be in excellent technical condition and be maintained according to the latest modification standards. Also the aircraft should have undergone the prescribed aging and anti-corrosion programmes;

c. The engines should meet the Stage 3 noise requirements to comply with Dutch noise regulations.

d. The two aircraft offered should be so-called sister ships, i.e. they had to be in an almost identical configuration and preferably be of a comparable age.

11. Seven companies offered thirteen DC-10 aircraft in passenger or convertible configurations. On the basis of the above criteria, four aircraft from two companies were selected. From the selected aircraft two were in a passenger and two in a convertible configuration. Another two passenger aircraft were chosen as back-up in case the selected aircraft had to be rejected.

12. The four selected aircraft were inspected by MDA. Also the records and modification standards were thoroughly verified. The inspection showed that all four aircraft were in excellent technical condition and suitable for modification into the desired tanker aircraft configuration. The two convertible DC-10 aircraft were from Martinair. The other two aircraft, from British Airways, were in a passenger configuration, which had the disadvantage that they first had to be modified into convertible aircraft. Although this modification is simple it has a price tag, which has to be added to the cost of the basic aircraft. For the RNLAF it was important to purchase the aircraft on short notice because of the modification preparations which had to be carried out in advance. Both companies agreed in the buy-and-lease-back agreement requested for this reason. The lease ends when the aircraft are sent to the modification centre. The price of the British Airways aircraft was extremely attractive. However, together with the necessary extra modification it came out higher than the Martinair aircraft. For this reason the Martinair aircraft were chosen. As a bonus, existing maintenance could possibly be continued. On 30 June 1992 the purchase contract and lease agreement with Martinair were signed by the State Secretary of Defense of the Netherlands. The aircraft type was labelled 'KDC-10' as a combination of KC-10 and DC-10 or Dutch KC-10.

(Note: As is well known, one aircraft was lost in a tragic accident at Faro, Portugal, in December last year. This aircraft has been replaced by another Martinair DC-10 aircraft, as agreed in the contract. Although the replacement aircraft is about one year younger than the lost aircraft, the configuration is identical, so the loss will have minimal implications on the programme.)

## Aircraft Modification

13. With the convertible (CF) configuration as the base line, the aircraft have to be modified to make them suitable for military cargo transport and air refuelling operations, with the exception that the KDC-10 can not be refuelled. Modification will be tailor-made, which means it has to be designed separately for each aircraft. The RNLAF contracted the USAF under the FMS agreement to manage the modification and to provide a number of long-lead items, i.e. the boom system. MDA, as prime contractor, is responsible for the design and delivery of the modification package and for the selection of the modification centre that will carry out the modification. The centre has to be recognised by MDA and certified by the FAA.

14. The major modifications required to convert the DC-10-30CF aircraft into the KDC-10 tanker/transport aircraft are:

a. Installation of a KC-10A centerline boom, hoist, latch and shock absorber;

b. Installation of aerial refuelling pumps on the centre wing tanks and installation of the fuel manifold from the pumps to the boom;

c. Installation of full provisions for wing hose/drogue pods in conformance with a proposed KC-10A modification;

d. Installation of KC-10A rendezvous, director, formation and flood lights;

e. Installation of a palletised remote aerial refuelling operator (RARO) station;

f. Installation of video cameras for the RARO;

g. Installation of military avionics and updating the INS with GPS capability;

h. Installation of interior accommodations for all cargo or 240, 170 or 110 passengers with cargo.

These modifications are the minimum required to make the aircraft suitable for the required military operations. The goal is to maintain as much as possible from the original Martinair DC-10 but to give the receiver aircraft the impression of a KC-10A. Contrary to the KC-10A the RNLAF aircraft will not have an additional fuel tank, owing to the difference in refuelling operations between RNLAF and USAF.

15. For the Aerial Refuelling Operator (ARO) station there was a choice between two options: either constructing the station in accordance with the existing station of the KC-10A in the tail, or building a completely new system with remote video control in the front section near the flight deck. The latter option was chosen because of the high cost involved in modifying the aircraft structure, especially the pressure bulkheads in the rear section. The concept of a Remote Aerial Refuelling Operator (RARO) Station is an existing one; it was implemented earlier on a B-707 but needs to be updated. The integration of the RARO and boom system into a DC-10 is new and has to be developed. The development of the RARO consists of:

a. A two-man console on a pallet located on the main deck just aft of the flight deck;

b. Replicates of the vision and controls and displays of the KC-10 Aerial Refuelling Operator station;

c. Four 19" monitors; three for the operator and one for the instructor. An observer position is not foreseen in the RARO station;

d. A number of video cameras; i.e. a stereo pair for 3-D viewing of the refuelling scene and surveillance cameras for a wing-to-wing panoramic view;

e. The following baseline features:

(1) Any monitor can be switched to any camera;

(2) 3-D viewing is possible on any monitor;

(3) Graphics presentation of boom envelope and other boom information can be done on 3-D view.

The video configuration is still subject to discussion and may therefore still change.

16. The air refuelling boom system is identical to the KC-10A system, however, the boom is not in production any more. To prevent a delay in the programme, the RNLAF will buy the KC-10A boom systems and a few other long-lead items from the USAF; these will be replaced afterwards

by new boom systems from the production line to be reopened.

17. To make the aircraft suitable for military use, the aircraft instrumentation and the freight cabin will be brought up to military standards. Therefore it is necessary to install UHF radios and an extended intercom, IFF, TACAN and provision for GPS. The cabin height will be brought up to the height of the freight door, which is 102". This is the same as the cabin height of the KC-10A.

It is expected that the modification centre will be selected in the course of this year.

### Maintenance

18. The aircraft are at present maintained by KLM in the KSSU organisation. The RNLAF has the intention to perform only a restricted level-A maintenance on the aircraft. Logistic support and the remaining aircraft and engine maintenance and repair will possibly be contracted to KLM. Configuration management and maintenance of the refuelling system will be contracted via the USAF.

### Certification

19. The KDC-10 will be certified by the FAA as a so-called amended type design of the KC-10A. To this end all modifications will be analyzed with respect to safety and they will be tested when required. The structural integrity will also be analyzed and tested if necessary. MDA is responsible for the acquisition of the type certificate. Certification will be limited to design and modification. Military operations as such are not certified.

### Time schedule

20. After parliamentary approval of the feasibility study on 28 February 1992, the contract for purchase of the two Martinair aircraft was signed by the State Secretary of Defense on 30 June 1992. The aircraft was transferred to the RNLAF on 3 August 1993. The LOA between USAF and RNLAF on the modification and delivery of long-lead items was signed on 31 August 1992. The letter contract between USAF and MDA on the design of the modification was signed on 9 February 1993. The definition of the aircraft specification and the attendant modification design is in progress. The modification centre is expected be selected within a few months, after which the contract between this centre and MDA can be signed. A contract for maintenance of the aircraft is under negotiation with KLM. A LOA on follow-on support from the USAF was signed on 31 March 1993. In this contract the maintenance of the refuelling system and the configuration management will be established. Negotiations on flight crew and maintenance crew training are under way. Delivery of the first aircraft to the modification centre is expected in July 1994, the second aircraft following in December 1994, based on in-operation dates of January 1995 for the first aircraft and March 1995 for the second. So far we are still on schedule.

# CC-130H(T) TACTICAL AERIAL REFUELLING TANKER

## DEVELOPMENT FLIGHT TEST PROGRAMME

Captain Andrew Reif, Flight Dynamics
Aerospace Engineering Test Establishment
CFB Cold Lake, Alberta, Canada, T0A 2M0

Major Marc Tremblay, Flight Dynamics
National Defence Headquarters
Ottawa, Ontario, Canada, K1A 0K2

**Summary**

This paper describes the development flight test programme for the CC-130H(T) Tactical Aerial Refuelling Tanker. The Canadian operational requirement is first described, followed by a detailed discussion of the test item, receiver aircraft, and the ground/flight test method and preliminary results. The development is significant since it represents the first certification of the Flight Refuelling Limited Mk 32B refuelling pods on a Hercules aircraft. Further flight testing to be conducted in the near future are also mentioned.

**Abbreviations**

| | |
|---|---|
| AAR | Air-to-Air Refuelling |
| AETE | Aerospace Engineering Test Establishment |
| AGL | Above Ground Level |
| CF | Canadian Forces |
| EMC | Electromagnetic Compatibility |
| FRL | Flight Refuelling Limited |
| FTZ | Fuel Transfer Zone |
| HQR | Handling Qualities Rating |
| LASC | Lockheed Aerospace Systems Corporation |
| LIFT | Lead-in Fighter Trainer |
| KEAS | Knots Equivalent Airspeed |
| KIAS | Knots Indicated Airspeed |
| MTE | Mission Task Element |
| NFTZ | Non Fuel Transfer Zone |
| NWI | North West Industries |
| PA | Pressure Altitude |
| RAT | Ram Air Turbine |
| WS | Wing Station |

**Background**

The Canadian Forces operate a fleet of C130 Hercules aircraft to perform military transport, search and rescue, open-skies verification, support to peacekeeping, and disaster relief missions. The Canadian Forces has recently acquired five C130 H model aircraft which are being configured as tactical air-to-air refuelling (AAR) tankers. The tankers will be used to provide airborne refuelling in support of CF-188 Hornet and CF-116 Freedom Fighter operations primarily for support to long range North America Region Aerospace Defence (NORAD) patrols in the far North. The current Canadian Forces airborne refuelling capability is provided by modified Boeing 707 aircraft.

The tactical tanker aircraft has been designated as the CC-130H(T). The aircraft were modified to accommodate a cargo fuel tank, two wing-mounted fuel dispensing pods, and associated fuel lines. The aircraft were produced by Lockheed Aerospace System Corporation (LASC). The refuelling system is based on the proven KC-130/HC-130 tanker configurations but utilizes the Flight Refuelling Limited (FRL) of Great Britain, Mk 32B-751 refuelling pods. The internal modifications were installed by North West Industries (NWI) in Edmonton Alberta and were based on previous LASC experience. The joint effort represents the first time that the Mk-32B-751 system has been certified for operation on a Hercules aircraft. This paper describes the method and preliminary results of the development test programme.

**Mk 32B-751**

The Mk 32B-751 aerial refuelling pod system was developed by FRL of Great Britain based on FRL Mk32/2800 AAR wing pod.(1) The system utilizes the probe and drogue aerial refuelling concept. The system provides the Canadian Forces with commonality of equipment with the Royal Air Force, the Royal Australian Air Force, and United States Air Force.

The Mk 32B-751 is a state-of-the-art, self contained system which includes built-in test equipment and can be repaired while installed on the wing. The system uses the existing internal wing fuel manifold eliminating an additional fuel line in the wing. The hose reel system uses a fueldraulic/tensator hose drogue auto-response system which eliminates high pressure hydraulics fed from the host aircraft. The pod has a unique ram air turbine that drives a pump for boosting fuel transfer pressure and drives the fueldraulic system. Each hose is capable of delivering 300 gallons per minute at a 50 psi delivery pressure. The hoses are 74 ft long and connect to a soft basket with a Mk 3 drogue coupling. The system is controlled by a software driven electronic control panel mounted overhead at the flight engineer station.

**CC-130H(T)**

The Hercules is an all metal, high-wing, long-range monoplane with a fuselage divided into a cargo compartment and flight deck. The aircraft has 4 Allison T56 turboprop constant-speed engines. The aileron, rudder, and elevator systems are controlled by mechanical systems with hydraulic boost. Trim tabs are controlled by electrical control systems. The auto-pilot, when engaged, controls the main flight control surfaces and elevator trim tabs. The maximum gross weight is 155,000 lbs. Aerodynamic performance will be discussed in detail later in the paper.

The modification components include: two Mk-32B-751 pods and two wing attachment pylons at Wing Station (WS) 330, a 3600 gallon fuselage fuel tank (or roughly 24,000 lbs of fuel), cockpit control panel, internal fuel line plumbing from the fuselage tank to the wing, external lighting, and an aftcabin door intercom panels. A side-view of the aircraft with hoses extended, hose dimensions, and comparison with the Sargeant Fletcher system are shown in Figure 1. The Pod and pylon is shown in Figure 2. The RAT is mounted on the nose of the pod. The fuselage tank and fuel lines are illustrated in Figure 3. The tank fills roughly half of the cargo compartment centered at the wing attachment point. Fuel may also be transferred from the aircraft tanks to the refuelling pods. In addition, the Canadian Forces operate the Hercules with external wing tanks and after body ventral strakes.

The Hercules fleet is heavily tasked so that it was imperative to have the five designated tanker aircraft available for both transport and tanker duties with minimal change-over time. To accomplish this, the design incorporated three possible configurations: tanker, transport, and convertible. The tanker configuration is comprised of all the modification components. The convertible configuration has the fuselage tank removed. The transport configuration has the fuselage tank, pods, and pylons removed. Both the convertible and transport configurations are capable of carrying cargo.

The desired AAR envelope defined by Canadian Forces operational requirements was: 175 KEAS to 250 KEAS from 500 ft AGL to 35,000 ft MSL. Further refinement of the AAR envelope was necessary to accommodate the limitations of the CC-130H(T) and the specific receiver aircraft. These compatibility issues will be discussed throughout this paper.

**Receiver Aircraft**

The Canadian Forces operate two fighter type aircraft which are capable of probe and drogue aerial refuelling: CF-188 Hornet and CF-116 Freedom Fighter.

The CF-188 is the primary fighter for the Canadian Forces and has two variants capable of AAR: the CF-188A (single seat) and CF-188B (dual seat). The aircraft were manufactured by McDonnell Douglas. The roles of the CF-188 are air superiority, interdiction, and ground attack. The aircraft possess a full-authority control augmentation system. Primary flight controls are the ailerons, twin rudders, differential leading and trailing edge flaps, and differential stabilators. Hydraulic actuators position the control surfaces with stick and rudder feel provided by spring cartridges. The refuelling probe on the Hornet is retractable.

The CF-116 is the other fighter aircraft operated by the Canadian Forces and has two variants capable of AAR: the CF-116A (single seat) and the CF-116A/R (reconnaissance single seat). The aircraft were manufactured by Canadair Limited on license from Northrop Corporation. The CF-116D (dual seat) aircraft are not capable of AAR. The CF-116A is used as a 'lead-in fighter/trainer' (LIFT) for the CF-188 Hornet with a secondary role in reconnaissance. The flight controls are hydraulically actuated by two independent systems and have artificial feel to assist the pilot. Stability augmentation is provided in the pitch and yaw axes. The moderately swept back wings incorporate both leading and trailing edge flaps for increased lift and improved slow-airspeed handling characteristics. The refuelling probe is removable but fixed in the extended position when AAR is to be performed.

**Test Responsibilities**

The test programme was a joint effort between LASC and the Canadian Forces. As the prime contractor, LASC had total responsibility for management, production, fitment of the unique systems, and delivery of the tanker aircraft. In addition, LASC was responsible to qualify the airworthiness of all tanker configurations and demonstrate the compliance with relevant specifications. The primary specification for compliance was Mil-A-19736A (3) with exceptions for the unique capabilities of the Hercules.

The category flight test approach is used by the Canadian Forces. This approach is divided into three categories which reflect the phases of test and evaluation. Category I includes all developmental tests and is generally the responsibility of the prime contractor. Canadian Forces personnel may be involved depending on the resources of the contractor. Following Category I testing, the prototype aircraft is accepted by the Canadian Forces and Category II testing is performed by the Aerospace Engineering Test Establishment (AETE) located at Canadian Forces Base Cold Lake in Alberta. The Category II testing includes independent proof of specification compliance and further refinement of the safe operating envelope. Category III testing is comprised of operational tests and in the Canadian Forces this responsibility is generally delegated to the operational group within Air Command, in this case Air Transport Group.

**Category I Test Programme**

The Category I test programme included ground tests of the CC-130H(T), flight tests for airworthiness of the CC-130H(T) modifications, and receiver compatibility testing. The specific tests performed were as follows:

a. Ground Tests:
   (1) structural static loads
   (2) ground vibration
   (3) fuel transfer functionals
   (4) electromagnetic compatibility
b. Airworthiness Flight Tests:
   (1) EMC safety of flight
   (2) flutter
   (3) safe carriage
   (4) performance
   (5) handling qualities
   (6) hose extension/retraction
   (7) hose jettison
c. Receiver Compatibility Tests:
   (1) tanker wake investigation
   (2) hose stability
   (3) CF-188 handling qualities
   (4) CF-116 handling qualities
   (5) night compatibility

LASC planned and conducted the ground and flight testing of the CC-130H(T). Canadian Forces participation during this testing included test observation, some ground tests and the receiver compatibility trials. The Canadian Forces provided the receiver aircraft and test pilots who performed the qualitative evaluations of the receiver handling qualities during AAR. This paper discusses the results of the Category I testing emphasizing the compatibility issues that have placed restrictions on the AAR envelope. The flight test programme was completed with 19 tanker flights for a total of 100 flying hours. A CT-133 Silverstar was used for photo-safety chase for a total of 21 flights or 40 flying hours. A total of 10 CF-116 flights for 20 flying hours and 20 CF-188 flights for 60 flying hours were also required to support the programme. Category II and III testing is ongoing at this time.

**CC-130H(T) Ground Tests**

Ground testing of the CC-130H(T) was conducted at Northwest Industries (NWI) Edmonton. Tests conducted included: proof static loads; ground vibration; fuel transfer; and electromagnetic compatibility.(2)

The structural proof load test was performed to verify the integrity of the pylon installation by applying limit loads and moments at the wing/pylon interface. A dummy refuelling pod was attached to the pylon and served as the means through which the proof loads were applied via five actuator assemblies. Test loads were derived from the aerodynamic, inertia, and hose loads for various aircraft configurations and flight conditions. These loads were combined to provide five critical limit load conditions. Strain gauges were used to verify the strain linearity and that the intensity was within limits. Visual inspection of the pylon installation and aircraft wing in the vicinity of the pylon attachment fitting revealed no damage to any structure.

Ground vibration testing was performed to determine the aircraft/pylon/pod modal characteristics. Landing gear struts were deflated and tire pressures reduced to fifty percent of the standard pressure to lower the rigid body modes below the major structural modes. All flight control surfaces were adjusted and blocked for zero deflection. Shakers were attached vertically and laterally to the pod nose. Symmetrical and anti-symmetrical sine sweeps and modal surveys were performed. The experimental mode shapes and frequencies were compared to analytically derived and measured data for clean and similar configurations. They compared well and the refuelling pod had minimal effect on the basic aircraft modal characteristics.

Steady-state and surge fuel transfer pressures were measured on the ground with several flowrates, dual/single tanker pump operation, and several receiver tank configurations. The tests were performed first with a simulated receiver followed by the CF-116 then the CF-188 aircraft. Tests with the simulated receiver demonstrated an average pod discharge pressure of 107 psig (120 psig limit). The peak pod discharge surge pressure was 255 psig (310 psig limit) at maximum fuel flow. Operating pressures ranged from 38 to 53 psig with surges not exceeding 50 psig (50 +/- 5 psig limit). Tests with the receiver aircraft demonstrated similar pressures.

Electromagnetic compatibility testing was jointly conducted by LASC and AETE personnel. A pre-test frequency coincidence analysis was performed by AETE in efforts to predict likely RF interference. Testing included bonding, electrical power characteristics, conducted/ radiated emissions, and source/victim interaction. Only some minor interferences were observed. One recognized difficulty with EMC testing with the Hercules aircraft has been the applicability of the results for the entire fleet because of differences between avionics configurations.

**CC-130H(T) Flight Tests**

Flight testing of the CC-130H(T) for airworthiness were conducted from Edmonton International Airport by a LASC flight test crew. Tests conducted included: EMC safety of flight test; flutter; safe carriage; performance; handling qualities; hose extension/retraction; and hose jettison tests. (2)

An EMC Safety of Flight Test (SOFT) was conducted on the first flight to corroborate the ground test results. No deficiencies were observed and the aircraft was cleared for IFR flight for the test programme.

A flutter test was performed to demonstrate freedom from any aeroelastic instability throughout the aircraft flight envelope. Stick raps and rudder singlets were performed in each direction to excite the structure at each test condition. Real-time on-board analysis of accelerometer measurements was performed to evaluate the aircraft response. The test proved that the aircraft is free from any aeroelastic instability throughout the flight envelope and that the damping trend in the lowest damped mode shows an increase with airspeed.

Since the wing pods are carried externally, limited stores safe carriage flight tests were conducted. A 30 minute speed soak at maximum level flight airspeeds were conducted at 500 ft AGL or 2,400 ft MSL. A post-flight inspection did not reveal any deficiencies. All other safe carriage test requirements were satisfied by the existing tests.

The drag index of the wing pods and pylons were measured first with the hoses retracted then both extended. Standard weight to pressure ratio test techniques were used. Baseline flight tests were performed before the modification using the same aircraft to make the comparison. Test airspeeds with the hoses retracted ranged from 1.2 Vs to 270 KIAS at 10,000 ft PA and 1.2 Vs to 230 KIAS at 25,000 ft PA. Test airspeeds with the hoses extended ranged from 160 to 250 KIAS at 10,000 ft PA. Test data shows the increased drag to be a constant increment throughout the flight envelope. The contractor determined that the drag index was +19 DI for the pods/pylons and +62 DI with the hoses extended. The after body ventral strakes reduce the drag by -10 DI therefore minimizing the impact of the AAR installation on Hercules performance.

The effects of the modifications on the handling qualities of the Hercules was qualitatively assessed using standard flight test techniques. Weight and center of gravity limits were established for the fuselage fuel tank and mid to aft center of gravity conditions were selected for the tests. Tests conducted by the LASC test crew were static longitudinal and lateral-directional stability, dynamic lateral-directional stability, roll performance, heading change characteristics, trim, and stall characteristics. No degradation or changes were observed due to the installation of the AAR system.

A series of hose extension and retraction tests were performed throughout the planned operating envelope to observe the hose motions and determine the rate at which the hose could be trailed and rewound. The left hose tended to rotate and whip during the first 10-20 ft when near the maximum level flight airspeed above 20,000 ft. Further investigation will be undertaken. The rate for trailing and rewinding the hoses ranged from 17-21 seconds throughout the envelope.

A hose jettison test was conducted to verify the functional operation of the safety feature. The right hose was jettisoned over the Primrose Lake Evaluation Range at 500 ft AGL and 250 KIAS. The hose was cut successfully and separated cleanly from the aircraft.

**AAR Terminology**

Prior to discussing the receiver compatibility phase of the testing it is necessary to define some of the AAR terminology. The complete task of AAR was broken into six mission task elements (MTEs). These MTEs were associated with position or procedure. They were: pre-contact, contact, fuel transfer zone (FTZ), non-FTZ, normal disconnect, and emergency disconnect. A side view of the refuelling positions are illustrated in Figure 4. The normal disconnect procedure required the receiver aircraft to slow down and disconnect when the hose was at full extension. The emergency disconnect procedure was performed by rapidly powering back to idle and descending straight ahead when disconnected.

**Receiver Compatibility**

Receiver compatibility testing was required to define the refuelling envelopes for the CF-188 and CF-116. Definition of the envelope depended on aircraft performance limitations, drogue stability in the wake of the receiver aircraft, receiver handling qualities at the altitude and airspeed conditions, hose stability, and ease of formation with the tanker. The following tests were conducted: tanker wake survey; hose stability test; individual receiver aircraft handling qualities evaluation at each of the AAR MTE described previously in daylight conditions; night compatibility tests; and operational pilot assessments.

Qualitative receiver test pilot observations were gathered to evaluate the workload and compensation required to perform the AAR MTEs. Multiple pilots flew the test points although it was not possible to repeat each specific test point numerous times. The Cooper-Harper Handling Qualities Rating (HQR) system described in reference 4 was used to assist in substantiating the qualitative observations. The HQR procedure detailed in Figure 5 was used to make the assessment of the compensation to perform each task. Task performance for the MTEs were based on time to perform the contact task or for all other tasks, the ability to maintain safe spatial position with respect to the CC-130H(T). The task performance criteria are also shown in Figure 4 for the AAR MTEs. When possible, the MTEs were also evaluated in turbulent conditions rated as either nil, light, moderate, or severe turbulence. All handling qualities testing was performed in daylight conditions.

In addition to test pilot observations, operational pilots flew a number of sorties to provide opinions early in development. Post flight, the operational pilots were asked to complete the following questionnaire:

(1) At what airspeed or range of airspeeds did you feel comfortable making contact? What altitude were you flying?
(2) At any time did you have difficulty controlling the aircraft?
(3) Was the aircraft response sluggish, comfortable, or too sensitive? Any differences due to airspeed?
(4) Did you experience any PIO in pitch, roll, or yaw? What was your corrective action?
(5) Did your aircraft exhibit any motions that your did not expect? At what position?
(6) Were you trimmed in the pre contact position?
(7) Did you use trim (lat or long) during the contact, in the fuel transfer zone, or during disconnect? If so what direction and why? Which hose?
(8) Did gross weight affect handling? At what airspeeds and at what gross weights? Did you change control position, trim, or power?
(9) What flap setting did you use? Was the attitude acceptable?
(10) Did you use rudder for any reason?
(11) Was power response adequate?
(12) Describe your technique used to make contact?
(13) Describe the effect of turbulence (if observed) on your technique. What was your workload for making contact in those conditions?
(14) Describe the hose behaviour in free-flight and in the bow wave of your aircraft. Did it affect your technique?
(15) How much did the hose motion change when flying in turbulence?
(16) Any differences between left and right hose?
(17) Do you see any potential problems with a student in the cockpit?
(18) How would fatigue influence your ability to make contact?
(19) Any other comments?

The results provided an early opportunity in the development process to judge the difficulty which an inexperienced student fighter pilot would be expected to have performing AAR with the CC-130H(T).

**Performance Limitations**

The first significant factor to define the AAR envelope was the performance limitations imposed by the Hercules, Hornet, and Freedom Fighter. Using a turboprop tanker for turbojet fighters obviously reduced the available refuelling airspeed and altitude range than that typical for a turbofan or turbojet tanker.

The Hercules maximum level flight airspeed limited the practical maximum refuelling airspeed to roughly 250 KIAS. This was further reduced above 25,000 ft as gross weight limited the maximum achievable airspeed. Furthermore, an operationally representative tanker fuel load lowered the maximum achievable ceiling. Therefore, refuelling could only be practically performed below roughly 28,000 ft to 30,000 ft PA. Addition of the after-body strakes reduced overall aircraft drag by several percent making operation at 250 KIAS slightly more efficient. Under these constraints the contractor selected a drogue with drag characteristics optimized for AAR in the airspeed range of 175 to 250 KIAS. Testing to determine the minimum hose stability revealed that the hose began to rewind at 136 KIAS at both 10,000 ft and 20,000 ft which was acceptable for the intended receiver aircraft.(2) Testing to determine the minimum airspeed for hose deployment revealed that at 10,000 ft the minimum was 185 KIAS and 190 KIAS at 30,000 ft. (2) The latter characteristics do not limit the lower airspeed range for actually conducting aerial refuelling as it is possible to trail the hose above these airspeeds and if necessary reduce speed. As will be discussed shortly, the controllability of the receiver aircraft hampered slow speed AAR near this minimum trail airspeed.

The CF-188 by virtue of its design for air-to-air combat and carrier landing capabilities has very good slow speed performance. The CF-188 could match the Hercules and drogue airspeed and altitude envelope. The only limit was a maximum angle of attack of 12 degrees for visibility over the nose. If reached in cruise flight flap selection could reduce the angle of attack.

The CF-116 incorporates trailing and leading edge flaps for low speed flight. Unfortunately, the aircraft possess severe engine throttle control restrictions at slow speed and high altitudes. The Freedom Fighter intake system has caused an extensive history of compressor stalls. The flight manual caution areas that are observed by the Canadian Forces in operating the aircraft are shown in Figure 6. This in conjunction with the 250 KIAS maximum tanker airspeed effectively limits the CF 116 to AAR below 20,000 ft. Heavy gross weight performance of the CF-116 can limit the maximum altitude further to as low as a maximum of 15,000 ft. Controllability is also of concern but this will be mentioned in the handling qualities discussion.

The performance constraints for the three aircraft can be simplified and presented as an airspeed versus altitude plot shown in Figure 7. The maximum altitude and airspeed limits shown may vary slightly due to gross weight and external configuration.

**Tanker Wake and Hose Stability Tests**

Prior to engaging the drogue, the hose stability and tanker wake were evaluated to ensure that no unacceptable risks to the receivers were present. The hose length placed the drogue 16 ft closer to the Hercules than the Sargeant Fletcher system used on the KC-130/HC-130 tankers. The impact of this situation can be seen in Figure 8 for the CF-188 and Figure 9 for the CF 116. Although no problems were encountered during day time operations added risks were present for night refuelling.

The tanker wake was observed by flying behind it in the pre-contact and contact positions with the hoses retracted. Both the CF-116 and CF-188 performed the tests. The receiver test pilots investigated the nominal and off nominal hose hang positions. The acceptable FTZ was determined to be the envelope illustrated in Figure 10. In this envelope several tanker wake effect were observed. The wing tip vortices and propeller wash were weak as was the wing wake if the receiver was repositioned directly behind and level with the wing. The fuselage vortices were however found to be very strong during changes between wing stations in the pre-contact position. These vortices tended to roll the receiver into the tanker. As long as the fuselage wake was avoided, the tanker wake was acceptable for AAR.

The stability of the hoses in free-flight were then observed to determine the expected ease for making contact. Tests included hose free-trail flight in calm and turbulent air and dynamic behaviour during control doublets. The control doublets in pitch and roll resulted in lightly damped vertical oscillations exhibiting a 3 second period. In some cases, the oscillations required 12 seconds to dissipate after controls were released. The hoses followed the tanker motion during the rudder doublets. The light weight basket and shorter hose was the probable cause of the low damping. In level flight and calm air, the drogue tended to oscillate +/- 2 to 4 ft vertically with the 3 second period. In maneuvering flight up to 30 degrees of bank a minor increase in the oscillations was noted. The hoses also tended to exhibit a 1 ft circular motion which may have been caused by self inducing the aircraft's dutch roll mode which was lightly damped at high altitudes. In turbulent air, the oscillations of the hoses increased dramatically. Light turbulence resulted in vertical hose oscillations of 5 to 10 ft. To some extent, the magnitude of the oscillations could be reduced by decreasing airspeed. The impact of the low hose damping will be discussed for each receiver aircraft. The majority of the flight testing was performed using the auto-pilot in the tanker. The auto-pilot provided a stable tanker and was acceptable.

**Envelope Expansion**

Daylight compatibility testing was planned for: 15,000 ft PA and 35,000 ft PA for the CF-188; 10,000 ft PA and 20,000 ft PA for the CF-116; and a common low altitude test sequence at 500 ft AGL for low level handling qualities. The medium altitudes were investigated first for safety and avoidance of any potential problems at high or low altitudes.

The airspeed envelope for the planned altitudes were investigated by starting at 250 KIAS then slowing down to any limiting controllability problems. Weather constraints, difficulties with the CF-188 bow-wave at 250 KIAS, and receiver aircraft sortie generation required some minor modifications, but overall, this approach worked very well.

The CF-188 test points investigated are shown in Figure 11. The maximum altitude explored was 34,000 ft PA and minimum 500 ft AGL. The CF-116 test points investigated are shown in Figure 12. To avoid the engine compressor stall region, the maximum test altitude was 20,000 ft PA. No testing in the standard day caution region was attempted.

Night compatibility testing was only conducted at medium altitudes. This approach was to avoid airspeeds where handling quality problems were discovered in day light conditions.

**CF-188 Compatibility**

During the first several approaches to contact, it was apparent that the bow-wave of the CF-188 seriously affected the drogue. For this reason, the precision contact task became the critical task for workload assessment by the receiver pilot. The right hose tended to be slightly harder to make contact due to the propeller wash and wing tip vortex interactions but was not objectionable. HQRs for the contact task on the right hose were 6 at 250 KIAS, 3 at 225 KIAS, and 5 at 175 KIAS. HQRs were less for contacting the left hose. The test pilot reported that the drogue could be easily perturbed and was very unpredictable in the bow-wave of the CF-188. This motion could exceed 10 ft at 250 KIAS. The affects could be minimized in the airspeed range 200-240 KIAS. A moderate closure rate was found to be optimum although some pilots preferred a high closure rate to catch the drogue prior to any large unpredictable displacements. Different external configurations and gross weight had no effect on the handling qualities at contact. Contacts were made as slow as 175 KIAS which also did not reveal any problems if the Auto Flaps mode was used.

The previous results were for nil turbulence conditions. When contacts were attempted in turbulence, the workload increased dramatically. If the turbulence intensity was moderate or worse, the time to make contact could be as long as 9 minutes. This resulted in one test pilot assigning an HQR of 7 at 220 KIAS in moderate turbulence.

Handling qualities while performing the pre-contact, FTZ, and NFTZ MTEs were acceptable. The test pilots assigned HQRs as 2 or 3 in the pre-contact position and FTZ. Some hose whipping occurred when in the NFTZ after the hose tensator limit was reached, but a warning light on the pod bellmouth illuminates when the region is reached which provides ample protection. Contacts were made in maneuvering flight up to a maximum of 30 degrees of bank. The test pilots reported HQRs of 5 at 250 KIAS on the right hose which was slightly harder than the left hose as in level flight. Formation flight at 30 degrees of bank in the FTZ were also performed which were assigned HQR of 3. Normal and emergency disconnects were performed throughout the envelope and no problems were identified.

Altitude did not have any significant effect on the handling qualities. The higher turbulence intensities were generally observed below 10,000 ft PA but if calm AAR as low as 500 ft AGL was acceptable.

The AAR envelope for the CF 188 was defined as 170 to 240 KIAS with Autoflaps required below 200 KIAS. The altitude range was 500 ft AGL to 35,000 ft PA.

**CF-116 Compatibility**

As for the CF-188, the contact task was the critical case for receiver pilot workload. The drogue only suffered from minor flow influences by the CF-116. At most the drogue was displaced by one drogue diameter and could be easily compensated for during contact. The optimum airspeed for making contact was found to be 250 KIAS with degrading handling qualities as airspeed was reduced to 220 KIAS due to worsening control response sluggishness. The test pilot assigned a HQR of 3 at 250 KIAS and a 4 at 220 KIAS. With all wing stations loaded and increasing gross weight also made the control response more sluggish but was not objectionable. As with the CF-188 the right hose was slightly harder to make contact.

By far the dominant factor affecting the workload to make contact using the CF-116 was the turbulence intensity. Again as for the CF-188, an intensity of moderate or worse made the task of making contact extremely difficult.

The handling qualities in the FTZ and NFTZ were found to be acceptable in both straight and level as well as maneuvering flight up to a 30 degree bank turn. On the right hose, the test pilot assigned an HQR of 5 for making contact at 30 degree of bank. No deficiencies were found during normal or emergency disconnects.

The AAR envelope was defined for the CF-116 to be 220 to 250 KIAS from 500 ft AGL to 20,000 ft PA.

**Operational Pilot Observations**

Overall, the CF-116 was observed to be an easier aircraft to refuel from the CC-130H(T) than the CF-188. This provided a suitable learning progression for student pilots. This claim could only be made though in calm air. As the turbulence intensity worsened, the CF-116 was far more difficult to make contact. One pilot remarked that a student fighter pilot with very little experience would not possess the necessary skill to make contact. Another pilot remarked that having made contacts on 6 other types of tankers including the KC-130, the CC-130H(T) required all his skill and experience to make contact in light to moderate turbulence. Further complications are expected from fatigue, however, regular training will be used to minimize the effects of this problem. The soft drogue was found very appealing to most pilots as the potential for receiver aircraft damage was low. This resulted in reduced tension in the cockpit.

The tanker wake caused the hoses to fly outboard of the pods requiring different references for making the precision approach to the drogue. One pilot remarked that there was a tendency for his attention to be drawn to the propeller arc as the separation distance between the receiver and the tanker was small. Finally, this close distance prompted the remark that there was alot of "metal" in the receiver pilot's field of view.

**Night Compatibility**

The initial night lighting system consisted of a strip light on the horizontal stabilizer, pod bellmouth light, drogue self-luminescent emitters, and wing tip lights. In addition the receiver aircraft have probe lights. Sufficient attitude cues were available for flying in trail, making station changes, and in the pre-contact position. Moving into the contact position, the horizontal stabilizer strip light provided satisfactory longitudinal cues. Once moved forward into the FTZ, though, the strip light was in the peripheral vision and insufficient cues were available. The hose markings could not be seen so that longitudinal position was very difficult to maintain. In maneuvering flight minimal attitude cues were available. The scanner in the cargo compartment also had difficulty seeing the receiver aircraft and hose. The right hose positions placed the receiver 2-3 ft closer to the tail of the aircraft. An improved lighting system is under investigation at this time.

## AAR Lessons Learned

This test programme was conducted safely and resulted in the successful certification of the tanker for flight and providing an initial refuelling envelope for both the CF-188 and CF-116. In spite of several unexpected hose motions no damage was sustained to any aircraft. The joint contractor-customer test team was efficient and eliminated the requirement for extensive Canadian Forces follow-on flight testing. The following are a number of lessons learned worth noting for future tanker compatibility trials.

Tanker/receiver compatibility trials are difficult to perform precisely as they are by nature qualitative. This fact lead to disagreement during interpretation of pilot comments. An opportunity to practise the handling qualities tasks is essential prior to gathering pilot ratings. This may not always be possible if other refuelling tankers are not available. Such as was the case in this situation. In lieu of this, scheduling time with the test aircraft prior to test runs for data was sufficient. The AAR evaluations can be sensitive to experience and techniques. Arguably, comments on compensations during development tests should form the basis for AAR technique development.

It is very difficult to gather large amounts of data for defining the envelope precisely and identifying all the handling qualities concerns. The compatibility trials required formations of four aircraft or more and were at times difficult to coordinate. Generating receiver aircraft sorties with briefed crews can be difficult to supply within the time constraints of a contractor schedule. Getting operational pilots involved early in the development was beneficial for judging acceptability. It was necessary to prompt their responses with well chosen questions as they are generally unfamiliar with experimental flight testing. Furthermore, these same squadron pilots can make observations after the aircraft enters into initial operational service. In fact this has been the case for the CC-130H(T) where minor observations have been made that were not seen previously.

Results should not be predetermined or success expected. Expected similarity between the FRL system and the Sargeant Fletcher system resulted in several surprises. The shorter hose length and the strong CF-188 bow-wave coupled with the light drogue where two examples. If a receiver aircraft has not been trialed with a particular tanker, a limited compatibility evaluation should be undertaken to avoid surprises in operation. This is especially the case for wartime multi-national operations when fatigue may be high.

It was very difficult to judge spatial formation positioning for quantification of refuelling positions. This was aggravated by variations in hose angle due to airspeed and trapped fuel effects. Rough order of magnitude comparisons were possible with simple scale drawings. Since training techniques need to be developed, operational pilots are familiar with using wing, pod, and receiver canopy references instead of using separation distances.

The importance of the effects of turbulence during AAR was underestimated. This aspect unfortunately added an extra dimension to the test matrix increasing the effort required. Turbulence has and continues to limit aerial refuelling. A tactical tanker which may operate at low altitudes in severe weather condition must be assessed to ensure the safety of the receiver. A more stable drogue design may also be worthy of consideration to reduce pilot compensation especially when fatigued.

## Future Activity

A number of outstanding test requirements are still to be investigated during Category II and III testing. This future activity includes: failure state testing of the tanker and receiver aircraft during AAR, e.g. single-engine receiver AAR; clarification of the hose extension and retraction envelope; heavy gross weight receiver handling qualities; and night lighting development.

## Conclusions and Recommendations

This paper presented the results of the developmental flight test programme of the CC-130H(T) tanker Hercules. Successful utilization of the FRL Mk 32B-751 aerial refuelling pod on the Hercules was demonstrated. The airworthiness of the modified Hercules was demonstrated. Air to air refuelling envelopes for the CF-188 Hornet and CF-116 Freedom Fighter were developed. Limited flight testing continues in preparation for operational service with the Canadian Forces.

As a recommendation for the development of future AAR pod systems, one potential improvement would be to make the hose/drogue assembly more stable in turbulent flight conditions and possibly in the bow wave of receiver aircraft.

## Acknowledgements

The authors wish to thank the LASC flight test team for their collaboration and support during the development flight test programme.

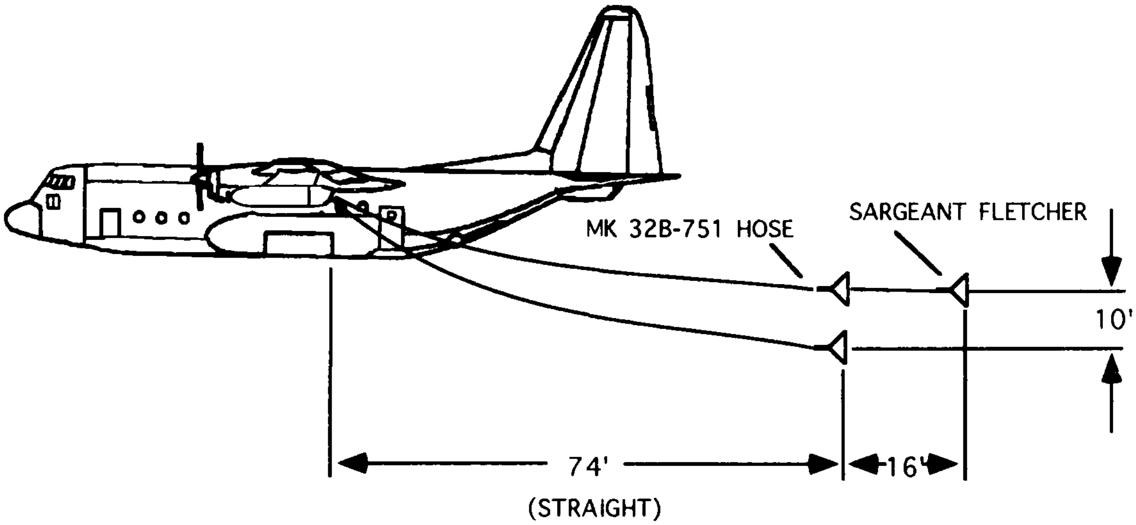
## References

1. FRL Product Information Pamphlet for the Mk 32B Refuelling Pod, 1990.

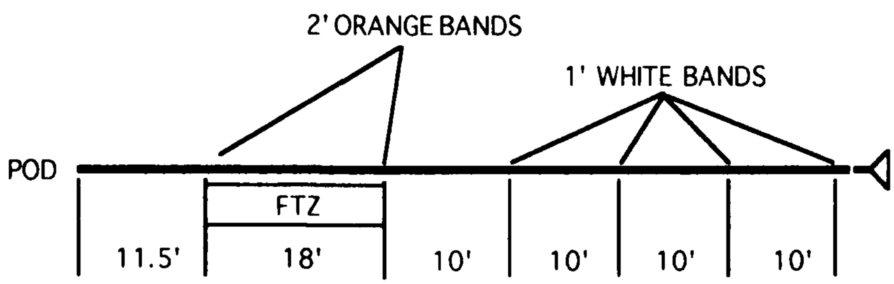
2. T.C. Castona and R.E. Pardue, CC-130T Ground and Flight Test Report, LG92ER0069, 10 Aug 92.

3. Mil-A-19736A, General Specification for Air Refuelling Systems.

4. G. Cooper, and R. Harper, The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities, NASA TN D-5153, 1969.




HOSE TRAIL CHARACTERISTICS




HOSE MARKINGS

**Figure 1. Sideview of the CC-130H(T) Hercules Tanker. (Hose Length Comparison - Mk-32/Sargeant Fletcher) (Mk-32 Hose Markings - below)**

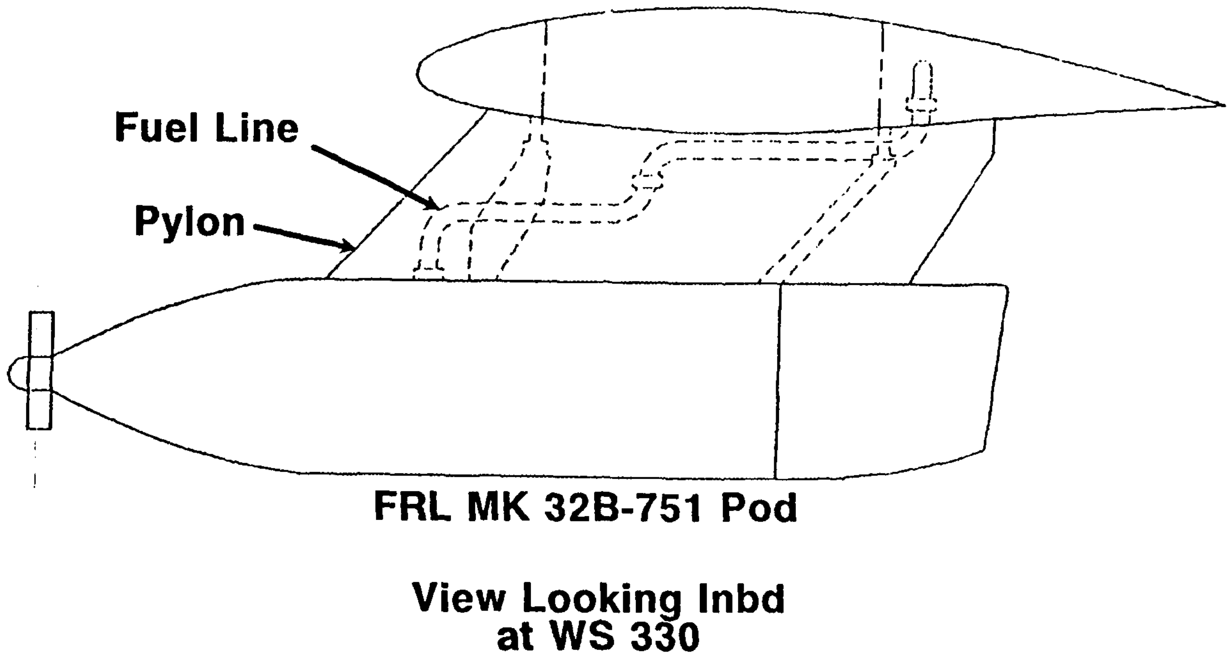



Figure 2. Mk-32B-751 Pod and Pylon.(1)&(2)

| | |
|---|---|
| Weight | 1300 lbs (with pylon) |
| Length | 170 inches |
| Diameter | 34 inches |

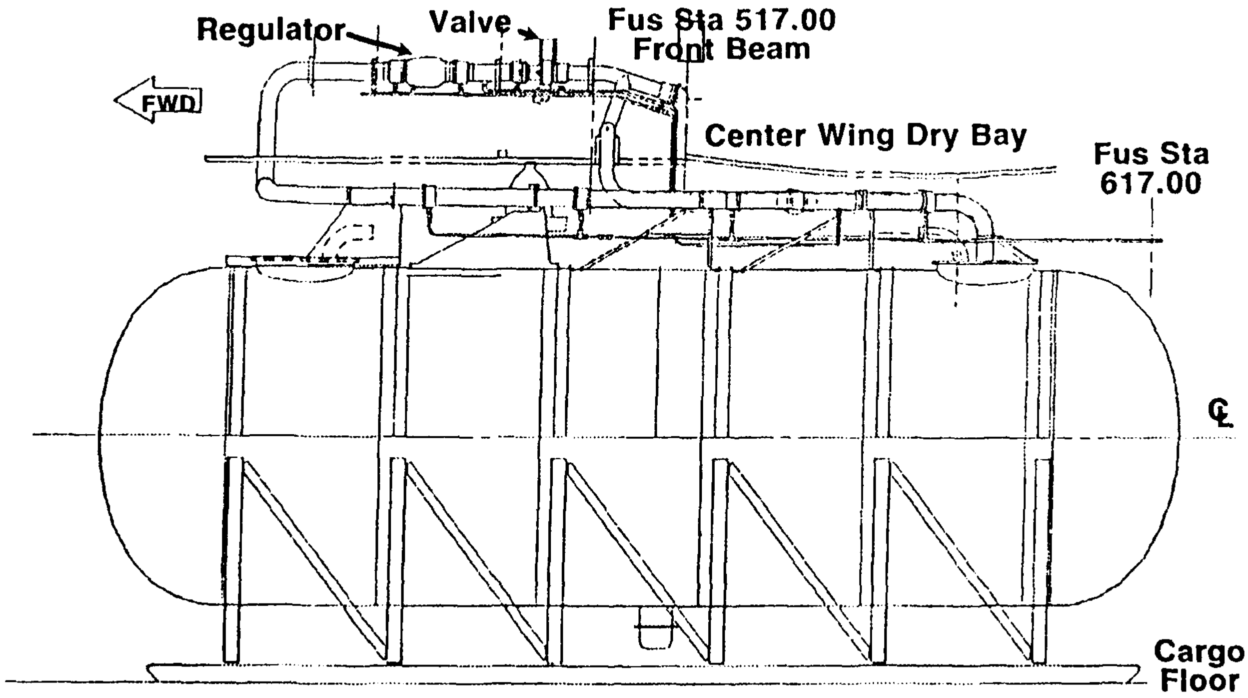
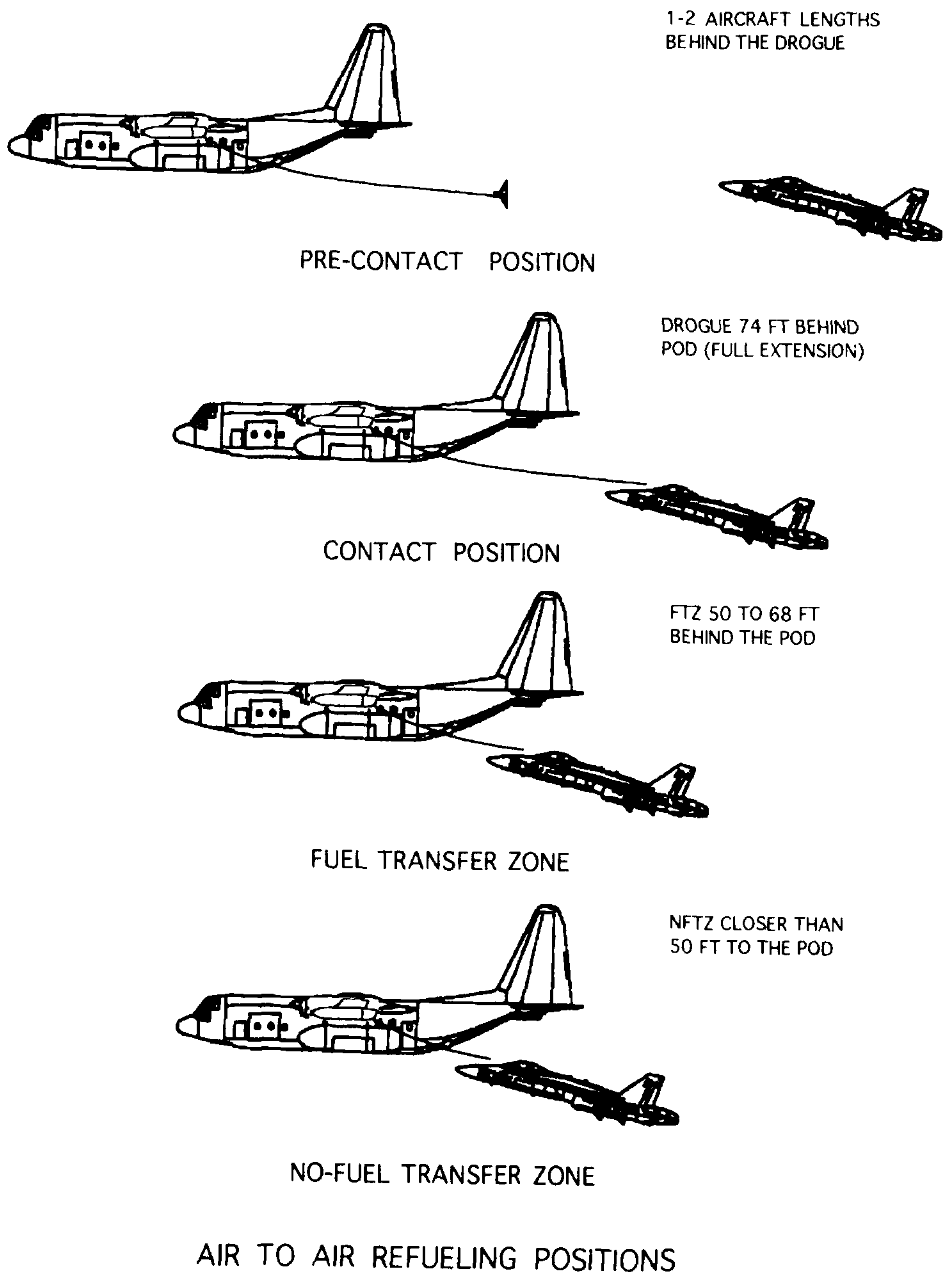



Figure 3. Fuselage Fuel Tank and Attachment Lines.

| | |
|---|---|
| Weight | 2600 lbs (empty) |
| Length | 231 inches |
| Diameter | 73 inches |




**Pre-Contact Task:**

**Desired:** one aircraft length behind the hose within half wing span of the drogue laterally and vertically.
**Adequate:** one aircraft length behind the hose within one wing span of the drogue laterally and vertically.

**Contact Task:**

**Desired:** contact within 3 minutes.
**Adequate:** contact within 9 minutes.

**FTZ and NFTZ Formation Tasks:**

**Desired:** within +/- 5 ft laterally and vertically of nominal hose hang position.
**Adequate:** within +/- 10 ft laterally and vertically of nominal hose hang position.

**Figure 4. AAR Mission Task Elements and the Handling Qualities Rating Performance Criteria.**

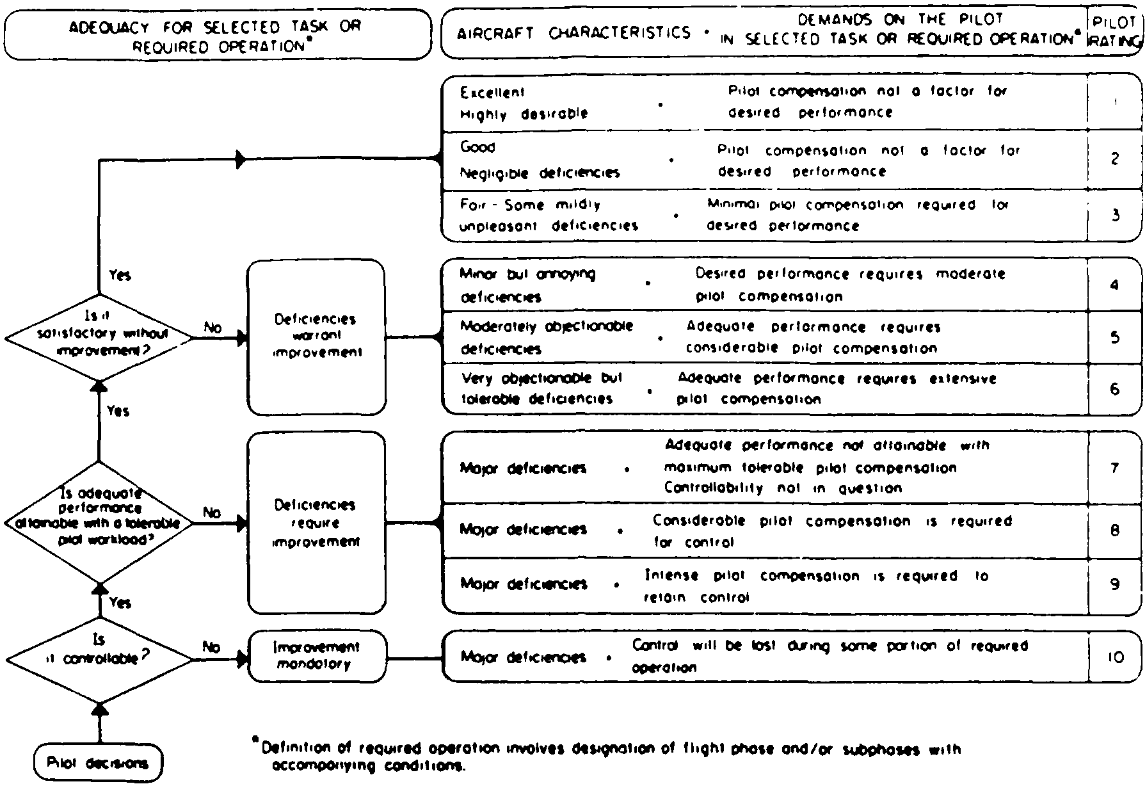
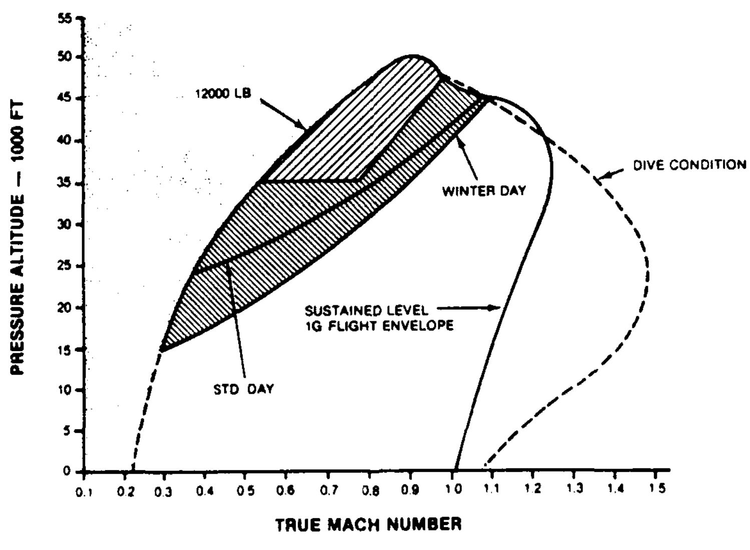



**Figure 5. Cooper-Harper Handling Qualities Rating Scale. (4)**




**COMPRESSOR STALL SENSITIVE AREAS**

| | | |
|---|---|---|
| (hatched) | Area A | Throttle movement into or out of AB or rapid throttle advancement to MIL not recommended. |
| (dense hatched) | Area B | Rapid throttle advancement to MIL or AB not recommended. |
| (blank) | Area C | Throttle movement not recommended. |

**Figure 6. CF-116 J85-CAN-15 Engine Compressor Stall Caution Area.**

an almost identical configuration and preferably be of a comparable age.



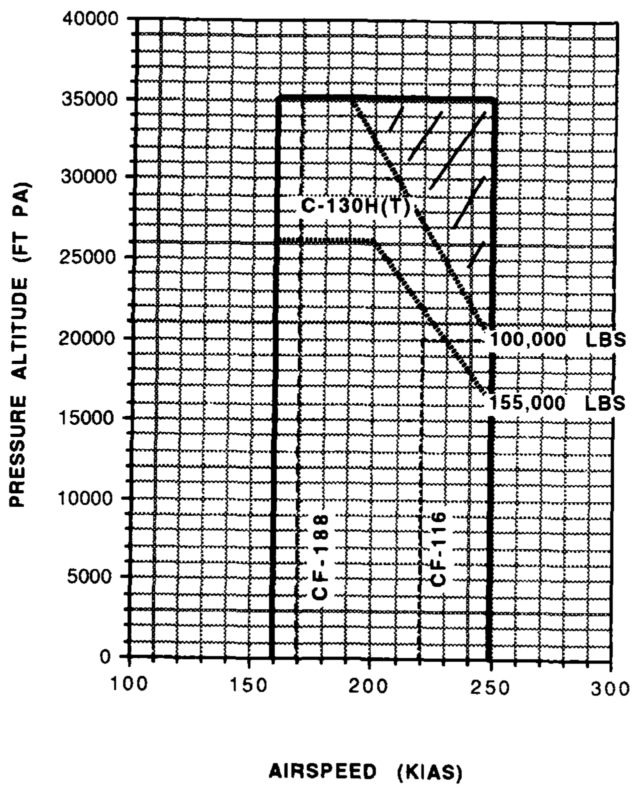
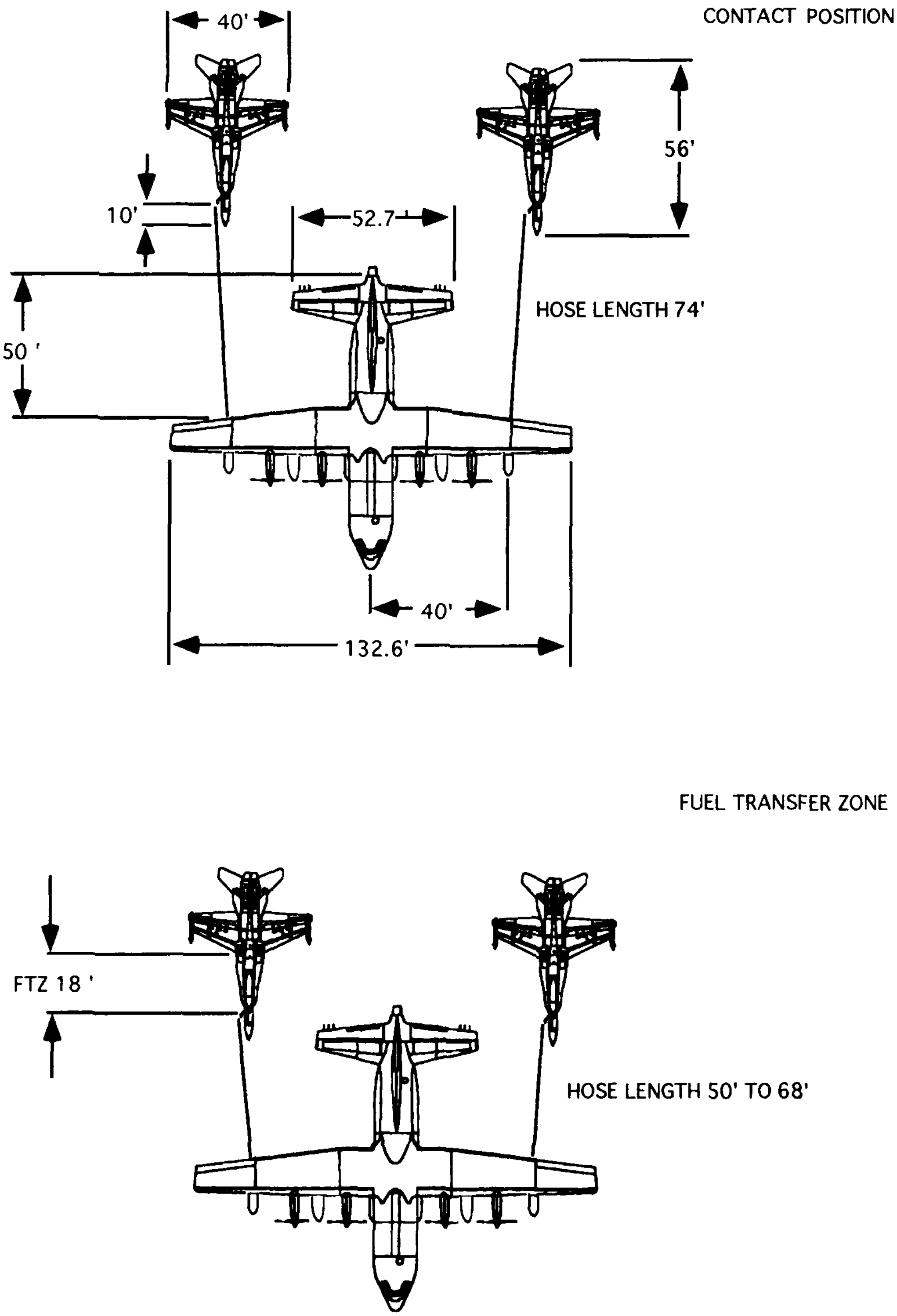



Figure 7. Performance Constrained Refuelling Envelope.




CF-188 AND CC-130H(T) SEPARATION

TOP VIEW

**Figure 8. Proximity of CF-188 to the CC-130H(T) in the Contact and Fuel Transfer Zone Positions.**

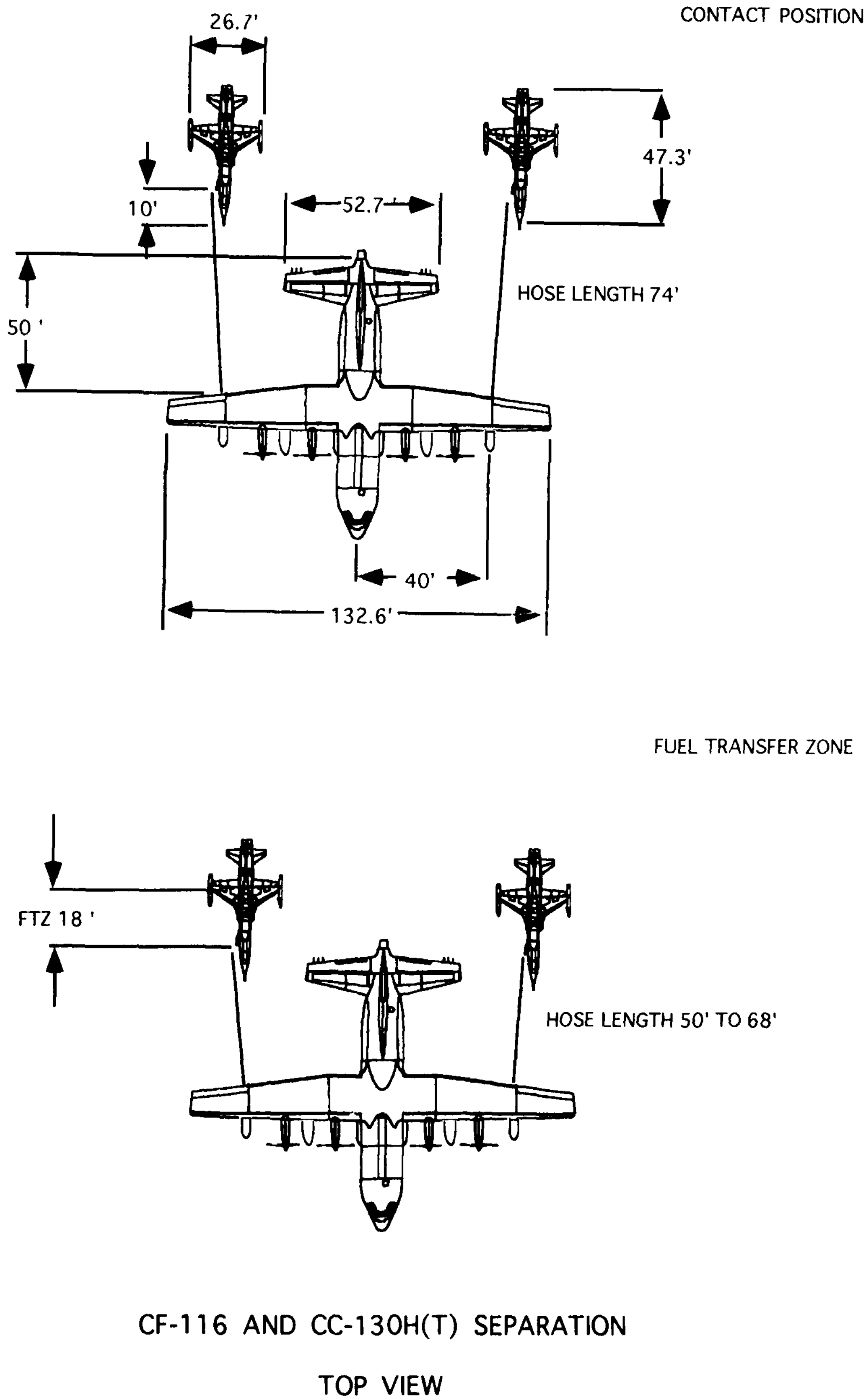



**Figure 9. Proximity of the CF-116 to the CC-130H(T) in the Contact and Fuel Transfer Zone Positions.**

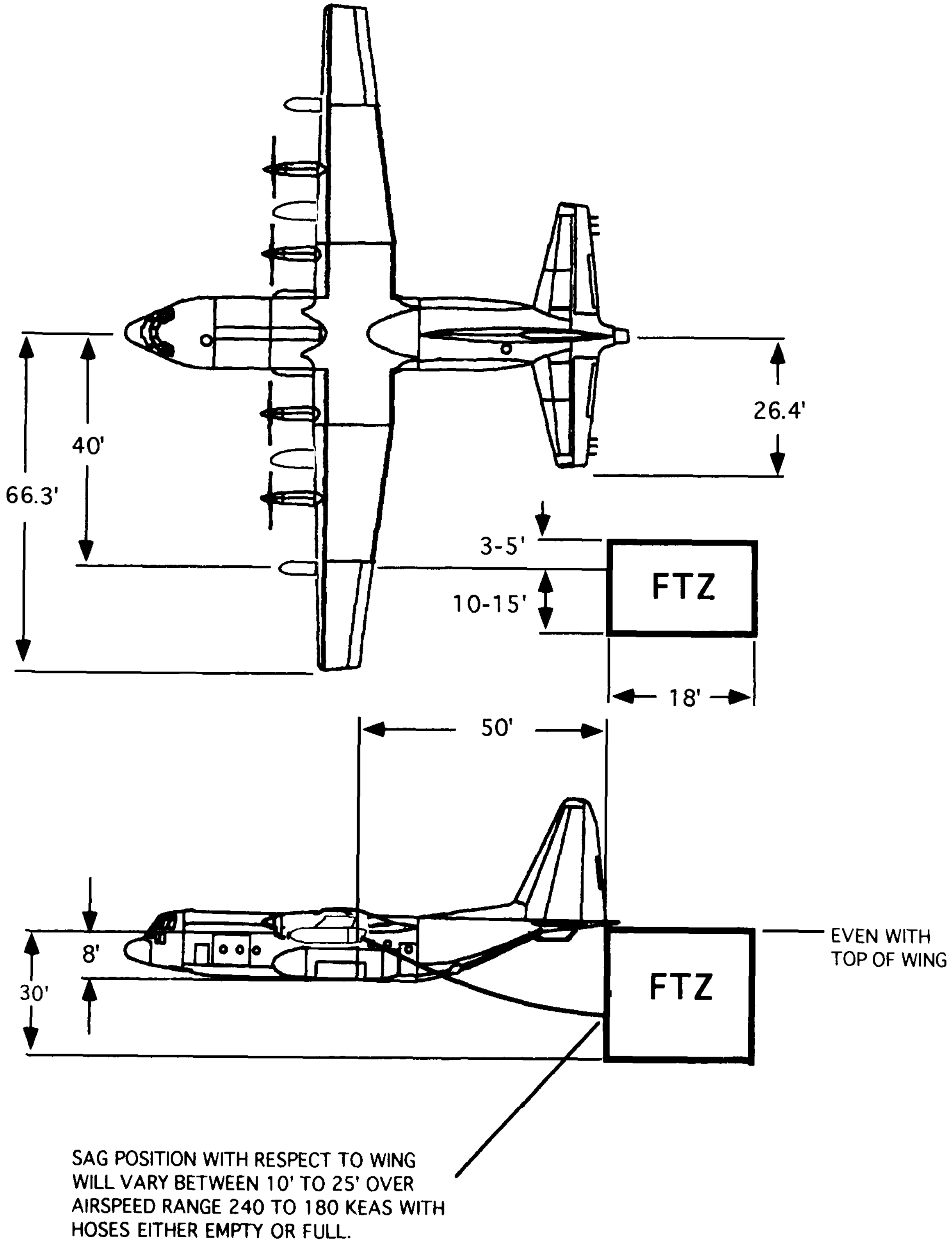



**Figure 10. The CC-130H(T) Fuel Transfer Zone Envelope.**

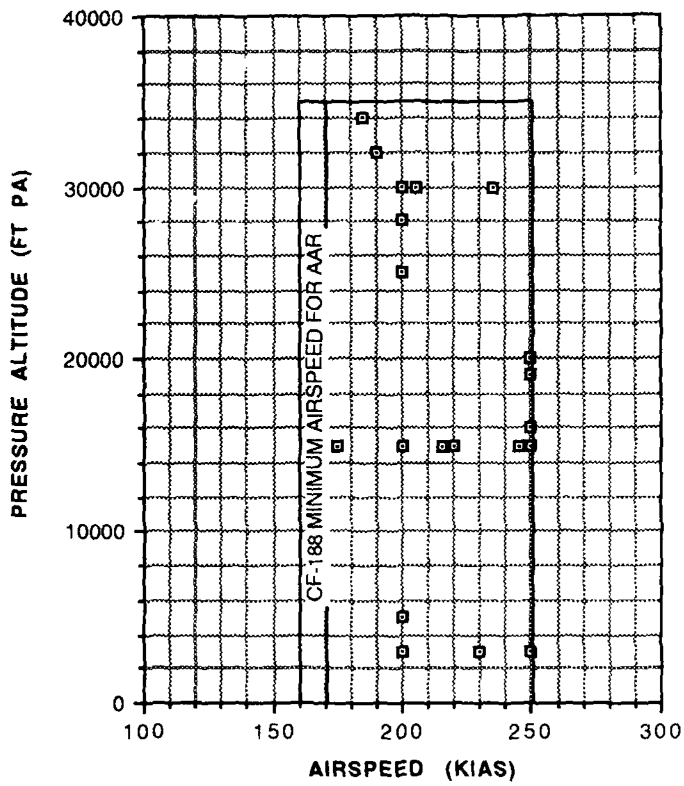



Figure 11. CF-188 AAR Envelope Explored.

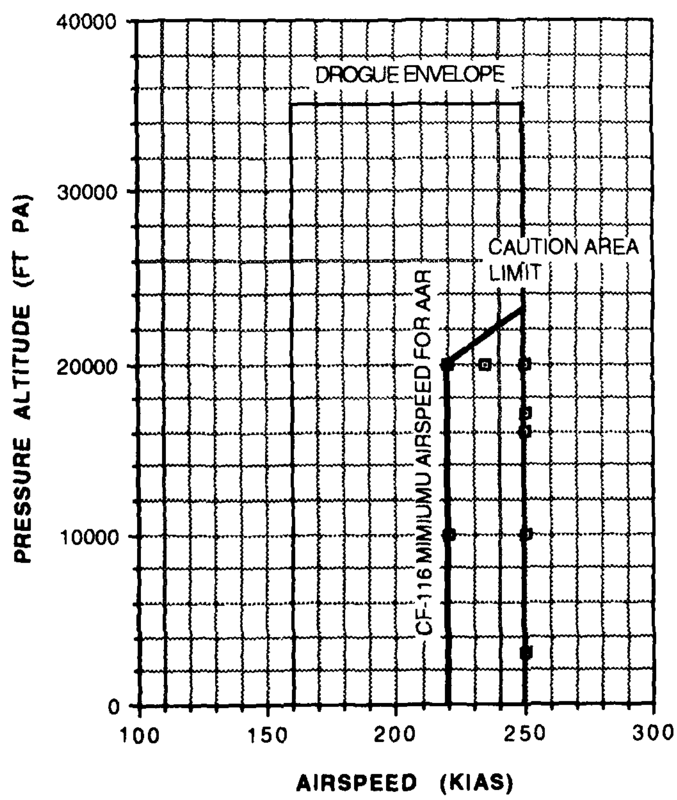



Figure 12. CF-116 AAR Envelope Explored.

## REPORT DOCUMENTATION PAGE

| 1. Recipient's Reference | 2. Originator's Reference | 3. Further Reference | 4. Security Classification of Document |
|---|---|---|---|
| | AGARD-CP-547 | ISBN 92-835-0726-6 | UNCLASSIFIED/ UNLIMITED |

**5. Originator** Advisory Group for Aerospace Research and Development
North Atlantic Treaty Organization
7 Rue Ancelle, 92200 Neuilly sur Seine, France

**6. Title** RECENT ADVANCES IN LONG RANGE AND LONG ENDURANCE OPERATION OF AIRCRAFT

**7. Presented at** the Flight Mechanics Panel Symposium, held in Kijkduin (The Hague), The Netherlands, 24th—27th May 1993.

| 8. Author(s)/Editor(s) | 9. Date |
|---|---|
| Various | November 1993 |

| 10. Author's/Editor's Address | 11. Pages |
|---|---|
| Various | 322 |

**12. Distribution Statement** There are no restrictions on the distribution of this document. Information about the availability of this and other AGARD unclassified publications is given on the back cover.

**13. Keywords/Descriptors**

| | |
|---|---|
| Airlift | Propulsion technology |
| Long distance flight | Aerodynamics |
| Long range | Structural design |
| Long endurance flight | Human factors |
| Air to air refueling | |

**14. Abstract**


Over the past few years, the use of aircraft in long range and/or long endurance operations has proved to be a successful use of military resources. Tactical strikes mounted from bases thousands of miles away, or the use of long endurance patrol aircraft over either the battlefield or maritime environment demonstrate the ability now contained in the NATO operational forces. The use of military airlift to position forces where they are most needed clearly is another operation where the range and endurance of the aircraft are pivotal to the success of the operation.

Technologies which improve the range and endurance of aircraft have seen considerable advances over the past ten years. Aircraft design for these features has matured considerably while the procedure of air-to-air refuelling has made global deployment and 24+ hour operations a reality.

This Symposium attempted to summarize the latest technological advances in the various fields which in a combined manner define the range and endurance of airborne vehicles, i.e.: airframe design technologies, including aerodynamics and structures; propulsion technology; the human factors problems associated with these types of missions; and air-to-air refuelling technologies and procedures.

The Symposium was opened by two Keynote Addresses, the first covering a military perspective on long range and long endurance operations, and the second describing the variety of technological and human challenges involved in the record breaking non-stop flight around the world of the Voyager aircraft.

This Conference Proceedings document also contains a brief Technical Evaluation Report.

AGARD Conference Proceedings 547
Advisory Group for Aerospace Research and Development, NATO
RECENT ADVANCES IN LONG RANGE AND LONG ENDURANCE OPERATION OF AIRCRAFT
Published November 1993
322 pages

Over the past few years, the use of aircraft in long range and/or long endurance operations has proved to be a successful use of military resources. Tactical strikes mounted from bases thousands of miles away, or the use of long endurance patrol aircraft over either the battlefield or maritime environment demonstrate the ability now contained in the NATO operational forces. The use of military airlift to position forces where they are most needed clearly is another operation where the range and endurance of the aircraft are pivotal to the success of the operation.

P.T.O.

AGARD-CP-547

Airlift
Long distance flight
Long range
Long endurance flight
Air to air refueling
Propulsion technology
Aerodynamics
Structural design
Human factors

AGARD Conference Proceedings 547
Advisory Group for Aerospace Research and Development, NATO
RECENT ADVANCES IN LONG RANGE AND LONG ENDURANCE OPERATION OF AIRCRAFT
Published November 1993
322 pages

Over the past few years, the use of aircraft in long range and/or long endurance operations has proved to be a successful use of military resources. Tactical strikes mounted from bases thousands of miles away, or the use of long endurance patrol aircraft over either the battlefield or maritime environment demonstrate the ability now contained in the NATO operational forces. The use of military airlift to position forces where they are most needed clearly is another operation where the range and endurance of the aircraft are pivotal to the success of the operation.

P.T.O.

AGARD-CP-547

Airlift
Long distance flight
Long range
Long endurance flight
Air to air refueling
Propulsion technology
Aerodynamics
Structural design
Human factors

AGARD Conference Proceedings 547
Advisory Group for Aerospace Research and Development, NATO
RECENT ADVANCES IN LONG RANGE AND LONG ENDURANCE OPERATION OF AIRCRAFT
Published November 1993
322 pages

Over the past few years, the use of aircraft in long range and/or long endurance operations has proved to be a successful use of military resources. Tactical strikes mounted from bases thousands of miles away, or the use of long endurance patrol aircraft over either the battlefield or maritime environment demonstrate the ability now contained in the NATO operational forces. The use of military airlift to position forces where they are most needed clearly is another operation where the range and endurance of the aircraft are pivotal to the success of the operation.

P.T.O.

AGARD-CP-547

Airlift
Long distance flight
Long range
Long endurance flight
Air to air refueling
Propulsion technology
Aerodynamics
Structural design
Human factors

AGARD Conference Proceedings 547
Advisory Group for Aerospace Research and Development, NATO
RECENT ADVANCES IN LONG RANGE AND LONG ENDURANCE OPERATION OF AIRCRAFT
Published November 1993
322 pages

Over the past few years, the use of aircraft in long range and/or long endurance operations has proved to be a successful use of military resources. Tactical strikes mounted from bases thousands of miles away, or the use of long endurance patrol aircraft over either the battlefield or maritime environment demonstrate the ability now contained in the NATO operational forces. The use of military airlift to position forces where they are most needed clearly is another operation where the range and endurance of the aircraft are pivotal to the success of the operation.

P.T.O.

AGARD-CP-547

Airlift
Long distance flight
Long range
Long endurance flight
Air to air refueling
Propulsion technology
Aerodynamics
Structural design
Human factors

Technologies which improve the range and endurance of aircraft have seen considerable advances over the past ten years. Aircraft design for these features has matured considerably while the procedure of air-to-air refuelling has made global deployment and 24+ hour operations a reality.

This Symposium attempted to summarize the latest technological advances in the various fields which in a combined manner define the range and endurance of airborne vehicles, i.e.: airframe design technologies, including aerodynamics and structures; propulsion technology; the human factors problems associated with these types of missions; and air-to-air refuelling technologies and procedures.

The Symposium was opened by two Keynote Addresses, the first covering a military perspective on long range and long endurance operations, and the second describing the variety of technological and human challenges involved in the record breaking non-stop flight around the world of the Voyager aircraft.

This Conference Proceedings document also contains a brief Technical Evaluation Report.

Copies of papers presented at the Flight Mechanics Panel Symposium held in Kijkduin (The Hague), The Netherlands 24th—27th May 1993.

ISBN 92-835-0726-6

Technologies which improve the range and endurance of aircraft have seen considerable advances over the past ten years. Aircraft design for these features has matured considerably while the procedure of air-to-air refuelling has made global deployment and 24+ hour operations a reality.

This Symposium attempted to summarize the latest technological advances in the various fields which in a combined manner define the range and endurance of airborne vehicles, i.e.: airframe design technologies, including aerodynamics and structures; propulsion technology; the human factors problems associated with these types of missions; and air-to-air refuelling technologies and procedures.

The Symposium was opened by two Keynote Addresses, the first covering a military perspective on long range and long endurance operations, and the second describing the variety of technological and human challenges involved in the record breaking non-stop flight around the world of the Voyager aircraft.

This Conference Proceedings document also contains a brief Technical Evaluation Report.

Copies of papers presented at the Flight Mechanics Panel Symposium held in Kijkduin (The Hague), The Netherlands 24th—27th May 1993.

ISBN 92-835-0726-6

Technologies which improve the range and endurance of aircraft have seen considerable advances over the past ten years. Aircraft design for these features has matured considerably while the procedure of air-to-air refuelling has made global deployment and 24+ hour operations a reality.

This Symposium attempted to summarize the latest technological advances in the various fields which in a combined manner define the range and endurance of airborne vehicles, i.e.: airframe design technologies, including aerodynamics and structures; propulsion technology; the human factors problems associated with these types of missions; and air-to-air refuelling technologies and procedures.

The Symposium was opened by two Keynote Addresses, the first covering a military perspective on long range and long endurance operations, and the second describing the variety of technological and human challenges involved in the record breaking non-stop flight around the world of the Voyager aircraft.

This Conference Proceedings document also contains a brief Technical Evaluation Report.

Copies of papers presented at the Flight Mechanics Panel Symposium held in Kijkduin (The Hague), The Netherlands 24th—27th May 1993.

ISBN 92-835-0726-6

Technologies which improve the range and endurance of aircraft have seen considerable advances over the past ten years. Aircraft design for these features has matured considerably while the procedure of air-to-air refuelling has made global deployment and 24+ hour operations a reality.

This Symposium attempted to summarize the latest technological advances in the various fields which in a combined manner define the range and endurance of airborne vehicles, i.e.: airframe design technologies, including aerodynamics and structures; propulsion technology; the human factors problems associated with these types of missions; and air-to-air refuelling technologies and procedures.

The Symposium was opened by two Keynote Addresses, the first covering a military perspective on long range and long endurance operations, and the second describing the variety of technological and human challenges involved in the record breaking non-stop flight around the world of the Voyager aircraft.

This Conference Proceedings document also contains a brief Technical Evaluation Report.

Copies of papers presented at the Flight Mechanics Panel Symposium held in Kijkduin (The Hague), The Netherlands 24th—27th May 1993.

ISBN 92-835-0726-6

NATO OTAN
7 RUE ANCELLE · 92200 NEUILLY-SUR-SEINE
FRANCE
Télécopie (1)47.38.57.99 · Télex 610 176

## DIFFUSION DES PUBLICATIONS
## AGARD NON CLASSIFIEES

Aucun stock de publications n'a existé à AGARD. A partir de 1993, AGARD détiendra un stock limité des publications associées aux cycles de conférences et cours spéciaux ainsi que les AGARDographies et les rapports des groupes de travail, organisés et publiés à partir de 1993 inclus. Les demandes de renseignements doivent être adressées à AGARD par lettre ou par fax à l'adresse indiquée ci-dessus. *Veuillez ne pas téléphoner.* La diffusion initiale de toutes les publications de l'AGARD est effectuée auprès des pays membres de l'OTAN par l'intermédiaire des centres de distribution nationaux indiqués ci-dessous. Des exemplaires supplémentaires peuvent parfois être obtenus auprès de ces centres (à l'exception des Etats-Unis). Si vous souhaitez recevoir toutes les publications de l'AGARD, ou simplement celles qui concernent certains Panels, vous pouvez demander à être inclu sur la liste d'envoi de l'un de ces centres. Les publications de l'AGARD sont en vente auprès des agences indiquées ci-dessous, sous forme de photocopie ou de microfiche.

### CENTRES DE DIFFUSION NATIONAUX

ALLEMAGNE
Fachinformationszentrum.
Karlsruhe
D-7514 Eggenstein-Leopoldshafen 2

BELGIQUE
Coordonnateur AGARD-VSL
Etat-Major de la Force Aérienne
Quartier Reine Elisabeth
Rue d'Evere, 1140 Bruxelles

CANADA
Directeur du Service des Renseignements Scientifiques
Ministère de la Défense Nationale
Ottawa, Ontario K1A 0K2

DANEMARK
Danish Defence Research Establishment
Ryvangs Allé 1
P.O. Box 2715
DK-2100 Copenhagen Ø

ESPAGNE
INTA (AGARD Publications)
Pintor Rosales 34
28008 Madrid

ETATS-UNIS
NASA Headquarters
Attention: CF 37, Distribution Center
300 E Street, S.W.
Washington, D.C. 20546

FRANCE
O.N.E.R.A. (Direction)
29, Avenue de la Division Leclerc
92322 Châtillon Cedex

GRECE
Hellenic Air Force
Air War College
Scientific and Technical Library
Dekelia Air Force Base
Dekelia, Athens TGA 1010

ISLANDE
Director of Aviation
c/o Flugrad
Reykjavik

ITALIE
Aeronautica Militare
Ufficio del Delegato Nazionale all'AGARD
Aeroporto Pratica di Mare
00040 Pomezia (Roma)

LUXEMBOURG
*Voir* Belgique

NORVEGE
Norwegian Defence Research Establishment
Attn: Biblioteket
P.O. Box 25
N-2007 Kjeller

PAYS-BAS
Netherlands Delegation to AGARD
National Aerospace Laboratory NLR
P.O. Box 90502
1006 BM Amsterdam

PORTUGAL
Força Aérea Portuguesa
Centro de Documentação e Informação
Alfragide
2700 Amadora

ROYAUME UNI
Defence Research Information Centre
Kentigern House
65 Brown Street
Glasgow G2 8EX

TURQUIE
Milli Savunma Başkanlığı (MSB)
ARGE Daire Başkanlığı (ARGE)
Ankara

**Le centre de distribution national des Etats-Unis ne détient PAS de stocks des publications de l'AGARD.**
D'éventuelles demandes de photocopies doivent être formulées directement auprès du NASA Center for Aerospace Information (CASI) à l'adresse suivante:

### AGENCES DE VENTE

NASA Center for
Aerospace Information (CASI)
800 Elkridge Landing Road
Linthicum Heights, MD 21090-2934
United States

ESA/Information Retrieval Service
European Space Agency
10, rue Mario Nikis
75015 Paris
France

The British Library
Document Supply Division
Boston Spa, Wetherby
West Yorkshire LS23 7BQ
Royaume Uni

Les demandes de microfiches ou de photocopies de documents AGARD (y compris les demandes faites auprès du CASI) doivent comporter la dénomination AGARD, ainsi que le numéro de série d'AGARD (par exemple AGARD-AG-315). Des informations analogues, telles que le titre et la date de publication sont souhaitables. Veuiller noter qu'il y a lieu de spécifier AGARD-R-nnn et AGARD-AR-nnn lors de la commande des rapports AGARD et des rapports consultatifs AGARD respectivement. Des références bibliographiques complètes ainsi que des résumés des publications AGARD figurent dans les journaux suivants:

Scientifique and Technical Aerospace Reports (STAR)
publié par la NASA Scientific and Technical
Information Program
NASA Headquarters (JTT)
Washington D.C. 20546
Etats-Unis

Government Reports Announcements and Index (GRA&I)
publié par le National Technical Information Service
Springfield
Virginia 22161
Etats-Unis
(accessible également en mode interactif dans la base de données bibliographiques en ligne du NTIS, et sur CD-ROM)

*Imprimé par Specialised Printing Services Limited*
*40 Chigwell Lane, Loughton, Essex IG10 3TZ*

AGARD

NATO OTAN

7 RUE ANCELLE · 92200 NEUILLY-SUR-SEINE

FRANCE

Telefax (1)47.38.57.99 · Telex 610 176

**DISTRIBUTION OF UNCLASSIFIED AGARD PUBLICATIONS**

AGARD holds limited quantities of the publications that accompanied Lecture Series and Special Courses held in 1993 or later, and of AGARDographs and Working Group reports published from 1993 onward. For details, write or send a telefax to the address given above. *Please do not telephone.*

AGARD does not hold stocks of publications that accompanied earlier Lecture Series or Courses or of any other publications. Initial distribution of all AGARD publications is made to NATO nations through the National Distribution Centres listed below. Further copies are sometimes available from these centres (except in the United States). If you have a need to receive all AGARD publications, or just those relating to one or more specific AGARD Panels, they may be willing to include you (or your organisation) on their distribution list. AGARD publications may be purchased from the Sales Agencies listed below, in photocopy or microfiche form.

NATIONAL DISTRIBUTION CENTRES

BELGIUM
Coordonnateur AGARD — VSL
Etat-Major de la Force Aérienne
Quartier Reine Elisabeth
Rue d'Evere, 1140 Bruxelles

CANADA
Director Scientific Information Services
Dept of National Defence
Ottawa, Ontario K1A 0K2

DENMARK
Danish Defence Research Establishment
Ryvangs Allé 1
P.O. Box 2715
DK-2100 Copenhagen Ø

FRANCE
O.N.E.R.A. (Direction)
29 Avenue de la Division Leclerc
92322 Châtillon Cedex

GERMANY
Fachinformationszentrum
Karlsruhe
D-7514 Eggenstein-Leopoldshafen 2

GREECE
Hellenic Air Force
Air War College
Scientific and Technical Library
Dekelia Air Force Base
Dekelia, Athens TGA 1010

ICELAND
Director of Aviation
c/o Flugrad
Reykjavik

ITALY
Aeronautica Militare
Ufficio del Delegato Nazionale all'AGARD
Aeroporto Pratica di Mare
00040 Pomezia (Roma)

LUXEMBOURG
*See* Belgium

NETHERLANDS
Netherlands Delegation to AGARD
National Aerospace Laboratory, NLR
P.O. Box 90502
1006 BM Amsterdam

NORWAY
Norwegian Defence Research Establishment
Attn: Biblioteket
P.O. Box 25
N-2007 Kjeller

PORTUGAL
Força Aérea Portuguesa
Centro de Documentação e Informação
Alfragide
2700 Amadora

SPAIN
INTA (AGARD Publications)
Pintor Rosales 34
28008 Madrid

TURKEY
Milli Savunma Başkanlığı (MSB)
ARGE Daire Başkanlığı (ARGE)
Ankara

UNITED KINGDOM
Defence Research Information Centre
Kentigern House
65 Brown Street
Glasgow G2 8EX

UNITED STATES
NASA Headquarters
Attention: CF 37, Distribution Center
300 E Street, S.W.
Washington, D.C. 20546

**The United States National Distribution Centre does NOT hold stocks of AGARD publications.**
Applications for copies should be made direct to the NASA Center for Aerospace Information (CASI) at the address below.

SALES AGENCIES

NASA Center for
Aerospace Information (CASI)
800 Elkridge Landing Road
Linthicum Heights, MD 21090-2934
United States

ESA/Information Retrieval Service
European Space Agency
10, rue Mario Nikis
75015 Paris
France

The British Library
Document Supply Centre
Boston Spa, Wetherby
West Yorkshire LS23 7BQ
United Kingdom

Requests for microfiches or photocopies of AGARD documents (including requests to CASI) should include the word 'AGARD' and the AGARD serial number (for example AGARD-AG-315). Collateral information such as title and publication date is desirable. Note that AGARD Reports and Advisory Reports should be specified as AGARD-R-nnn and AGARD-AR-nnn, respectively. Full bibliographical references and abstracts of AGARD publications are given in the following journals:

Scientific and Technical Aerospace Reports (STAR)
published by NASA Scientific and Technical
Information Program
NASA Headquarters (JTT)
Washington D.C. 20546
United States

Government Reports Announcements and Index (GRA&I)
published by the National Technical Information Service
Springfield
Virginia 22161
United States
(also available online in the NTIS Bibliographic
Database or on CD-ROM)

*Printed by Specialised Printing Services Limited*
*40 Chigwell Lane, Loughton, Essex IG10 3TZ*

ISBN 92-835-0726-6