AGARD-CP-600 Vol. 1

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AGARD

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

AGARD CONFERENCE PROCEEDINGS 600

Future Aerospace Technology in the Service of the Alliance

(les Technologies aéronautiques et spatiales du futur au service de l'Alliance atlantique)

Volume 1:

Affordable Combat Aircraft
(le Coût de possession des avions de combat)
and

Plenary Sessions:

Future Directions in Aerospace Systems
(Futures orientations pour les systèmes aéronautiques et spatiaux)

Future NATO Trends and Mission Scenarios
(Tendances et scénarios futurs des missions de l'OTAN)

Human Machine Interaction in the Future
(Interactions homme-machine du futur)

Unclassified papers presented at the AGARD Symposium held at the Ecole Polytechnique, Palaiseau, France, 14-17 April 1997.

NORTH ATLANTIC TREATY ORGANIZATION

Published December 1997

Distribution and Availability on Back Cover

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The other volumes contain:

Volume 2:

Mission Systems Technologies
(les Technologies des systèmes de conduite de mission)

Volume 3:

Sustained Hypersonic Flight
(le Vol en croisière hypersonique)

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North Atlantic Treaty Organization
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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.

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Printed on recycled paper

Published December 1997

ISBN 92-836-0047-9

Printed by Canada Communication Group Inc.
(A St. Joseph Corporation Company)
45 Sacré-Cœur Blvd., Hull (Québec), Canada K1A 0S7

Affordable Combat Aircraft

(AGARD CP-600 Vol. I)

Executive Summary

For many years, advances in defence technology focused primarily on improving performance. Improvements in military systems were made in order to maintain superiority over potential adversaries and to counter potential threats, with little regard to cost. However, in recent years, increasing technological sophistication has caused the unit cost of military systems to increase dramatically. Initially, increasing unit cost could be accommodated because adequate military capability could be maintained with smaller numbers of more advanced systems. However, if allowed to continue, this trend must lead to the situation in which there are too few units to ensure they are available when and where they are needed.

The Joint SMP/FVP Conference on "Affordable Combat Aircraft" considered the approaches necessary to ensure that future manned combat aircraft continue to be affordable. Sessions on affordability of procurement, combat effectiveness, affordability of ownership, and the human element, contained papers which illustrated some of the very wide range of topics which need to be addressed. The presentations and discussion led to the conclusion that life-cycle cost must be considered as a primary design parameter and that, to control cost, performance goals must be defined in terms of the function of the system rather than at the detailed technical level. Concurrent engineering and virtual manufacturing will have an increasingly significant impact in this area. New technologies should be introduced into systems only when they can be shown to buy their way in. Modular systems which allow cost effective maintenance, repair and updating, and the exploitation of commonalties with civilian equipment should also be encouraged. The investment necessary to support an on-board pilot must be maximised. In summary, cost considerations have already resulted in major changes to our approach to the development of manned combat aircraft. Future technological developments are expected to permit further radical changes over the next 25 years.

Le coût de possession des avions de combat

(AGARD CP-600 Vol. 1)

Synthèse

Pendant de nombreuses années, les progrès réalisés dans le domaine des technologies de la défense ont principalement concerné l'amélioration des performances. Les systèmes militaires étaient améliorés pour préserver une supériorité sur des systèmes adverses et pour contrer d'éventuelles menaces, sans tenir compte des coûts. Or, la sophistication technologique croissante de ces dernières années a eu pour effet d'augmenter de façon spectaculaire le coût unitaire des systèmes militaires. Dans un premier temps, ce coût unitaire a pu être absorbé, puisque les capacités militaires adéquates ont pu être assurées grâce à un nombre restreint de systèmes très avancés. Toutefois, si cette tendance devait persister, elle conduirait à une situation où les moyens seraient trop peu nombreux pour assurer une disponibilité minimale en temps et en lieu.

La conférence conjointe SMP/FVP sur "le coût de possession des avions de combat" a examiné un certain nombre d'orientations permettant d'assurer l'acceptabilité financière des futurs avions de combat pilotés. Les communications présentées lors des sessions sur l'achat, l'efficacité au combat, le coût global de possession, et le facteur humain ont témoigné du grand éventail de sujets qui doivent être abordés. Les présentations et les discussions qui ont suivies ont permis de conclure que le coût global de possession doit être considéré comme un paramètre de calcul essentiel et que, pour contrôler les coûts, les objectifs de performance doivent être définis par la fonction remplie par le système, plutôt que par rapport aux détails techniques.

La conception simultanée et la fabrication virtuelle auront de plus en plus d'impact dans ce domaine. Les nouvelles technologies ne doivent être intégrées aux systèmes que lorsque leur rentabilité aura été démontrée. Les systèmes modulaires qui permettent de rentabiliser la maintenance, la réparation et la rénovation, ainsi que l'interopérabilité avec des systèmes civils, doivent également être privilégiés. L'investissement consacré au pilote à bord doit être poussé au maximum.

En résumé, les considérations de coûts ont déjà provoqué des changements majeurs dans notre approche du développement de l'avion de combat piloté. Les développements technologiques prévus amèneront d'autres changements, de caractère plus radical, au cours des 25 années à venir.

Contents

SESSION 2: COMBAT EFFECTIVENESS

SESSION 3: AFFORDABILITY OF OWNERSHIP

SESSION 4: THE HUMAN ELEMENT

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* Published in Classified Supplement
† Paper not available for publication

Preface

In the Spring of 1997, AGARD (NATO's Advisory Group for Aerospace Research and Development), which was celebrating its 45 years of dedication to the improvement of military and civilian aerospace research and development in the NATO nations, held a major conference on "Future Aerospace Technology in the Service of the Alliance" at the Ecole Polytechnique at Palaiseau near Paris, France. The conference comprised three main parallel symposia, three forward-looking plenary sessions, and a presentation of the results of a two-year visionary study entitled "Aerospace 2020"*. Each symposium was organised by two AGARD Panels, with contributions from the Aerospace Medical Panel.

The papers presented at the conference are contained in this and three other volumes, one of them classified.

This volume contains the papers from the three plenary sessions:

- **Future Directions in Aerospace Systems**
- **Future NATO Trends and Mission Scenarios**
- **Human Machine Interaction in the Future**

and the symposium on "**Affordable Combat Aircraft**", which was organised by the 'Flight Vehicle Integration' and 'Structures and Materials' Panels (FVP and SMP). It had sessions on:

- Affordability of Procurement
- Combat Effectiveness
- Affordability of Ownership
- The Human Element

Vol. 2 contains the papers on "Mission Systems Technologies"

Vol. 3 contains the papers on "Sustained Hypersonic Flight"

*The results of Aerospace 2020 are contained in an Advisory Report, AR-360, "Aerospace 2020". Vol. I is the Summary, Vol. II contains the full text of the report, and Vol. III contains supporting papers. It is planned to issue translations into French of volumes I and II later.

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CONSIDERATIONS FOR AFFORDABLE AEROSPACE SYSTEMS

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The central issue facing the NATO Alliance is the affordability of aerospace systems in the future. Since the defense budgets of all the NATO members is decreasing, it is imperative that we get as much system effectiveness for our investment as possible. This paper will address some considerations for reducing the cost of conducting tactical warfare. The AGARD Aerospace 2020 activity has addressed this critical concern and identified several initiatives to ameliorate the problem. These initiatives will be noted by a ★ in the following text. The paper will also address the Unmanned Tactical Aircraft as one of the truly revolutionary new concepts for reducing the cost (both financial and human lives) of conducting tactical air warfare.

The cost of conducting and supporting tactical air warfare can be reduced by the implementation of the following four considerations.

CONSIDERATION #1 – Fewer systems through optimum and timely deployment of resources

1. Full theater/real time situation awareness ★

   The battlefield commander that has full theater/real time situation awareness can determine the optimal deployment of his limited resources. Over the next 25 years information will become the most important resource at the command of governments, business leaders and military decision makers. Secure platforms with full spectrum sensors (visual to RF) and near real time communications links will provide the military commanders at all levels with unprecedented information on the status of the theater.

2. Time critical targets

   Some targets are time critical in that engaging the target sooner rather than later can greatly reduce the force required to stop the enemy. The battlefield awareness capability discussed above will be combined with zero to short time–of–flight weapons to destroy time critical taragets. For example, engaging an enemy while it is massed waiting to attack takes a lot less force than engaging it after it has dispersed and is overunning a town. Similary, engaging a theater ballistic missile during its slow moving, vulnerable and high signature boost phase is more effective than intercepting it during the high speed, terminal phase where debris can rain down on the friendly masses.

Paper presented at the AGARD Symposium on "Future Aerospace Technology in the Service of the Alliance", held at the Ecole Polytechnique, Palaiseau, France, 14-17 April 1997, and published in CP-600 Vol. 1.

By the year 2020 a hypersonic air breathing vehicle ★ could be available flying at Mach 8. Such a vehicle would be capable of being on target within 20 minutes, at its maximum range of 2500 km. It would have adequate payload capacity to carry a mutispectral reconnaissance sensor and information package, or a warhead and fusing package. This hypersonic vehicle could conduct several tactical missions: extended air defense, reconnaissance, strike against hardened or buried targets, strike against time critical targets, and space access.

Also by the year 2020, zero time–of–flight, directed energy weapons ★ will be available on airborne platforms. A high power laser aboard an airborne platform at 65000 feet could provide defense against theater ballstic missiles and satellites. In the medium term (2010), the US is planning to field a high powered, chemical oxygen iodine laser mounted on a Boeing 747–400 for theater ballistic missile defense. At 45000 feet the ABL (airborne laser) system is expected to destroy theater ballistic missiles at 200 km during their boost phase. Figure 1 shows a sketch of the USAF/Boeing/Lockheed Martin/TRW airborne laser aircraft which is currently in development.

Figure 1 USAF/Boeing/Lockheed Martin/TRW airborne laser aircraft

3. Timely movement of very large payloads

It is very unlikely that the Allies will have the luxury of time to build up for an offensive as was the case in Desert Shield, the prelude to Desert Storm. The movement of division resources is a Herculean effort and if its not done in a timely fashion, the enemy can gain a significant positional advantage. Current air transport is timely but woefully inadequate to meet an army division's equipment and resupply requirements.

Near term strategic airlift requirements for NATO will be met by the US C–5 and C–17 transport aircraft. The US C–130J will probably fill in the medium airlift void unless the European Future Large Aircraft (FLA) materializes.

For the year 2020, NATO members are studying advanced air transport concepts ★ capable of moving large payloads (several hundred thousand pounds). These concepts encompass lighter–than–air (neutrally bouyant), hybrid (partially bouyant) to very large heavier–than–air aircraft.

CONSIDERATION #2 – Fewer systems through higher effectiveness

Current and new systems can be made more effective by increasing their lethality with modern weapons, increasing their survivability through stealth features, ECM and standoff weapons, and increasing their availability with all weather features and crew fatigue management.

1. More lethal (Weapons)

   Increasing the lethality of new or improved weapons can breathe new life into tired and worn out weapon systems. Weapons for the year 2020 will feature lower cost, smaller and lighter (will impact aircraft size), and accuracies of less than one meter. The unitary weapons will feature improved penetration through higher length–to–diameter, nose reshaping and hardened cases.

2. More survivable (standoff weapons, decoys and stealth ★)

   Stealth will continue to be a standard feature for the year 2020 combat aircraft and will work in concert with decoys (flares, chaff, towed and powered decoys, and ECM) to increase survivability. Standoff weapons (such as the US JASSM and the UK CASOM) will permit launch well outside the threat defenses at affordable cost.

3. More available (All WX and fatigue management ★)

   Modern warfare is conducted in all weather and 24 hours a day. For example, most attack operations during Operation Desert Storm occured at night. Both vehicle and operator must be able to operate around the clock in all weather. Fatigue can dramatically degrade the normal human response time and accuracy rate , with the potential for catastrophic consequences. Performance loss can be reduced with better fatigue intervention strategies. Aerospace 2020 is researching both non–pharmaceutical and pharmaceutical techniques whih can extend the duration and quality of opeerator responsiveness.

CONSIDERATION #3 – Reduced acquisistion Cost

1. Smaller vehicle

We tend to buy aircraft by the pound of empty weight. Current US fighter/attack aircraft cost between $1100 and $1600 (US) per pound of empty weight. Thus, anything that can be done to make the aircraft smaller and reduce the empty weight will reduce the acquisition cost. Some considerations are:

Smaller weapons
Lighter weight structure
Lighter/smaller equipment
More aero/fuel efficient technologies

2. Keep It Small and Simple (KISS) with minimum part count

The aircraft design must incorporate the features of a manufacturing friendly design. This means that the design adheres to the time–proven guidelines of KISS and minimum part count for reducing the fabrication and assembly manhours.

3. Lower cost avionics

It was only a short 25 years ago that avionics was the most expensive part of the air vehicle system (approximately one–half). The avionics industry has responded very responsibly by driving the cost of their avionics down (and the reliability up) until todays avionics comprises about 20 to 30 percent of the aircraft unit cost. Employing best commercial practices and benefiting from commercial learning curve should reduce the cost of avionics even further.

4. Increase the use of commercial off–the–shelf (COTS) equipment

Increasing the use of COTS equipment can have a dramatic impact. For example, a US AWACS control power supply module cost dropped from $65K (US) as a milspec item to $27K for a new design to $10K for a commercially available unit. Developers should insist that any new technology or equipment must "buy its way" onto the aircraft.

5. Multirole/Modular/Joint ★

The design of a multi–role combat aircraft is driven by the fact that nations of today cannot afford numerous single purpose tactical aircraft. The universal goal is to have a single multi–role aircraft that can perform the tactical missions of air superiority, strike, intercept, support and recce in an acceptable fashion. The key to the successful design of a multi–role aircraft is the agreement by the users (one for each mission area) as to what is acceptable performance. Oft times the different users are from different services. If the users hold firm for superior performance in all mission areas the effort is doomed since a single affordable design does not exist. The users must understand what level of performance is absolutely critical for each mission area and not ask for more.

History is sprinkled with aircraft that performed multiple combat roles. In a few cases this design flexibility was intentional, but in most cases it was fortuitous. An example of the latter was the US McDonnell F–4 Phantom. The F–4A was designed for the US Navy as a fleet interceptor. When external fuel was replaced with external weapons it became a first class strike/interdiction aircraft, the US Air Force F–4C. Another example was the US McDonnell F–15 Eagle. When the F–15A was first designed in the early 1970's for the US Air Force it was designed for air superiority and featured a large wing (low W/S) and high thrust (high T/W). The large wing provided ample wing stations for carrying external weapons. With minimal configuration changes, the F–15E could carry a substantial external weapons load and still have the design features to perform a high performance strike mission. The performance penalty in converting a design from air superiority to strike/interdiction is small, whereas the reverse incurs a large penalty.

The Tornado MRCA (multi role combat aircraft) has successfully served the European NATO members with its multi role capabilities for several decades. It remains to be seen if the near term Eurofighter 2000 (IOC: 2002) and far term Joint Strike Fighter (IOC: 2015, shown in Figure 2) can match its flexibility.

CONSIDERATION #4 – Reduced O&S Cost

1. Reduced support manpower

Over half of the O&S cost is direct manpower and indirect manpower support. Most of the direct manpower is assigned to service and maintain the aircraft (ground support). Anything that can be done in the design to reduce the manpower for unscheduled maintenance (fixing things that break) or servicing the aircraft (moving the aircraft around the base, weapons loading, refueling, inspection, and scheduled maintenance) will have a big impact on O&S costs. Vehicle equipment should be made more reliable so that it would operate for extended periods without main-

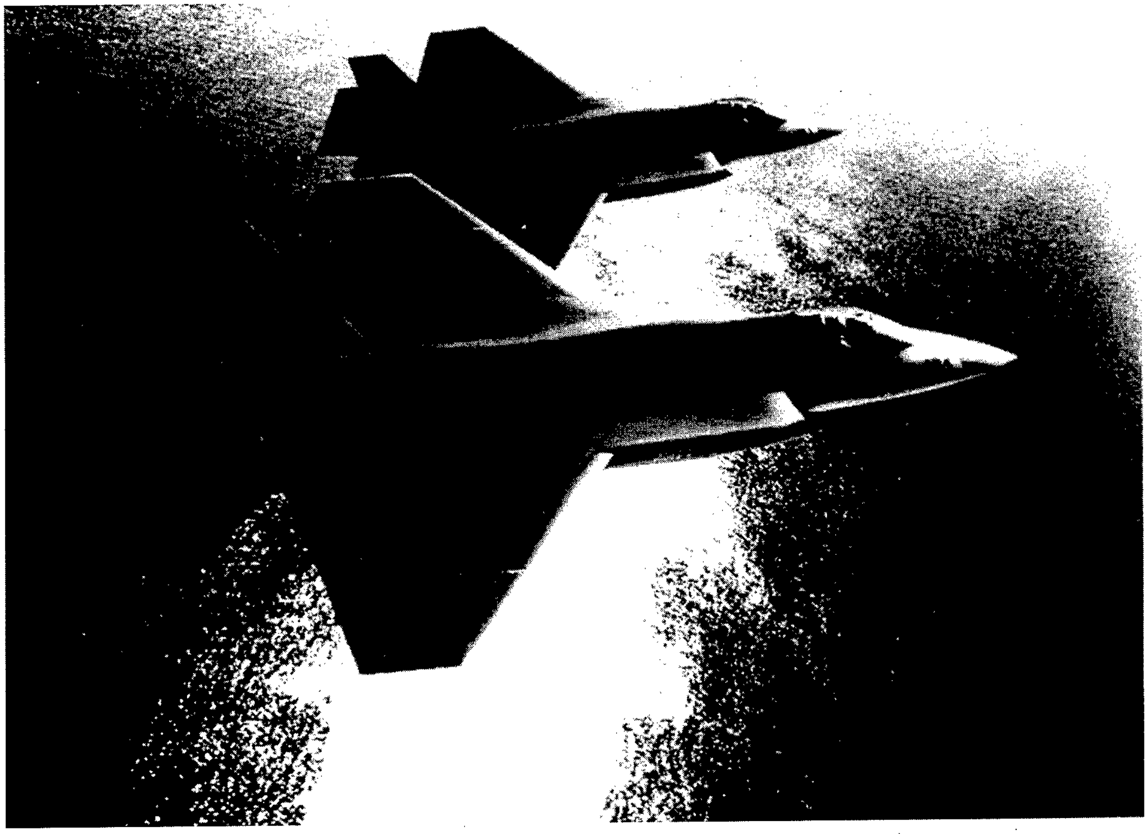


Figure 2 Lockheed Martin candidate for the Joint Strike Fighter

tenance. Aircraft should be designed with built–in test features and easy access to troublesome equipment.

2. Reduced peacetime training flights

The best way to reduce peacetime O&S is to not fly the aircraft for training. Thus, an alternative to flying the aircraft for operator proficiency must be found. Two considerations are:

Use synthetic environment for training ★ – The contribution of simulation for military training is not new. Simulation has been employed in aviation for over 35 years in many different ways. Simulations are currently divided into three broad classes: Constructive simula tion, virtual simulation and Live simulation. It has been said that "everything is simulation except actual combat". Constructive simulations involve simulated people using simulated equipment. An example is the TAC Thunder analysis model. Virtual simulations involve real people using simulated equipment. An example is the pilot–in–the–loop flight simulator used in engineering design or in training. Live simulations involve real people using real equipment. An example is the Red Flag style of exercise. However, even with the simulation for the pilot proficiency, the current aircraft themselves need to be flown to keep their systems in operating order.

Unmanned Tactical Aircraft (Uninhabited Combat Air Vehicle)★ – The revolutionary feature of the UTA (or UCAV) is that during peacetime the UTA is kept in flyable storage and not flown, and the remote operators stay proficient through synthetic environment. The vehicles are designed for extended storage with minimum service required. Thus the peacetime O&S is an order of magnitude less compared to a manned aircraft doing a similar mission. Over 20 years this has the potential for a 70% reduction in LCC (Life Cycle Cost).

Unmanned Tactical Aircraft (Uninhabited Combat Air Vehicle)

The Unmanned Tactical Aircraft is viewed by many as the centerpiece for affordable tactical air warfare in the year 2020 due to its potential for a revolutionary reduction in LCC and the fact that it embodies most of the Aerospace 2020 technology initiatives. The remainder of the paper will discuss the UTA concept.

The definition of a UTA (or UCAV) is any uninhabited vehicle that is recoverable and reusable with autonomous operation and man–in–the–loop that performs tactical missions. The man–in–the–loop feature is very important since there is always the possibility of an unknown or unforeseen event (inflight emergency, target not where or what it is supposed to be, hostages chained to the target, etc). The distribution of autonomous operation (preplanned in the near term and adaptive in the far term) versus man–in–the–loop is not known at present since the extent to which artificial intelligence or preprogrammed logic can accommodate unknown or unforeseen events has not been established. This automation technology is one of the enabling technologies that must receive significant attention in the future. The man–in–the–loop is a fall–back feature that permits a remote operator to interrupt the autonomous operation and assess the situation, make a decision and tell the UTA what to do next.

In the case of a UTA with weapons onboard, this man–in–the–loop feature permits the remote operator to make a rational, judgemental and moral assessment of the situation before the automatic weapons delivery. Onboard sensors would survey the target area and the target imagery would be data linked to the remote operator for target verification. This man–in–the–loop feature is often described as "removing the pilots body from the vehicle but leaving his head onboard".

The advantages of an uninhabited system over a manned system are:

1. Reduced Life Cycle Cost
    a. Lower acquisition
    b. Greatly reduced O&S
2. Human crew not at risk
3. Performance not tied to human frailties
4. Reduced political sensitivity

The reduced LCC is viewed as the most important benefit in this period of reduced defense budgets in the US. NATO's extreme interest in UTA is motivated by a similar trend towards massive reductions in the member countries defense budgets. This benefit comes from reductions both in acquisition and O&S. With the elimination of the pilot from the vehicle and the relaxation of the structural design criteria, the UTA can be made lighter, smaller and cheaper. For manned aircraft the crew station features account for approximately 6 percent of the empty weight and 2 percent of the unit cost. Eliminating the requirement for a crew station gives the designer more freeedom in configuring and packaging a new UTA design. Relaxing the structural design criteria (lower factor of safety and reducing durability requirements due to reduced design life) can reduce the structural weight compared to a manned aircraft.

Since the UTA does not have to be flown during peacetime to maintain operator proficiency, there is a large reduction in peacetime O&S costs by not having the maintenance and support manpower. The problem is to have the maintenance and support personnel available during wartime but not have to pay for them in peacetime.

Since a human pilot is not onboard the UTA, the loss of human life is not a concern. This means of course that the UTA could be assigned missions deemed too risky for its manned counterpart.

The UTA can be designed for environmental conditions that are unacceptable for a human pilot. Maneuver g's greater than the human limit of nine are a design option as well as flight durations of days or weeks. Exposure to nuclear, biological and chemical environments would not be a major concern for the UTA. However, exposure to chemical or biological agents could be an issue if the UTA returns to base in a contaminated state. It would need to be decontaminated prior to its next mission or servicing task.

Since the crew has been eliminated from the vehicle, the political sensitivity of the UTA mission is reduced since there is no crew to be held hostage or crew remains to recover. In an extreme case, a country could deny ownership of a "laundered" UTA.

The class of UTA vehicles extends from more flexible and capable versions of currently deployed UAVs to future full spectrum uninhabited aircraft. Missions for UTAs in order of increasing complexity are as follows:

1. Intelligence, surveillance and reconnaissance and battle damage assessment
2. Electronic warfare
3. Suppression of enemy air defenses (SEAD)
4. Fixed target strike
5. Theater ballistic missile and cruise missile defense
6. Air defense
7. Interdiction anad mobile target strike
8. Close air support
9. Air–to–air combat

The UTA configurations designed to perform the above missions can range from very small to very large with flight speeds from low speed to hypersonic. The elimination of the human from the vehicle opens up the design space enormously, giving rise to revolutionary configurations, capabilities and concepts of operation.

A Concept of Operations for a strike UTA doing a SEAD (Suppression of Enemy Air Defenses) and fixed target strike mission is shown in Figure 3. Since the strike UTA is a revolutionary concept, the Concept of Operations presented in this section is very preliminary and is offered as a departure point for further discussion.

The UTA is a complement to manned aircraft, not a replacement. There are many reasons for having a viable manned strike aircraft force. During peacetime and low tension situations, the UTA would probably not be flown, relying on the manned aircraft to project airpower and control situations. During wartime, the UTA would be deployed and conduct integrated tactical strike with the manned aircraft fleet.

Since the UTA is autonomous, it does not need to fly during peacetime for the operator to stay proficient. Thus, the UTAs are not flown during peacetime, but rather are stored in a humidity controlled, flyable storage facility. Eliminating peacetime flying reduces the peacetime O&S costs significantly. To ensure readiness, several UTAs would probably be taken out of storage and flown each year for training exercises, but the total 24 unit squadron flying hours would be less than 100.

MISSION AREA: SEAD AND FIXED TARGET STRIKE

FEATURES:

INDEPENDENT OR INTEGRATED WITH MANNED STRIKE

AUTONOMOUS MISSION WITH MITL FOR AUTHORIZATIONS

GREATLY REDUCED PEACETIME O&S
- **AIRCRAFT IN FLYABLE STORAGE**
- **MINIMAL FLYING (ANNUAL SQUADRON FLYING)**
- **REMOTE PILOT PROFICIENCY THRU SIMULATION**
- **GROUND SUPPORT CREW PROFICIENCY THRU TRAINING DEVICES AND FEW ACTUAL FLIGHTS**

SEPARATE BASING WITH HIGHLY AUTOMATED GROUND HANDLING (SMALL MANPOWER REQUIREMENT)

AIRCRAFT DESIGNED FOR 500 HRS STRUCTURAL LIFE AND MAINTENANCE FREE OPERATION

Figure 3 Notional Concept of Operations

In contrast, a 24 unit F–16 air–to–ground squadron would fly about 8300 hours each year.

Since the UTA is essentially not flown during peacetime, the number of active duty ground crew (maintenance and support personnel) is very small. During peacetime, the ground crew would support the few actual flights, maintain the UCAVs in flyable storage (assumed to consist of monthly external inspections), and train reserve ground support crews. This UTA concept is very much different than the concept for manned aircraft. Manned aircraft must be operated regularly in peacetime in order to maintain aircrew proficiency, exercise avionics and weapon systems, and keep the aircraft in flying condition. The active duty UTA ground crews are estimated to consist of less than 20 people per squadron in peacetime. In contrast, the F–16 squadron requires over 240 ground crew personnel to support the peacetime flying operations of 24 aircraft. When the UTA is deployed during wartime, the ground support crew would be augmented by reserve crews.

The UTA system would be designed so that it can be deployed during wartime needing only a fraction of the ground crew personnel required for a manned strike aircraft unit. The UTA airframe and equipment are designed to a limited life ... time spent in actual wartime. A manned aircraft is designed to something like 7000 hours (15 year lifetime with 30 hours of training per month plus 1000 hours of deployment and 500 wartime hours) whereas the UTA is designed to only the wartime hours. Both the structural design life and the equipment life of the UTA is designed for about 500 hours. The equipment would have a design goal of operating maintenance free for 500 hours. Scheduled maintenance (replacement of brakes, tires, batteries and POL) would be performed during wartime, but no unscheduled maintenance. This 500 hour maintenance free operation greatly reduces the number of ground crew personnel needed in wartime since no maintainers are needed.

In addition the UTA ground handling would be highly automated so that the active duty ground crew plus 4 reserve unit ground crews can support the wartime operation of a 24 unit strike UTA squadron. A ground handling concept would consist of automated ground equipment and activities. The UTA would taxi around the airfield under its own power following a ground map and plan (using differential GPS) under the control of a ground operator.

A conceptual design was conducted of a near term strike UTA having requirements similar to an F–16C in order to quantify the projected LCC savings. This study permitted a one–to–one cost comparison with a current manned strike aircraft. The UTA had an empty weight of approximately 7000 lb and a unit cost of $7M in 1996 $ (the resulting $1000/lb is about ten percent less than a manned aircraft).

A 24 UTA squadron manning for peacetime is shown on Figure 4 and compared with a 24 strike F–16 squadron. The number of officers (primarily pilots or remote operators) is about the same for the two stike squadrons, but the number of enlisted personnel doing maintenance and support is very much less for the UTA squadron. The UTA peacetime O&S cost is an order of magnitude less than a comparable manned squadron for this near term example..

The projected 10 year life cycle cost for a UTA squadron is shown on Figure 5 in comparison with a strike F–16 squadron. The squadron amortized RDT&E and acquisition costs are about the same for the two squadrons. The UTA acquisition cost includes the unit cost of $7M each plus 6 ground stations and the ground support equipment (GSE) for the automated ground handling. The big difference is in the O&S cost which gives a greater than 50% reduction in 10 year LCC for the

F–16 Annual O&S (per AFI 65–503)		Strike UCAV Annual O&S (per modified AFI 65–503)	
Unit personnel (42 off./307 enl.)	$14.3M	Unit personnel (30 off./32 enl.)	$3.25M
Fuel for 8300 flying hours	5.0M	Fuel for 100 flying hours	.06M
Personnel support	9.2M	Personnel support	1.31M
Depot maintenance	6.1M	Training and personnel acq	.63M
Training and personnel acq	4.8M	System support and mods	.60M
Replenish spares	6.0M		
System support and mods	3.9M		
Munitions and missiles	1.1M		
Total	**$50.4M**	**Total**	**$5.85M**

All $ in 1996 $M

Figure 4 Strike UTA peacetime O&S cost compared to an F–16C unit

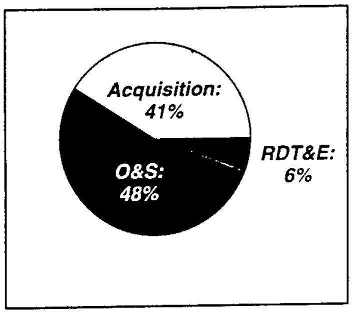
UTA. It is expected that a year 2020 UTA, "pushed" by an ambitious technology program, would exceed this LCC savings significantly.

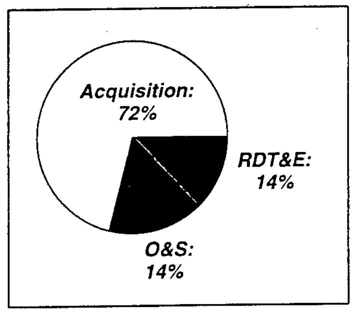
The technology areas critical to developing a UTA are:
Communication and control
- Adaptive autonomous vehicle control systems
- Man/Machine Interface – extent of autonomous operation vs man–in–the–loop
- Near–real–time, secure, long range data communication

Reduced O&S
- Long term storage of engine and vehicle sysstems
- Automated ground handling
- Extended maintenance free operation

The extent to which the UTA advantages are realized is as much a cultural challenge (how it would be implemented) as it is a technology challenge (what can the warfighter have). Since the impact of the UTA is a revolutionary reduction in the cost (both financial and human lives) of conducting tactical air warfare, it is imperative that both challenges be met.

Squadron:	F–16 C/D Manned Strike	Strike UCAV
No. of Aircraft:	24	24
Peacetime Annual Flying Hrs:	8300	< 100
Squadron Amortized RDT&E:	$60M	$60M ($2B est. over 33 squadrons)
Squadron Acquisition Cost:	$381M	$310M *(24 UCAV @ $7M each, 6 ground stations @13.7M each, $60M GSE)*





Annual O&S	$50.4M	$5.9M
Total 10 Year LCC	$945M	$429M (all $ in 1996 $M)

Figure 5 Ten year squadron Life Cycle Cost comparison

TECHNOLOGICAL TRENDS TOWARDS AUTONOMOUS UNMANNED COMBAT SYSTEMS

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SUMMARY

The development, procurement and utilization of defense systems will in future be strongly influenced by affordability. A considerable potential for cost reduction is seen in the extended use of unmanned systems. This paper will describe important enabling techniques and technologies as a prerequisite for the implementation of future autonomous systems with goal- and behavior-oriented features. Main emphasis is being placed on information technology with its soft-computing techniques. The treatment of conceptional system approaches will be followed by design considerations and then a global methodology for the engineering of future autonomous systems will be dealt with. Critical experiments for technology evaluation and validation will be mentioned together with a brief description of the main focus in future research.

1 INTRODUCTION

Tactical systems are implemented as Integrated Mission Systems (IMS) such as e.g. air and space defense systems. Key elements of IMS are - among others - platforms with sensors and effectors, ground based components with communication, command and control etc.

In technology, evolutionary progress is generally determined by the interaction between the "Requirements Pull (RP)" and the "Technology Push (TP)" (Fig. 1).

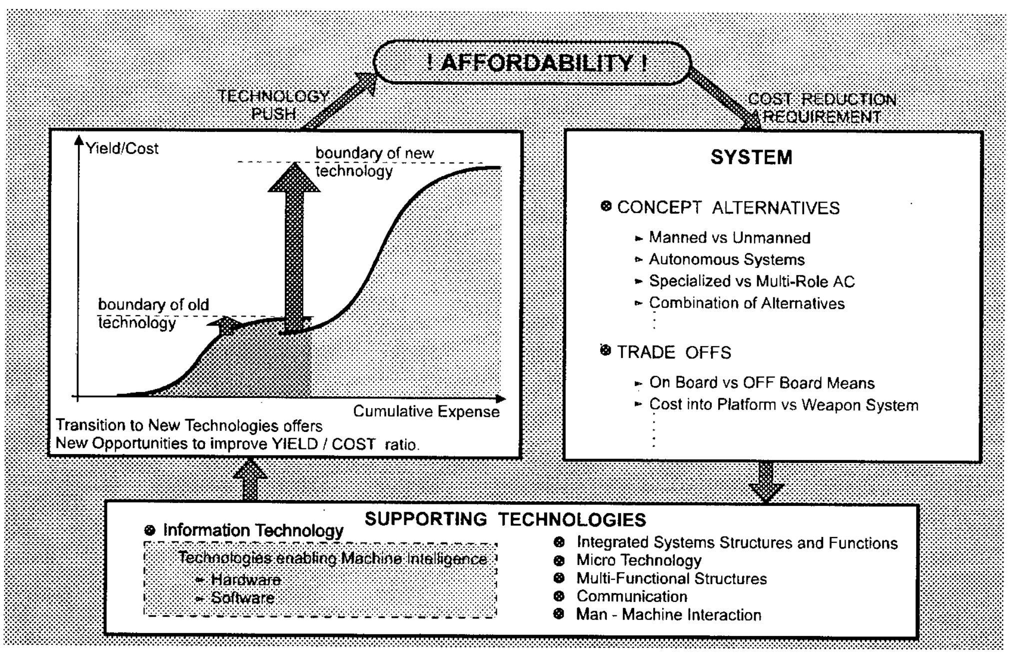


Figure 1: Requirements pull vs. technology push

Paper presented at the AGARD Symposium on "Future Aerospace Technology in the Service of the Alliance", held at the Ecole Polytechnique, Palaiseau, France, 14-17 April 1997, and published in CP-600 Vol. 1.

Ever increasing requirements for more and more complex systems and their functions activate individual key technologies within the technological basis available or possibly to be created. However, new technologies - such as currently the new Information Technology (IT) and Micro Technology (MT) - exert pressure towards increased requirements for new systems.

In the future progress primarily will be driven by economic aspects rather than by technological advances alone. Within this context "affordability" is of decisive importance. Advancing Technologies are essential for achieving unprecedented capabilities for new systems at affordable cost. Looking at Fig. 1 (upper left) the yield/cost ratio is plotted against the commulative expenses for old and new technologies (e.g. Information Technology). Considering the general performance potential, the transition to new technologies is mandatory to offer new opportunities and improved yield/cost ratios. Autonomous unmanned tactical systems surely are a viable step to cope with the cost reduction challenge and to improve cost effectiveness in the future.

It is impossible to treat all important related techniques and technologies (see Fig. 1.e.g.) within the scope of this paper. The key notion „autonomy“ is intimately connected with advances in Information Technology. Therefore emphasis is placed on this aspect.

2 AUTONOMOUS SYSTEMS

Autonomy is the ability to function as an independent system, unit or element over an extended period of time, performing a variety of actions necessary to achieve predesignated objectives while responding to stimuli produced by integrally contained sensors. The following characteristics are therefore typical of an autonomous, behavior-oriented system:

- An "environment" (real world) is allocated to the system
- There is an interaction between the system and the environment via input and output information and possibly output actions
- The interactions of the system are concentrated on performing tasks within the environment according to a goal-directed behavior, with the system adapting to changes of the environment.

The interaction of the systems with the surrounding world can be decomposed into the following elements of a recognize-act-cycle (or stimulus-response-cycle).

- Recognize the actual state of the world and compare it with the desired state (which corresponds to the goal of the interaction). (MONITORING)
- Analyse the deviations of actual and desired state. (DIAGNOSIS)
- Think about actions to modify the state of the world. (PLAN GENERATION)
- Decide the necessary actions to reach the desired state. (PLAN SELECTION)
- Take the necessary actions to change the state of the world. (PLAN EXECUTION)

To perform these functions, first of-all appropriate sensor and effector systems must be provided, as mentioned earlier. In the case of unmanned autonomous systems information processing means must be incorporated that apply machine intelligence to perform the tasks mentioned.

3 ENABLING NEW INFORMATION TECHNOLOGY

Paradigm shift to brainlike structures

The expected unprecedented advances in computing based on the conventional architecture, where processing is performed sequentially, do not yield the power for computational and machine intelligence. This becomes ultimately evident if we compare a contemporary high performance computer (Cray YMP/8) with the brain of an insect, as represented in Fig 2. A vast amount of hardware and software consuming a lot of power is needed to build and operate the Cray-machine, as compared to the biological brain. What is even more impressive is the level of capabilities achieved with the latter. To make at least a small step towards a technical implementation of biological intelligence, as it is needed for autonomous systems, new computational techniques and architectures must be considered and introduced.

There is a paradigmatic complementary shift from symbolic artificial intelligence techniques to a new paradigm, which is inspired by modelling the conscious and unconscious, cognitive and reflexive function of the biological brain.

Important related computing methodologies and technologies include inter alia fuzzy logic, neuro-computing and evolutionary and genetic algorithms.

Fuzzy Logic

The theory of fuzzy logic provides a mathematical framework to capture the uncertainties associated with human cognitive processes, such as thinking and reasoning. Also, it provides a mathematical morphology to emulate certain perceptual and linguistic attributes associated with human cognition. Fuzzy logic provides an inference morphology that enables approximate human reasoning capabilities for knowledge-based systems. Fuzzy logic/fuzzy control has developed an exact mathematical theory for representing and processing fuzzy terms, data and facts which are relevant in our conscious thinking.

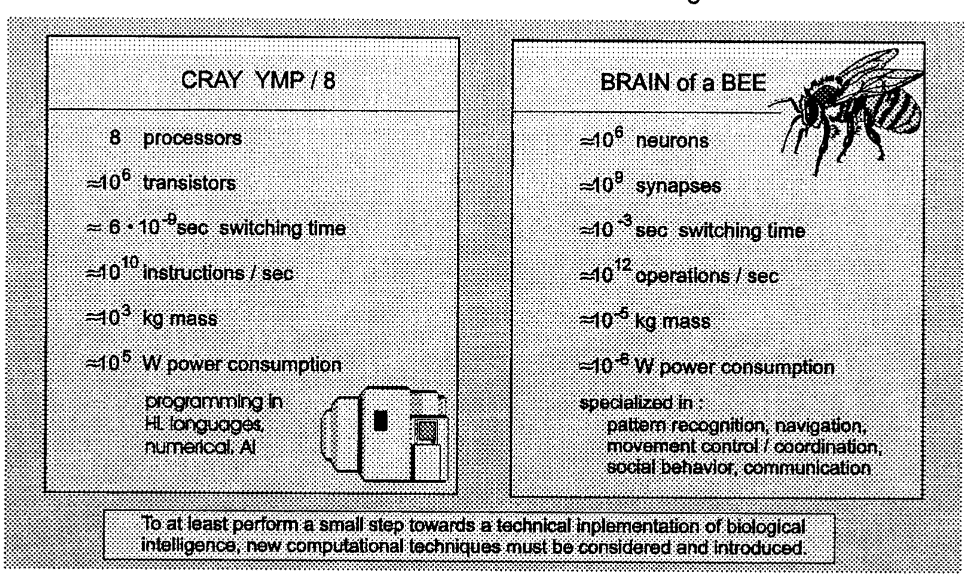


Figure 2: Comparison computer and brain of an insect

A unit based on fuzzy logic represents an associator that maps crisp spatial or spatio-temporal multi-variable inputs to corresponding associated crisp outputs. The knowledge which relates inputs and outputs is expressed as fuzzy if-then rules at the form IF A THEN B, where A and B are linguistic labels of fuzzy sets determined by appropriate membership functions.

Fuzzy rule based systems enable endomorphic real world modelling. With this technology human behavior can be emulated in particular as far as reasoning and decision making and control is concerned taking into account the pervasive imprecision of the real world. Fuzzy logic strongly supports realistic modelling and treatment of reality.

Artificial Neural Networks (ANN)

Neural Networks are derived from the idea of imitating brain cells in silicon and interconnecting them to form networks with self-organization capability and learnability. They are modeled on the structures of the unconscious mind.

Neurocomputing is a fundamentally new kind of information processing. In contrast to programmed computing, in the application of neural networks the solution is learnt by the network by mapping the mathematical functional relations. Neural networks are information processing structures composed of simple processor elements (PE) and networked with each other via unidirectional connections. The "knowledge" is contained in the variable interconnection weights. They are adjusted during a learning or training phase and continue to be adapted during operational use. With this capability the ANN represents an associator (like a fuzzy logic unit) that maps spatial or spatio-temporal multi-variable inputs to corresponding associated outputs. However, in contrast to a fuzzy-rule-based system the mapping function is learnt by the ANN. Neural Networks are capable of acquiring, encoding, representing, storing, processing and recalling knowledge. These are important prerequisites for endomorphic real world modelling.

Genetic and Evolutionary Algorithms

Genetic and evolutionary algorithms represent optimization and machine learning techniques, which initially were inspired by the processes of natural selection and evolutionary genetics.

To apply a genetic algorithm (GA) potential solutions are to be coded as strings on chromosomes. The GA is populated with not just one but a population of solutions, i.e. GA search from a population of points rather than from a single point. By repeated iterations a simulated evolution occurs and the population of solutions improves, until a satisfactory result is obtained. This is accomplished by iteratively applying the genetic operators reproduction, crossover and mutation.

Computer simulation is a viable tool to optimize behavior oriented systems by utilizing genetic or evolutionary techniques. Ever increasing processing speed enables the quick motion representation of events and processes, for which nature requires millions of years.

Conclusions

It was shown that fuzzy and artificial neural network techniques enable the endomorphic modelling of real world objects and scenarios. Together with conventional algorithmic processing, classical expert systems, probabilistic reasoning techniques and evolving chaos-theoretic approaches they enable the implementation of recognize-act cycle functions as mentioned. Genetic and evolutionary algorithms can be applied to generate and optimize appropriate structures and/or parameters to acquire, encode, represent, store, process and recall knowledge. This yields self-learning control structures for dynamical scenarios that evolve, learn from experience and improve automatically in uncertain environment. Ideally, they can be mechanized by a synergetic complementary integration of fuzzy, neuro and genetic techniques. These techniques support the move towards adaptive knowledge based systems which rely heavily on experience rather than on the ability of experts to describe the dynamic, uncertain world perfectly. This is accomplished by consideration of the tolerances for imprecision, uncertainty and partial truth to achieve tractable, robust and low cost solutions for complex problems.Thus, these techniques in conjunction with appropriate system architectures provide the basis for creating behavior-oriented autonomous systems.

4 CONCEPTUAL IDEAS

System architectures

The viable architecture must represent the organization of the systems intelligence and capability to behave, to learn, to adapt and to reconfigure in reaction to new situations in order to perform in accordance with its functionalities. Based on fundamentally different philosophies regarding the organisation of intelligence, two different architectures can be basically considered (Fig. 3). With the well known top-down approach as prevalently used to date a hierarchically functional architecture results. It structures the system in a series of levels or layers following the concept of increasing precision with decreasing intelligence when going from top to bottom. Implementation is characterized by the fact that for as many contingencies as possible the allocated system behavior is fixed in top-down programming. In fact, the real world is so complex, imprecise and unpredictable that the direct top-down programming of behavioral functions soon becomes very difficult if almost not impossible.

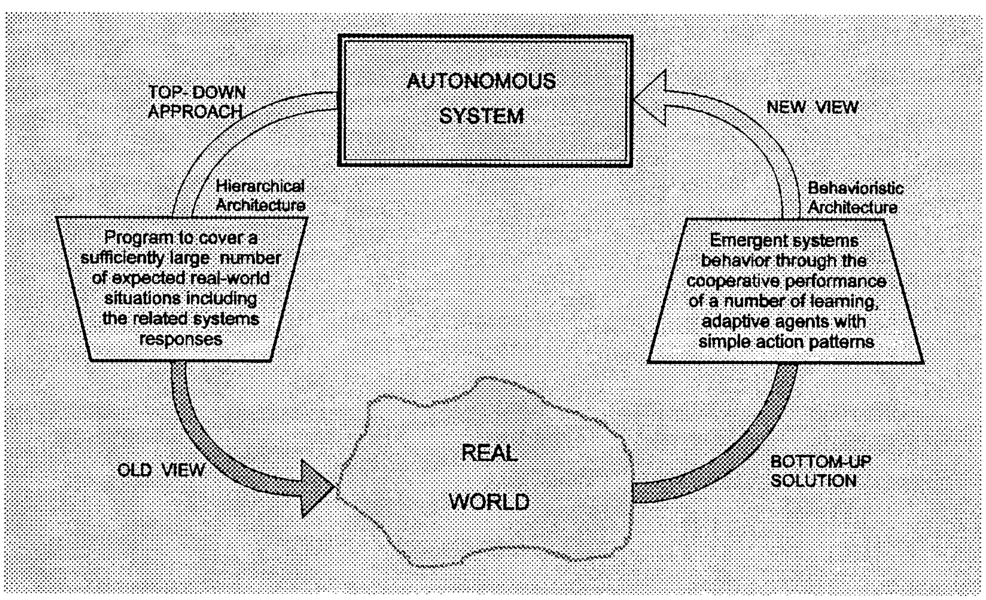
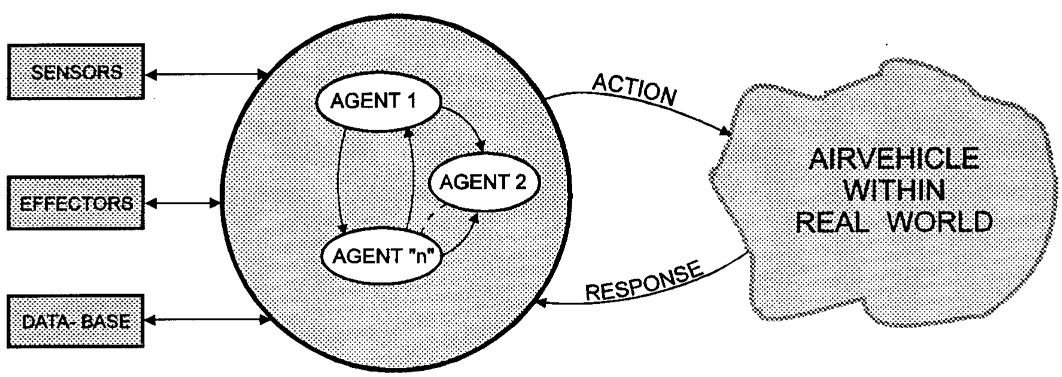


Figure 3: Top-down vs. bottom-up approach

Considerably different from the hierarchical structure is the subsumption architecture. It is based upon building functionality and complexity from a number of simple, parallel, elemental behaviors. It is sometimes called the behaviorist architecture and is based on a buttom-up approach. In this approach, so-called agents are implemented with the most simple action and behavior patterns possible so that the resulting emergent system behavior corresponds to the desired global objective. The system is able to adapt itself to changing situations in the environment by learning. The specific local intelligence of the individual agents generates a global intelligent behavior of the integrated overall system. Multi-agent systems are complex and hard to specify in their behavior. Therefore there is the need to endow these systems with the ability to adapt and learn. This can be acomplished by the application of the technologies mentioned before.

A simplified block diagram of an autonomous system based on such a concept of cooperative AI/KB-Agents, is depicted in Fig 4. The objective is to implement as many simple agents as possible with the associated behavior pattern, which then make the system act in a flexible, robust and goal-oriented manner in its environment through their additively complementary interaction. To enable the generation of emergent characteristics it must be ensured that the agents can influence each other mutually. Emergent functionality is one of the major fields of research dedicated to behavior-oriented systems.

Intelligent hardware/software agents will fuse sensor information, monitor critical variables, generate optimized plans, alert operators through communication to problems as they arise and recommend optimized solutions in real time. Response agents capture basic data, communication (forecast and other information) and apply optimization technology to generate new plans based on changed conditions and states.



AGENTS						
SENSOR DATA FUSION	PERCEPTION, SITUATION ASSESSMENT	PLANNING	....	PILOTING	THREAT	COMMUNICATION

Figure 4: System representation by agents

Design Considerations

Like in Engineering, it is also an indispensable prerequisite for an autonomous system that it is designed, constructed and trained according to a strict methodical approach. Fig. 5 shows such an approach in a very simplified form from today's technological point of view [1].

It starts with the description of the physical system, its application, the initial environment, and the behavior requirements, with the latter being usually informally stated in natural language. The following behavior analysis is one of the major tasks. This step involves the decomposition of the target behavior in simple behavioral components and their interaction. Part of the specification is the architecture of the intelligent control system. It is the second key point during the engineering process. With the specification all information is available to design, implement and verify a nascent system, which is endowed with all its hardware and software components, however, prior to any training.

Based on a suitable training strategy the system acquires its knowledge during a training phase which is mandatory and prerequisite for appropriate behavior of the system. Training can usually be speeded up applying simulation including virtual reality. Within this context environments can be used that are much more changeable than the real ones.

After completion of training the behavior is assessed with respect to correctness (target behavior), robustness (target behavior vis-à-vis changing environment) and adaptiveness. Based on this assessment, further iterations during the engineering steps might become necessary in order to make the satisfactorily behaving system evolve from them in a step by step sense.

Implementation issues

Implementation issues like

- hardware for computational and machine intelligence
- software technology, software generation techniques
- autonomous control technology
- autonomous planning and routing
- integrated system structures and functions
- adaptive autonomy management

could not be treated here. It is referred to the Literature, e.g. [2].

5 EMERGENCE OF AUTONOMOUS SYSTEMS

The critical technologies, such as the new paradigm information and control technologies are indeed highly developed activities, however still mainly in universities and industry R.a.D. branches. Thus a time interval of 10 to 20 years is likely to elapse, until applications can be expected within systems as treated here.

Beyond the enabling technologies further technical issues such as

- maturity assessment
- system concepts
- critical experiments
- validation, certification techniques
- future research focus

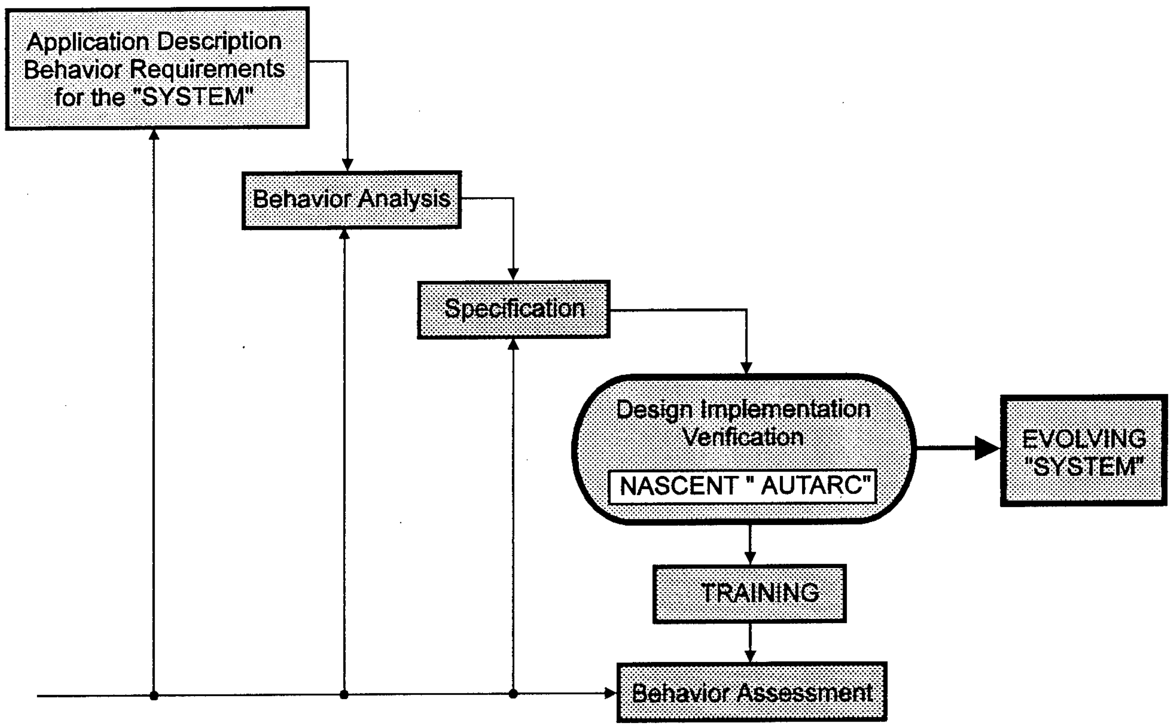


Figure 5: Engineering of the autonomous system

shall be emphasized, because they critically influence the emergence of autonomous systems. Stepping back to the first chapter and recalling the interdependence of the Requirements Pull and the Technology Push it is of paramount importance for research planners to identify applications and requirements indicating the indispensable need for such systems and their capabilities. In this context the Uninhabited Tactical Aircraft (UTA) concept of variable autonomy currently under investigation, offers an ideal platform to perform critical experiments for the evaluation, validation and possibly certification of techniques and technologies.

Autonomous unmanned systems will be designed such that they offer fully autonomous operation. However, provisions will be incorporated allowing a human to monitor the system´s operation and to intervene if required.

6 FINAL REMARKS

Significant changes are currently taking place in the new IT, MT and other technological areas as far as functional capabilities, performance, characteristics and cost are concerned. These changes will influence the users of these technologies and the supporting industries as well as their technical and organisational structures. Organizational structures have always reflected system structures. The rate of change and related realizations will exceed normal evolution and will have great social impacts accompanying the technological and functional advances. Instead of spin-offs considerable spin-in effects from commercial research and industry will impact military applications. Simultaneously a global availability of commercial High-Tech must be assumed.

In order to accommodate all this, the strategies of users and industry must be adapted accordingly. Looking at the interdependence of requirements, technologies, procurement processes and time behavior, 20 years is a short period.

WE MUST BEGIN NOW!

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MILITARY IMPLICATIONS OF AUTONOMOUS UNMANNED COMBAT SYSTEMS

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THE PREVIOUS TWO PRESENTATIONS OF THIS PLENARY SESSION HAVE, FIRSTLY, DRIVEN HOME A PERSUASIVE CASE FOR NATO MEMBERS TO GIVE INCREASED PRIORITY TO THE DEVELOPMENT OF AN UNMANNED TACTICAL AIRCRAFT (UTA) TO MEET FUTURE CONTINGENCIES AND, SECONDLY, PRESENTED AN OPTIMISTIC VIEW THAT TECHNICAL CHALLENGES CAN BE MET TO PERMIT THE DEVELOPMENT OF AN AUTONOMOUS UTA WITHIN THE TIME FRAME IN FOCUS. THE TASK OF THIS PRESENTATION IS TO BRIEFLY IDENTIFY THE MILITARY IMPLICATIONS OF INTRODUCING A FULLY CAPABLE UTA INTO THE NATO FORCE STRUCTURE, TO INCLUDE AN AUTONOMOUS VERSION. SINCE IT CONCEPTUALLY IS ASSUMED THAT THE AUTONOMOUS VERSION WILL GROW OUT OF THE BASIC UTA AND THAT THEY WILL SHARE THE SAME OPERATIONAL CHARACTERISTICS, THE TWO WILL BE DISCUSSED TOGETHER WITH APPROPRIATE ADDITIVE COMMENTS ON THE AUTONOMOUS AIRCRAFT INTERJECTED AS APPROPRIATE.

THE MOST IMPORTANT AND OVERRIDING MILITARY IMPLICATION OF THE ULTIMATE FIELDING OF A UTA SYSTEM WILL BE THE INCREASED CAPABILITY IT WILL PROVIDE NATO FIELD COMMANDERS IN DEALING WITH FUTURE CONTINGENCIES- PARTICULARLY AT THE HIGHER END OF THE SPECTRUM. AS HAS BEEN POINTED OUT EARLIER, THE UTA IS INTENDED FOR USE AGAINST HIGH-RISK TARGETS WHICH USUALLY ARE THOSE OF PRIME IMPORTANCE TO ANY POTENTIAL ENEMY. THE UTA WILL NOT ONLY TAKE A SIGNIFICANT STEP TOWARD THE GOAL OF MINIMIZING CASUALTIES, BUT IT WILL ALSO SATISFY THE TEST OF AFFORDABILITY WHICH HAS BECOME SO IMPORTANT THROUGHOUT THE ALLIANCE IN RECENT YEARS. THE UTA IS EXPECTED TO PROVE ITSELF TO BE AN EXCEPTIONALLY FLEXIBLE WEAPON AND LONG RANGE PLANNERS ENVISION ITS USE IN THE FOLLOWING MISSION TASKS:

1. INTELLIGENCE, SURVEILLANCE, RECONNAISSANCE AND BATTLE DAMAGE ASSESSMENT
2. ELECTRONIC WARFARE
3. SUPPRESSION OF ENEMY AIR DEFENSES (SEAD)
4. FIXED TARGET STRIKE
5. THEATER BALLISTIC MISSILE AND CRUISE MISSILE DEFENSE
6. AIR DEFENSE
7. INTERDICTION AND MOBILE TARGET STRIKE
8. CLOSE AIR SUPPORT
9. AIR-TO-AIR COMBAT

MOST PROPONENTS, IN SUPPORTING THE UTA, USE THE SUPPRESSION OF ENEMY AIR DEFENSES (SEAD) MISSION AS A CLEAR EXAMPLE OF THE NEED FOR THE UTA CAPABILITIES. IN ANY AIR CAMPAIGN, THE FIRST PRIORITY MUST BE GIVEN TO NEUTRALIZING THE OPPONENT'S AIR

Paper presented at the AGARD Symposium on "Future Aerospace Technology in the Service of the Alliance", held at the Ecole Polytechnique, Palaiseau, France, 14-17 April 1997, and published in CP-600 Vol. 1.

DEFENSE CAPABILITY SO THAT FRIENDLY AIR CAN CONDUCT ITS OFFENSIVE OPERATIONS RELATIVELY UNMOLESTED. BUT AIR DEFENSES, BY THEIR NATURE, ARE CERTAINLY HIGH-RISK TARGETS AND HISTORY HAS SHOWN THAT IT IS THERE THAT WE HAVE SUFFERED OUR MOST WIDESPREAD LOSSES IN THE PAST. THE ENVISIONED UTA, SUPPORTED TO A DEGREE BY OTHER SYSTEMS, IS EXPECTED TO BE HIGHLY EFFECTIVE AGAINST SUCH TARGETS AND WHATEVER LOSSES IT MIGHT SUSTAIN WOULD NOT RESULT IN THE DEATH OR CAPTURE OF AN AIR CREW.

NOW THAT THE ENABLING TECHNOLOGIES ARE ADVANCING AT AN EVER-INCREASING RATE AND WE HAVE GAINED SOME VALUABLE OPERATIONAL EXPERIENCE WITH CURRENT UNMANNED SYSTEMS, THE ALLIANCE AS A WHOLE APPEARS TO BE COMFORTABLE THAT UNMANNED SYSTEMS HAVE A GREAT DEAL TO OFFER US IN THE FUTURE. IT WOULD FOLLOW, THEREFORE, THAT NOW IS THE TIME TO LOOK FORWARD AND BEGIN THE PROCESS WHICH WOULD LEAD TO THE ULTIMATE FIELDING OF OUT FIRST UTA. THE FIRST STEP WOULD BE THE FORMULATION OF A GENERAL CONCEPT OF OPERATIONS, FOLLOWED BY THE INITIATION OF LONG-RANGE OPERATIONS AND SUPPORT PLANNING. THIS PLANNING WOULD BE NECESSARY TO ENSURE THAT THE ENTIRE SYSTEM CAN OPERATE EFFECTIVELY IN VARIOUS CIRCUMSTANCES AND THAT IT CAN BE PROPERLY SUPPORTED THROUGHOUT ITS LIFETIME. AS FOR A CONCEPT OF OPERATIONS, I BELIEVE THAT THE AEROSPACE 2020 TOPICAL AREA DOCUMENT ON UNMANNED TACTICAL AIRCRAFT WOULD PROVIDE AN EXCELLENT BEGINNING. AS FOR OPERATIONS AND SUPPORT PLANNING, THERE ARE MANY FACTORS WHICH MUST BE CONSIDERED AND I WOULD LIKE TO BRIEFLY COMMENT ON SOME OF THE MOST IMPORTANT.

AS FOR <u>CONTROL</u> OF THE UTA VEHICLE ITSELF, AS CURRENTLY ARTICULATED, A BASIC UTA WOULD BE CONTROLLED BY AN OFFBOARD CONTROL OPERATOR THROUGHOUT THE MISSION. AS THE BASIC UTA MATURES AND ITS RELIABILITY AND CREDIBILITY ARE PROVEN BY INTENSIVE OPERATIONAL TESTING, NEW STATE-OF-THE-ART FEATURES CAN BE EXPECTED TO BE PERIODICALLY INCORPORATED TO INCREASE ITS CAPABILITY TOWARD AUTONOMOUS OPERATION. WHEN THIS PROCESS IS COMPLETED IT IS EXPECTED THAT AN OFFBOARD CONTROL OPERATOR WOULD STILL BE PROVIDED IN THE LOOP TO <u>MONITOR</u> THE MISSION SO AS TO BE ABLE TO ASSIST IN CASE OF AN EMERGENCY OR AN UNSCHEDULED EVENT-FOR EXAMPLE, RECOVERY BASE DESTROYED, DIVERSION TO ANOTHER TARGET, DECONFLICTION, BATTLE DAMAGE, ETC. THIS MISSION CONTROL COULD BE PROVIDED FROM THE GROUND, FROM A NAVAL VESSEL, OR FROM AIR VEHICLES TO INCLUDE AWACS, J-STARS OR ACCOMPANYING FIGHTER AIRCRAFT. THE FLEXIBILITY PROVIDED BY THESE OPTIONS WOULD CERTAINLY PROVE VALUABLE IN A FAST MOVING SITUATION.

AIRSPACE MANAGEMENT OF TACTICAL AIR FORCES HAS ALWAYS PRESENTED A DIFFICULT AND COMPLEX PROBLEM TO OPERATORS AND PLANNERS, AND UNMANNED AIR VEHICLES HAVE COMPLICATED THE PICTURE

EVEN MORE. SOME BASIC WORK HAS BEEN DONE WITH THE OPERATIONAL USE OF UAV'S IN PREVIOUS AND ON-GOING OPERATIONS; HOWEVER THE NUMBERS HAVE BEEN LIMITED. THE ADDITION OF BOTH CONTROLLED AND AUTONOMOUS UTA'S TO THE FORCE WILL COMPLICATE THE CHALLENGE EVEN MORE. IT MUST BE ANTICIPATED THAT BASIC SAFETY ISSUES WILL GET MUCH SCRUTINY, PARTICULARLY AS THEY PERTAIN TO PROXIMITY OF FLIGHT AND THE RESPONSIVENESS OF UNMANNED VEHICLES WHEN POTENTIALLY DANGEROUS SITUATIONS ARE ENCOUNTERED. IT IS, THEREFORE, IMPORTANT THAT SERIOUS PROJECTIONS BE MADE EARLY-ON TO SCOPE THE ANTICIPATED PROBLEM. WE MUST THEN WORK TOWARD A SOLUTION WHICH WOULD PROVIDE FOR THE APPLICATION OF AN INTERNATIONAL FORCE MADE UP OF LARGE NUMBERS OF AIRCRAFT- FIXED WING AND ROTARY WING; SLOW MOVERS AND FAST MOVERS; MANNED AND UNMANNED. THE GOOD NEWS IS THAT SEVERAL TECHNICAL INITIATIVES ARE ALREADY IN MOTION IN PURSUIT OF THE "SITUATION AWARENESS" GOALS WE MUST ATTAIN.

THE QUESTION OF FORCE MIX BETWEEN MANNED AND UNMANNED AIR VEHICLES IS EVER PRESENT AND UNAVOIDABLE. THERE IS, AT THIS TIME, NO FINITE ANSWER AND ANY DISCUSSION IS HIGHLY DEPENDENT UPON WHERE THE PARTICIPANTS STAND ON THE "CULTURE CURVE." EVERYONE HAS BIASES AND IN THE PAST UNMANNED PROGRAMS HAVE SUFFERED CONSIDERABLY BECAUSE OF LACKLUSTER SUPPORT. BUT THIS IS A DIFFERENT TIME, AND WE HAVE SEEN A CONVERGENCE OF EXPANDED TACTICAL REQUIREMENTS, SWEEPING ADVANCES IN TECHNOLOGY, AND NEW POST-COLD-WAR PHILOSOPHIES HIGHLIGHTING AFFORDABILITY AND MINIMAL CASUALTIES. AS A RESULT, THE CULTURE HAS BEEN CHANGING AS WE ALL GAIN AN APPRECIATION FOR THE EXPLOSION OF CAPABILITIES WHICH UNMANNED SYSTEMS CAN OFFER. ALL OF THIS IS A LONG WAY OF SAYING THAT THE MANNED/UNMANNED RATIO SEEMS UNDEFINABLE AT PRESENT AND, THEREFORE, MUST EVOLVE WITH TIME. AS A STARTER, HOWEVER, IT APPEARS THAT, AT THIS TIME, THE CONSENSUS STANDS AT A VERY TENTATIVE APPROXIMATION OF 20% UNMANNED AND 80% MANNED. AS TIME GOES ON, WE MAY WELL SEE THIS BALANCE SHIFT SOMEWHAT FURTHER IN FAVOR OF THE UTA IN THE MINDS OF THE LONG RANGE PLANNERS.

LOOKING FOR A MOMENT AT SUPPORT PLANNING, WE RECALL THAT ONE OF THE BASIC PROVISIONS OF THE UTA CONCEPT IS THAT THE AIRCRAFT WILL NOT BE FLOWN REGULARLY IN PEACETIME, BUT INSTEAD WILL BE STORED IN HUMIDITY CONTROLLED, FLYABLE STORAGE FACILITIES. THIS, OF COURSE, ENABLES THE SUBSTANTIAL SAVINGS IN MANPOWER, FUEL, SPARE PARTS AND TRAINING HOURS WHICH RESULT IN LOW LIFE CYCLE COSTS. ALTHOUGH THIS CONCEPT APPEARS QUITE SOUND, IT IS TOTALLY RELIANT ON EXTREMELY EFFECTIVE MAINTENANCE PRACTICES, AS WELL AS THE USE OF LONG LIFE MATERIALS AND SUBSYSTEMS. RECOGNIZING THIS, IT IS EXTREMELY IMPORTANT THAT APPROPRIATE STANDARDS BE SET AT AN EARLY DATE SO THAT THE SCIENTIFIC AND TECHNICAL WORLD WILL HAVE TIME TO RESPOND IN TIME.

THE AUSTERE MANPOWER REQUIREMENTS JUST NOTED CAN BE REALIZED IN PEACETIME BY PARTIAL UTILIZATION OF RESERVE FORCES FOR GROUND SUPPORT AND MAINTENANCE. THESE RESERVES WILL ALSO PROVIDE THE BULK OF AUGMENTATION REQUIRED TO OPERATE IN A WARTIME FOOTING. THE TRAINING OF THESE RESERVE GROUND SUPPORT PERSONNEL WOULD BE ACCOMPLISHED BY THEIR ACTIVE DUTY COUNTERPARTS USING APPROVED SYLLABUSES, ALTHOUGH SOME FORMALIZED COURSES MAY BE REQUIRED. MISSION CONTROLLERS MUST BE PILOT QUALIFIED WITH A SPECIFIED LEVEL OF EXPERIENCE IN TACTICAL FIGHTER OPERATIONS. MAXIMUM USE WILL BE MADE OF SIMULATIONS TO DEVELOP THEIR ABILITY TO PROPERLY CONTROL THEIR VEHICLE USING SIMULATED MISSION PROFILES. IN ADDITION, CONSIDERABLE SCHOOLING WILL BE REQUIRED TO INSURE THEIR DETAILED KNOWLEDGE AND UNDERSTANDING OF SUCH MATTERS AS NATIONAL AIR TRAFFIC CONTROL PROCEDURES, RULES OF ENGAGEMENT, TACTICAL AIRSPACE MANAGEMENT, ETC.

THE FINAL AREA WHICH MUST BE CONSIDERED IN IDENTIFYING THE MILITARY IMPLICATIONS OF FIELDING THE FIRST UTA RELATES TO ITS INFRASTRUCTURE REQUIREMENTS. HERE WE ARE FORTUNATE BECAUSE THE CONCEPT OF OPERATIONS CALLS FOR THE AIR VEHICLES TO OPERATE FROM STANDARD TACTICAL AIR BASE RUNWAYS. THUS THE NORMAL FORWARD AREA BEDDOWN OF UTA ASSETS WOULD BE AS TENANTS ON A MANNED FIGHTER BASE OR THEY MAY BE ASSIGNED AS AN INTEGRAL PART OF THE HOST UNIT. THEREFORE, A HIGH PERCENTAGE OF THE REQUIRED INFRASTRUCTURE WOULD ALREADY BE AVAILABLE, EXCEPT FOR CERTAIN SPECIALIZED EQUIPMENT AND COMMUNICATIONS WHICH WOULD BE PROVIDED SEPARATELY. DURING PEACETIME THE UTA VEHICLES AND EQUIPMENT WOULD BE STORED ON REAR AREA BASES WHERE THE FLY-AWAY STORAGE FACILITIES WILL BE LOCATED. HERE AGAIN, THE HOST OR PARENT UNIT WOULD PROVIDE FOR ALL INFRASTRUCTURE REQUIREMENTS AT MINIMAL ADDED COST. ONE CRITICAL CAUTION WHICH MUST BE RAISED REGARDING INFRASTRUCTURE INVOLVES TRANSPORTABILITY. IT IS MOST IMPORTANT THAT, IN THE UTA DEVELOPMENT PLANNING, FULL COGNIZANCE BE GIVEN TO DIMENSION AND WEIGHT LIMITATIONS TO ENSURE THAT THE VEHICLE ITSELF, ITS CONTROL HARDWARE AND ITS COMMUNICATIONS EQUIPMENT ARE ABLE TO BE RAPIDLY TRANSPORTED BY AIRCRAFT TO FORWARD AREA LOCATIONS AND BE BROUGHT TO OPERATIONAL READINESS STATUS RAPIDLY.

ALTHOUGH THERE MAY BE SOME MINOR MILITARY IMPLICATIONS IN ADDITION TO THOSE ALREADY MENTIONED, IT IS APPARENT THAT THEIR NET EFFECT WOULD GENERATE A STRONG POSITIVE POSITION IN THE SUPPORT OF THE INITIATION OF A UTA PROGRAM AS A MATTER OF SOME PRIORITY. THEREFORE, IT WOULD APPEAR EXTREMELY IMPORTANT THAT THE NECESSARY EARLY PLANNING FOR THE INTRODUCTION OF THIS EXTREMELY VALUABLE WEAPONS SYSTEM INTO THE NATO INFRASTRUCTURE BEGIN AT AN EARLY DATE.

ENVISIONED UTA MISSIONS

- INTELLIGENCE, SURVEILLANCE, RECONNAISSANCE AND BATTLE DAMAGE ASSESSMENT
- ELECTRONIC WARFARE
- SUPPRESSION OF ENEMY AIR DEFENSES (SEAD)
- FIXED TARGET STRIKE
- MISSILE DEFENSE
- AIR DEFENSE
- INTERDICTION / MOBILE TARGET STRIKE

Future NATO Trends and Mission Scenarios

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NATO enters the 21st Century facing unprecedented challenges and unique opportunities. Rather than simplifying NATO's security equation, the demise of the Warsaw Pact and the resultant reshaping of Europe's geopolitical landscape have only served to complicate NATO's operating environment. In particular, the threat, the character of the players, and the emerging types of operations and conflicts have merged with declining budgets and dramatic changes in the nature the security arrangements through which NATO and its member nations operate to create whole new arrays of challenges for security managers. This paper forecasts some of the more significant trends which will impact NATO through 2020 and postulates some key technological developments that will impact NATO member nations, regardless of the specific scientific and technical investment programs endorsed by NATO. These trends were developed by the Aerospace Applications Study Committee (AASC) of NATO's Advisory Group for Aerospace Research and Development (AGARD) and reflect that group's best judgement on which developments will have the greatest impact on the Alliance's ability to meet its security goals. The effort was intended to help guide the Aerospace 2020 effort and provide the current generation of military planners a useful context for thinking about the future. To this end, the AASC brought over 450 years of combined experience in military operations and the application of technology to security issues. This paper summarizes the trends identified by applying that experience through several meetings over a two year time period. It lists the key trends and scenarios expected to shape military thinking and future operations, with special emphasis on the technological aspects of the geopolitical, industrial, operational, and scientific developments that will occur, regardless of specific NATO plans, policies, or activities.

The paper will outline a number of trends, discuss specific scenario situations that could be faced by the Alliance, and then focus on seven areas that were judged to have the greatest potential for impacting the battlespace of the future. These trends provide a reference point for scientists and planners as they review the Aerospace 2020 presentations on military needs, promising technologies, and recommendations for future programs. While the paper will provide some implications for each trend, the discussion is by no means exhaustive. If anything, the pace of change in technological development will continue with corresponding implications for military planners. Major trends expected to impact technology and the security equation of 2020 are:

- Increasing impact and importance of information systems
- Proliferation and portability of technology
- Cost effectiveness of offensive systems over defensive capabilities
- Increasing lethality of the combat environment
- Time compression in the application of military force
- Availability of synthetic environments to assist all aspects of planning, training, decision making, and system acquisition
- Distribution of organizations and abilities to cope with the proliferation of technology

Basic assumptions

The primary purpose of the Alliance will continue to be to provide military security for its member nations. This and the following assumptions form the foundation upon which the AASC based its discussions:

- NATO must remain prepared to act in direct defence of its member states.
- NATO must remain prepared to take action against threats to vital interests of the Alliance outside the NATO area. Such operations may range from large-scale war to low intensity conflicts to counter-terrorist activity.
- Ethical constraints that exist within NATO regarding the conduct of violent conflict and warfare will not diminish and, in fact, are likely to increase. Potential opponents, however, may not respect or practice the same constraints.

Paper presented at the AGARD Symposium on "Future Aerospace Technology in the Service of the Alliance", held at the Ecole Polytechnique, Palaiseau, France, 14-17 April 1997, and published in CP-600 Vol. 1.

- NATO membership may expand in the coming decades. Such expansion will require the integration of new national forces and infrastructures.

In addition to remaining a strong and independent alliance, NATO will continue to work closely with the United Nations in its efforts to resolve international conflicts by diplomatic and/or military means. The UN will continue to support military forces involved in a number of operations around the world. As today, NATO may serve as the primary contractor with operations conducted under full NATO command or as a contributor to forces under UN command.

Geopolitical Trends

New membership and the potential requirement to conduct non-traditional missions with non-NATO nations who do not share the same technological, organizational, or command and control approach were considered to be key challenges facing the Alliance in the next quarter century.

New Threats. For the near term, the AASC saw little future to the centuries old paradigm of massed opposing armies facing each other across traditional boundaries. Instead, several relatively new stressing factors were identified which complicate the task of providing security for the Alliance, identifying enemies, or preparing for military operations.

In an increasing number of cases, ethnic bonding and religious affiliations will cross and obscure national boundaries. The former Yugoslavia is only the most obvious example of this phenomena. Rwanda, Somalia, and Kurdish activity in the Middle East show the volatility of the ethnic dimension and portend increasingly violent conflict outside of the traditional model of nations fighting nations.

Religious fundamentalism - which can lead to the belief in a single religion intolerant of any other - will also be increasingly responsible for tensions within nations. When separated from civil authority and nurtured against a background of tolerance, such movements contribute to both security and stability. But when religious leaders preach intolerance and violence against opponents, militant fundamentalism can threaten the peace and stability of a region. Such movements are incompatible with Western democratic thought which is based on the right of an individual to decide independently and hold contrary views. An intolerant religious leadership which dominates government institutions and seeks to eliminate all opposition can create major frictions with its neighbors and across the international community.

North-South Tensions. There is a clear and growing difference between wealthy nations in the Northern hemisphere with high per capita income, advanced education levels, and lower birth rates, versus poor nations in the Southern hemisphere which have low incomes, limited education, and high birth rates. These differences create a potential source of North-South tension made worse by differing interests and priorities which are increasingly difficult to bridge in the global community. In addition, the differences in income create a magnet for migration, with large numbers of refugees and immigrants attempting to move to the richer nations thereby creating a potentially dissatisfied and destabilizing force.

Unfortunately, the largest population growth is and will continue to be in the poorest nations. This means an ever increasing internal competition for a fixed or shrinking set of resources in nations that already have inadequate national infrastructure and insufficient economic resources to bear the burden. Adding to the problem is that many of the governments of these poorer nations are focused on the survival of the leadership, rather than on benefiting the population. This creates growing discontent in an environment that is already characterized by explosive urbanization, millions of people living in conditions with limited social, political, or physical support infrastructures, and concurrent destruction of traditional supporting family, societal, and economic systems. Scenarios envisioned by the AASC included those addressing threats to the borders and Southern tier of NATO, based on intensification of the ethnic, religious, and immigration trends discussed above, and the potential for urban environments to breed terrorism and national sentiments that are anti-Northern in focus.

Value Systems. Differences in culturally embedded values and attitudes have always been an important factor in warfare. While NATO policies are continuously adjusted to reflect more restrictive definitions of tolerable risk-of-loss and unintended harm, it is becoming increasingly apparent that such restraint is not universally supported or practised. In fact, it is now reasonable to assume that future adversaries may try to maximise the advantages they can gain through "asymmetries of conscience;" that is, the willingness to pursue means which NATO Nations find unacceptable.

Some asymmetries of conscience are based on ethical standards; some include practical considerations. For example, despite the great costs involved, NATO has strict requirements for the safe storage and handling of the systems it develops and accepts. Some opponents, however, may be more interested in less expensive systems that can be used immediately, rather than in quality systems which are safe.

Other examples of constraints which the West finds necessary and imposes upon itself range from environmental considerations to the use of chemical and biological weapons. Although, in many cases, international treaties have been signed acknowledging agreements to restraining principles, many nations have not joined in these treaties, and even some that have signed do not appear to take them seriously.

Thus, NATO is faced with defending itself against tactics and weapons which it finds unacceptable to use. To prevent such asymmetries of conscience from providing a decisive military advantage against the Alliance, it becomes even more important to fully exploit the advantages NATO has with respect to its financial resources, technology, and its ability to organise effectively.

An additional impact of these asymmetries of conscience is the requirement for NATO to continuously examine its deterrent posture. This is particularly important for future adversaries that include factions with fundamentally different belief systems then those associated with current western democracies. Deterrence in the classical sense results when a potential adversary understands that attacks against NATO personnel or territory will result in sure retaliation and unacceptable consequences for the attacker. For terrorists and other groups, this deterrence formula may prove ineffective, since martyrdom may be seen as enhancing the cause, rather than detracting from it, and "unacceptable consequences" may not be understood in western frames of reference. Compounding the problem is that such organizations may not present a recognizable target after an attack. Because the time, location, and means of terrorist attack may be unpredictable and the perpetrators unknown, the how, where, when, and against whom to respond is often unclear. There are many recent examples that illustrate that respect for life in other cultures and within terrorist organizations may be very different from western values. The result is that NATO will need to examine its deterrence formulas and possibly to develop a new set of equations to deal with these threats.

Organized Crime. For good reason, organized crime has been outside the focus of most western military forces. In the next century, however, organized crime in some nations may wield as much power and influence as the official government in the countries in which they operate. Even today, Colombia, where the drug cartels exert immense influence and power, and parts of the Former Soviet Union, where organized criminal organizations have created an unofficial economy by protecting business concerns in cooperation with corrupt government officials, demonstrate the potential security problems associated with such organizations. Drug cartels, crime organizations, and terrorists will pose an increasing challenge to NATO in the next 25 years. The availability of nuclear, biological, and chemical (NBC) weapon technology and the potential breakdown in effective government control over weapons of mass destruction that could occur in some parts of the former Soviet Union, means that such groups might achieve a portable NBC capability in the future. To counter this threat, NATO nations may call upon all resources, military and otherwise, to help prevent the movement of NBC materials across national borders and the threat of such weapons against their citizens. Effective control will require 24 hour surveillance by personnel and equipment/sensors capable of detecting, tracking, and intercepting such materials.

Organizational Entities.

United Nations. While it is likely that the UN's Security Council will grow to include new permanent members in the next 25 years, the UN itself is expected to continue to maintain standing military forces involved in a number of operations around the world. NATO nations will need to liaison with these forces, either in an alliance activity (as in Bosnia) or as member nations involved with specific UN activities. To meet its requirements, the UN forces will have to be equipped for rapid and flexible employment worldwide. Unfortunately, the slow, methodological decision-making process of the UN will make the timely employment of these forces problematical, and likely that NATO and UN forces will overlap in areas of NATO interest.

NATO. In the next 25 years, NATO will grow in numbers, requiring special attention to command and control requirements and the necessity to integrate new partners which may not share the same levels of technical or organizational sophistication. At the same time, NATO military forces may become smaller in size due to budget pressures, while reorienting and enlarging their area of interest to take into account the new members and NATO's broad range of security interests. Further, the role of NATO could evolve from that of traditional collective defence to a full range of operations other than war, such as peace support operations on NATO borders as well as humanitarian operations in concert with non-traditional allies.

Western European Union (WEU). The WEU is envisioned to become more active and influential. It is anticipated that in the timeframe of this study, it will achieve a significant military capability that would enable it to act independently from NATO if desired. Like NATO, the role of the WEU will evolve from that of Western European collective defence to humanitarian operations in concert with new allies such as eastern European nations.

Economic Factors.

It is expected that national defence budgets will continue to decrease as a percentage of national spending. The resources will continue to be spent, but investment will focus on social and national infrastructure issues requiring continuing reorientation and consolidation of defence industry. Cost will take on increasing importance in a military system's cost effectiveness equation.

New world economic and military powers are expected to appear in the Far East. Further, this geographic area is expected to experience the greatest growth in economic power due to its large, educated population base, natural resources, and growing industrial manufacturing capability. China already is a primary military power in that region and is expected to rival Japan in economic power.

With the growth of worldwide industrialization, competition for markets will intensify. This will be particularly true in the defence area as more producers will compete for a stable market. As the health of Western industry is difficult to separate from the world economy, there will be growing pressure from multi-national industries on western governments to liberalize export rules. The inevitable result will be the proliferation of high-technology equipment to rogue nations. World-wide competition for markets will intensify, increasing the possibility of international economic warfare which could spill over into military competition.

Proliferation and Portability of Technology.

The cost of computer technology and systems will continue to decrease with important consequences for future warfare. This trend means that systems that have been developed at great cost by one organisation, such as a Ministry of Defence, will be copied very cheaply and proliferated among possible opponents, including less developed countries and terrorist groups.

An example of this situation is the Global Positioning System (GPS), which was developed at great expense, but is now available commercially for so little cost that most small boats are now fitted with the system. In fact, GPS transponders are being used by some public transport systems to check the location of buses and tell passengers where they are. Such systems are equally useful to possible enemies developing cheap versions of cruise missiles, or in guerrilla warfare, in identifying the exact location of opponents' weaponry or command centres.

Another aspect of the same problem is that commercial computer and communications technology, which does not require a complex procurement process, often provides capabilities that can be used immediately by enemy forces, while the military requirements and standards of the NATO nations enforce a much longer development cycle. The result is that an agile enemy, using systems available in the market place, could actually stay ahead of NATO capabilities in some technology areas. An example of this was the initial development by the British Army of a prototype command and control system using commercial hardware and software, which took far fewer resources than the system finally developed to military standards, but was perfectly adequate for the majority of tasks.

A third problem is that a full range of weapons systems, as well as computers and other communications systems are available from former Warsaw Pact, and particularly Soviet Union, countries. In addition, engineers and scientists from these countries, including those who have worked on nuclear, biological and chemical weapons and/or technologies, but who now find their skills are no longer needed, are emigrating to developing nations with the potential of supplying their knowledge to their new homelands.

A fourth area of concern is the proliferation of information - scientific, technical, administrative and other - through computer systems such as the Internet to any user. Not only can information be obtained, it can also be manipulated or deliberately destroyed if care is not taken by the user. One aspect of this is the abstraction of money through access to banking card systems or credit card numbers. It is estimated that very large sums are already being lost in this way, and it could well be that terrorist organisations and indeed dishonest administrations of lesser-developed countries could use this method to finance the arms in the future.

A subset of technology proliferation, the potential availability of Weapons of Mass Destruction will pose the single biggest threat to the security of Western nations in the next 25 years. As indicated above, other technologies will also proliferate due to a variety of forces, but there is no doubt that NBC proliferation could cause the greatest impact to the security of NATO members. There is currently a rather wide spectrum of national abilities to manufacture NBC weapons. For organizations or governments without this capability, the appropriate expertise can be purchased and a program implemented at costs well within the means of the involved group or nation. Thus, it may be a matter of time before a hostile group attempts to enter a nation with a portable NBC weapon with the intent of holding a key population center or other important facility hostage. To counter this threat, nations will require 24 hour positive border control with the proper resources - people and equipment/sensors - to detect, track, and ultimately interdict NBC materials and weapons.

Industrial Trends

The evolving geopolitical environment, with its lack of a well recognized and massively capable enemy and a concomitant reduction in defense spending will continue to put unique pressures on the defence aerospace industry. This situation will spawn a number of trends in industrial development which may both influence and be influenced by technology development.

Finance. By far the biggest influence on current industrial development is the massive reduction in defence budgets, particularly in procurement accounts, over the past seven years. Barring the emergence of a new global competitor, this downward trend will continue well into the next century and has led to the imperative that weapon system and infrastructure development and procurement programmes must either cost less, become less frequent, or both. Cost sharing between Alliance members and/or between military and civil sectors will be essential for large programmes. Similarly, because there will be less defence R&D investment per nation, technology development and maturation activities must increasingly become international to succeed. In particular, these R&D programs will require close collaboration between government and industry to ensure that technical developments are capable of effective realisation.

Various other routes to spreading the cost burden will be adopted. A general trend, mentioned above, will be towards wider export of defence equipment outside the NATO area. This will not only be due to investor pressure to increase profit, but also in direct response to Government pressure to spread - and hence reduce - cost in order to make programmes affordable. This will increasingly lead to demands for technology transfer or for joint opportunities working with indigenous industries with accompanying questions about access to and control of critical technologies. It will also increase the problem of how to ensure the maintenance of a performance differential against possible future opponents. However, the availability of even differential equipment, combined with competition from former Warsaw Pact nations and other developing military powers, such as China, will keep capable equipment in the hands of all but the most economically disadvantaged nations.

To deal with these market circumstances, acquisition policies and processes will need to be reconsidered to ensure that the NATO nations retain the ability to specify and procure combat systems with a performance advantage over potential enemies. They will also need to maintain a viable and efficient industrial base while obtaining value for money for the military customer and the tax-payer. This will potentially require NATO nations to find alternatives to straight competition as the main mechanism for stimulating cost and price challenges for suppliers. A shrinking industry combined with fewer/rarer product starts means that competition losers exit the industry and competition ceases to be an option because of the resultant monopoly supplier situation.

Organisation (The Shape of the Industry). The prime response to the changed financial climate will continue to be an inexorable "shake-out" of the industry. This will create a defence industrial environment of much fewer companies remaining as a result of sell-offs, acquisitions, exits and mergers. Significant consequences include, in established economies, a reduced "gene pool" for defence product development. At the same time, this reduction also means less opportunity for competition (i.e. loss of customer power even for governments) and a growing pressure for international links to stay abreast of all current technological developments. Within a single nation, the ability to maintain a "critical mass" across a number of technological areas will be reduced with the expectation of less opportunity for new entrants except in dual-use areas.

Within this environment, several points are worth noting and may continue well into the next century. These include the potential for European defence industry to lag USA developments, government development to lag industry, and an exacerbation of both problems by NATO expansion.

To cope with this changing competitive environment for NATO aerospace, there will be some moves towards product diversification. Generally, however, current business wisdom favours the opposite, concentration on core business to assure survival. This then leads to collaborations and mergers as the key route towards economies of scale. A prime concern must be the appearance of new entrants and emergent industries outside the NATO area, particularly in the Far East.

Processes (The Character of the Industry). The shape and impetus of individual companies within the defence industry will be determined in response to a number of general problems including those described above. Additional factors include :

- less frequent product starts,
- smaller production runs/cost base,
- high capital investment needed,
- short term expectation of return on investment (not in all NATO nations).

To deal with these problems, surviving aerospace companies will increase their search for competitive advantage/market share/niche roles, aggressively adopt cost reduction strategies, and focus on time compression (time to market) techniques to improve market position and eliminate carrying costs.

From these pressures and resultant coping strategies, a number of evolving features will develop. For example, the dominant role of information technology in advanced military systems is rapidly becoming subservient to the massive advances of this technology in civil and commercial applications. This may become a more widespread phenomenon with increasingly fewer defence specific technologies or processes. Because of the larger volume production base for non-defence items and its associated lower production costs, there will be an increasing tendency for defence industries to follow commercial/civil sector leadership in many areas (especially information technology) where defence previously had the lead. Two clear resultant trends include the use of commercial off the shelf equipment in defence products and a search for dual-use technologies (i.e. civil applications of defence technology developments or the defence applications of civilian technologies) to spread the cost base and reduce defence product costs.

A second feature is the struggle to achieve compressed development cycles. This will be driven by a push to achieve quicker time to market to meet commercial pressures as well as to minimize the potential for obsolescence at IOC. These shortened development cycles will be achieved by introduction of a high degree of process integration, much earlier technology demonstration, and the use of synthetic environments for user /customer exploration of system concepts.

A third feature will be a move towards flexible manufacturing. This will be aimed at achieving the following benefits:

- Minimising the cost of tooling for short production runs
- Facilitating dual-use technology implementation
- Allowing responsive manufacturing in times of crisis or wartime emergencies
- Minimising amortised investment costs
- Shortening production investment cycles

Within the flexible manufacturing process we can expect to see facilities such as CAD/CAM expanding with increasing integration of the total design and manufacturing process via broader concepts of digital product definition, synthetic environments, virtual manufacturing and other advanced concepts as part of the overall cost reduction/cycle compression thrust. An additional component of manufacturing cost reduction will be the expanded implementation of lean manufacturing, to include "Just In Time" methods.

Skill retention is likely to be a continuing problem in the implementation of these industrial developments. Long intervals between programmes mean little experience carry-over by individual personnel. Rapid technology development means less read-across between programmes. A shrinking defence industry leads to the retirement of skilled staff and the need for the resultant smaller staff pool to have a wider individual skill base (highlighting the problem of how to optimise the balance between breadth and depth).

Operational Trends

During the next 25 years, the trend towards smaller force structures within NATO will continue. Up to now, force structures have been reduced without significant enhancement to unit capabilities. However, the demands and uncertainties of future operations against a variety of threats with readily available sophisticated weapons will necessitate smaller forces be accompanied by improvements to unit and individual weapon system capabilities. Remaining units will need to be able to cope with a broad range of threats and an increasingly lethal battlefield.

Future Battlefield. The operational environment in which future forces will operate will be significantly more lethal than experienced in the past. Due to the proliferation of high technology, high precision weapon systems, sophisticated sensor and information processing systems, and weapons of mass destruction, military personnel on the battlefield of the future will experience a time compression which will demand rapid execution, high mobility, and preemption of opposing force action. Improved sensors and information processing will result in 24 hour a day operations, further accelerating the pace of war and putting a premium on the application of counter-force weapons. Improved battlefield awareness will make it nearly impossible to mass forces without risking detection and attack.

Lethality. Each generation of war-fighting technology has brought with it the potential for major increases in casualties on the battlefield. While the nuclear weapons of the second world war have provided an upper bound to the equation, they did not eliminate warfare altogether. As experiences in Southwest Asia and Bosnia attest, warfare with conventional weapons has not been eliminated and the lethality of these conventional weapons continues to increase toward that upper bound. Precisely applied weapons now allow a single fighter carrying four laser guided bombs to do the same damage to a ground force that full bomber squadrons were able to accomplish 50 years ago. The beneficial result is a reduction in the collateral effects of the bombs, but to the military forces, the risk of being destroyed on the battlefield has increased multi-fold.

Several implications flow from the realities of the increasing lethality of the battlefield. First, forces and nations will put a higher premium on protection of their assets, to include active and passive means of self protection. While there may be little that can be done to ameliorate the effects of a munition once it hits the target, there will be increasing focus on attempting to deny the detection, targeting, and guidance systems of munitions, so that weapons are either not released or else denied vital information once launched in order to move the impact point. Because of the lethality of the battle space, airmen and decision makers will favor longer range, stand-off, precision capabilities to keep their systems and warfighters away from the lethal environment as much as possible. This in turn will lead to an increased role for unmanned systems in all aspects of the battlefield, from sensors, to smart weapons, to launch platforms for smart munitions. While the cost of such systems could be significant, the failure to have them, could result in unsustainable and unacceptable attrition on the battlefield.

Other aspects of lethality on the battlefield include intended or unintended effects of new classes of weapons, sensors, or enabling technologies. For example, some laser ranging devises have already been shown to have detrimental effects on the eyesight of lased soldiers or airmen. Increases in power without providing for the protection of these individuals could result in permanent damage and loss both of the individual and the equipment for which they are responsible. Technological solutions will be necessary to limit these known effects as well as to understand the effects of an increasingly robust range of electromagnetic and other directed energy options.

Time Compression in the Application of Force. The ability to react immediately during the beginning of a new conflict might be the major advantage that technologically advanced societies will have against attacks by enemies using highly effective offensive weapons. A future conflict will emphasize tactical and strategic intelligence systems to offer a broader range of options to achieve this advantage. Combat operations will be increasingly synchronized to enable simultaneous attacks across axes and from various platforms in all media. Communication technologies will improve the quantity and quality of information flowing to military commanders. They will deliver information to the battlefield quickly and necessitate the commander having tools to help him react quickly and decisively to take advantage of the new information. Humans in the loop will increasingly require a broad set of real time decision aids. The need for real time decision tools to aid military commanders is crucial. Improved C4I systems will operate 24 hours a day in all weather and electromagnetic environments. In short, the shrinkage of time between receiving new information and reaction time means it will be essential to get the right information to the right person at the right time.

Cost Effectiveness of Counter-Force Systems over Defensive Systems. The initiative and effectiveness of offensive systems which led to the nuclear age's precarious balance of offensive systems confronting each other to maintain the peace will be mirrored in the increasing effectiveness of conventional offensive systems. Time compression, the ability to mass offensive systems along different axes to overwhelm weaknesses in the defense, the advent of long range, stand-off, precision munitions, and improvements in reconnaissance, surveillance, and target acquisition systems all tend to shift the balance in warfare away from the defender. Fixed basing sites, home fortresses, and large and cumbersome support systems will become increasingly vulnerable to the offensive potential of hostile groups or nations. While offensive strategies are more cost effective, NATO will also need to investigate selected defensive approaches to include distributed basing systems, developing the ability to operate from unimproved or semi-improved sites, lean logistics systems, and built-in reliability and self-diagnosing fault systems to reduce its vulnerability to attack. At the same time, because many of these systems are more expensive than traditional support systems, planners will need to explore other military strategies, such as preemption and Information Warfare, to ensure the best use of military force to resolve specific conflict situations.

The example of Bosnia may be a precursor of things to come. Because NATO forces lacked the technological capability to intercept mortar shells in flight and then to follow up with precise, surgical strikes on the specific perpetrator of a mortar attack on Bosnian safe zones, it elected a preemptive strategy to enforce the pull back of weapons threatening the protected cities. By leveraging on the offensive capabilities inherent in its air forces, NATO is using a preemptive strategy to bring about the favorable solution it desires in Bosnia. Such choices will increasingly be required of NATO planners in dealing with the broad range of threats to NATO's security goals.

Information dominance. This capability will be a critical element toward success in the commercial world as well as victory on the future battlefield. Denying the enemy access to information, while assuring information access to friendly troops, will be a primary objective on both sides. NATO will need to ensure defence against intrusion in its information systems, hardware, and software, as well as the capability to detect "spoofing" by hostile forces. It will become increasingly necessary to control the high ground, i.e., space, in order to ensure information dominance. This means assured access to space, with the ability to deny space access to the enemy.

Distributed Organisational Systems. As the military forces of NATO face increasingly complex tasks, the technology needed to execute these tasks is likewise increasing in complexity. This is driving change in two respects: first, military organizations are having to adapt to more flexible ways of decision making so as to be able to cope with complex, fast changing situations and directives. Secondly, cooperation of NATO nations in various missions is driving the requirement for an organisational structure which can integrate various combinations of equipment and various combinations of military forces in order to insure success for any given military task.

Ensuring this will work efficiently in all cases requires adequate analysis, planning, and implementation. Military forces of NATO nations as well as NATO itself are already beginning to operate to these requirements, but the increasing complexity and variety of tasks and technologies will induce qualitative changes in the next 25 years. The industrial sector is already developing knowledge and experience in this kind of operations which can be drawn upon by the military.

Just as the commercial sector is re-engineering itself to deal with the global market place and the competitive pressures placed by a new range of companies and groups adapting technology to meet the demands of the market place, military organizations will increasingly be under pressure to develop new organizational structures and attitudes which

- are able to deal with different threats and intensities, implementing the political guidance as given by the relevant political entity.
- have the flexibility to deal with changes in guidance, composition of forces, and operational and tactical situation

- build on the full width of knowledge available and are developed in a manner which permits the participating Nations to put full trust in them.

The width of threats and the degree of flexibility required may necessitate shifting weights amongst human behavioural factors influencing operation - putting more stress on understanding of challenges, situations and on flexibility of decision-making within a given frame. They may also require technology shifts in supporting information technologies - in particular from digital technology and software to applications which are better able to analyse situations for their structural content.

The main thrust of trend is that organizational structures themselves will not be immune from the realities of the next century's technological environment. In fact, military organizations and individuals will adapt just as commercial enterprises are reshaping themselves to take advantage of the realities of the global environment. NATO planners must not overlook the opportunity to shape their organisational concepts as well as to indicate technology gaps not visible from a technology push position alone. Exploring the organisational implications in connection with technologies may also lead to additional conclusions such as:

- An armed force not built on human capital which has been brought up and trained in the appropriate manner and not having at its disposal the supplementing technology that will be available, will be much less efficient in using a complex technology, thus reducing the risk arising from its proliferation; .

- Adversaries not able to employ complex technologies may choose very "primitive" ways of reaction and any organisational setup must be able to identify such non standard behaviour and cope with it by design.

The need to develop flexible organizational structures will only be strengthened by the potential expansion of NATO and the need for NATO force to integrate with forces of other nations in operations other than war.

<u>Other Factors</u>. The "CNN Syndrome" will continue to create political pressure to avoid collateral damage, minimize casualties, and avoid protracted conflicts. At the same time this effect will promote engagement in humanitarian and peacekeeping operations to relieve global suffering. On the other side of the equation, multinational, independent media organizations will provide hostile groups with useful information on a near real time basis to better inform their operational decisions.

<u>Non-Traditional Tasking</u>. The nature of conflict will be expanded beyond the traditional physical limitations of the historical battlefield, as challenging as that may be itself. Information and economic warfare, offensive and defensive, will create a complex continuum of conflict which will extend into civilian and non-military arenas. New political-economic-military relationships will be developed as the extent of these operations become evident. The effectiveness of nebulous combatants such as terrorists, special operations forces, and specialists in information and economic warfare will frustrate traditional defense practitioners and necessitate the development of new defensive concepts and systems. As mentioned above, worldwide instantaneous news coverage will promote continued involvement in humanitarian and peacekeeping operations by forces which may not be well designed for these activities. Further economic pressures created by population growth, resource limitations, and illegal commerce as well as concerns about NBC weapons may result in military involvement in border protection as well as the monitoring, protection and policing of international trade, commercial, and industrial activities.

<u>Scenarios and Measures of Merit</u>. While considered unlikely, the AASC evaluated the requirements of dealing with a global power threatening NATO interests in the year 2020. The potential for a major conflict with a regional power or consortium which attacked an Alliance member in the south or east was also evaluated. In addition, the looked at a variety of more likely scenarios involving NATO forces in peace operations and other operations other than war. In general terms, technologies received highest marks when they either enabled NATO forces to accomplish missions that are not possible with current forces and capabilities; or they allowed NATO forces to accomplish standard missions more quickly and effectively than with current capabilities; or else they accomplished missions at less cost than with existing force structure.

Technological Trends

In addition to the above trends, many of which are influenced by technological developments either currently ongoing or anticipated in the next 25 years, at least four areas will continue to undergo technical advancement, whether or not NATO nations choose to invest in military applications. These include technologies associated with the development and exploitation of information technology; the emergence of synthetic environments, which leverages off information technology but includes a number of unique integrating technologies; the range of technologies associated with communication, navigation, and imaging from space; and the new technologies emerging from biomedical research. As such, these technical trends need to be well understood by policy-makers, planners and decision-makers. By leveraging off them, NATO may be able to focus specific programs to take advantage of the broader technological environment to improve its military effectiveness at reasonable cost. Conversely, the pursuit of technologies without understanding the full technological environment that will exist in the future could be both counterproductive and expensive.

Information technology. Information is already crucial in today's environment. Over the next 25 years it will become the most important resource at the command of governments, business leaders and military decision makers. Information will increasingly dominate all aspects of economic development and will become a dominant aspect of warfare. As such, information will have both strategic and tactical importance. Just as business leaders and investors will need reliable real time information to fuel economic decisions, commanders will be dependent on reliable information delivered to the battlefield in real time. New generations of computers, adaptive software, multimedia integration of text, audio and video, will provide unprecedented capabilities which could be adapted by the battlefield commander and the troops under his or her command. Because of its importance, the security and integrity of that information must be ensured against deliberate or accidental manipulation or destruction and technological faults. System redundancy will be a necessary consideration. 'As in business, the military will need to place an increasing emphasis on the use and protection of equivalent C4I and embedded computer and control systems. Unlike business, the military will need additional levels of emphasis on the exploitation, disruption, neutralization and destruction of the enemy's C4I. The impact of a global information infrastructure that allows crucial information to be delivered to any place at any time is both an asset and a threat. Global communication systems coupled with the portability of computer systems can not only deliver the latest news and weather to friends and enemies alike, but will also underscore evolving public opinion and perception. Military leaders will be required to act quickly and decisively while trying to minimize casualties and collateral damage which affect public opinion.

Synthetic Environments. The same technology that is driving information technology is also leading to synthetic environments in all aspects of commercial development, test, and production, as well as in military training and operational rehearsal environments. Microelectronics and integrating technologies will allow training applications extend the state of the art beyond existing business applications and skill development simulators with potential military applications taken from computer-modeling, war-gaming, and new cockpit technology.

The major differences from stand-alone simulators are that a number of people can be involved in the environment; that the environment being simulated can include other players and their actions operating independently; and opponents, their actions, and reactions can be introduced via constructive models or by players orchestrating competitor moves in real time. These simulations can link geographically separated locations in real time to enhance the training received by all participants.

While training will be only one of the uses of the system, synthetic environments will allow personnel to become expert on specific equipment in an environment that is not available even in live exercises because of safety restrictions or the physical limitations of the training space. From a military perspective, these environments will also permit the training of a whole unit acting together as a team, and not just as a series of individuals. Moreover, this training will not be merely how to use equipment and communications systems but also how to react to the enemy's actions, and with the concurrent operations of other friendly forces. Thus a number of simulations of a battle could be run credibly, with different actions and reactions taking place. They will be realistic options, but will be randomly introduced in order to make the training more varied and enable the team to be better equipped mentally to deal with alternative situations.

Training such as this can be used at the tactical level, at the strategic level, and for the operation of command and control systems. In all these areas the result will be a fundamental shift in training methods, requiring fewer resources, yet producing much better and more realistic results. In addition to training, synthetic environments will allow commanders to learn in real time the potential results of their decisions in combat situations. By using the system to explore a number of potential decision alternatives, the result could be not only improved performance at the unit level, but also improved force application decisions at the command level.

While the above refers to the decision-making, training, and situation analyses aspect of synthetic environments, the technology may also permit simulating the use of all equipment employed. This will support the whole Research, Development, and Procurement process. At all stages of the process, it will be possible to test the equipment being developed in a realistic situations, and with expected developments in other equipment being modeled at the same time to provide appropriate external inputs. This will give much more realistic results than available in previous computer simulations, to include easier setup and calibration. Of particular value is that military operators will be able to be involved at all stages of the procurement process, not just in providing an initial requirement and a final test of procured equipment. By keeping the operator involved at all stages of a system's development, the full implications of tradeoff decisions can be better understood by both the user who needs the capability as well as the developer who is trying to meet the requirement in the most cost effective way. Simulation will allow the operator and the developer to see 'for real' what the effects of tradeoffs will be in terms of both costs and military effectiveness, provided the simulations are reliable.

Because synthetic environments will enable the design and test of commercial and military systems in a virtual world, they could contribute, together with other technologies on a longer time horizon, to advanced "just-in-time" manufacturing capabilities that would delay the fielding of new systems until they are needed for combat operations. This would ensure that such systems were completely up-to-date with the most recent technologies at the time of production. Pursuing standardized synthetic environments could have profound implications for the relation between NATO governments, their defense organizations, and the commercial sector which currently produces the needed military equipment. Close cooperation between all three sectors will be necessary to ensure the development and application of this technology will produce the desired structures and not the loss of vital military production capabilities.

To summarise, the increasing availability of synthetic environments will fundamentally change the way the military trains forces for combat at all levels. This approach will revolutionise all aspects of research, development and production and could dramatically alter the current military/industrial relationships and structures.

Space. The commercialization of space will provide increasingly more affordable options for general economic uses of space as well as its exploitation by the military. Markets for communication, navigation, and earth sensing capabilities associated with space will multiply and help to drive developments in microelectronics, reliable power sources, and some integrating technologies. This market will also help drive the price of space launch down, reward novel solutions to communication bandwidth problems, and increase interest in multispectoral sensors for purely profit motives. At the same time, these same developments will provide the opportunity for potential adversaries to improve their military capabilities by leveraging off what is available in the market place. For example, these developments may allow enemies who do not have a reliable communications infrastructure to leapfrog the expense of laying telephone lines and fiber optic cables and instead move directly to cellular phone systems or other space-borne options to meet their communications, command, and control requirements. For NATO, cheaper space access and improved sensors and communications links could offer new opportunities and allow the military to focus on fusion, correlation, and reaction time issues. At the same time, these capabilities ensure that less sophisticated enemies in the future will rely on affordable and near equivalent communications, navigation, and earth sensing technologies available through the market place to overcome specific NATO advantages in specific combat operations.

Human and machine partnership. By the year 2020, an operator will interact with an electronic workspace as a cooperative partner. Dialogue between the system and the operator will be based not only on operator inputs but the machine's ability to accurately assess the physical and mental state of the operator. Operator inputs may be communicated by deliberate voice commands, gestures, or even subtle muscle movements. The machine will sense the operator's state with signals from the brain measured by EEG in conjunction with other biological readings. Assessment will be based on artificial intelligence technologies and an improved understanding of the relationships between electrical brain activity and the performance of cognitive and motor tasks.

This human-machine partnership will reduce the number and intensity of tasks which require uniquely human contributions. The operator remains fully conscious of the environment and maintains authority over system functions.

The partnership will be made possible by advances in information assessment, artificial intelligence, psychophysiological processing, and advanced models of human performance and behavior.

Biomedical. Genetic engineering, and the full spectrum of insights arriving from the study of human life and its structure could be the wild card technological development of the next quarter century. Improved efficiency and effectiveness of military leaders and troops in the field will contribute to the increased pace and lethality of battlefield operations

Summary

While this paper covers a broad range of geopolitical, economic, operational, and technical trends, seven were judged by the AASC to have the greatest impact on the battlespace of the future and could have profound implications for NATO planners and warfighters. These trends are summarized below and provide a reference point for readers as they review the Aerospace 2020 report. Some implications for each trend are provided, but the discussion is by no means exhaustive. If anything, the pace of change in technological development will continue to accelerate with corresponding implications for the military. The major trends impacting technology and the security equation of 2020 are as follows:

- Increasing impact and importance of information systems
    - Information will increasingly dominate all other aspects of warfare
    - There will be increasing emphasis on the use of as well as the defence and protection of C4I systems
    - There will be increasing importance attached to attacking the enemy's C4I capabilities
    - Redundancy will need to be considered for all aspects of C4I systems
    - Global systems, both civil and military, will have a major impact
    - Multi-media capabilities, integrated text, audio and video, will dramatically improve support to the commander and troops in the field
- Proliferation and portability of technology
    - Computers, satellite support, and surplus systems from the Cold War will increase the availability of weapons and systems to even the most backward nations
    - Poorer countries will pose a credible threat to richer countries and alliances;
    - Weapons of mass destruction and other technologies can make desperate peoples, terrorists or small groups of fanatics strategically important
    - Direct access by hostile end users to information or technology generated for nonmilitary uses can have very undesirable effects
- Cost effectiveness of offensive systems over defensive capabilities
    - Will drive potential adversaries to invest in offensive systems
    - Increases the vulnerability of fixed sites
    - Will increase the value of distributed basing structures, built-in reliability and lean logistics
    - Will drive planners to explore alternative strategies, such as preemption and information warfare options
- Increasing lethality of the combat environment
    - Will place a higher premium on the protection of assets using active and passive means
    - Will encourage the continued development of long-range, stand-off, precision capabilities
    - Will increase the requirement for unmanned systems in missions with high exposure to that increasingly lethal environment

- Time compression in the application of military force

    - Increased use of synchronized attacks, from all axes, in all conditions, will stretch the ability of military forces to respond adequately to the threat
    - Twenty-four hour a day systems, capable in all weather, geographic and electromagnetic environments, will increasingly dominate the battlespace
    - Effective, real-time tactical and strategic intelligence systems will be required to guide military leaders and political decision-makers in this environment
    - Complex, real-time decision aids to assimilate rapid changes in the battlespace will be required

- Availability of synthetic environments

    - Will fundamentally change the way the military trains forces for combat at all levels
    - Will revolutionise all aspects of research, development, and production;
    - Could radically alter existing military/industrial relationships and structures.

- Distribution of organizations and abilities to cope with the proliferation of technology

    - Organizational thinking will fan out to deal with different intensities and threat levels
    - There will be a premium on system flexibility
    - Will push human factors and other technologies not currently envisioned
    - Requires attention when shaping future NATO structures
    - Will be even more important should NATO expand

HUMAN MACHINE INTERACTION

NATO Research and Technology Organization
AGARD Conference on Future Aerospace Technology in the Service of the Alliance
16 April 1997

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1. INTRODUCTION

The interaction between machines and humans is, and will continue to be, a pervasive technological challenge which must be engaged by NATO's science and technology community. Optimal effectiveness of current and future weapon systems will only be achieved if the interactions between the operator, or group of operators, is efficient and intuitive. This paper provides a vision of the environment in which the technology challenges of human-machine interaction within military systems will be met. It will describe future mission context, future control and display devices, and human-centered integration concepts.

2. THE 2020 COCKPIT

In an ideal military world, the role of an aircraft is driven by only operational requirements and, generally, there needs to be a range of aircraft to meet the number of requirements (e.g., Offensive Counter Air [OCA], Defensive Counter Air [DCA], Close Air Support [CAS], etc.). In reality, however, there are mediating factors that are becoming increasingly relevant and affecting aircraft design and subsequently the integration of the aircrew with the aircraft platform. One all-encompassing factor is affordability - both in the initial airframe cost and the overall operational life cycle costs - and there are a number of additional pragmatic issues that will affect the evolution of a cockpit for an aircraft in the 2020 timescale - one of which is the balance of technology push with operational pull.

Operational capability, however, remains of central importance, and there will remain a need for a range of aircraft to meet operational requirements, although for some cases the roles can be combined without unacceptably compromising the aircraft performance in that role (e.g., Air Defense and Ground Attack). However, some operational tasks may be better implemented by a different class of aircraft (e.g., Helicopter) particularly where threat scenarios make the use of fixed wing aircraft a high risk solution (e.g., Battlefield Air Interdiction/Close Air Support). Each class of aircraft, and indeed, each role of the aircraft may need different information fed to the aircrew during the sortie and this could imply, in current aircraft, different displays and cockpit layouts.

Over the next 20 years (2.1), it is unlikely that the basic operational roles that aircraft will be called on to complete will be significantly different from those laid down in the current air power doctrine. It is likely that greater emphasis will be placed upon participation, perhaps within the NATO or United Nations umbrella, in out-of-area conflicts involving multi-national forces. Such scenarios will, by definition, embrace a wide range of geographic, meteorological and threat environments demanding highly accurate 24-hour all-weather capability.

Within individual Air Forces, Defensive Counter Air (DCA), Offensive Counter Air (OCA) and Air Interdiction/ Battlefield Air Interdiction (AI/BAI) will still remain the cornerstone of aircraft operations. However, the continuing development, and increased sophistication, of air-to-air weapons and the developments of optical/ blinding weapons will require different approaches to some aspects of weapon delivery.

By 2020, many nations will be operating combat aircraft with, at least, F-16 class performance. Whilst these aircraft may, in terms of sustained maneuverability in combat, fall short of Eurofighter & F-22 performance, the development and availability of sophisticated and high performance avionics & weapon systems (for example off-boresight targeting) will enable these aircraft to pose a significant threat, and the usability of these systems could negate the 'quality of aircrew' operational advantage that is often cited as a consequence of Air Force and NATO training procedures. Both air-to-air and ground-to-air weapon engagement envelopes will continue

Paper presented at the AGARD Symposium on "Future Aerospace Technology in the Service of the Alliance", held at the Ecole Polytechnique, Palaiseau, France, 14-17 April 1997, and published in CP-600 Vol. 1.

to expand, and by 2020, safe flight regimes may have virtually disappeared - putting greater emphasis on ECM and both the platform and operational aspects of stealth to minimize attrition. Optical weapons have emerged as a significant threat and it is feasible that, in the timescale, they may have become the single greatest threat to aircraft, sensors and aircrew. The mobility of air threats and the increasing need for minimum probability of detection throughout a mission, will require highly flexible route planning (both pre-flight and en-route) to avoid high threat airspace, and aircraft will need to be capable of receiving and rapidly & unambiguously interpreting real time intelligence updates, and presenting the pilot with suitable and timely advice.

All this information flow, combined with more constraining politically based rules of engagement - minimizing own aircraft attrition rates and the minimization of collateral damage and civilian casualties - will conspire to increase the workload on an already heavily loaded operator.

Thus, the design of the cockpit, the aircrew interface (controls & displays) and the integration of the "simple" operator with the "complex" avionics and sensors systems will be a core issue for the 2020 aircraft, and a crew-centered approach must be considered as one critical part of the design process, and of equal importance as airframe and aerodynamic design, propulsion, weapons, stealth, etc.

2.1. THE PILOT'S JOB

In simple terms, the job of the aircrew in a combat aircraft is to fly the machine to a location, often via a predetermined routes, where the target, in the air or on the ground, can be found and attacked before returning to a friendly base.

Different aircraft, roles, locations, weather conditions, targets, defences, equipment failures and interactions with other forces generate a plethora of specific demands and concerns which the crew must deal with in order to complete the mission satisfactorily. However, it is reasonable to describe the job as being composed of a number of separable high-level tasks:

Aircraft control	Controlling the vehicle speed & flight path safely
Navigating	Determining location and required course
Managing the mission	Planning, scheduling, maintaining tactical awareness and making en-route interactive tactical decisions
Managing aircraft systems	Taking care of fuel, electrics, hydraulics, etc.
Communicating	Managing radios and sending/receiving information
Targeting	Locating and identifying targets
Managing weapons	Selecting, arming and assigning weapons to targets
Countering threats	Being aware of threat sites & vehicles, and deploying appropriate countermeasures

This classification corresponds to the service nomenclature in that the primary skills of controlling an aircraft, planning a flight, navigating, communicating and dealing with aircraft systems are taught as basic flying training. These are then refined for a particular aircraft type in an operational conversion unit before the crew member is assigned to a squadron where he undergoes an operational work-up which exposes him to the military tasks of dealing with tactics, targets, weapons and threats.

It is in this latter phase of preparing for operational readiness that the full complexity of operational flying becomes apparent, particularly if high and consistent levels of mission success are to be achieved.

2.2 MANNED or UNMANNED AIRCRAFT?

For certain types of military operation, generally where operational conditions and roles are predictable, particularly in OCA and some AI roles, there will be an increasing use of Stand-off Weapons for precision strike, along with the increased use of Unmanned Aircraft. These types of weapon systems can have either autonomous control or have a man-in-the-loop capability. The political constraints and rules of engagement for future battlefields may dictate the potential use of both, either, or neither.

In an unmanned system, the removal of the man could bring a number of important benefits:

Structural	with no requirement to protect the man or supply a control/display interface, the aircraft can be simplified and made lighter
Logistic	removing the need for training, accommodation etc., reduces costs
Physiologica l	there is no deterioration or limitation to performance due to high-g, vibration, noise, distortion or fatigue
Cognitive	the avionics aids attend to all tasks consistently, all of the time

However, against this must be balanced the advantages of retaining the pilot:

Perceptual	direct external vision is an independent, high proficient means of noticing, identifying and interpreting features and conditions in the external world
Cognitive	human decision making can utilize a greater awareness of context, priorities and consequence, it can learn and adapt readily; it can exercise common sense and make judgments of value

Although the relative operational merits of manned and unmanned aircraft are liable to depend always upon the maturity and proficiency of intelligent electronics and the information contained in the electronic memories, it seems reasonable to assume that the manned military aircraft will continue to be fielded where operational deployment of the vehicle remains ill-defined or accurately definable. In these circumstances, the quality and flexibility of human vision and thinking are useful military qualities.

2.3 NUMBER OF AIRCREW

For the fast jet manned cockpit, there will be a need to house a one or two-man crew - although a one-manned crew is liable to be the preferred option. Various advantages have been postulated for both single and twin crew aircraft and the factors that affect the debate have been put forward as:

Single Crew	Twin Crew
No second pilot required	Increased role flexibility
Increased range of operations or reduced aircraft weight	Increased probability of survivability
	Increased Situational Awareness
Reduced training costs	Reduced Workload
Reduced life-cycle costs	Reduced stress

In practice, the crew complement is decided on the trade-off between cost and effectiveness. However, it must be recognized that the functionality and complexity of the aircraft avionics and mission support systems required to enable effective single crew operations are considerably more than for twin crew operation.
Whether a single or twin crew cockpit is chosen, the physical size of the cockpit will not reduce substantially. However, the range of aircrew sizes that must be accommodated in the cockpit will increase, particularly for smaller female aircrew. The subsequent difficulties of providing aspects such as ejection seat height adjustment to accommodate the operationally important tasks, such as the ability to reach controls and switches, will increase, but alternative control technologies, such as the use of voice control for switching radios, displays, etc., will provide some alleviating solutions. A further confounding factor may be the design of the cockpit transparencies to meet the requirements for stealth and to some extent laser protection. The use of flatter and faceted canopies may well restrict both pilot head movement and external vision -- not so much a problem for medium level bombing runs, but certainly a problem for many aspects of ground attack and air combat.

2.4 AIRCREW PROTECTION

It is probable that the greatest change in cockpit configuration to the 2020 aircraft will come about from the need to protect aircrew against optical/directed energy weapons. A reliable counter to the optical threat is essential, and this will be in the form of protection for the pilot's eyes. Both operational requirements and peacetime considerations suggest that a closeable solution - protection deployment as required under aircrew control - is a more acceptable solution. Current protection is by the use of helmet visors using single or multi filters and this provides a short term partial solution, but such techniques are recognized to be ineffective against variable frequency lasers. Reactive dyes or other elements may well provide a longer term solution against agile lasers, but the density of the visor is liable to leave a pilot, in a crucial part of the mission, with a partial or fully restricted vision of the world outside of his cockpit. Full closure may be achieved either on the helmet visor, or the cockpit canopy, but, in either case, the direct view of the outside world would be obstructed, and the information needed would have to be presented either from the range of sensors, or synthetically from aircraft data bases, or both, probably via the Helmet Mounted Display. This concept of display will begin to open the way to, eventually, the Virtual Cockpit.
A further, and more radical, approach would be to use a fully immersed cockpit, where there is no direct view of the outside world and piloting is accomplished solely from sensor information and onboard data bases.

2.5 OVER-ARCHING ISSUES

The basic functions of a cockpit are not expected to change radically for aircraft of the 2020 timeframe.
There remains a number of criteria that any cockpit - that is a space in the aircraft that houses a piloting operator - must meet and the basic cockpit design must ensure that the aircrew have:

- an adequate view of the outside world - directly or indirectly through sensors & data bases
- control & display facilities to enable accurate and timely completion of all or their tasks
- accommodation in a safe environment
- protection from a mixture of natural and deliberate hazards

A further integral part of cockpit design and the man-machine integration is the cockpit operating philosophy. This philosophy defines the interaction between the crew and vehicle systems through the cockpit MMI. It defines the modeing and the use of the cockpit displays and controls in their broadest sense, including the aural channel as well as the visual and tactile. It links the individual and collective tasks of the aircrew to the operating of the aircraft systems, and to the difficulty or ease-of-use of the interaction with these systems. By this means, the definition of activities that have to be carried out by Voice, HOTAS, or manual control through multifunction or dedicated controls and displays and that also require to be visible and operable with the crew in any of the head out, head in, or head up conditions, leads to the requirement for the technology to be integrated into the cockpit.
The increasing capability and speed of electronic processing in aircraft avionics, the wide range of sensor capabilities and the speed and depth of signal processing available for the 2020 aircraft will stretch the capability of the human operator. However, that same processing capability in the form of alternative control technologies and the use of decision support and automatic control of the mission systems for the aircrew - perhaps intelligent and capable of simple learning - will also be necessary to provide the processes by which the integration and interaction of the pilot with the machine can be effectively and efficiently accomplished.
Aircrew of the 2020 aircraft are just in nursery school today and their education in computing skills and mental and manual dexterity, learned from computer manipulation, should make them fully suitable for 2020 air operations - both for the air-based cockpit and for the unmanned air vehicles with a ground based cockpit.

3. CONTROL AND DISPLAY

The past 15-20 years have seen the implementation of two major concepts in the control and display area which are now generalized for fourth generation combat aircraft:

- The *Glass cockpit* replacing classical dedicated intrumentation and providing to the pilot, integrated information.
- The *HOTAS* concept (Hands On Throttle And Stick), enhancing pilot effectiveness, but, in counterpoint, rapidly inflating the number of real time commands.

Though, despite optimistic claims (1), two major advanced concepts suggested in the beginning of the 80s, to stand along with improvement of guidance and control automation, (9) are still quite far from being technologically mature at the end of the nineties:

- The *big picture, little picture* concept
- The *Virtual cockpit* concept

For the twenty years to come, the major challenge we will have to face in regard of Human-Machine Interaction is mostly based on a quite simple consideration. For many years now, we have contemplated with great fascination a continuous increase in machine computational power. The trend is clearly to a geometrical progression and the ratio of power will probably reach 100.000 by 2020, possibly 10^9 (13).
On the other hand, in terms of control and display capacities, improvements would rather follow an arithmetic trend with a quite slow step by step move. One can see here effects of technological and technical limitations (either physical and economical), but also consideration of the limited perceptive and cognitive resources of the human operator (saturation of working memory as an example).
The divergence resulting from the above considerations may induce a serious risk, that no one would reasonably accept. As the future systems will grow more and more powerful, but also more complex, the human operator could progressively lose his pilot role, even as system supervisor, becoming insidiously more a spectator than an active participant.
The possible emergence of this kind of situation would probably raise various questions. At this time, it may be of some interest to consider what we can expect from Human-Machine Interface improvement to limit and balance the harmful effects of an excessive dominance of the system on the man.

3.1 DISPLAY ISSUES

It is really commonplace to state that in aeronautics, more generally vehicle design, visual displays are and will certainly remain the dominant modality of information presentation to the human operator. The technological trend is here to display large size images, either real (Head in) or virtual (basically head out). This trend is visible in military avionics, clearly linked to tactical awareness needs, but also in commercial aviation where motivations could be more complex. One of the questions immediatly raised is: *how large the image?*

3.1.1 Large Area, In-cockpit Displays
The notion of large image was already a key element at the origin of the *little picture-big picture* concept proposed by Adams (23), but also in the virtual *panoramic* cockpit suggested by others (7, 11). Though refering to operational needs, these two concepts, aiming to year 2000, include strong technology-driven considerations along with human factor aspects. That makes such concepts highly dependant on technology evolution (or non-evolution). As an example, the *little picture* (so called *micro situational awareness* was clearly based on assumption of technological possibilities of the 80s, while the *panoramic display* (11) was optimistically understating the technical difficulties to be overcome for mid-term introduction.
As the introduction of lightweight Flat Panel technology appears now as a strong technical trend, both real and virtual displays are likely to offer the large image capacity. That would mean that probably none of the above cockpit concepts would have a chance to become <u>individually</u> mature and dominant. In the future, we can expect a dilution of those concepts into a, hopefully, Human-Centered crew station, based on a comprehensive philosophy of operators' information needs, relatively independant of technology considerations. On this basis, Head-in and Head-out display are likely to coexist as, besides redundancy, they would bring different advantages in regard of building good situational awareness.
Introducing large size head-in (HID)display in combat aircraft constitute a real challenge, not only in regard of display technology but also due to usually limited space in fighter cockpit. Among modern aircraft, the largest image displayed is probably found in the Rafale, with the color head-level display concept. Using LCD valves and collimation optics the head level display offers a square field of view of 20 degrees by 20. At normal distance of vision for HID, achieving an identical image size would require a 12 inches by 12 display. Intending basically to display complex tactical situation, the head level display of the Rafale is also used for map presentation, more demanding in regard of display resolution. As an example, the functional analysis of needs for a navigation aid imply the ability to display 5-6mn flight time (7.5NM/mn) ahead of the aircraft with 50NM range on the display, or 15 mn with 150NM. It was shown that with its 1000x1000 pixel resolution, the head level display surface was just offering an adequate trade-off of density/visibility/surface to be able to use raster maps.
Some studies (8), however, mention that numerous situations would require a simultaneous management of short, mid and long term information, requesting a frequent swapping between different map scales. To reduce pilot workload, this indicates that it could be of some interest to have a larger display size allowing simultaneous presesentation of navigation information. More generally, following operational context, it may be of great interest to allow different information to be displayed contiguously, with variable window size. For the future, such considerations are leading to a concept of large, reconfigurable and interactive display (21). Size of such display could be, as an example, in the range of 20 X 15 inches. Some of the benefits expected would be:

- Increased flexibility, as the displays windows size or location could rapidly be reconfigurated following mission type, phase or even user experience or cognitive style. On request, most adapted size for a given situation could be rapidly obtained, from full screen to iconic
- Capacity to display complex tactical situations with an always appropriate size and resolution
- Allow inflight mission planning and rehersal.

Current evolution trends in Flat Panel Display technology show that quite large size display with adequate resolution are starting to appear on the commercial market. It seems very likely, though, that the availability of such display will be very dependant of civil applications. On the other hand, optical systems, using smaller, very high resolution matrix, may offer good solutions for a large reconfigurable display.

3.1.2 Egocentric vs Exocentric Displays
In recent articles (28), Wickens stressed the notion of egocentric versus of exocentric presentation of the situation, offering an interesting thread to follow. According to different studies, egocentric displays would allow better flight path control, while exocentric fixed map displays would provide superior situation awareness for *tasks requiring access to knowledge in a world-referenced frame.* Recently, in a study of taxiing in low visibility, Mc Cann and Al. (15) have shown the complementarity between

HUD egocentric information and Head in, exocentric representation of airport taxiways. More generally, relationship between egocentric and exocentric (allocentric) frame of reference are of particular importance in such areas as processing of spatial information (19). From egocentric perception at the *sensorimotor* level, the Central Nervous System generates, at a *representational* level, in an allocentric frame of reference, a stable representation of spatial information, a condition to projective motor activities. Implications of such considerations are that information related to immediate spatial situation awareness building, self and immediate environment, would preferably follow the natural pathway while cognitive (god's eye view style) representations would provide global (*evocational*) situation awareness.

An operational illustration of the need for this dual mode of representation could be found in the way young pilots coming in fighter squadrons are instructed on mission preparation. Once the mission has been prepared on the map (typical exocentric representation), they are taught to hold the map horizontal at the eye level to reconstruct a spatial perspective (egocentric) representation of what will be on their flight path. One can see here a clear atttempt to complement the global awareness given by the map with more immediate *sensorimotor* information.

Situation Awareness is now a key word for most people. Depending of field of expertise, however, it sometimes takes very different meanings for each one, despite official definition. Once again, the multidimensional and complex nature of situational awareness construction has to be stressed. Of course, the ability to provide information is necessary, but in no way is sufficient by itself to build a correct mental image of the situation, the basis for Situation Awareness. That means that the real challenge of situational awareness is not on the technical side. Even if information provided in the different domain constituting Situational Awareneness are valid and individually pertinent, the way information is organized and displayed remains the major factor to consider. Vaguely talking about intuitive man-machine communication is far to be enough. Identifying information display modalities answering to operators' needs, instead of being dictated by a *system point of view*, constitutes a crucial element for a *human-centered* approach of building Situational Awareness.

From a practical standpoint, consideration of egocentric and exocentric display modalities could provide useful guidelines for information repartition. In a very simplified way (may be simplistic), egocentric, 3D, conformal information should be presented head-out, while exocentric representation of the situation would probably be the rule for head-in. Alternative display technologies, such those using the auditory channel, desserve some attention, as the visual channel could be rapidly saturated by an excessive flow of information.

3.1.3 Head-up and Helmet-mounted Displays

It is quite likely, that Head-Up Displays (HUD), if they remain in the cockpit, will see very little evolution from their current status for military aircraft application. Some progress have been made on color HUDs and, few years ago, a color HUD was tested on a Mirage 2000 test-bed aircraft at the French Flight Test Center of Brétigny sur Orge. Nevertheless, cost effectiveness consideration becoming a crucial factor, development of such equipment is very unlikely. As a matter of fact, it can be expected from progress in Helmet Mounted Display (HMD) technology that, at term, helmet mounted equipment will supercede the HUD in the cockpit.

First generation of helmet mounted equipment (sight only, using a head-tracker) is already in service on fighter aircraft as the Mig-29. Second generation HMD (symbology only) or even third generation (symbology and sensor imagery) are now quite close to be ready for application on fighter aircraft. For all generations, besides display aspects, head-trackers constitute a key element to be considered.

Interest of third generation HMD for helicopters is now well recognized and clearly established, either for monocular or binocular equipments, as an important part of the aircraft system during night operations. The situation is not so clear for fixed-wings fighter aircraft. If introduction of HMDs has been formally decided for the Rafale and EFA 2000 programs, it is likely that the equipments will not appear in the first standard of the aircraft. Somewhere, it means that the basic capabilities of aircraft systems do not really require HMDs to carry out the missions. Testing of second generation HMD have convinced most pilots, who had the opportunity to use such equipment in flight, about the great potential it has for close in air to air combat superiority. Advantages in terms of radar or seeker lock on, reverse cueing and

off-boresight missile launch have been reported in many places. However, in regard of very elaborated systems of modern aircraft, mostly designed for *Beyond Visual Range*(BVR) combat, HMDs unfortunately appear sometime as *add on* equipment. Some human factors and system integration issues desserve to be rapidly clarified to accelerate the introduction of the equipments. After promising flight tests results of third generation HMD with head-slaved IR sensors (13), the future of such equipments on modern fixed-wings fighter aircraft appears quite unclear. They certainly help pilots to build better situation awareness and confidence, real effectiveness and objective contribution to mission success remain to be clearly demonstrated. We are here in a situation where potential situation awareness benefits may not directly impact on nominal mission effectiveness, as aircraft systems have been designed to carry out the mission without such equipments. In the current *cost saving* context, temptation may definitely be great to rapidly sacrifice *what could be perceived as extra*-situational awareness following a strict and short term cost-effectiveness rationale. A better understanding of the potential gain offered by third generation helmets on Fixed-wings in difficult or degraded situations should be investigated.
In the long run, HMDs have a great technological evolution potential, which would make them able to support more ambitious goals than current ones. Fourth generation HMDs should have the capability to fully use the possibilities of synthetic imagery, displaying information from geographical and tactical database consolidated or enhanced by sensor information or imagery. Very large field of view (over 100 degrees) would allow to maintain situation awareness at a very high level in any condition. Use of color for imagery and symbology will improve efficacy of the systems and offer such possibilities as virtual color HUD, assuming progress are made in the head-tracker domain. Coupling of such equipment with alternative control and display technologies as DVI, Eye-Tracking and 3D localized sound would contribute to optimize the use of human operators resources. Technological improvements will be necessary on head-trackers (accuracy and dynamic characteristics) whichever technology is used, optical or electromagnetic. Key points are also on lightweight optics and image sources.

3.1.4 Alternative Displays

Several attempts have been made to introduce alternative display technology in the cockpit, mostly focused on the auditory channel, but also on more *exotic* sensorial pathways, as tactile or haptic interface. In that case, one of the goal is to enhance or restore *natural* sensations.

3.1.4.1 *Audio symbology*

After the visual channel, the audio channel has always been an important display in aeronautics, essentially based on voice communication (GCA as an example). More recently, attempts have been made to investigate the interest of acoustic orientation cues 14). What is new with the current trend is the expansion of *audio symbology* far beyond the current status of auditory warnings. Synthesized voice messages are now a classical feature of commercial and military cockpit. Advantages and the inconveniences of such communication mode have been widely reviewed (26). Use of attensons (20) looks as a very promising area. Iconic and metaphoric representations associated with comprehensive understanding of sound signal characteristics were used to build a set of threat warning, currently under evaluation by DERA at Farnborough.
During the last ten years a large amount of laboratory work and some flight testing 16) has been devoted to investigate 3D localized sound. Results obtained in flight and with simulation work have confirmed the interest of localized auditory information, especially when coupled to HMDs (3, 5). Applications include following areas:

- Threat or waypoint spatial localization
- Spatial separation of audio communication
- Warnings and alarm (coupled with attensons).

3.1.4.2 *Tactile and Haptic Display*

The use of tactile interface to convey spatial orientation information has been suggested by some authors (22). Application of such techniques could also be advocated in the context of synthetic environment. First application of haptic display is certainly to restore feed-back cues for aircraft control, lost with introduction of fly by wire controls. Such techniques may also prove to be useful in synthetic environments.

3.2 CONTROL ISSUES

Most modern aircraft have now adopted the *Hands On Stick And throttle* (HOTAS) concept, initially implemented on the F-18 (18) for sensor and weapons management. This concept is closely linked to the notion of *real-time command*, where the pilot can operate immediately a control, whithout the need to release stick or throttle to reach a switch on a dedicated control panel. It is now well recognized that this concept greatly enhance the pilot's effectiveness during combat mission.

Initially intended to mostly control the weapon system in the final phase of the mission, the HOTAS concept has been progressively extended to other phases, with the wishful intention to reduce pilot workload, as an example for aircraft system configuration during ingress. In return, the number of real time commands available from HOTAS has considerably increased, heavily solliciting the pilot working memory. The inflation in the number of real time commands raises the question *how far is too far?*

This is not really a new question, since in 1984 the F-18 was severely challenged on this point (25). Despite progress in automation, there is obviously some limits to the resources of the human operators that cannot be crossed without consequences. The problem here is basically linked to the saturation of working memory, inducing the need for additional training hours, without totally suppressing the risk of high error rates and poor results.

A solution to this problem probably lies in the introduction of alternative control technologies, satisfying the operators' needs for real time command, while utilizing limited but multiple human resources in a better way. Some of the expected benefits potentially offered by alternative control technologies could be summarized as follows:

- A way out of the pilot if the command fails with manual control (alternative)
- A reduction in hard control (simplification)
- Enhancement of pilot efficacy and reduction in training duration to reach a given level.
- Facilitation of control modes with very large displays.

A quite exhaustive review of nonconventional control technologies has been recently published (17).There is, however, large variations in level of maturity among alternative control technologies in regard of usability and integration, especially in a fighter cockpit. Some technologies, as eye tracking, have now a very long history but are not totally mature. Others as DVI and touch-screen are already flying or close to be integrated in aircraft systems. It then seems legitimate to consider these technologies in regard of their level of maturity, even if some have a fast progression rate as biopotentials.

3.2.1 Near-term Control Technology

Two items can be considered as able to find short term application in aircraft cockpits: Direct Voice Input (DVI) using speech recognition technology and tactile controls (Touchscreen, Touchpad). Head-trackers also belong to the same category, though they are closely tied to the HMD concept, wich has been already discussed.

3.2.1.1 *Direct Voice Interaction (DVI)*

Numerous studies and test flights have been devoted to Voice Control in the first half of the 80s. Results obtained at that time were quite mitigated and the general feeling was that substantial progress had to be made in this area before DVI can really be used in a cockpit. Nevertheless, DVI was very early included in the EFA program. It is currently considered as an option on the Rafale. As a matter of fact, decisive progress have been made in the early 90s, which makes DVI quite attractive now for complex *glass cockpit* environments, already crowded with many multifonction manual controls.

Results of test flights presented recently (24, 4) are quite interesting to consider. UK and France have independently tested voice recognition system currently under development in their respective countries. Despite the fact that different test-beds aircraft and methodologies were used, there is a striking convergence of results obtained in UK and France.Recognition rates reach in both cases 98% for short sentences in stable flight conditions and remain between 85 to 89% under G-load.

Though the effects of stress and G-load constitute a current subject of research, that area may not be so critical from a practical stand point. In fact, some pilots consider that using DVI in these conditions is not very realistic since voice could be too slow to operate in very dense and fast changing situations as close in combat. Promising areas of research are offered by de-noising raw voice signal and modelisation of the vocal dialogue as a function of tasks.

3.2.1.2 *Touch screen - Touch pads*

Strictly speaking, touch screen and touch pads belong to the manual control category. They present, however, particularities which allow to class them in advanced controls. The use of touch screen is now well established in civil application, as terminal for banking operations. Touchpads can replace joysticks, to move a cursor as an example, and allow input validation. Both are flying for quite a long time on the Rafale. They are used now routinely by pilots, with very positive results so far. They may rapidly become a common feature for other cockpits.

3.2.2. Mid-term Control Technology

This section includes an old dream of MMI engineers and scientists, eye-tracking, along with more recently promoted technologies as gesture or biopotentials, this last one being based on signal processing of electro myographic (EMG) or electro-encephalographic (EEG) signals.

3.2.2.1. *Gaze*

Gaze is usually defined as the resulting line of sight (LOS) from a combination of head and eye movement. Measuring point of gaze in a given environment implies to be able to give orientation and origin of the line of sight in the coordinate system related to this environment. Most gaze measurement methods require to measure separately eye and head movements. As head-tracker are a basic feature of HMDs, measuring gaze in the aircraft reference frame requires to be able to measure eye movement relatively to the head, assuming a fixed geometrical relationship of the head coordinate system into the helmet coordinate system. Currently such techniques as the *pupil + corneal reflection* are considered as the best way to take if accurate measurement are required (approximately 1 degree in laboratory conditions). Signal processing of this kind of technique is now quite mature allowing acceptable measures in daylight conditions. Current efforts bear on opto-mechanical integration of the eye-tracker in the HMD. Some results have been obtained with simulation helmets (CAE) and integration study is underway in France on a third generation HMD.
Gaze control would correct the physiologically non-natural aspect of head tracker based HMDs, which basically create a disruption of eye-head coordination mechanisms. Used as a sight, the combined head tracker and a eye tracker also allow the two sensors to operate in better condition for a given gaze movement. For a given angle, head-free gaze accuracy is usually better than the sum of the head and eye tracker isolated errors. Use of gaze control takes its full interest when used in conjunction with large image. Slaving a cursor to the point of gaze should allow to save time when working on large surface, compared to classical manual control. Last but not the least, gaze tracking offers a good monitoring indicator of pilot activity and would provide useful inputs to an electronic copilot.

3.2.2.2. *Gesture*

Gesture-based controls have been used for years now as a human computer interaction device in numerous laboratories involved in virtual realty. Various technologies are used, as magnetic or electro-optic trackers to characterise dynamic movements of the hand, while other devices using glove-based system allow to recognize static posture of the hands (signs).
Many applications have been suggested in the virtual reality domain. Use of gesture-based control has been investigated recently in a virtual controller application (6).
Typically, gesture base control appear quite difficult to integrate in an aircraft cockpit environment. Other environments as command centers or control rooms could find benefits in using such technologies.

3.2.2.3 *Biopotentials*

EMG and EEG signal processing to provide control input currently elicits a considerable interest in advanced research laboratories, specially in the US. EMG signals have been used for quite a time for prosthetic device operation and this kind of technique is recognized now to have a significant clinical value. EEG-based signals are currently under investigation. Results looks surprisingly promising as it appears quite easy to control various dynamic process or even fly a simulator with such techniques. Though many applications could be suggested, including the very mediatic *fly by mind,* the practical use of such devices in a cockpit seems quite remote. Interest as reflex control in highly time constrained situation has been identified by Working Group 25 on *alternative control technologies*(currently in activity).

3.3 COCKPIT INTEGRATION

Cockpit integration of the various advanced concepts and technologies of displays and control should be mainly designed to better support operators' situation awareness, through optimization of sensorimotor and cognitive resources, and to simplify and facilitate control.
In this regard, Table 3.3-1, elaborated as an example during the activities of Working Group 25 summarize some problems encountered with conventional controls and suggest possible alternative control modalities.

Integration issues should be considered very early in the development process and include global considerations. In a Man Machine Interface subsystem, human factors considerations underlying introduction of a multimodal dialogue should be carefully evaluated. Such considerations must be based on a thorough analysis of operators' sensorimotor and cognitive caracteristics in regard of tasks to be accomplished.

3.4 ALTERNATIVE ENVIRONMENTS

Most of the considerations developed above are related to introduction of advanced technology in a conventional aircraft cockpit. By 2020, other environments may exist.

3.4.1 Windowless cockpit

Windowless cockpit design is basically the ultimate answer to laser and directed energy weapon threats , especially tuneable lasers. Such a design as been already advocated by some authors (10). It may also have an interest in making the aircraft stealthier.
The good point with such a design is that it greatly simplifies the luminance requirements for the different displays, as the environment can be strictly controlled. On the other hand, flying the aircraft using synthetic vision (SVS) only may not be so simple that enthusiastic promoters of the concept think. The basic issue is at the level of building the confidence into the database and SVS system, with situation awareness being quite restricted to the *system view point.*

Means of control \ Uses		Continuous control (eg flight-path control)	Emergency actions (eg jettison stores)	Time-critical selections (eg transmit radio message)	Routine selections (eg change map scale)	Routine data entry (eg insert waypoint co-ordinates)	Cursor slewing (eg move cursor on HDD)	External feature designation (eg designate visible target, slew VCS)	Virtual switch selection (eg on virtual HDD)	Pilot state monitoring (eg level of consciousness)
Existing means of control	Throttle, stick & pedals	■								
	Guarded switches		■							
	HOTAS switches			■						
	HOTAS inceptors	■					■	□		
	Hard keys (single function)			□	□	□				
	Soft keys (multi-function)				□	□				
	■ Satisfactory □ Problematical									
Novel means of control	Voice recognition		☆		★	★				
	Helmet sensing						☆	★	☆	
	Eye sensing						☆	☆	☆	☆
	Gesture sensing	☆							☆	☆
	Bio-potential sensing		☆							☆
	★ Accepted ☆ Possible									

Table N Summary of the potential usefulness of alternative control techniques in aviation

3.4.2. Virtual Cockpit

The virtual cockpit concept implies that all information is presented in a 4th generation HMD, either head in and head out, bringing cockpit simplification (no head-down display) and great flexibility. It is quite likely that components of such a view will take place in future cockpits.
The need to present some information in a stabilized mode relatively to the airframe structure, especially for flight path control were a great accuracy may be required, inducing, in this case, the need for considerable inprovement of head trackers. Both accuracy and dynamic characteristics of trackers should be improved to achieve the required spatial stabilization level.

3.4.3. Remote Cockpits (UCAV)

Even if the UCAV concept will be based on a large autonomy of the platform, this man-in-the -loop concept implies the need for mission management systems probably close or higher than current ones. That probably means that advanced MMI techniques could be quite useful in this environment. The big difference with conventional cockpits here is that technologies may be totally different for airborne applications with a large use of Components Off The Shelf (COTS).

4. ADAPTIVE OPERATOR INTERFACE TECHNOLOGY

Scientists and engineers within several of the NATO countries are developing and evaluating human-machine interface concepts to enhance overall weapon system performance. The increasing complexity of the aerospace mission in the year 2020, in terms of the mission's dynamic characteristics and number of interacting friendly and adversary platforms requires a revolution in the capability of the operator's interface to the individual platform and to the battle-space in general. This revolution will be brought about by embedding knowledge of the operator's state inside the interface, enabling the interface to make informed decisions regarding many of the interface's information management display characteristics. Some of these characteristics may be information modality, spatial arrangement, temporal organization, and control utilization. By increasing the ability of the interface to respond, or adapt, to the changing requirements of the human operator in real-time, the interface will provide required control capabilities and information management which appears intuitive to the operator.
The adaptation of the interface to operator state can occur across two different domains,

the first being function allocation and the second being perceptual characteristics. The adaptation is enabled by the availability of three technologies; (1) highly flexible display and control devices, (2) computational models of situation awareness, workload and operator performance, and (3) direct physiologic and behavioral measurement of the operator. Examples of highly-flexible displays include helmet mounted displays, head-up displays, and large in-cockpit displays coupled with advanced graphics generators, as well as 3-dimensional sound generators and haptic/tactile displays. Examples of flexible controls include brain-actuated control and virtual manual control. The foundation for computational models of situation awareness and workload is formed by applied behavioral research and advanced computational modeling techniques. Computational models of situation awareness and workload enable extrapolations of near-future operator state. Direct real-time measurement of physiological characteristics of the operator, correlated with operator behavior and environmental situation, provides indices of current operator state.

Within the adaptive interface, operator state indices are combined with operator performance and capability models to form a real-time display/control adaptation strategy optimizing the performance of the human-machine weapon system. Currently, there are exploratory development programs within the NATO countries involved, to varying degrees, in the development of the enabling technologies and the evaluation of how performance is affected by adaptive interface utilization. This paper will detail some of these development and evaluation efforts and provide a potential framework for a future a collaborative effort focusing current NATO research and development in this technology area onto a transition path. The following paragraphs are organized around the adaptive interface enabling technologies, those being highly flexible display and control devices, computational models of situation awareness, workload and operator performance, and direct physiologic and behavioural measurement of the operator.

4.1 DEVELOPMENT OF FLEXIBLE CONTROL AND DISPLAY DEVICES

The flexibility of control and display devices varies continuously across a broad range. Individual instruments, such as altimeters, exhibit a low flexibility. Heads-up Displays and multi-function in-cockpit displays exhibit much more flexibility than do individual instruments with devices such as helmet-mounted displays increasing flexibility further. Current research and development into advanced displays and controls is producing devices and techniques that continue to push the limits of flexibility. For example, the Human Engineering Division of the USAF Armstrong Laboratory is evaluating several novel alternative control devices.

Recently, two separate experimental evaluations of a combined EEG-EMG alternative control device were conducted. The first evaluation revealed that subjects could learn to perform a discrete response task with this EEG-EMG device with very high accuracy and, perhaps more importantly, approximately 20 msec faster than with the use of a manual response device. The second evaluation revealed that subjects could learn to perform a continuous control task (control of simulated self motion through a series of 10 circular hoops positioned above a virtual terrain) with an accuracy of 78%, which is less accuracy than would be expected under conventional manual control, but indicates promise in applications where conventional manual control may be impractical, such as multi-axis control(4.1-1).

The Human Engineering Division is also currently evaluating the use force-reflection as a display technique. An evaluation of a force-reflecting, haptic stick was conducted which revealed significant improvements in instrument landing performance when compared to a standard displacement stick, particularly in high turbulence conditions (e.g., avg. 4 ft. closer to runway center line) (4.1-2,4.1-3).

In addition to force reflection, the Human Engineering Division is currently investigating the development and potential application of direct electrical vestibular displays. The Electrical Vestibular Stimulus (EVS) technology uses electrodes located behind the ears to deliver a low-level electrical current in the area of the eighth cranial nerve of the central nervous system to produce a compelling sensation of roll motion about the body's fore-aft axis. In a recent study, subjects experienced the EVS display while simultaneously observing a large field-of-view visual roll display, and were asked to rate various aspects of quality and magnitude of self-motion. Both EVS and visual displays were driven in a sinusoidal fashion at various phase relationships relative to one another. After observing the two displays, subjects were asked to rate various aspects of quality and magnitude of self-motion. Results revealed that the fidelity of the motion experience depended upon the phase relationship between the EVS and visual displays. Results also indicated that leading the visual display with the vestibular display significantly improved the fidelity of motion experienced by subjects when compared to a visual-only display (4.1-4)(Cress, Hettinger, Cunningham, Riccio, McMillan, & Haas, 1996). In a separate study following similar procedures but using curvilinear motion through a tunnel as the visual display, similar results were obtained (4.1-5).

4.2 DEVELOPMENT OF WORKLOAD AND SITUATION AWARENESS MODELS

Current activities in situation awareness have been collaborations between several NATO countries. As an example, to competitively validate predictive models of mental workload, the Cognitive Assessment Laboratory's Simulator for Tactical Operations Research and Measurement (STORM) facility was used to collect a preliminary database of subjective and objective measures of performance and situation awareness from a simulated, generic Theater Missile Defense mission. The simulated missions were executed with cockpit designs that provided varying levels of information support and in environments that had several different levels of threat present. In addition to performance measurement, standard subjective tools for assessing mental workload (i.e., the Subjective Workload Assessment Technique, SWAT) and situation awareness (i.e., the Situation Awareness Rating Technique, SART) were collected. A preliminary set of predictions were generated by a MicroSAINT implementation of a McCraken-Aldrich workload model. An interesting, and unexpected, finding of this first study was that the models predictions were more strongly correlated with the situation awareness measure than with the mental workload measure. The data from this experiment will be shared within the US as well as other NATO researchers to provide a test condition for predictive models developed in their laboratories. The initial results from this program have already been described in a pair of Armstrong Laboratory Technical Reports (4.2-1,4.2-2).

A second major thrust in the Cognitive Assessment Laboratory research program in the US is the validation of new measures of cognitive compatibility and situation awareness. The Cognitive Compatibility - Situation Awareness Rating Technique (CC-SART) was developed as part of the TTCP UTP-7 program by British researchers at Farnborough. Studies performed within the Armstrong Laboratory's Synthesized Immersion Research Environment (SIRE) and Cognitive Assessment Laboratory have begun an initial validation of the CC-SART in a flight simulation utilizing pilots from three countries (4.2-3). More recently, a simplified version of the CC-SART was used to support an evaluation of proposed attitude displays for the JPATS program. An elaboration of the CC-SART to parse out the cognitive impacts of specific subsystems in a complex simulation is currently being planned.

Mental workload is a major consideration in the design and operation of modern weapon systems. Objective measures of mental workload that are sensitive and diagnostic are required to meet the needs of both weapon system's operators and designers. Due to the multifaceted nature of complex mental demands in current crew systems, multiple measures are required.

Psychophysiological and subjective measures provide unique information about mental workload during flight. In a recent study, cardiac, eye, brain and subjective data were collected during a flight scenario designed to provide tasks which required different piloting skills at several levels of mental workload. The results of this study indicated that heart rate was sensitive to the demands of flight but not diagnostic with regard to determining the cause of the workload. Heart rate increased during take off and landing and to an intermediate level during IFR segments. By showing sensitivity to only the visual demands of the various segments of flight, eye activity was more diagnostic. The theta band of the EEG demonstrated increased power during those flight segments which required in-flight mental calculations. The subjective measures showed trends suggesting different levels of mental demand but demonstrated few statistically significant differences. The conclusions of this study indicated that multiple measures, especially psychophysiological measures, may provide a comprehensive picture of the mental demands of flight. The measures used in this study

were shown to provide unique, non-overlapping information (4.2-4,4.2-5,4.2-6).
In another investigation, eight Air Force ATCs performed three scenarios on TRACON, a computer-based ATC simulation. Two scenarios were used each with three levels of difficulty. One scenario varied traffic volume by manipulating the number of aircraft to be handled and the second scenario varied traffic complexity by manipulating arriving to departing flight ratios, pilot skill and mixture of aircraft types. A third scenario, overload, required subjects to handle a larger number of aircraft in a limited amount of time. The effects of the manipulations on controller workload were assessed using performance, subjective (TLX), and physiological (EEG, eye blink, heart rate, respiration, saccade) measures. Significant main effects of difficulty level were found for TRACON performance, TLX, eye blink, respiration and EEG measures. Only the EEG was associated with main effects for the type of traffic. The results provide support for the differential sensitivity of a variety of workload measures in complex tasks, underscore the importance of traffic complexity in ATC workload, and support the utility of TRACON as a tool for studies of ATC workload (4.2-7).

4.3 INTEGRATION OF ADAPTIVE INTERFACE CONCEPTS

The Human Engineering Division of the USAF Armstrong Laboratory has been developing virtually-augmented crew station concepts for several years. The development of helmet-mounted displays in the mid-1960s was the genesis of the virtually-augmented concepts being developed within the US and in Europe today. Only recently did the use of additional virtual display and control devices necessitate the use of the term virtual-augmentation to represent combining conventional control and display devices with numerous virtual display and control devices. The evaluation of performance utilising non-adaptive virtual-augmented crew stations forms a performance baseline for assessing implications of adaptive interface technique utilisation.
Several studies have recently been conducted evaluating combinations of advanced head-down/head-up displays, helmet-mounted displays/trackers, 3-dimensional auditory displays, and haptic displays. In one of these studies, eighteen pilots from three NATO countries participated in simulated air combat scenarios in which they either flew a *conventional* cockpit consisting of standard F-15 types of cockpit displays, or a *virtually-augmented* cockpit consisting of a variety of novel visual and 3-D auditory displays. Pilots flew simulated air intercept missions versus two other pilots who operated adversary aircraft networked in the same virtual flight environment as the principal cockpit. A variety of pre-programmed aircraft models were also included in the scenario, including a patrol of four bombers and a *friendly* F-16 aircraft. The pilot flying the principal cockpit was instructed to try to shoot down all four bombers and return to a predefined safe air space without being shot down by the enemy aircraft protecting the bombers. The degree to which pilot performance was differentially affected by the *conventional* versus *virtually-augmented* cockpit manipulation was assessed using the following general classes of measures: pilot-aircraft system output, pilot workload, and pilot situation awareness measures. Results indicated a significant advantage for the virtually-augmented interface condition in the number of missions won, exchange ratio, mission length, and number of ground strikes. In addition, the performance improvements yielded by the virtually-augmented crew station were realized with enhanced situation awareness and a reduction in workload compared to the conventional crew station. Furthermore, post flight debrief questionnaires produced highly favorable subjective reports from pilots (4.3-1,4.3-2,4.2-3,4.3-3).
The US has recently competed initial development of an adaptive pilot/vehicle interface prototype that uses measures of pilot workload and computational situation assessment (SA) models to drive the content, format, and modality of a simple display. The overall system architecture consists of three distinct but tightly coupled modules:

A) an on-line **situation assessor** that generates a "picture" of the tactical situation facing the pilot, from which we determine the pilot's information needs for accurate SA;
B) a **pilot state estimator** (PSE) **module,** which uses physiological signals and other measures to generate an estimate of pilot workload; and
C) the **PVI adaptation module**, which uses the assessed situation to determine the pilot's tactically relevant information requirements, and the pilot state estimate to determine the most appropriate modality and format for conveying that information.

The situation assessor module was implemented using belief networks, for probabilistic reasoning in the presence of uncertainty. Event detection algorithms using fuzzy logic, which simultaneously allows quantification of events into a small set of tactically relevant levels (e.g., *short*, *medium*, and *long* range), while maintaining smooth network inputs and outputs were used to feed the belief networks with data from aircraft information systems. The pilot state estimator also used belief networks to fuse several signals relating to the pilot's mental state and thus, integrated physiological and performance-based measures of pilot workload. Like the situation assessor, the pilot state estimator produced quantified characterizations of workload (e.g., *low*, *medium*, *high*)using fuzzy logic to process input signals. A candidate *taxonomy of interface adaptation*, consisting of five levels of increasing adaptation was developed. This adaptive system is currently being evaluated within the Armstrong laboratory's Synthesized Immersion Research Environment facility.

5. SUMMARY

The overview of current trends in displays and control indicates that, to allow pilot to build correct situation awareness, progress must occur in both domains to match and fully exploit the growing informational capabilities of future systems. On the display side, visual presentation of information could be improved by more flexible displays, designed under guidelines including a comprehensive approach of operators' information needs. Alternative display technologies, such as 3D localized sound, should allow a better use of operators' multiple resources. Due to system complexity and the expressed need for real time command, manual control, especially HOTAS, is beginning to reach limits where its intrinsic advantage of reliability has to be weighted against training and human errors issues.
Alternative control technologies may provide a way to simplify manual control, while satisfying operators' need in real time commands.
If appropriately used, implementation of advanced concepts of control and information displays may somehow contribute to enhance pilot situational awareness. Besides displays and control technology, this would require a thorough understanding of operators' information needs and careful management of sensorimotor and cognitive resources. To achieve this goal, it is crucial to promote a strong Human-Centered approach, supported, but not driven by, technological evolution. This applies to any operational context, conventional or non conventional cockpit, UCAV crew station etc.
It has to be clearly understood by all that communication improvement at the Man-Machine interface level will be really efficient only if identical efforts are conducted on the system side. Systems should <u>also</u> be carefully designed to match the resources and capabilities of operators (2), which may give us the best chance to globally achieve an optimal cost-effectiveness ratio.
The performance enhancements seen in flight simulation resulting from integrated combinations of flexible control and display devices indicate promise for transition in the future. Prototypes of adaptive interfaces have proven their feasibility but many aspects of this interface type are still technically immature. As an example, much research is needed to ascertain the relationships between adaptation technique and performance effects. The criterion upon which adaptation is based is still an area of research (5-1). However, adaptive interfaces hold the promise of providing a more intuitive link between humans and advanced systems and could have considerable use outside of military applications. The development and evaluation of adaptive interface concepts are planned to continue as collaborative efforts between the Research Laboratory scientists and engineers from the NATO countries. However, to fully capitalize on the research and development currently underway in NATO in this area, and to increase the transition of adaptive interface technology from the laboratory to the operational arena, additional collaboration must occur.

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TRENDS IN FUTURE COMBAT AIRCRAFT DEVELOPMENT

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1. INTRODUCTION

The United States Air Force is currently going through a planning process to structure itself for the 21st Century. There have been several studies on this subject such as " Joint Vision 2010" that discuss mission requirements and the Air Force Scientific Advisory Board's " New World Vistas" that discuss relevant technology issues for the future. Figure 1 shows the six core competencies that the Air Force will maintain into the 21st Century. These core competencies will focus the Air Force mission areas and shorten the lines of communication between the user and the acquisition/ research community through a new concept for the Air Force called Battle Labs. Purpose of the Battle Labs is to provide for the rapid assessment of technology on operational requirements under realistic conditions. This paper provides an update to these initiatives and provides the reader with an overview of the current Air Force Modernization Planning Process (AFMPP) and how it is effecting the Air Force Science and Technology Plans into the next millennium. This paper highlights several technology thrusts that will have an impact on air operations in the next Century.

2. PLANNING PROCESS

The Air Force Modernization Plan uses a strategy to task process to define operational requirements. These requirements are then matched against current and future aerospace systems to determine if current systems need to be modified and/or new systems need to be developed. Integral to this process is the simulated introduction of technology into current and future systems and the impact of this new technology on solving operational requirements and /or offering the potential for new capabilities. Although it was always considered in the development of a system, total life cycle costs are now the dominant consideration in the fielding and modernization of systems. It is anticipated that affordability and cost as an independent variable will be discussed in papers the Joint Strike Fighter and Uninhabited Combat Aircraft, so it's impact on systems development programs will not be discussed in this paper. However, the question of affordability is also dominating the science and technology planning process now. Performance is still a major factor but the thrust of technology today is to lower life cycle cost while maintaining performance.

Paper presented at the AGARD Symposium on "Future Aerospace Technology in the Service of the Alliance", held at the Ecole Polytechnique, Palaiseau, France, 14-17 April 1997, and published in CP-600 Vol. 1.

With defense budgets being reduced, the application of technology to reduce life cycle costs will be the force multiplier in the next millennium.

3. IMPACT OF ADVANCED TECHNOLOGY

The results of the planning process are succinctly summarized in figures 2 - 4. It is easily visualized that most of the systems available through 2010 are already built or in advanced stages of development. The major change in force structure will be in the area of unmanned air vehicles. After 2010, it is recognized that new systems will be required because of the age of the current force, ability to supply parts to obsolete subsystems and the availability of new technology to potential adversary. Although some systems will still be in use through the 2021 time frame, they will be required to be modified with new technology. These requirements will have to be satisfied with a defense budget that is still projected to decrease in buying power over the same time period. Again, the theme of maintaining force structure while budgets decrease emphasizes the importance of maintaining Science and Technology Budgets in order to reduce the Life Cycle Costs of current and future systems. The following paragraphs provide an overview of the potential that technology has to reduce life cycle costs. The results are articulated in operational terms with only broad reference to the required technologies. Figure 5 shows the Wright Laboratory vision. Because of paper and presentation limits, this paper will only discuss a few of these areas. The areas selected are based not on any priority but on a presumption that they will not be discussed by someone else in this conference. As shown in previous figures, the current force structure will be active well into the next century. This has caused the technology community to look at the problems associated with an aging force structure. An example of technologies addressing this problem are advances in inspection methods and advanced wear monitoring sensors that will allow the maintenance concept to transition from a periodic/ time based system to a condition based maintenance. Potential payoffs are 50% reduction in aircraft maintenance hours and 35% reduction in spare parts inventories. Figure 6 contains three integrated technology efforts that will be discussed in more detail.

IHPTET

The long range goals of the Integrated High Performance Turbine Engine Technology program (IHPTET) are shown in figure 7. This program is a joint DoD/NASA/Industry effort focused on developing turbine engine technologies for more affordable, more durable, higher performance military propulsion systems. Historically the propulsion system is 40-60% of aircraft takeoff weight and 20-40% of acquisition and operating costs so any changes in engine characteristics has a significant effect on Life Cycle Costs.

The following systems examples will illustrate the impact of these goals. An Air Launch Cruise Missile (ALCM) sized missile will have intercontinental range. Tactical missiles will have a five-fold increase in speed. 100% increase in range/ payload is achievable for the same sized vehicle. 35% reduction in weight and production costs for a new fighter are possible.

IHPTET TECHNOLOGIES

Super cooled turbine blade designs will permit 300 degree higher gas temperatures for increased thrust, or a 30% reduction in cooling air for reduced fuel consumption, or a 2 - 4 fold increase in turbine blade life while still reducing manufacturing costs. This capability coupled with a variable cycle engine concept would have significant impact on engine life and durability.
The variable cycle engine eliminates the augmentor with it's high maintenance, fuel usage, and high signature plus the variable geometry exhaust nozzle with it's high weight, complexity, and cost. A major change in engine accessories and power takeoff drives will be possible with the incorporation of integrated subsystems and distributed control systems. This will dramatically improve the reliability and maintainability of the engines.

Reduced engine and aircraft fuel systems fouling and coking will be realized with the increased use of JP-8+100. To date, the limited use of JP-8+100 increased the time between fuel related augmentor anomalies by 340%, reduced fuel control change outs by 80%, and reduced fuel systems maintenance by 70% per flight hour. Additional performance data is being gathered so that this fuel can be used by all forces.

FIXED WING VEHICLE PROGRAM

REDUCING DESIGN/ DEVELOPMENT COSTS

Figure 8 is a sketch of a Fighter Class Technology Demonstrator. Purpose of the program is to address the costs associated with the design and development of a new airframe. Specific goals have been developed for several classes of air platforms and these are summarized in figure 9. In order to attain these goals, several technology advances are required. The first issue is the development and calibration of design tools that accomplish a totally integrated design on the first pass with life cycle cost as a design variable. This will significantly reduce the design time and provide the capability to reduce first production article cost. Embedded in this process is a design to cost capability that lets the user make meaningful requirements trades early in the design process in order to see what impacts this makes on total life cycle costs.

Major efforts are ongoing to address the issue of producability. The Lean Aircraft Initiative has been well publicized. Coupled with that program is a Composite Affordability Initiative that addresses the fabrication and processing costs associated with today's use of high strength composites. An example is the development of fabrication and processes for thermoset composites using fiber and tow placement to effect a 30% cost savings on an F-22 wing control surface.

TECHNOLOGY FOR CURRENT FORCE

There is a major effort to reduce the cost of ownership for current systems. The effort is to use technology to replace unreliable / high maintenance parts with new parts of same fit and function but with increased reliability. A few examples will make the point. The Extended Life Tire program's objective is to demonstrate a 175% increase in tire life over the current F-16 tire life. This has a profound effect on the quantity of tires needed to support a deployment. The environment in Desert Storm accentuated the problems associated with canopies and lenses covering seekers. Programs are in place that will reduce the O&M costs in transparencies by 50%.
There are several cockpit integrated display programs that will demonstrate a 30-100 fold increase in mean-time-between failure (MTBF).

SURVIVABILITY

Discussion in this area will have to be at the broad overview level for security reasons. Goals in this area are as follows: approximately a 30 - 45% reduction in IR signature; approximately 30 - 40% reduction in RF signature. Programs addressing these issues are the Advanced LO Air Data system, Advanced Compact Inlet, and Aeroelastic Wing.

CONVENTIONAL MUNITIONS

SMALL SMART BOMB

Figure 10 shows a physical comparison between models of a and a small smart bomb integrating concept called Miniaturized Munition Technology Demonstration (MMTD). The objective of the program is to demonstrate that a 250 lb. class munition is as effective against a majority of hardened targets previously vulnerable to only 2,000 lb. class munitions. The weapon is only six feet long and six inches in diameter.

The operational impact of this technology is enormous. With autonomous guidance and independent targeting capability, the number of targets killed by a single fighter or bomber can be tripled or even quadrupled. Besides the increased sortie effectiveness and kills per pass, the smaller volume and weight of 250 lb. munitions means that 3 to 4 times as many bombs can be transported per airlift sortie, thereby significantly reducing the logistics tail. Concern about collateral damage continues to impact operational requirements and this smaller bomb with increased accuracy and lower explosive yield will reduced the potential for this damage.

LOCAAS

Figure 11 is an artist concept of the Low Cost Autonomous Attack System (LOCAAS). The weapon uses a state of the art seeker and an advanced technology warhead that has three different kill modes. The capability of the laser detection and ranging seeker (LADAR) including accuracy, autonomous operation and the ability to acquire, identify and track targets will significantly increase sortie effectiveness. A fighter armed with 24 LOCAAS units will have the same effect as 12 fighters armed with 2 Maverichs each.

The warhead is called a selectable multi-mode warhead (figure 12). The three different kill modes are achieved by selectively detonating high explosives behind a copper plate. In one mode, the explosive forms the copper plate into a long arrow shaped rod. The second mode forms the plate into a shape that looks like a badminton shuttlecock. The third mode is a multiple fragment mode.

DUAL RANGE MISSILE

The Dual Range Missile (figure 13) is a good example of the results of the Air Force Modernization Planning Process as described earlier in this paper. This air-to-air concept was developed to satisfy the requirements from this planning process and the visions expressed in New World Vistas. The technology incorporated into this concept emphasizes several core weapons performance attributes: increased no escape zone; increased average velocity; and increased multi-target/ multi-mission capability.

Figure 14 is depiction of the operational concept and some of the required technologies. The main technologies that have to be demonstrated on the missile are: a hybrid tailfin/ reaction jet flight control system that will increase maneuverability and reduce overall missile's drag; and a conformal array seeker that will provide near full spherical within visual range target acquisition with virtually unlimited target track rate. The missile concept capabilities coupled with a Helmet Mounted Display, all aspect fire control technologies, enhanced situational awareness, and a high off boresight look and shoot capability will provide an increased no escape zone.

THE FUTURE

Future technology efforts will be defined within a systems of systems concept of technology development. System and corresponding technology requirements will be defined using advances in simulation capability balanced by selective ground and flight demonstrations. The end goal will be the capability to define, design, fabricate and test a new vehicle via simulation with a direct transfer to a manufacturing capability. End result will be an affordable system that can be produced in low volume to satisfy changing operational needs while negating parts obsolescence. This will significantly reduce the total time required to field a new system

The following two examples illustrate the potential for the future and the opportunity to make a real paradigm shift in the way we design, fabricate, maintain, and operate future systems.

UNINHABITED AERIAL VEHICLES

Figure 15 is a pictorial of where the future of unhabited vehicles may lead us. A later paper will describe the planned program for unhabited vehicles within the Wright Laboratory. The point to be made in this paper is that this class of vehicles allows us unprecedented opportunity to try new processes and practices because the requirement for man rated systems is not there. In addition, new technologies will now allow us to start thinking of using this type of system where human presence is now required for either mission or political reasons. Figure 16 highlights the technology areas that will require further development in order to reach the vision of a UCAV as shown in the previous figure.

MANUFACTURING TECHNOLOGIES

Figure 17 shows three major technology programs that are supporting the Joint Strike Fighter (JFS) Program. The JSF Manufacturing Demonstration (JMD) will provide an integrated manufacturing design and cost data base wherein the cost implications of a particular design trades can be assessed. The Manufacturing Capability Assessment and Toolset (JMCATS) will define the required manufacturing capability early in the design process. The Simulation Assessment Validation Environment (SAVE) Program ties it altogether by providing the overarching computer architecture to enable all of these programs and also current design and manufacturing programs like CAD/CATIA to work together to provide a total design solution on the first pass. Of particular note is that vendors of commercial design software have agreed to use this architecture, once proven as their communication link with other commercial software similar to the way WINDOWS software is the communication link with other software programs. It is planned that this software will be licensed for commercial use. These processes will significantly reduce the total life cycle cost of a new system. Figure 18 shows some of the interim validation milestones that will be used to benchmark this effort. Figure 19 is the goal and the future.

SUMMARY

This paper has described the Air Force Planning Process. How this process effects the Science and Technology Planning Process and the future capability that will be available to the operators. It highlighted the fact that all technology planning and insertion will be judged by the affordability issues it either raises or solves. Last but not least, it gives hope that Augistine's principle, that if aircraft costs keep growing at their historical rate, a nation will only be able to afford one aircraft and it's pilots will have to take turns flying it, will not be true in the next millennium.

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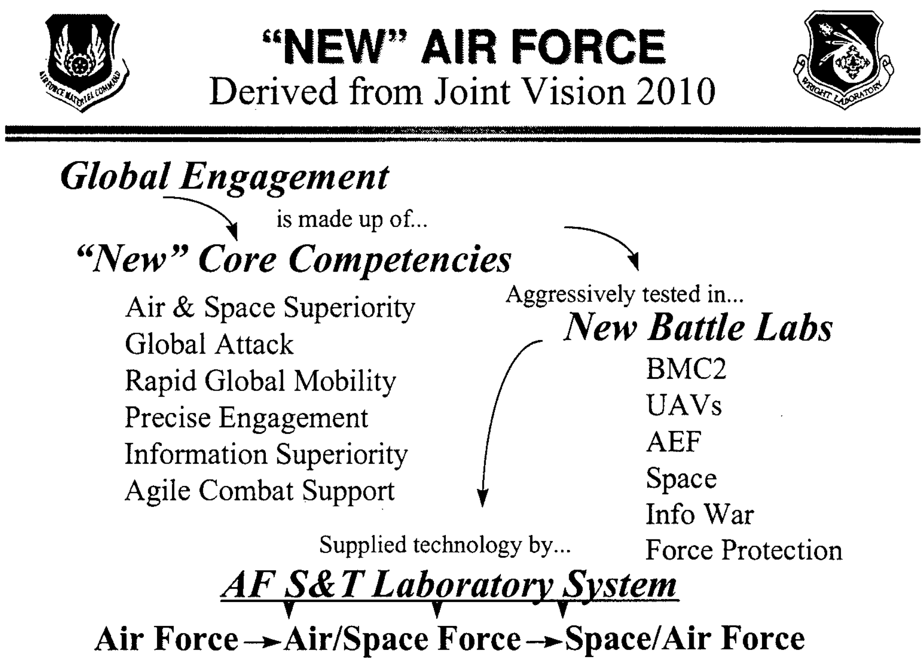

Figure 1. Air Force Core Competencies

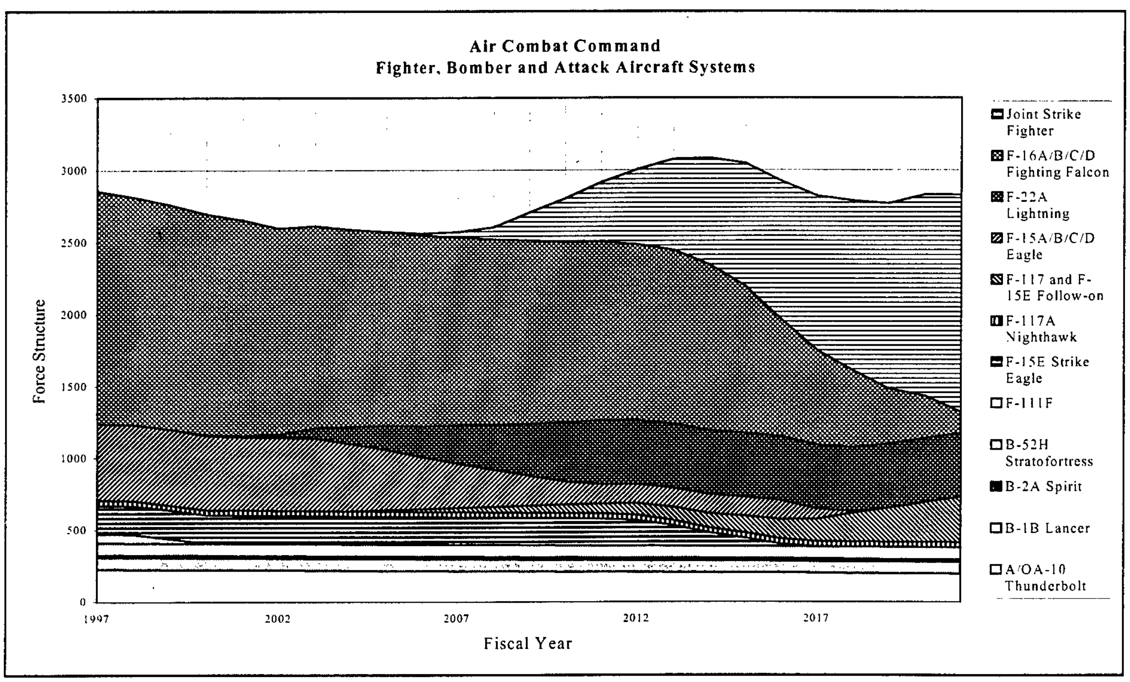

Figure 2. Air Combat Command

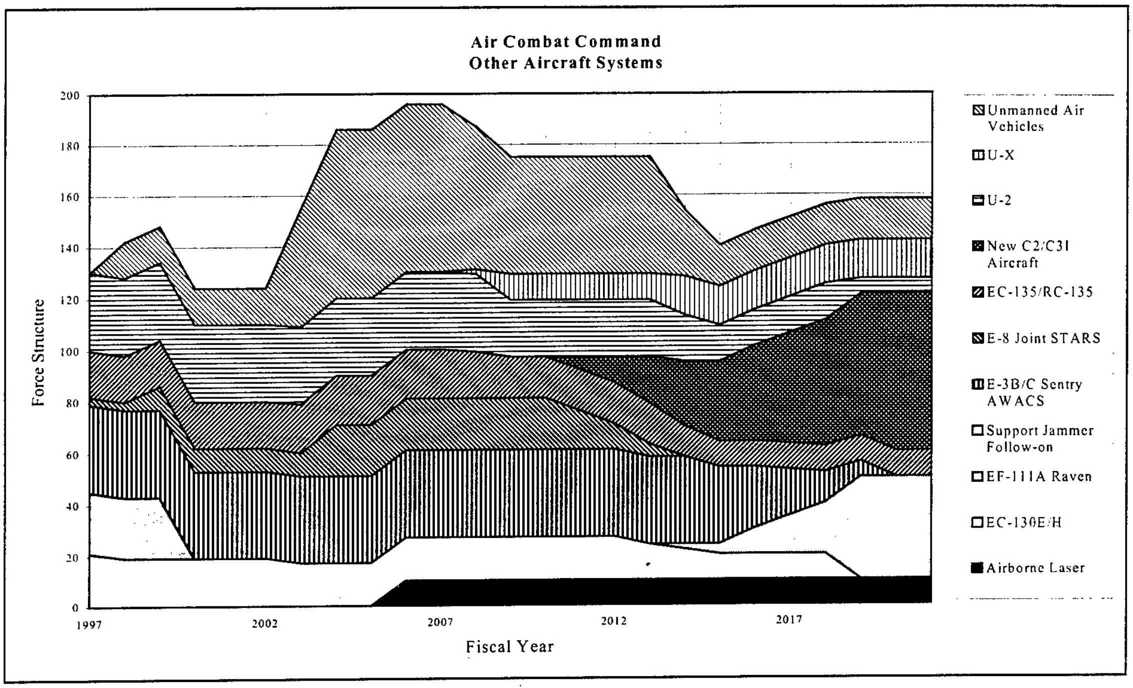

Figure 3. Air Combat Command - Other Aircraft Systems

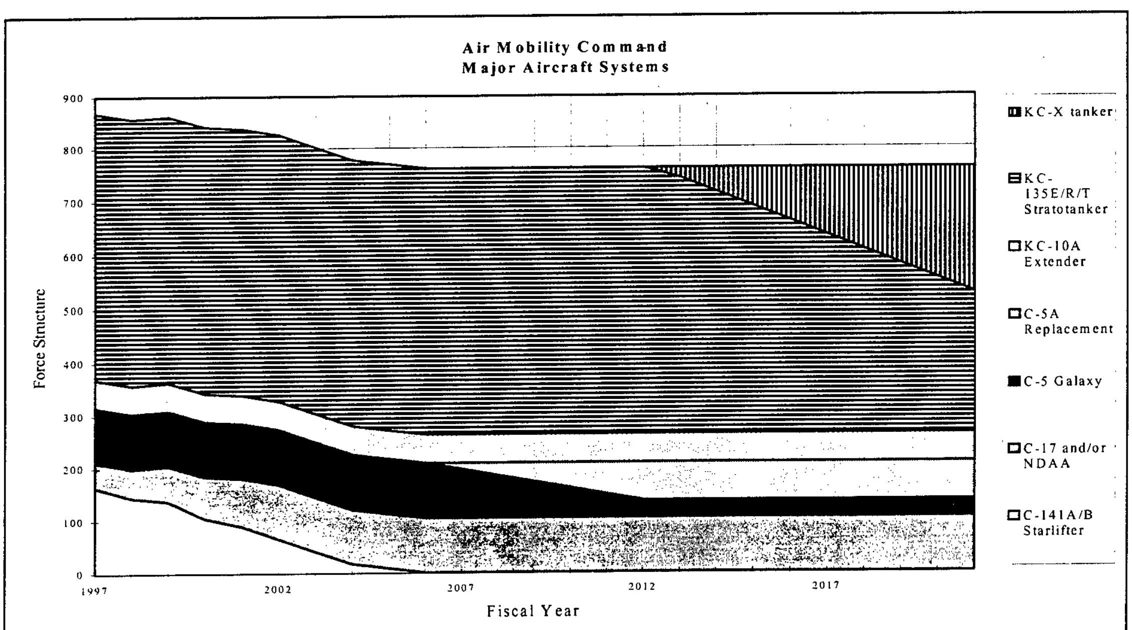

Figure 4. Air Mobility Command

Vision

Recommendations on how to focus WL's Vision

- 50% reduction in systems and operational costs and product realization time
  - Affordability Initiative
  - Modeling and Simulation
  - Standards and Data Exchange Format
- Double Life Expectancy of Our Systems (B-52 is Paragon)
  - Life Extension Initiative
- Pre-eminent New Capabilities that Deter/Destroy our Adversaries
  - Global Mobility
  - New World Vistas
  - Integration of Air/Space
  - Classified Programs
  - "Wildcatting"

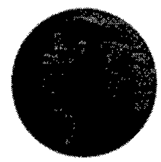

Figure 5. Long Range Goals

Integrated Technology Investment

EFFORT	AF FUNDING (FY97-02)	PAYOFF
IHPTET Turbofan/Turbojet Turboshaft/Turboprop Expendables	$680M	+100% T/W -35% Production Cost -35% Maintenance Cost
FIXED WING VEHICLE PROGRAM Fighter/Attack Aircraft Airlift/Patrol/Bomber Special Operations	$560M	Future A/C Tech Enhancements - Affordability - Survivability - Speed/Range :
CONVENTIONAL MUNITIONS INTEGRATING CONCEPT Small Smart Bomb Dual Range Missile AntiMaterial Munition Smart-Hard Target Munition Smart Soft Target Munition	$420M	Future Munition Enhancements - Increased Standoff Range - Improved Terminal Accuracy - All-Weather - Enhanced Penetration Capable :

Figure 6. Integrated Technology Investment

IHPTET GOALS

TURBOFAN / TURBOJET
- + 100% Thrust/Weight
- - 40% Fuel Burn
- - 35% Production Cost
- - 35% Maintenance Cost

TURBOSHAFT / TURBOPROP
- + 120% Power/Weight
- - 40% SFC
- - 35% Production Cost
- - 35% Maintenance Cost

EXPENDABLES (UAVS)
- + 100% Thrust/Airflow
- - 40% SFC
- - 60% Cost

Figure 7. IHPTET Goals

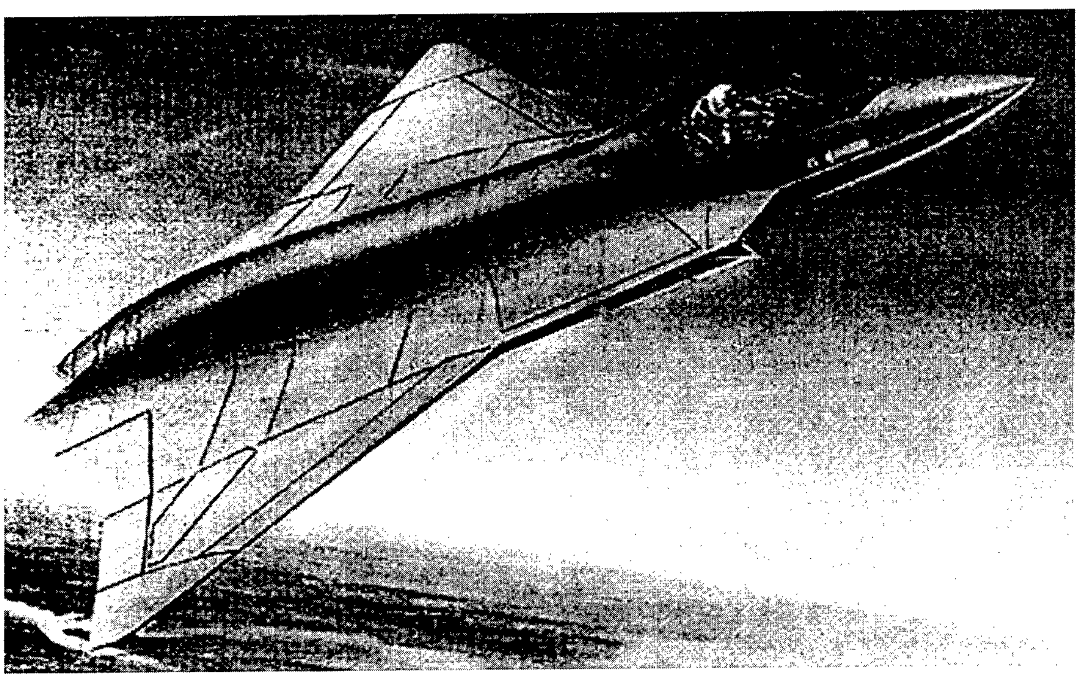

Figure 8. Fighter Aircraft Technology Demonstrator

Design / Development Cost Goals

30% Reduction in Cost of First Production Article

30-35% Reduction in Support Costs

40-50% Increase in Reliability

15% Reduced Support Volume

Figure 9. Design / Development Goals

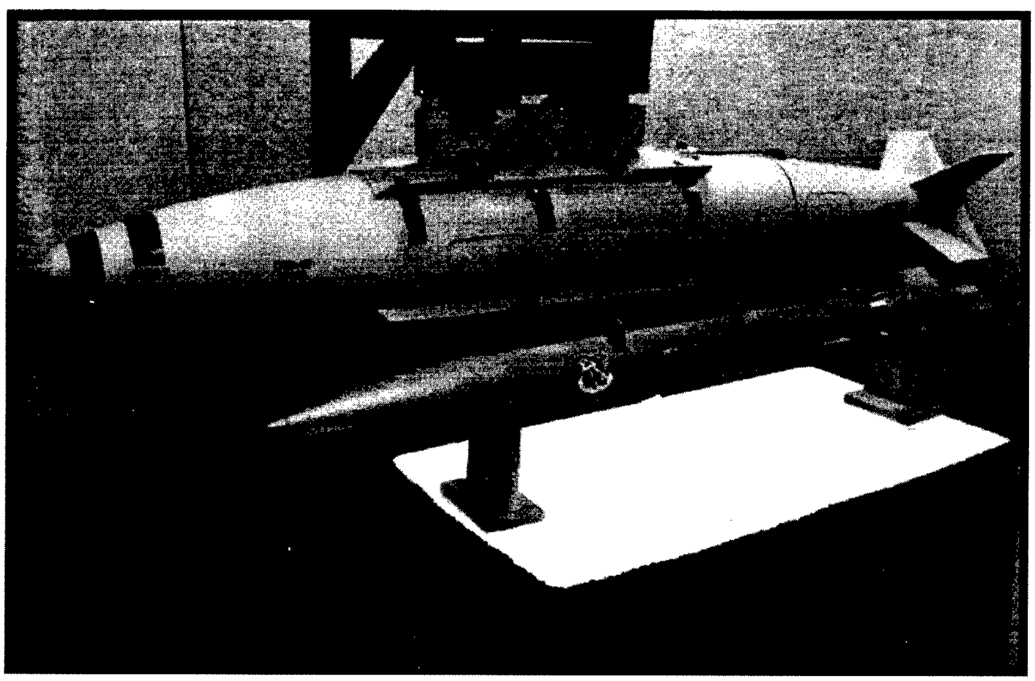

Figure 10. Small Smart Bomb

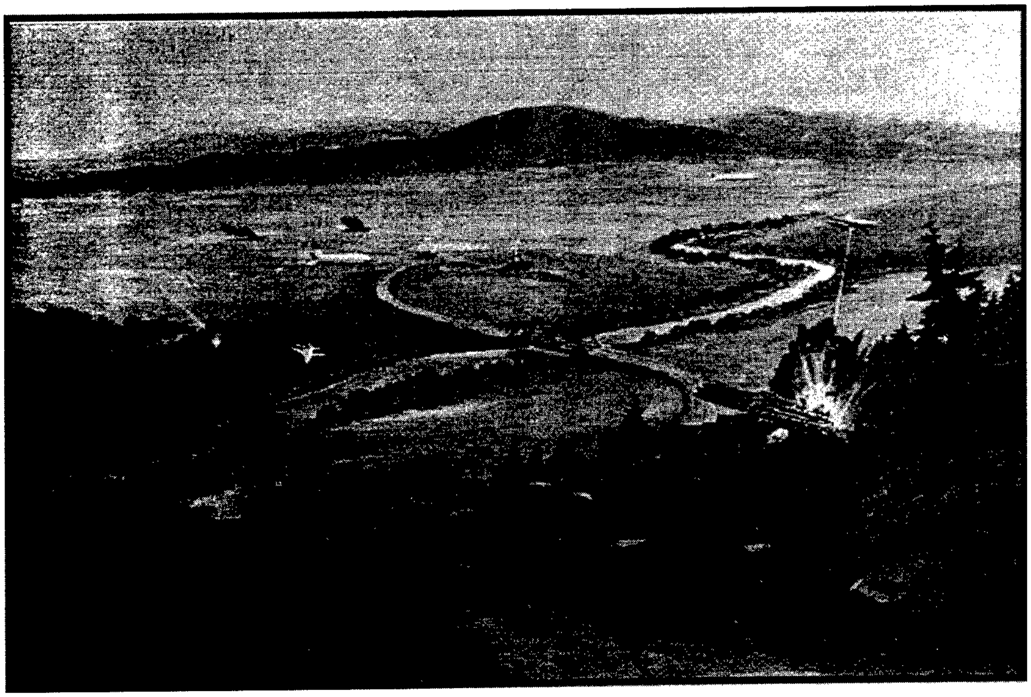

Figure 11. LOCASS in Futuristic Battlefield

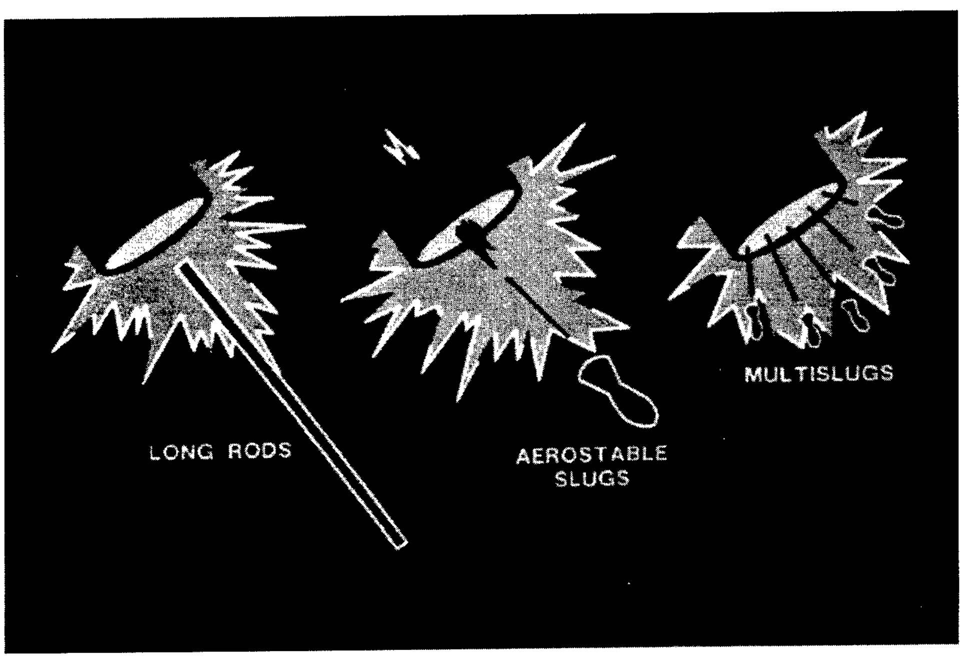

Figure 12. Three Modes of Anti-Armor MultiModal Warhead

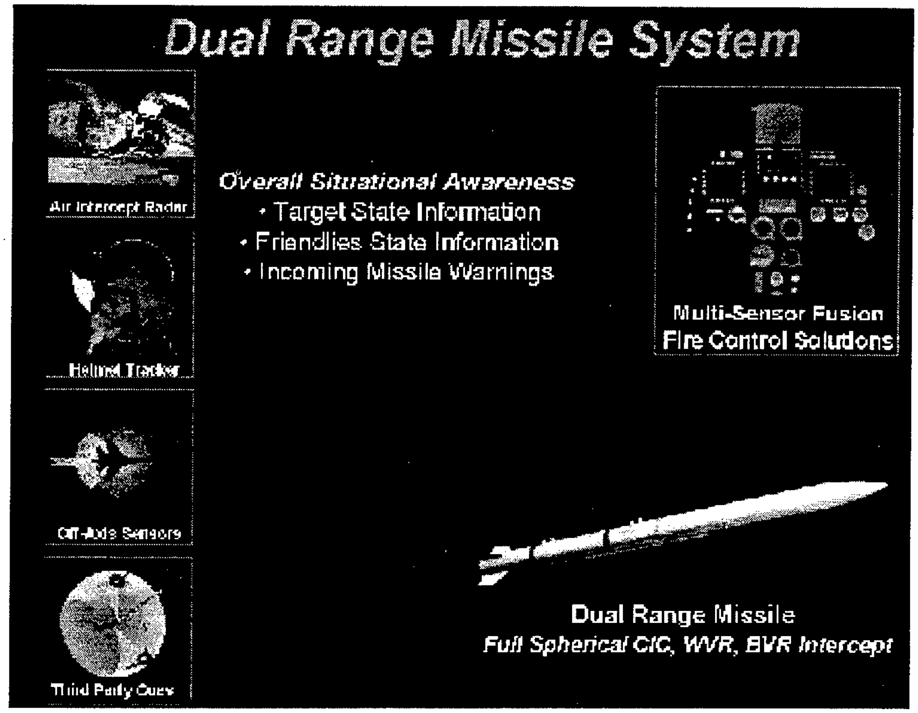

Figure 13. Dual Range Missile System

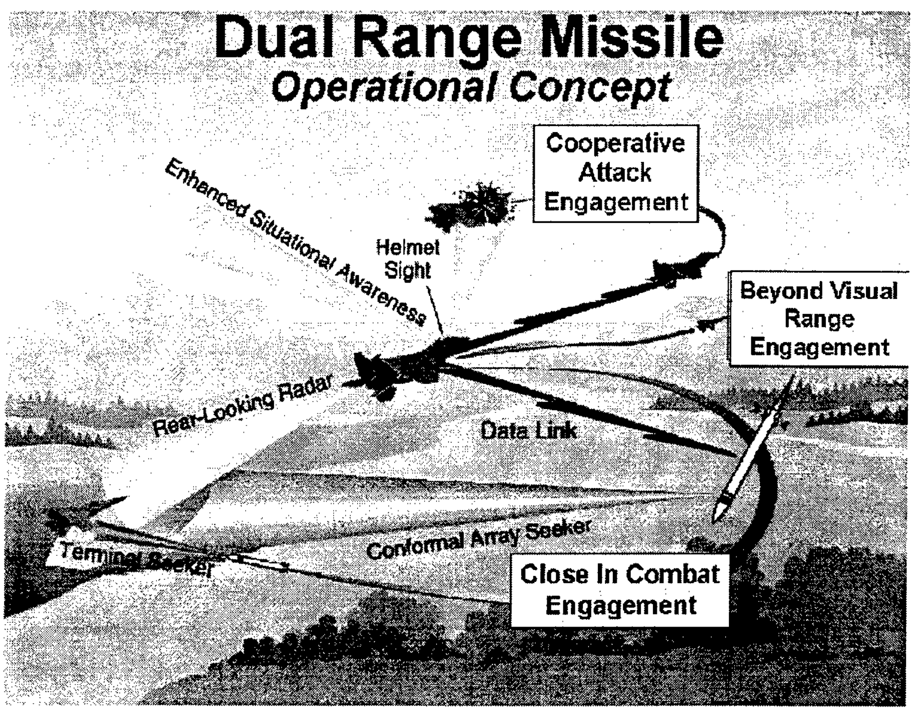

Figure 14. Dual Range Missile Operational Concept

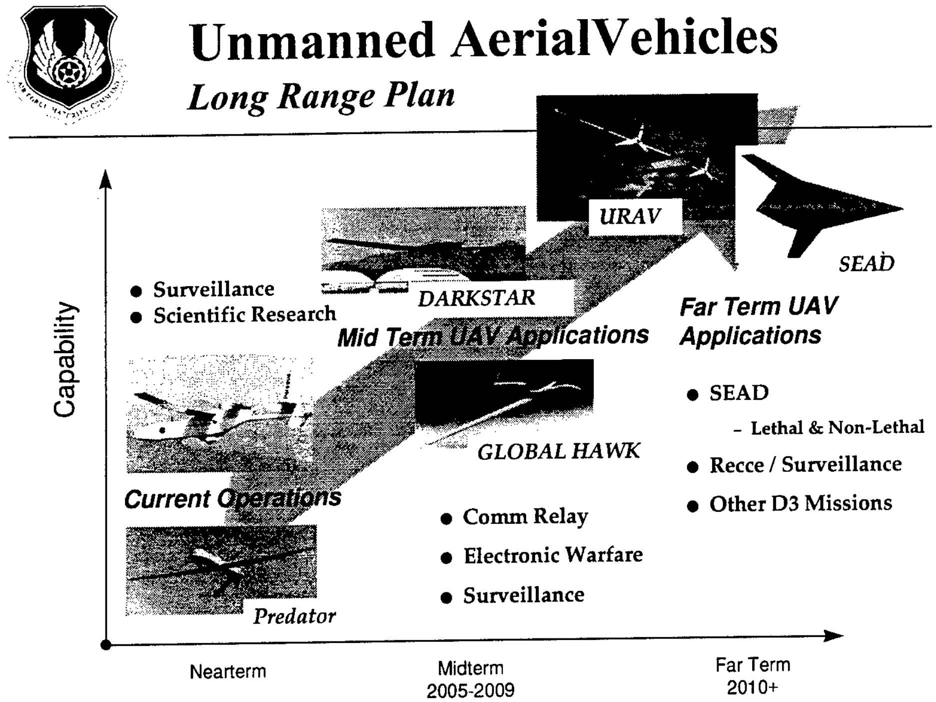

Figure 15. Unmanned Aerial Vehicles

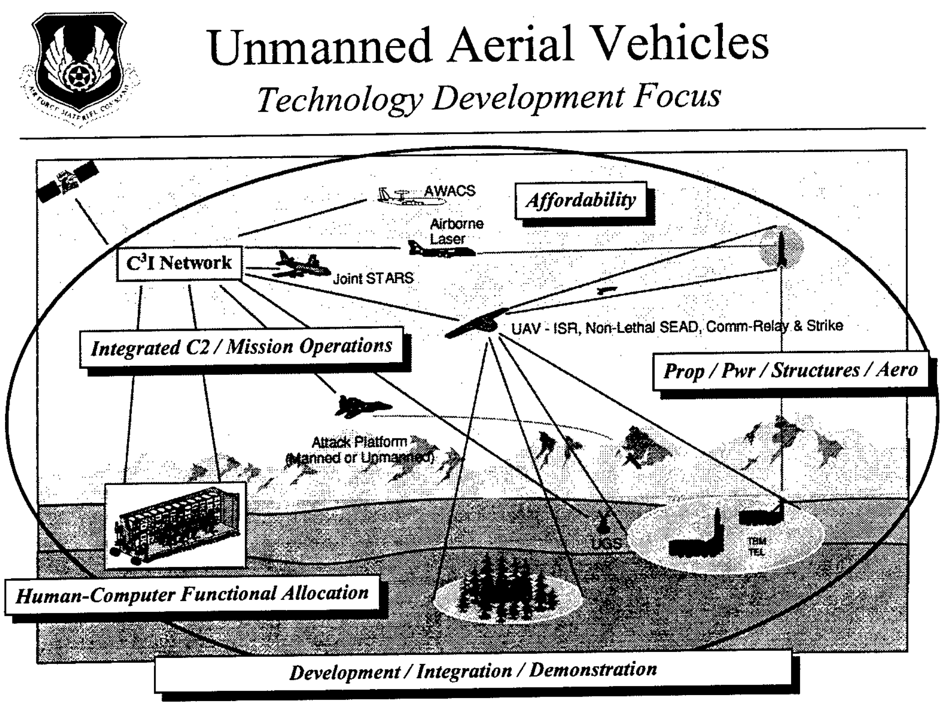

Figure 16. Emphasis Area Development

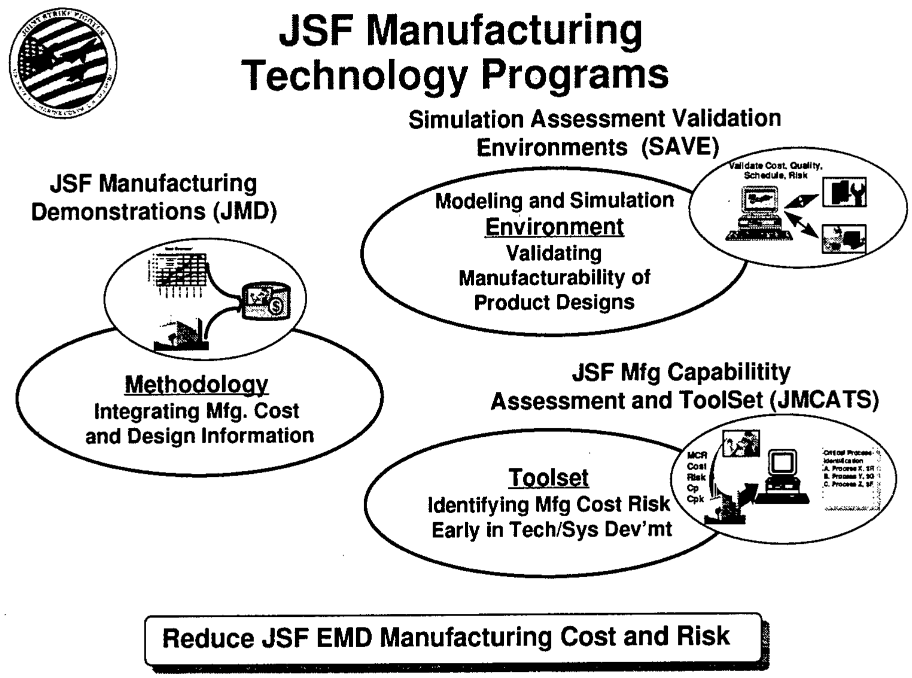

Figure 17. JSF Manufacturing Technology Programs

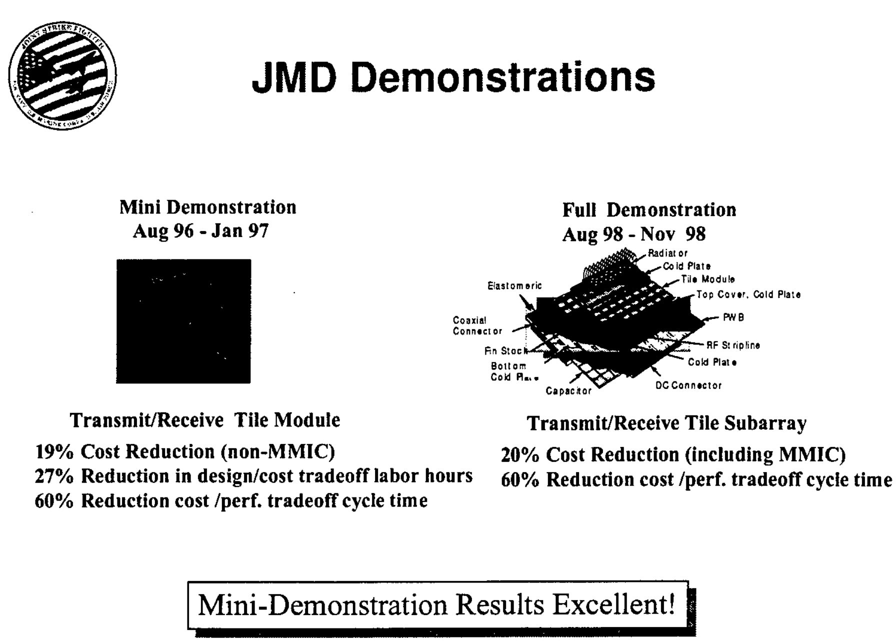

Figure 18. JMD Mid-Term Demonstrations

Figure 19. The Future - Virtual Design, Test, and Manufacturing

Future Combat Aircraft Development in Europe

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Abstract

Within the last decade three new combat aircraft have been developed in parallel in Europe: The Eurofighter, the Rafale and the Gripen. This happened probably for the last time.

New scenarios and missions, but in particular reduced defence budgets, the growing integration into a European Union and strong competition on the European and world market, -in particular from the US and Russia-, will eventually force

- European nations to formulate common requirements,
- the national Governments to coordinate their research and development efforts
- the airforces to coordinate their training, operation and maintenance activities and
- the national industries to form a common European military aircraft company

if a truly competitive militarry aircraft development and production capability in Europe is to be maintained.

It will be a long and stony way before a new European combat aircraft will take off in the time period beyond 2015. National and international technology programs as well as technology demonstrator aircraft will have to pave the way.

Breakthroughs in various technologies require a broad conceptual approach considering new systems such as unmanned /manned aircraft, air and spaceborne vehicles as well as highly integrated information, communication and survaillance systems.

This paper dicusses general aspects which are considered to be a prerequisite for the next generation combat aircraft in Europe and some important technologies which are a key for the development of these aircraft.

1. The Challenge

Cooperation in military aircraft development has quite a history in Europe **(Fig.1-1):**

- Germany and Italy jointly developed the VTOL aircraft VAK 191 in the early Sixties. The program got into flight test, but never entered production.
- France and the UK jointly developed the SEPECAT Jaguar in the Seventies.
- France and Germany jointly developed and produced the Alpha Jet trainer and light attack aircraft starting in the mid seventies
- Germany, Italy and the UK made the first step towards a bigger alliance with the joint development and production of the Tornado in the early Seventies
- The next step in this chain was the development of the Eurofighter started in the mid Eighties. Inititially the consortium was to be expanded to also include both Spain and France. However, after a year of negotiations and studies France opted for the national development of the Rafale.

The inventories of the six western European nations, which have an own aircraft development capability, have been reduced by about one third during the last 25 years **(Fig.1-2)** to a total number of 2450 combat aircraft. This number is only slightly smaller than the USAF inventory of 2800 aircraft. The current national inventories range from 162 (Spain) to 520 (France). The replacement market of these countries(about 50% of the inventory) has a very attractive size if the nations and the industries pool their resources. However, it is also evident, that no single nation has a national market size big enough to justify a cost effective development and production of a new combat aircraft by its own.

The current geopolitical and military situation is characterized by the political development following the fall of the iron curtain resulting in a considerable reduction of high intensity threat in middle Europe. Shrinking defense budgets are the consequence inspite of increasing political, ethnical and economical instabilities on Europes flanks and worldwide.

Paper presented at the AGARD Symposium on "Future Aerospace Technology in the Service of the Alliance", held at the Ecole Polytechnique, Palaiseau, France, 14-17 April 1997, and published in CP-600 Vol. 1.

Therefore there is no other way, -if a European military aircraft development and production capability is to be maintained-, but to pool the resources.

What are the hurdles? They are political-, military-, economical- and industrial ones. They result from different geographical locations, different national policies, intentions and needs with respect to global involvement of national forces, different statii with respect to membership in European or transatlantic organizations, different ideas and budgetary plans for supporting the high-tech military industry, and, at least currently, a different status in the concentration of national industrial capabilities and resources.

Quite often these conflicting national elements have their origins more in traditions and political /emotional and momentary attitudes than profound reflections. They may cloud the way to the neccessary future compromise.

Nevertheless, all of the above mentioned factors will need to be considered by the European Governments, the airforces and the industries to find a way for the formation of a „common" European military aircraft company. This company will have to develop the next generation combat aircraft/weapon system to satisfy European and export requirements at affordable costs.

It is evident that the need for consolidation within the next ten years is a heavy burden in addition to the normal challenge to develop the right requirements, the right technologies and the right technical solution in time for a next generation weapon system envisaged for the time period beyond 2015.

However, Europe must react upon the mergers within the defence industry of the United States of America resulting in few very strong industrial entities.

National pride and interests, technical dreams, stubborn fights for the own technical concept will have to give way to a more rational approach and a sense for true compromise for developing a European military industry serving the needs of the European Airforce(s).

2. Military Cooperation, Joint Requirements

2.1 Political/Military Background

Defense cooperation in Europe has achieved already a remarkable level: The Eurocorps is the first large multinational unit formed from Belgian, French and German army units. The multinational corps's staff reportedly works exceptionally well.

Long term military cooperation between the European Air Forces is still in its infancies. National interests and incompatibilities still dominate the development of national requirements. The airforces operate separately from each other, primarily due to the different aircraft types and equipment, education and training and last not least tradition.

There is a joint French/UK Airforce operational planing group located in High Wycombe, UK. Finally, there is a nucleus of a European Procurement agency, „OCCAR" formed by France, Germany, Italy and the UK in 1996.

However, there are (too) many organisations in Europe, which have (too little) input/influence on future military aircraft development **(Fig.2-1)**. They are either national or reflect the membership to a particular international organization, like EU, WEU, WEAG, NATO. Most of them have evolved during the last 35 years and do not yet reflect the European needs for the next century.

NATO has taken another step by forming the new Research and Technology Organization (RTO) absorbing AGARD and the RDA. The WEU will have to follow quickly to establish/maintain its role as a player in the political-, military-, economical field in the next century.

However, there is not yet a European organization responsible for a joint defence policy, and the associated forces. Therefore task definitions and capability requirements for a „European Airforce" are still missing.

2.2 Requirements

Multinational development programs are characterized by a lengthy and exhausting struggle for a set of joint/compromised requirements satisfying every participant.

It took almost ten years to melt four national requirments into a common requirement for the Eurofighter, currently developed for the airforces of Germany, Great Britain, Italy and Spain. The aircraft will be operational in 2001 and is expected to be in service for 30 to 40 years.

The Eurofighter has been developed as a multirole aircraft with Air Superiority as the primary mission. Since three of the nations participating in the EF development (exception is Spain) have already been members of the tri-national Tornado aircraft program preceding Eurofighter, the next weapon system is most likely dominated by a multirole / air to ground requirement.

Current inventory planning based on aircraft utilization calls for a replacement of the Tornado's / Mirage's / Jaguar's in the time frame beyond 2015 **(Fig. 2-2)**.

Studies of future scenarios and their potential impact on national forces are ongoing in a number of European nations (e.g. Streitkräfteeinsatz 2020 of the German MOD).

Great Britain has defined an initial requirement for a new system to replace Tornado (Air Staff Target 425). Other nations are still more orientated towards technology development for future systems and potential upgrades of their current systems.

However, certain trends can be observed within European nations with varying emphasis on the realisation due to technical and financial constraints. The most obvious requirements, - not neccessarily in a priority order -, are

- out of area capability,
- high mobility of forces
- in-flight refueling capability
- improved reconnaissance systems
- improved integration of recconaissance, surveillance, control and weapon systems

- improved interoperability, in particular with the US
- long range missions capability and precision stand off weapons
- smart munitions
- increased flexibility of weapon systems to cope efficiently with low and high intensity threats.
- precision navigation/strike capability
- all weather/night capability
- autonomous operation

Assuming at least a timespan of 10 years before a final set of requirements will be agreed upon for the next European air system, any current requirement will see considerable change based on the results of operational studies and analysis still to be performed. However, it is not to early to start investigating a broad range of scenarios, missions and potential technical solutions. The solution(s) will be driven by operational requirements as much as by affordability. New technologies will be developed and applied to improve costeffectiveness and flexibility.

In addition to the European countries with national aircraft development capabilities, there is the group of western European nations, flying primarily US aircraft: Belgium, Denmark, Netherlands, Norway, Portugal fly F-16, Switzerland F-5 and F-18, Spain F-18 and AV-8B **(Fig.2-3).**

The fight for upgrades/replacements on this market will intensify in the next ten years. European countries and industries will have to make strong efforts to maintain competitiveness compared to the „blue threat".

There is also the group of formerly eastern block nations which are eager to join NATO and/or modernise their inventory with western equipment (Finnland, Hungary, Poland, Romania, Tschechien etc). The political and industrial competition for this market is already in full swing (in particular from the US side), though the financial resources of these countries are incompatible with their requirements. This is probably a near term market (for a small number) of aircraft provided from the current inventories of western airforces.

One aspect which has received a lot of attention in recent years in the USA has not yet found its way accross the Atlantic: The requirement of global presence in a very short time, which,-if realised-, would lead to the evolution -similar to the US Air-Force- to an Air- and Space Force. This concept will have to be dealt with at a later point in time. The question „Will Europe remain/become engaged in global affairs like the US?" has still to be answered. However, initial steps are visible by the French/German agreement to develop military reconnaissance satelites. European hypersonic research and technology demonstration programs as a basis for high speed weapons, reconnaissance vehicles and reusable aerospace transportation systems are an indication, that these options are kept open.

3. Research and Development Activities

Aerospace research and development activities in Europe are characterised by funding of national programs and normally not very well coordinated with other European Nations. Most of the time they are directed at similar technological goals. National resources do not allow to keep up with the US pace in all fields. Technological breakthroughs are achieved in many areas or specific products (e.g. HMD's, ejection seats, optical sensors, electronic equipment). However, the commercial success/break-throughs on the international market are even harder to achieve because of the small quantities of the home market.

Typical data for R&D expenditure for the European Nations (including military aircraft, missiles, space, engines and equipment) are shown in **Fig.3-1.** shows The message is clear: relative to the USA the European figures on a national basis are very small. Only if the total money available in Europe will be spent in a coordinated way avoiding parallel funding of the same topics can Europe stay competetive in the aerospace field.

Progress has been made in various areas: For example German and Dutch windtunnels (subsonic, transsonic, cryogenic) are now run by a binational organization (DNW), and a number of national tunnels have been shut down.

A new large Cryogenic windtunnel was developed by a multinational team (France 28%, Germany 38%, Netherland 6% and the U.K. 28%) and is approaching operational status in 1997. (Location: Cologne/Germany. Investment about 650 Mio DM, development period 1987-1994).

Several joint civil/dual-use technology programs are being sponsored by EURECA, the EU Research and Coordination Agency, e.g. BRITE EURAM (Basic Research in Industrial Technology for Europe & European Research in Advanced Material), ESPRIT (European Strategic Program for Information Technology)). Effectivity of these programs, however, need to be improved by reduction of the administration and bureaucracy.

In the area of basic research -long before the industrial competition starts- cooperation is on a better way. The closer a technology comes to production the higher are the difficulties.

Good examples of cooperation are projects for the development of numerical methods, computer programs and advanced computer systems. These pave the way for the exploitation of the still tremendously growing computer power, leading to very large improvements of prediction and optimization capabilities in the the areas of multidisziplinary design and development.

Fig.3-2 shows the international cooperation in five selected project areas.

Key Technologies

Critical technologies relevant to future weapon systems are kept national. A typical example is stealth technology. Europe has yet to earn its wings in this area with a flying vehicle demonstrating and testing the full range of benefits and the cost implications for development, production and operation.

In the French-UK cooperation on future offensive weapon systems stealth technology is excluded.

Technology reviews have been made or are underway in the European nations with an aircraft industry. It is not surprising that the emphasis in the field of military technologies is directed towards similar objectives. There is common interest in a number of areas including

- low cost development and manufacturing processes
- materials and processing, advanced structures
- reduced signature technology
- man-machine interface, situation awareness
- secure datalink
- guidance and control of unmanned vehicles
- modular avionics
- new generation sensors and sensor fusion
- agility concepts for airborne weapon systems
- computational fluid dynamics

The need for (ground and airborne) technology demonstration has been realized and joint demonstration and development programs are evolving between

- France and UK: Technology Demonstrator Programs for Future Offensive Aircraft Systems
- France, Germany, UK: Airborne Phased Array Radar
- France, Germany, UK: Modular Avionic
- Germany and Sweden: Stand-off weapons
- Germany and Spain: Thrust Vectoring
- France/UK: FMRAAM
- Germany/Sweden: Stand-off missile

However, these activities are more often driven by the industry than by political/Governmental and military institutions. Economical considerations to assure the survival of a company over the next decades are a stronger motivation than the political restructuring of Europe.

4. Airforce Training, Operation and Maintenance in Europe

Basic and Advanced Training

Like many other nations -even the USA- European airforces are training the fighter pilots of tomorrow with the aircraft from yesterday.

The US has made the first step towards modernisation of their training fleet with an affordable aircraft, the turboprop powered Joint Primary Aircraft Trainer (JPATS).

The advanced trainer is slowly coming above the horizon. There have been initial studies by Aermacchi / Dasa-Dornier / Dassault about requirements and markets.However, third world nations such as Taiwan, South-Korea, South Africa are currently showing an even greater interest than Europe.The US is upgrading the more than thirty year old Northrop T-38 to last until around 2010. Russia, having the problem with aging trainer aircraft of foreign design, is already starting to flight test new aircraft (Jakowlev/Aermacchi YAK-130 and Mikojan AT).

Germany is committed to use Sheppard Airforce Base for its basic and advanced training until 2005. This training centre has become a truly international establishment since many of the European Airforces are performing their training on this base **(Fig. 4-1).** This is probably the biggest contributor to interoperability. France, Spain, Sweden and UK perform all their pilot training on the home territory.

Budget constraints will force new ways into the future for European training: In 1993 the EURAC Group (European Air Chiefs Conference) was formed from senior officers of 16 European Nations. One of their primary objectives is the definition of joint training concepts/requirements and a common European training aircraft. However, comming to an agreement among all participants leading to real actions is a challenge.

A Joint „European“ training centre for the Tornado aircraft was established by the Luftwaffe, the RAF and the Italian Airforce in Cottesmore, UK in 1980 and will be in operation until 1999 when the German Tornado training will be moved to Holomann AFB in the USA. Prime reason for this move is the better and more predictable weather at Holoman AFB.

The ASTA concept (Aircrew System Training Aids) for the participants of the Eurofighter program is another step towards standardising European training. It is to develop a set of synthetic training aids for the Eurofighter aircrews. However, it does not include common ground training nor facilities at this time.

Maintenance

Maintenance of the trinational Tornado aircraft is performed nationally. Economical considerations as well as „national“ variants, primarily in the weapon and electronic (warfare) equipment area, are the reasons for this situation.

An International Weapon System Support Centre with associated National Support Centres is currently considered for the Eurofighter.

Midlife update Programs

Reduced budgets lead to a maximum utilization of the weapon system fatigue life and consequently to consecutive product improvement programs throughout the extended aircraft life primarily in the area of electronic equipment and weapons. In case of the Tornado this is also predominantly performed on a national basis.

5. European Aerospace Industries

There are 6 Nations in Western Europe with an aerospace industry capable of developing (or participating in a substantial way in) miltary aerospace products or weapon systems:

- France (Aerospatial/Dassault)
- Germany (Dasa)
- Italy (Alenia, AerMacchi)
- Spain (CASA)
- Sweden (SAAB)

United Kindom (BAe)

Other nations such as Greece, Norway and Turkey do have industries performing maintenance activities and even license production but (currently) lack a development capability.

With the exception of France, where the consolidation of the national aerospace industry is ongoing, all others have completed their concentration process resulting in a single company for civil and military aircraft development.

France and Sweden are further characterized by the fact that their latest products, i.e. Rafale and Gripen, have been developed strictly on a national basis, whereas the other four nations have joined in the development of the Eurofighter.

In the past the usual practice in Europe for international cooperation was to form a joint venture company for a particular product (e.g. PANAVIA for Tornado, Eurofighter, Eurojet, Euromissile or Airbus) with the actual work done in the national companies and the intention to retain key capabilities at the home base.

Shrinking markets and budgets in the defense scene will require further rationalization by the formation of international companies like in other industries. Eurocopter is one of the first examples in the defence industries.

The sum of the national capacities in the areas of research and development, design, manufacturing, final assembly and flight test exceed in total the future needs for military aircraft development .

Comparing economic figures of European aircraft companies, e.g. the number of employees **(Fig. 5-1)** or the turnover **(Fig.5-2)** with those of the new US giants it becomes clear, that in a competition on the global markets there is only one way for survival: A common European Military Aircraft Industry.

This solution will be accelerated by the fact, that Airbus Industry will become a European Company for commercial aircraft by 1999 to maintain and improve the competetiveness with Boeing. That requires that Aerospatiale, BAe,CASA and Dasa will have to transfer all or at least a great part of their commercial activities (personal, facilities and other resources) into the new company. The remaining industrial homebase will thereby further reduced.

The commercial aircraft activities in Europe have been concentrated in France under French leadership. BAe has over the last ten years consequently concentrated and invested for military aircraft development and production activities in Warton, Dasa, Alenia and CASA have done considerable investments for the Eurofighter at their national facilities and Dassault and SAAB have done the same for the national developement of Rafale and Gripen. This sets the scene for a logical yet painfull concentration of military aviation in Europe.

A few questions remain :

- When will the process start?
- Who will be the first to join?
- How will the European governments support the process?
- How will the airforces support the process?
- Will European organizations be formed simultaneously (joint crisis reaction forces,joint procurement office, „European Airforce")
- How can the „Competition" between the Rafale and the Eurofighter be resolved?

Whatever the answers may be, the development of a new combat aircraft in Europe will be strongly influenced by an evolutionary development which may not be free of revolutionary events.

The race for the pilot seats in a „Common European Military Aircraft Company" is on.

6. Conclusions

There have been a number of bilateral and multinational aircraft development programs in the last 30 years which provide the basis for the formation of a truly „European" military aircraft development capability.

The

- continuation of political, military and economical integration
- definition of Europe's role in global affairs and a resulting defence policy
- establishment of a European procurement office
- coordination of military technology research and development definition of European Requirements and the
- formation of a „common" European military aircraft industry

will allow the development of a next generation European weapon system without the currently still existing and dominant national egoisms.

Primarily this process will be driven by those nations which currently have a national aerospace industry and request a share in a European aerospace industry, i.e. France, Germany, Italy, Spain, Sweden and the UK **(Fig.6-1).**

The integration of France and Sweden into a common European military aircraft industry will be of prime importance.

The various groups involved in military aircraft R&D within the nations, EU, and WEU need to be streamlined and objectives and funding to be better coordinated.

A considerable number of European countries are currently operating US aircraft. The competition for this market has already started and will get even more intense. Success in this European and global market will require a common European military aircraft industry with a technical capability, economical size, financial strenght and marketing skills comparable to those of the evolving big US giants **(Fig.6-2 and 6-3).**

Civil Aerospace industry in Europe may very well serve as a trendsetter for their military counterparts, because they need to form a competetive company still in this century. The formation of AMC (Airbus Military Company) for the development of the Future Transport Aircraft (FTA) with participation of France, Germany, Italy, Spain, Turkey and the UK is yet another step of industrial consolidation towards a truly „European" military aircraft industry.

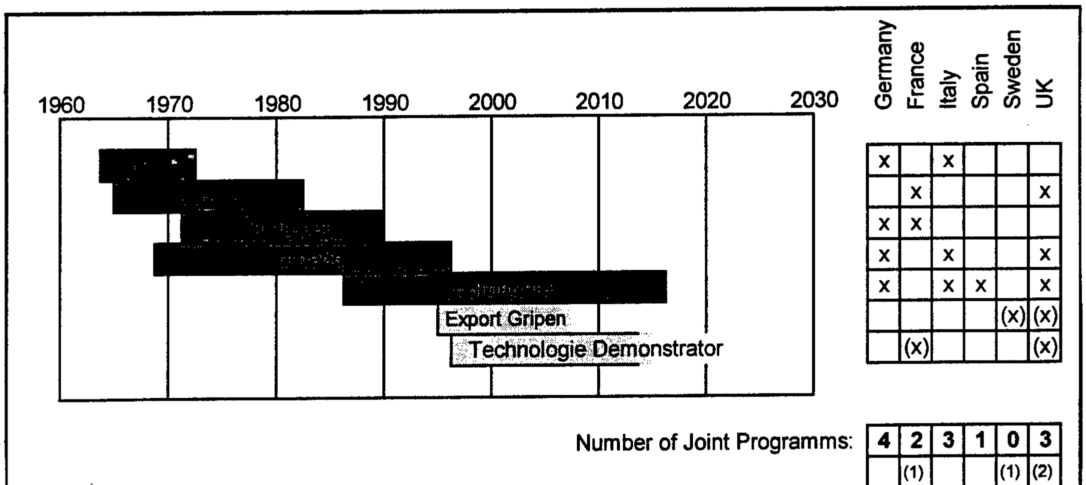


Fig. 1-1: Cooperativ military aircraft development in Europe

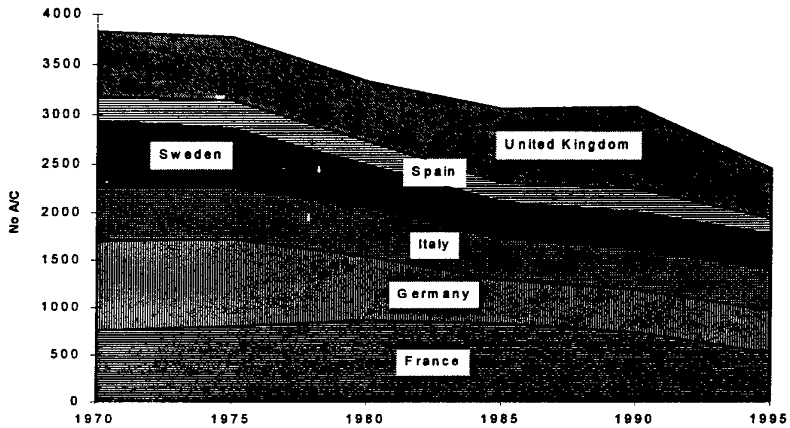


Fig. 1-2 : Combat aircraft inventory development

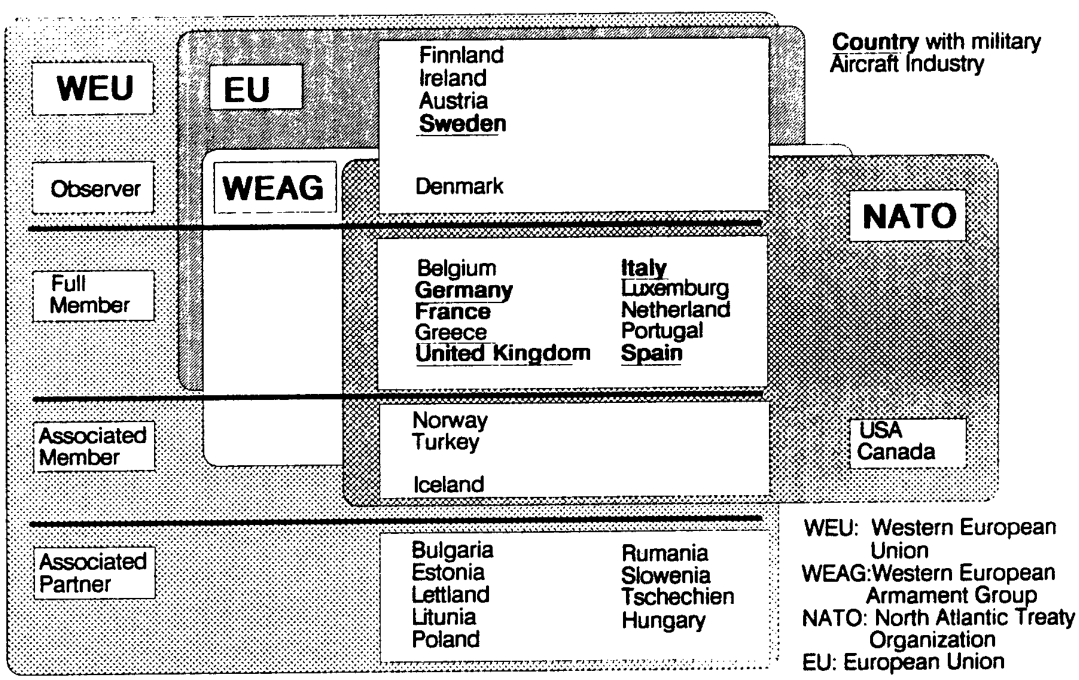


Fig. 2-1: Organizations and Members

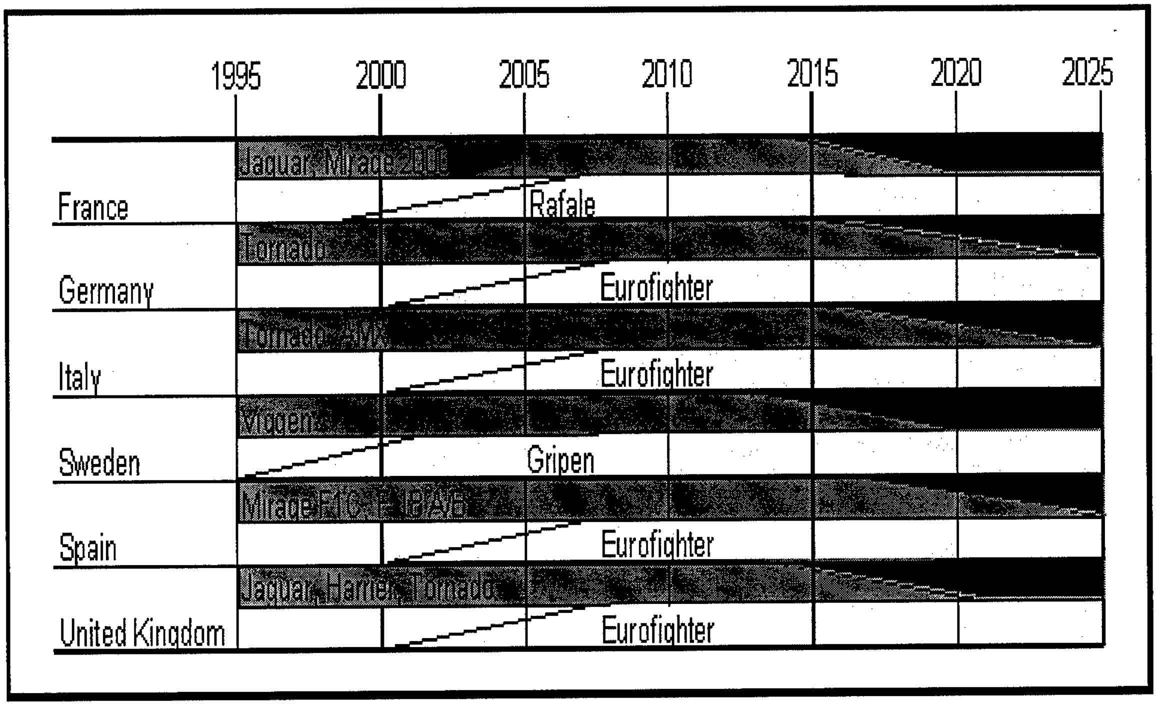


Fig. 2-2: Time frame for the introduction of a new generation weapon system

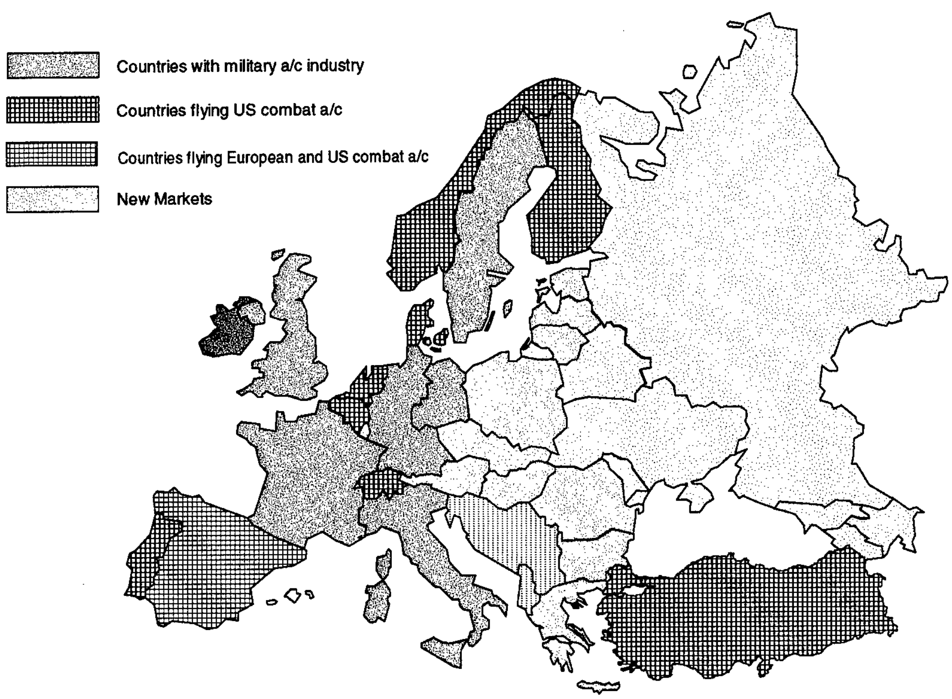
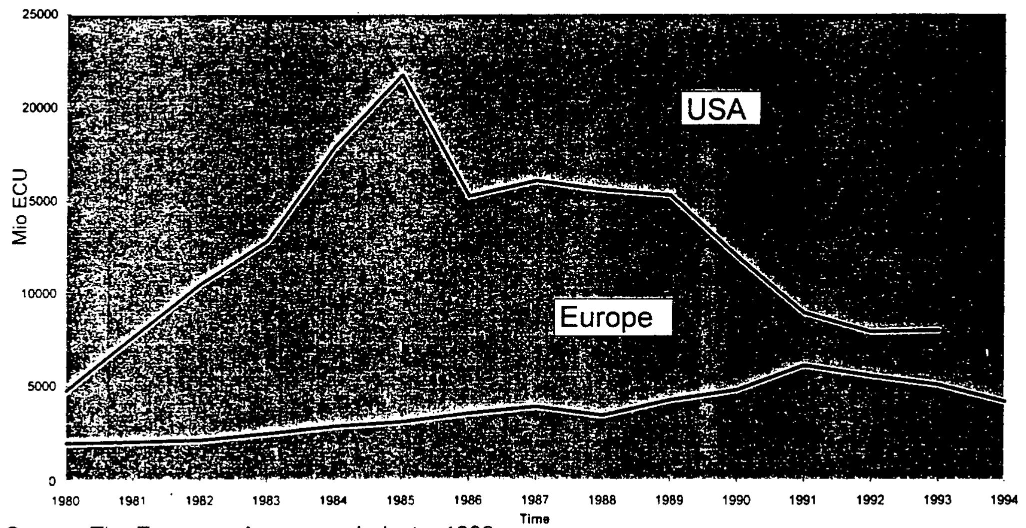


Fig. 2-3: European Countries with Military Aircraft Industry



Source: The European Aerospace Industry, 1996
European Commission

Fig. 3-1 : R&D funding. Europe vs. USA. (Aircraft, space, missiles, equipment, engines. Source: European Aerospace Industry, European Comission)

			Industrial Partners								National Research Establishments					
Organization	Project	Topic	Aerospatiale	Dassault Av	Aermacchi	Alenia	BAe	CASA	Dasa	SAAB	CIRA	DLR	DRA	FFA	NLR	ONERA
WEAG	TA 15	Computational methods for vortex flow past slender wings	●		●		●		●			●	●		●	
EU	Brite Euram AUTAC	Computation methods for viscous wing flow		●		●	●	●	●	●	●	●	●	●	●	●
EU	Brite Euram MDO	Multidiszipinary Optimization methodology (aero.structures, flight dynamics)		●		●	●	●	●	●			●		●	●
EU	ESPRIT Frontier	Genetic optimization algorithms for aerodyn and structures					●		●				●			
EU	ESPRIT Julius	Multidiszipinary design environment for aerodyn structures etc		●			●		●							

EU: European Union
Brite Euram: Basic Research Industrial Technology for Europe & European Research in Advanced Material
ESPRIT: European Strategic Program for Information Technology
WEAG: Western European Armament Group

Fig .3-2: Selected Research Projects and Partner from Industry and Research Establishments

Location of European Airforce`s Training Sites					
Country	Screening	ENJJPT* basic + adv.	IWSC	LCR	CR
Belgium	n	**n/US**	n	n	n
Denmark	n	**n/US**	n	n	n
France	**n**	**n**	**n**	**n**	**n**
Germany	US	**US**	US/UK	n	n/CAN/IT/US
Greece	n	**n/US**	n	n	n
Italy	n	**n/US**	n	n	n/(US)
Netherland	n	**US**	US	n	n/(CAN)
Norway	n	**US**	n	n	n
Portugal	n	**US**	n	n	n
Spain	**n**	**n**	**n**	**n**	**n**
Schweden	n	**n**	n	n	n
Turkey	n	**n/US**	n	n	n
UK	**n**	**n**	**n**	**n**	**n(CAN/IT)**

- ENJJPT = Euro-NATO Joint Jet Pilot Training, n = inational in Country

Fig. 4-1: Training locations of European Airforces

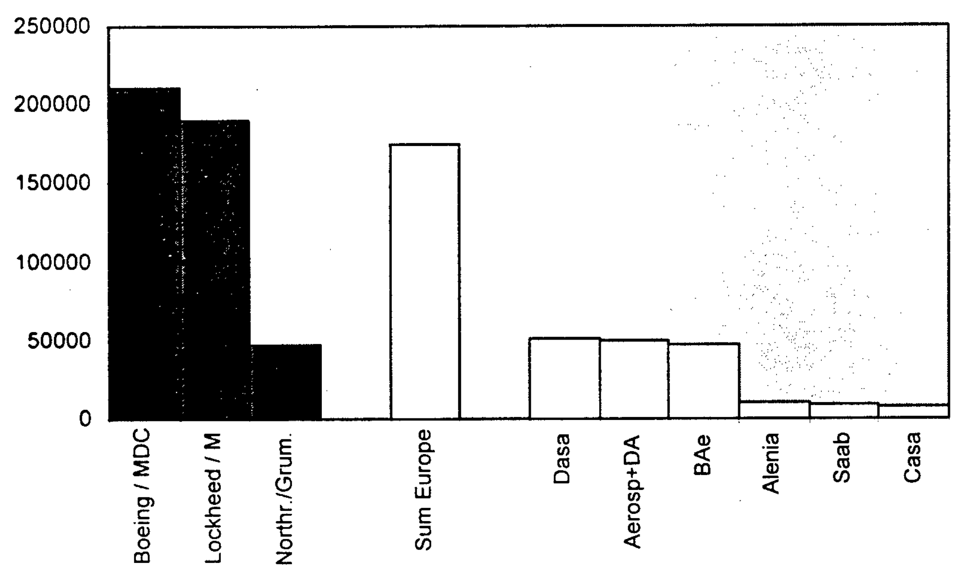


Fig. 5-1: Number of Employees, US vs. European Aerospace Companies

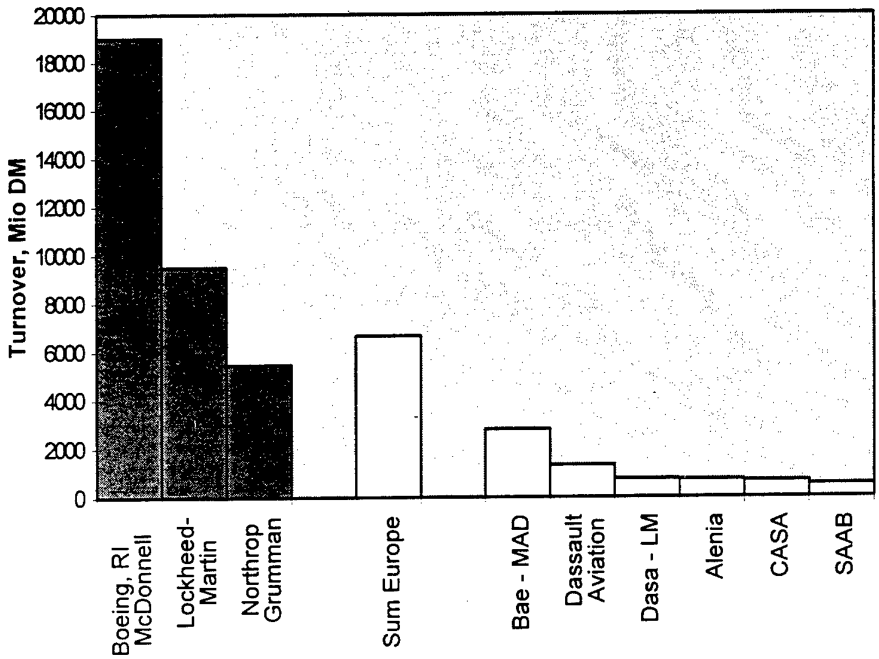


Fig. 5-2 : US vs. European Military Aircraft Companies, Turnover 1995

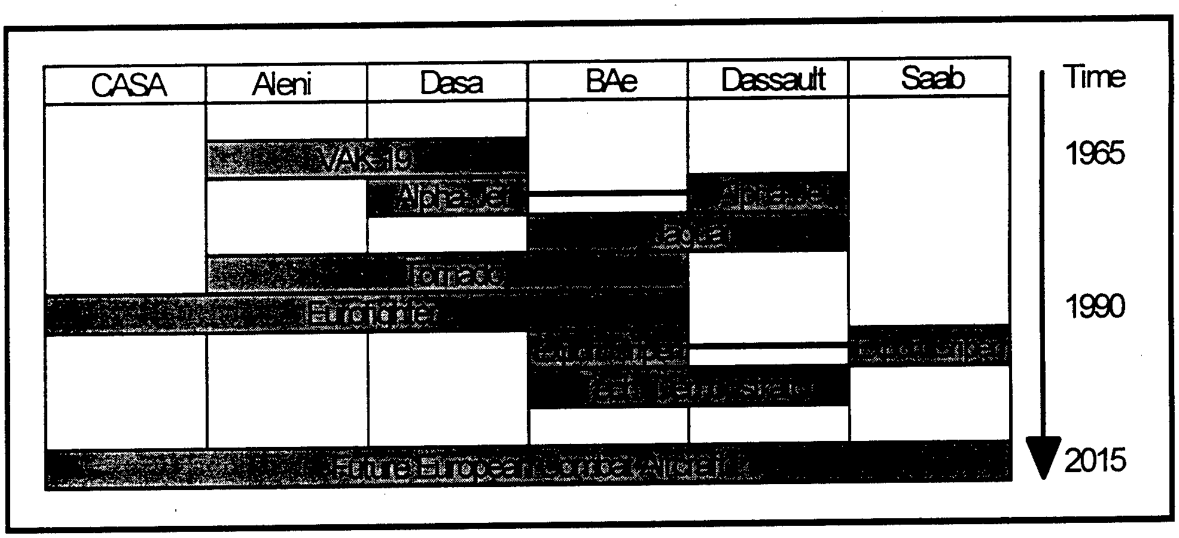


Fig. 6-1: Potential European Industrial Cooperation for the Development of Military Aircraft

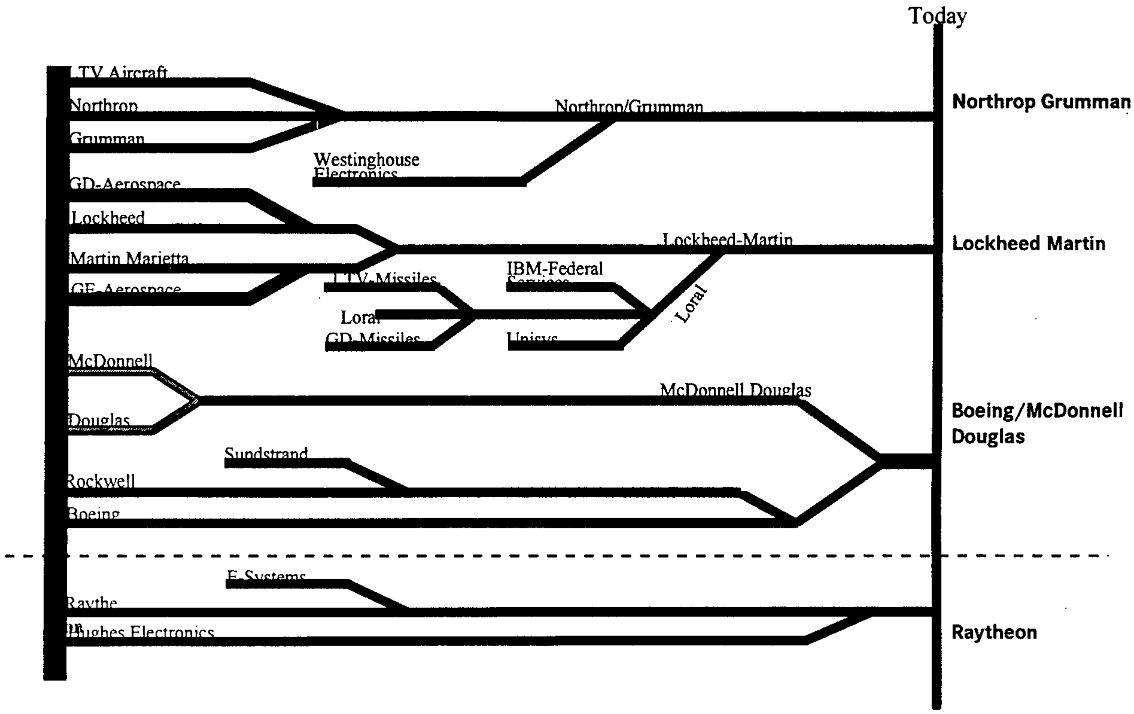


Fig. 6-2: Company Mergers, USA

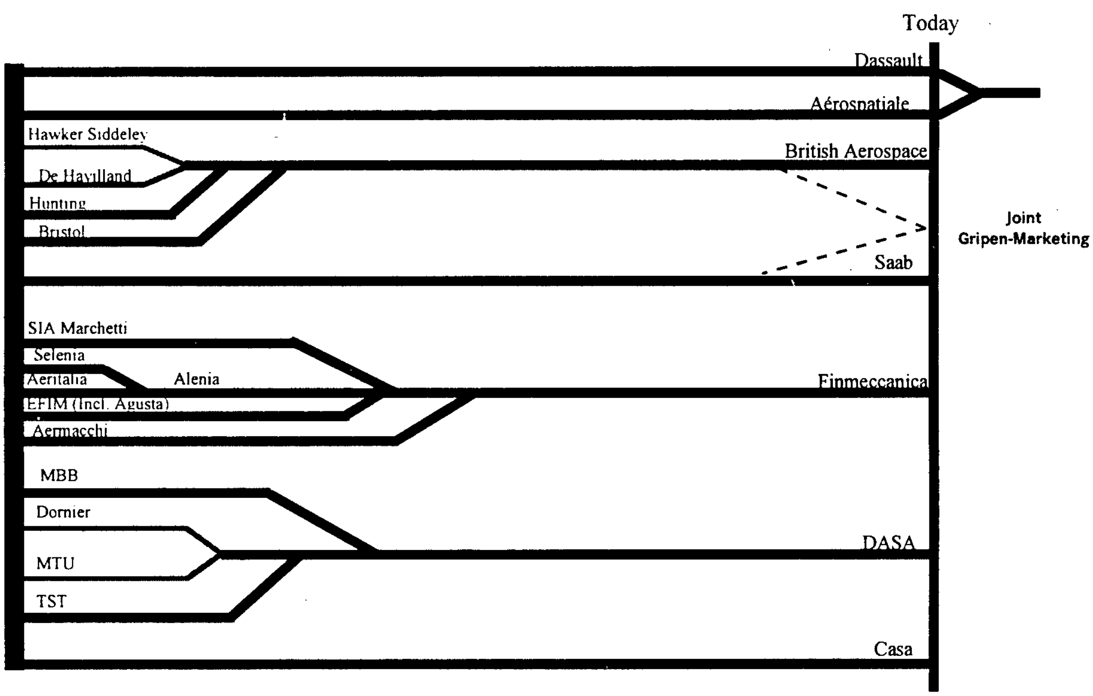


Fig. 6-3: Company Mergers, USA

The Use of Technology Demonstrators to Reduce System Acquisition Cost

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SUMMARY

In the definition and design of a new aircraft system, the choice of technologies to be incorporated is a major decision. Although the latest technology usually yields the maximum (predicted) performance, the readiness of each technology must be carefully assessed. The less the readiness or maturity, the greater the risk to development schedule and cost. There is a premium therefore, on demonstrations that validate the appropriate maturity of each technology. For some things ground demonstration is adequate to reduce the risk to an acceptable level. Some technologies, on the other hand, can only be validated through flight demonstration. Technology flight demonstration programs have been accomplished in many forms, explicit prototype vehicles, the X-plane series from the X-1 to the X-31 and technology demonstrations with an explicit military objective.

This paper discusses technologies that can be adequately ground demonstrated, and suggests guidelines to decide what needs to be flight demonstrated. The paper provides a brief history, current status and a future projection of the benefits of technology demonstrators. Examples are presented to show the impact of selected flight demonstration programs. There is a description of the Wright Laboratory (WL) vision of future, a modular testbed vehicle capable of flight validating multiple technologies, to be developed in parallel with a virtual design/demonstration capability. The paper concludes with the authors' opinions and suggestions as to how technology demonstrators should be considered within the context of Aerospace 2020, and concludes with their projections for the future.

1. INTRODUCTION

The development of aircraft from before the Wright Brothers to today can be considered as one almost continuous technology development. It has occurred across many different countries, driven by both war-time and peace-time reasons and also by both military and commercial needs. Many of the early aircraft were built as prototypes, *de facto* technology demonstrators, to incorporate one or more new technologies (see Reference 1). This has continued to the present with some interesting examples such as the YB-49 in the 1940's. This prototype bomber

Paper presented at the AGARD Symposium on "Future Aerospace Technology in the Service of the Alliance", held at the Ecole Polytechnique, Palaiseau, France, 14-17 April 1997, and published in CP-600 Vol. 1.

demonstrated flying wing technology - but it reached fruition approximately 40 years later. Conversely, the YF-16 demonstrated new technologies such as fly-by-wire controls, relaxed static stability and blended wing/body aerodynamics that transitioned into a system acquisition program.

Within the USA, there has been a series of experimental aircraft designated "X-planes" in addition to explicit experimental bomber (XB-), fighter (XF-) or vertical takeoff and landing (XV-) configurations. The X-plane series has explored (demonstrated) various technologies to conduct more basic aeronautical research with both civilian and military payoffs (see Reference 2). The Bell X-1 was designed to explore flight faster than the speed of sound, and there is a rich legacy through to the latest X-31. This vehicle explored controlled flight at high angles of attack using thrust vectoring by means of paddles and was also unique in having an international partner - Germany. Wright Laboratory (including it's predecessor organizations) were partners in the X-24, exploring the flight dynamics of re-entry configurations, and the X-29 which explored a primary technology of aero-elastically-tailored forward-sweep wings.

This paper is not an historical review, nor is it our intent to trace the origins of airplane technology. In order to narrow the scope and also focus on our objectives, we consider examples only from a class of technology demonstration programs, considered applied research with military objectives, but not as prototypes of any new system. In addition, we only use examples from programs by Wright Laboratory (and its direct predecessor organizations).

2. DEMONSTRATION GUIDELINES

In choosing the technologies or levels of technology that need to be used in order to develop a new acquisition system a primary factor is the risk or, conversely, the maturity of each technology. One method that has been used to assess the maturity of technologies is given in Figure 1. This shows a 9-point scale from basic research to fully mature technology in actual operation. The descriptors for levels 1-4 definitely imply a ground test, although there are flying "laboratories". Levels 5 & 6 use the term "relevant environment" - so the question becomes a definition of what is the relevant environment to demonstrate a given technology. Ground testing has been involved in every aircraft built, so we need to distinguish between this testing and that which is required to provide the confidence that an unproven technology can be included in the design. The next two sections discuss examples of both ground and flight demonstrators. The decision that a technology requires flight demonstration is most often a subjective judgement about the relevant environment of Figure 1.

3. GROUND DEMONSTRATION

In the USA, engine technology is matured by the Integrated High Performance Turbine Engine Technology (IHPTET) program. The technology goals of this government/industry program are validated by means of a set of ground demonstration engines. This integrated set of demonstrators is summarized in Figure 2, together with some of the individual technologies being demonstrated. Both large and small turbine, plus turboprop/turboshaft, engines are covered. As an example, component technologies are incorporated into the Joint Technology Demonstrator Engines. Thrust can be a measured and a flight weight calculated in order to provide the progress towards the quantitative thrust/weight goals. It is accepted that this process can mature engine technologies, through the ground demonstrators, to approximately level 6 on Figure 1.

4. FLIGHT DEMONSTRATION

The legacy of WL flight demonstration programs is illustrated in Figure 3 and selected examples will be used in the following discussions, although it must be recognized that much of the discussion is subjective or even speculative in nature.

4.1 Fly-by-wire control

The USAF Project 680J developed along two primary phases. Phase I involved the installation of a Simplex Integrated Actuator Package to operate a YF-4E's stabilator (for pitch control) in a so-called power-by-wire arrangement. In 1970 this approach was proved practical as demonstrated by several very successful flight tests. Phase II provided for development and flight test of the world's first fully operational fly-by-wire flight control system of a high performance military aircraft. Between April and September 1972, 27 near-perfect test flights were accomplished with a limited partial mechanical backup system on board the airplane. It was never used by necessity and its utility in fact was even questionable. The YF-4E's hydro/mechanical flight control system was then replaced with a quadruplex analog fully fly-by-wire control system that had no possible reversion in flight to mechanical control. On 22 January 1973, the YF-4E made its first fully FBW flight at Edwards AFB, and the program proceeded smoothly to completion on 31 May 1973. A total of seventy two highly successful flights demonstrated an acceptable level of maturity for the FBW technology.

The removal of the mechanical control system, even for flight test, was a very emotional issue and flight validation was absolutely necessary for general acceptance. Fly-by-wire control was one of the new technologies that were integrated into the YF-16 which had a first flight in 1974. Even though the FBW F-4 program was done by a different company, the success of the program was well known and the results were disseminated. The YF-16 builder, General Dynamics, accepted the maturity of the FBW technology but now there was emotional opposition on the part of the customer. It must be remembered that the YF-16 was a competitive prototype - in effect a system-level technology demonstrator. In this context, the YF-16 demonstrated blended wing/body aerodynamics and used other technologies demonstrated in previous programs. We claim that these technology demonstrators reduced the cost of the production F-16.

4.2 Mission Adaptive Wing

The technology demonstrated in the Mission Adaptive Wing (MAW) program was variable wing camber to provide high levels of aerodynamic efficiency over a large envelope of subsonic, transonic and supersonic flight conditions (see Reference 3). The concept consisted of leading and trailing edge variable camber surfaces featuring smooth, flexible upper surfaces and fully enclosed lower surfaces, as opposed to conventional discrete flaps. The variable camber system was structurally designed for high speeds, driven by dual hydraulics and controlled by dual digital/dual analog flight computers.

The objective of the flight demonstration program, on a modified F-111 testbed, was to quantify improvements in range, buffet-free lift and sustained load factor; a reduction in wing root bending moment during high-g maneuvers; and a general reduction in airplane response to atmospheric turbulence. Phase 1, with wing shape set manually by the pilot, was flown in 1985-86. In Phase 2, the wing contours were controlled by various automatic modes setting camber as a function of pilot inputs, flight condition and structural loads. This phase was flown from August 1987 through 1988, and demonstrated significant increases in maneuver efficiency and combat range.

The MAW program was technically very successful, the predictions were validated, ten patents were awarded and a symposium to disseminate the results was held at NASA Dryden Flight Research Center in April 1989. Although the performance predictions were validated, the flight demonstrator uncovered the real-world problems of weight, complexity and reliability. The technology does not appear to have been transitioned to any aircraft, as of this date, although simplified versions using conventional control surfaces have been used. A research organization can conduct "research for its own sake". The MAW program developed and validated a technology without an explicit military customer, so it is available as a design choice, with both advantages and the disadvantages identified. For a military-oriented organization, however, there is a question to be posed: Should only technology be demonstrated that has an application defined?

4.3 STOL & Maneuver Technology

The STOL & Maneuver Technology Demonstration (S/MTD) program was also being formulated in the early 1980's. The genesis of the program was a desire to obtain flight data on 2-dimensional (rectangular) engine exhaust nozzles. By contract award in October 1984, it had evolved into a program to demonstrated technologies explicitly for the Advanced Tactical Fighter (ATF) program that led to the F-22. The technologies were:

- 2-D pitch vectoring/thrust reversing exhaust nozzles
- Integrated flight/propulsion control
- High sink/rough field landing gear
- Advanced pilot/vehicle interfaces

The above technologies were incorporated into an F-15B, with the flight test program from 1988 through 1991.

Program results have been well documented (e.g. Reference 4), but there are other aspects related to this topic. Prior to the contract, there was a 2-dimensional exhaust nozzle operating on a test stand. This ground-test component provided confidence in the internal aerodynamics but was not flight weight. Not having a comparable light-weight proof of concept nozzle resulted in a major impact on the S/MTD design development - the materials and manufacturing problems to achieve flight weight caused approximately a six month delay and $10M cost overrun (shared with the contractor).

The nozzles on the F-22 are "second generation" S/MTD nozzles, and the costs of the S/MTD program were more than compensated by the avoidance of problems in the acquisition program. There were cost savings from learning "how not to do it".

The use of a technology demonstrator to reduce risk/cost of an acquisition program also has political implications. Prior to contract award, the funding for the S/MTD program was cancelled "because there are too many STOL programs", but then reinstated with a 12-month delay. The ATF program, however, was accelerated with the result that the lead of the S/MTD program became marginal. Interim results were provided equally to the ATF contractors, and there were elements of confirmation of the work in progress. Technically, it would obviously have been better with the original lead time between the programs. The point is: for a technology demonstrator to effectively reduce acquisition cost, the technical connection must be supported by a political connection.

Another aspect of technology demonstration was illustrated by the S/MTD program. A capability to perform a precision landing at night, with no external guidance or runway lights was defined as a program objective although there was no customer or expressed need. We felt that this was complementary with the other program objectives of short landings and takeoff from a damaged runway. Once the specified capability was successfully demonstrated in flight test, it was selected for incorporation into the F-15E fleet. In this instance, a technology demonstrated without a defined customer was transitioned into an existing aircraft rather than the acquisition program for which the overall S/MTD program was intended, but only after flight demonstration.

5. THE FIXED WING VEHICLE (FWV) PROGRAM

The preceding section presented three examples - two technology demonstrators did not have identified customers and one technology was successfully transitioned and the other was not. The third example had an identified customer and did transition technology to the acquisition program.

This section is a brief discussion of the USA national program to develop technologies for fixed wing vehicles in a coordinated strategy. Figure 4 illustrates the Technology Development Approach (TDA) process to quantify goals which link the technology areas to the warfighter needs. The bottom row of the figure shows the classic technical disciplines, there are objectives in aerodynamics, flight controls, subsystems and structures. Technology programs are defined to address these individual objectives. These feed up into 'integration technology' - the process of considering the interactions between the individual technologies and validating that the subarea goals have been achieved. Achievement of these subarea goals has already been identified as the means to provide the indicated aircraft payoffs. There is a different set of goals for different aircraft families, such as fighter/attack, and for phases in approximately 5-year increments. These goals are intended to be met simultaneously, which puts a very strong emphasis on the means of demonstrating these goals. There is a requirement to define what can be adequately demonstrated in ground tests, and what requires flight testing. Wright Lab is proposing a new approach to address these issues, this new approach is a key component of the FWV program demonstration plan.

5.1 The FWV Demonstration Program

The overall objective of the program can be stated as: "Develop and demonstrate high payoff, mission relevant technologies to validate the FWV goals; and to reduce the risk as necessary to support application of the technologies". It follows, therefore, that we need a process to quantify the performance benefits, especially when we consider sets of technologies that may have favorable or adverse interactions when they are integrated together. Ideally, the process should support faster and cheaper technology demonstration. Individual technologies are generated in the basic technology disciplines at the bottom of Figure 4. The FWV process should then determine which technologies need to be integrated into sets, and what is the appropriate demonstration mechanism. Wright Laboratory is proposing that the most appropriate mechanism is a combination of a) ground-test demonstrations; b) flight test using current testbed aircraft; c) design and flight of new airframes as technology testbeds, and d) demonstration through modeling and simulation that is referred to as Virtual Demonstration/Design (VDD). Only the last two of these options are discussed further in this paper.

5.2 The New Technology Demonstrator

Wright Laboratory is proposing to build a new technology demonstration testbed to meet requirements that represent validation of the FWV program goals. It is expected to be uninhabited to address the issue of reducing the costs of technology demonstration. In this case, uninhabited is linked to the scale of the vehicle - large enough for meaningful measurements but probably smaller than a piloted aircraft. The conflicting requirements of modularity vs design optimization will be subject to trade-off in the vehicle development. A modular airframe may be considered as one factor supporting a longer life for demonstrating a variety of new technologies. Conversely, a more optimized airframe could be the basis for transition to performing the Uninhabited Combat Air Vehicle (UCAV) missions.

Requirements for the testbed airframe were expressed in general terms, i.e. maneuverability of at least 7g at 500psf dynamic pressure; at least 500 nm radius which equates to flight test time for a demonstrator; and "moderate to high risk" technologies to be incorporated into the vehicle. The actual list of technologies is to be defined as part of the development effort in conjunction with the FWV program government/industry team. The generation of this new high-technology testbed affords an opportunity which leads to the next subject of this paper.

5.3 Virtual Demonstration/Design

The vision of the VDD program is for "a national optimal fixed-wing vehicle research and design process which enables technology development and validation in virtual space with user confidence and acceptance". In other words, all aspects of modelling and simulation can be developed to the point that a technology can be developed and matured by analysis. Modelling and simulation is a part of every aircraft development, of course, and Reference 5 is an indictment of the current state of the art. This implies that a variety of building blocks need to be developed and linked together, although most components exist to some level of fidelity and all are being pursued by many different organizations. The basic 'modules' are such things as multi-disciplinary design, virtual manufacturing, computational fluid dynamics, etc. Also needed are supporting technologies such as high performance computing, advanced visualization techniques, etc.

The needs for technology demonstration can be considered to be a subset of a more global capability. We need an acceptable process of validation of new technologies through appropriate measurements. Industry needs a capability that provides confidence in the technologies plus customer acceptance. Finally, the system acquisition community needs the confidence to commit to system production without an extensive/expensive demonstration/validation phase. Systems have been acquired without a dem/val but the most recent new programs, the Advanced Tactical Fighter (F-22) and the Joint Strike Fighter have large dem/val investments. It would appear to be cost effective to develop the tools so that accurate dem/val can be done in virtual space.

The only way virtual technology demonstration will be accepted is if the tools are fully validated. The VDD effort is being initiated to assemble and validate the necessary tools by a formal connection to the testbed vehicle developments. This is shown schematically in Figure 5 - a continuous cycle of using the tools to predict the characteristics, performance, cost, etc., etc., of the new vehicle and then a formal feedback of actual data to correlate and validate the tools. An example product could be a piloted simulation where we know exactly how the simulated vehicle would be manufactured, exactly what it would cost to build the vehicle, accurately determine its performance and flying qualities. In short, we would have complete confidence that the simulated vehicle is (or could be) "real".

There is the promise of a true paradigm shift in our assessment/management of risk. Risk is in the broadest possible context of costs, schedule and performance. Currently, the readiness or maturity of technology is assessed according to the readiness levels shown in Figure 1. This shows a 9-point scale from observation of basic principles through to operationally proven. Note that technology demonstration, levels 5 and 6, refers to a "relevant" environment which is often interpreted to be flight test. Now, if we have confidence in our virtual design/demonstration we can shift to the Future Vision of Technology Readiness Levels shown in Figure 6. For relevant environment we now would have a choice of virtual or real environment. In addition, technology demonstration is now following some of the subsystem developments. As a fallout of the validation process discussed previously, we can develop criteria for when to use virtual or real environments. If the new technology lies too far outside the validated design space, flight test data is absolutely required. This judgment is also part of continually extending the validation process into future technology developments.

There is a connection from the preceding discussion to consideration of Aerospace 2020. This study considers a wide range of technologies, from evolutionary to extremely revolutionary. In any technology forecast, it is also wise to consider how the technologies will be demonstrated and validated as an acceptable risk for incorporation into new weapons systems. It is suggested, therefore, any consideration of implementing Aerospace 2020 should include the formulation of a technology demonstration plan.

6. CONCLUSIONS

For the next century, we suggest an increased and expanded use of modelling and simulation, i.e. virtual technology demonstration. We foresee a capability where, for example, a piloted simulation could validate some technologies because we have designed and modelled a virtual prototype and know it can be manufactured, know what it would cost, have confidence in the performance and flying qualities, etc, etc. Many components are available or in development but with different levels of fidelity, but insufficient in today's state of the art.

The key to the achievement of a credible virtual technology demonstration will be the validation of all the individual pieces. This requires a parallel development of the virtual capability in conjunction with actual ground and flight demonstration programs. For the alliance, we recommend that consideration should be given to a Technology Demonstration Plan to mature the specific technologies of Aerospace 2020 that are judged to be necessary for any new system. This process will focus on the demonstration of technology to a level that will be considered low risk for both a new system acquisition as well as retrofits to existing aircraft.

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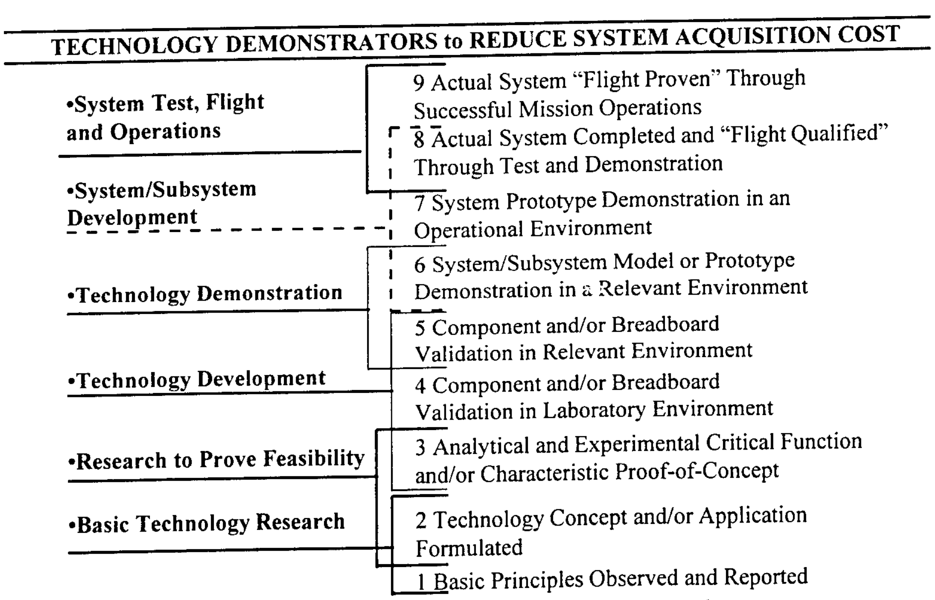
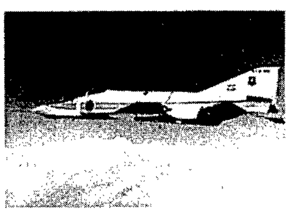


Figure 1. The Current Technology Readiness Levels

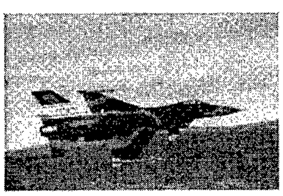
TECHNOLOGY DEMONSTRATORS to REDUCE SYSTEM ACQUISITION COST

- Joint Technology Demonstrator Engine
  - P&W demonstrated +30% T/W and 25% better fuel burn
  - GE demonstrates fuel efficient variable cycle technology
- Joint Turbine Advanced Gas Generator
  - Allied Signal demonstrated Ph I turboprop/turboshaft goals
  - GE/Allied Signal demonstrated SFC and horsepower/weight
- Advanced Turbine Engine Gas Generator
  - Allison demonstrated Phase II turbine inlet temp.
- Joint Expendable Turbine Engine Concept
  - Teledyne targeted SFC goal
  - Williams targeted specific thrust with low cost
  - Allison demonstrated Ph I specific thrust & Ph II turbine temp.

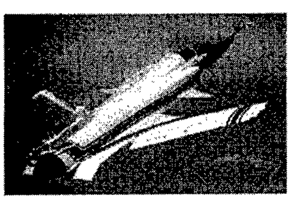
Figure 2. List of the IHPTET Ground Demonstrators



Fly-By-Wire F-4 1970 - 1973
Analog FBW control system
replaced mechanical system

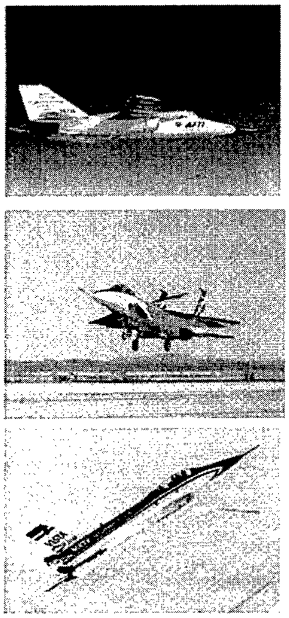


AFTI/F-16 1981 - present
Multi-mode task-oriented controls
Automatic ground collision avoidance



X-29 1984 - 1992
Aeroelastic structural tailoring
Forward-sweep wings
Forebody Vortex Flow Control

Figure 3a. Wright Laboratory's Flight Demonstration Legacy



Mission-Adaptive Wing 1985 - 1988
Optimized variable-camber wing
with smooth continuous surfaces

STOL/Maneuver Tech Demo 1988 - 1991
2-D Thrust vectoring/reversing nozzles
Integrated flight/propulsion controls
Autonomous landing guidance

Multi-Axis Thrust Vectoring 1992 - 1993
Pitch & yaw vectoring nozzles
High-angle-of-attack air combat

Figure 3b. Wright Laboratory's Flight Demonstration Legacy

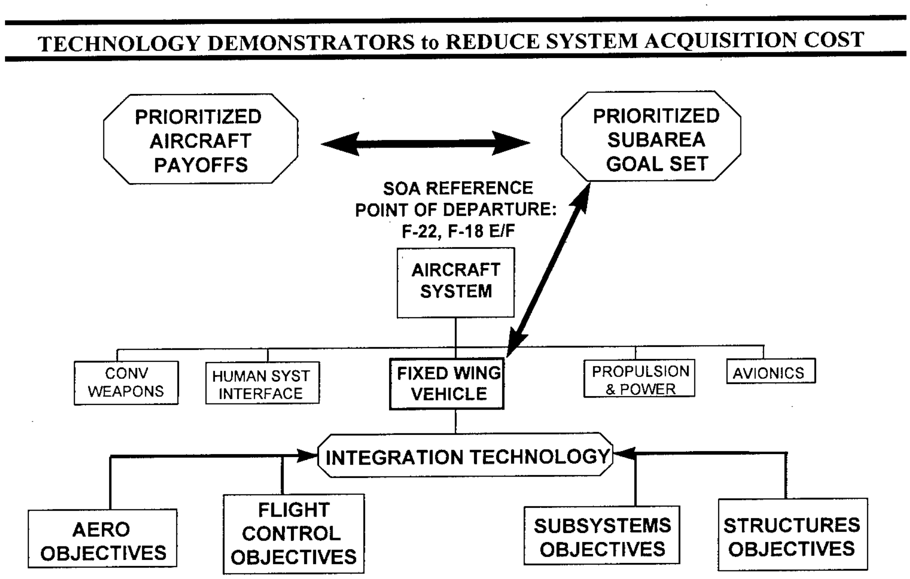


Figure 4. Fixed Wing Vehicle Technology Development Approach

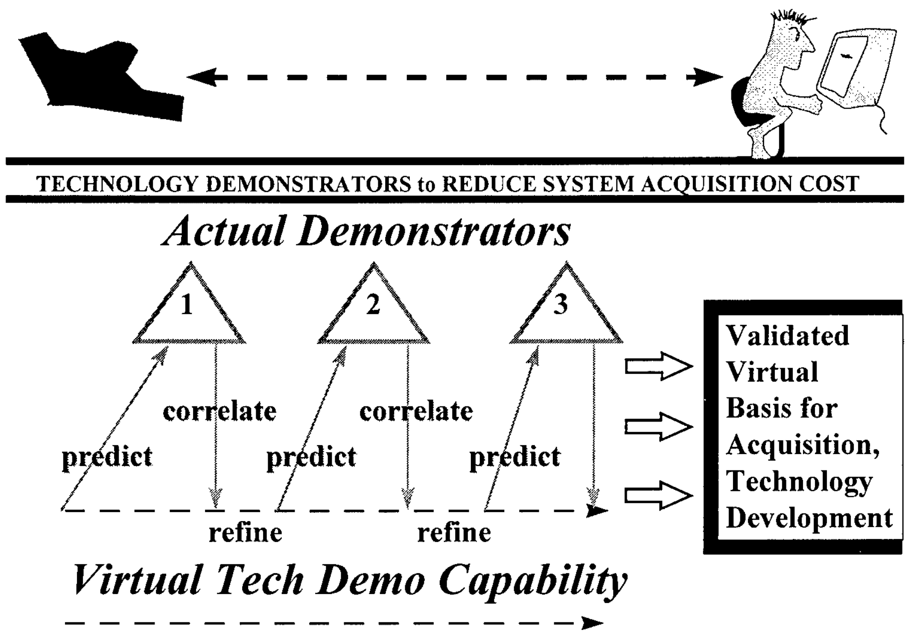


Figure 5. The Virtual Demonstration Validation Process

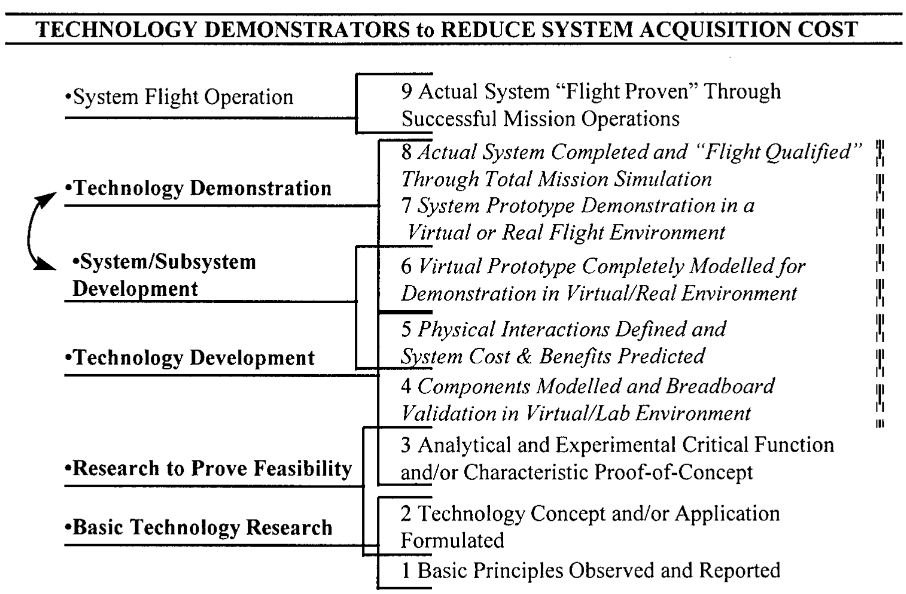


Figure 6. Potential Future Technology Readiness Levels

Cost Benefits in the Acquisition of a Utility Tactical Transport Helicopter Fleet for the Canadian Forces

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BACKGROUND

The requirement for a Utility Tactical Transport Helicopter (UTTH) fleet is derived from the roles of the Canadian Forces and the specific missions assigned to the Land and Air Forces. In general, UTTH resources can be called upon to conduct operations in any of the following general mission areas:

a. Operational and training support to the land forces and other CF organizations;

b. International peacekeeping operations; and

c. Operations in aid of the civil authority.

Other unique missions include:

a. Fire-fighting operations to include water bucketing;

b. Administrative airlift of personnel and equipment;

c. Reconnaissance and surveillance in support of civilian agencies;

d. Support to civil authorities including special operations; and

e. Secondary search and rescue (SAR) response.

To maintain this capability in the Canadian Armed Forces (CF) beyond the mid-1990s, significant expenditures were necessary to either retrofit existing fleets or to replace them. In September 1992, the Minister of National Defence (MND) announced that a contract had been awarded to Bell Helicopter Textron, Canada (BHTC) for 100 helicopters. Designated the CH146 Griffon by the CF, the Bell 412 is a 15-place aircraft powered by the Pratt and Whitney of Canada, Ltd. Model PT6T-3D twinned turboshaft engine. As of end-March 1997, 76 aircraft entered into service.

AIM

The aim of this paper is to document the cost benefits achieved as a result of the selection of a civil certified aircraft fleet customized for military employment.

Paper presented at the AGARD Symposium on "Future Aerospace Technology in the Service of the Alliance", held at the Ecole Polytechnique, Palaiseau, France, 14-17 April 1997, and published in CP-600 Vol. 1.

SCOPE

It is not the intention of this paper to compare the cost of retrofit of existing fleets with that of procuring a new fleet but rather, to provide illustrations where cost benefits were achieved in the CH146 procurement and implementation. Several approaches could have been taken to present the cost benefits achieved in this case. Ideally, a purely quantitative analysis with a "bottom line" could prove very convincing. This course of action is not followed as it is not without difficulty. A number of assumptions would have to be explained, the methodology would need to be established, certain financial data would be rough order estimates and the resulting paper would not satisfy the size limitation imposed. Alternately, a description of cost benefits achieved in key areas allows the reader to make his own conclusion. Specifically, the originating operational requirement, the approach taken in the certification of the helicopter and mission kits, as well as other implementation opportunities are examined.

PROJECT EVOLUTION

A 1991 internal study established options for continued employment of utility tactical transport helicopters (UTTHs) by validating the statement of operational requirement (SOR), assessing various options against the SOR, and examining support alternatives. The cost and benefits analysis of each option led to the conclusion that a single fleet offered many operational benefits including improved capability to conduct national and international tasks, elimination of cross-training inefficiencies, improved standardization and interoperability, enhanced operational performance and improved survivability. It was also concluded that the most economical ownership option would be through direct acquisition of new, civil certified helicopters and, that the Bell 412 was significantly lower in cost than other compliant helicopters assessed.

Under traditional military aircraft procurement, a Project Management Office (PMO) is established to extensively define the prime mission vehicle through use of specifications based on numerous military standards. Other tasks include the definition of government and military processes which the selected contractor would need to follow in the delivery and support of the product. To accomplish these and other tasks, project offices with personnel numbering in the 150 to 200 range were traditionally the norm taking anywhere from 72 to 84 months prior to contract award.

The use of military specifications and standards are intended to ensure a quality weapons system that is not only safe and survivable but which is also durable and meets minimum flight performance requirements essential for mission accomplishment. This is important but this type of process tends to be different from that used in industry.

Following this exhaustive definition activity and receipt of a contract, the original equipment manufacturer (OEM) would need to translate the military standards and specifications into that used for their production aircraft. Those specifications which had not been specifically identified during aircraft design would invariably require extensive analysis for conversion into OEM terms. Test plans and procedures would then be required to demonstrate that the minimum standard had been achieved. Other OEM activities such as finding suppliers capable of filling the order and the re-work of the production line would add time and effort driving aircraft costs upwards by at least a factor of two.

Naturally the government decision to acquire 100 Bell 412 helicopters impacted the traditional procurement process and the work required of the PMO. An automatic benefit accrued to the CF as in this case it only took 20 months from the start of the 1991 study to contract award with BHTC. Considerable savings were realized in PMO costs alone as on average there was only 37 personnel on staff for a period much shorter than used previously.

The decision to adopt a civil-based helicopter not only affected the prime mission vehicle selected, it also influenced most other project elements. It impacted the selection of avionics equipment, mission kits and the approach to maintenance and supply support. A "commercial" theme was adopted challenging the traditional military way of doing business. It permeated the work environment as the often heard phrases attest: "We're just another commercial customer" and "If it's good enough for the civil operators, it's good enough for us". This open-mindedness had significant impact on the cost benefits which were later to be realized.

CERTIFICATION/ AIRWORTHINESS

In particular, acceptance of civil certification avoided the traditional cost drivers of other military procurement initiatives. While the CF is responsible for the issue of a Canadian Military Airworthiness Type Certificate (CMATC) for each aircraft type, the US Federal Aviation Agency (FAA) issued a 412CF Type Certificate (TC). This 412CF baseline includes several design requirements, some common to the commercial community and some unique military. Unique military requirements were cleared for carriage on a non-hazard basis and thus certification "in-house" of CH146 unique military systems was minimized. The amount and scope of the OEM flight test and evaluation program were significantly reduced and aided in keeping program costs down. Albeit, the certification of non-civil equipment and the operational test and evaluation of the helicopter as a weapon system was required subsequent to delivery, this requirement would normally have been done earlier in a full development project.

Another typical DND approach had been the employment of a sizeable CF quality assurance (QA) staff at the manufacturer's facility. Given that the civil approach was adopted i.e. civil inspectors on-site issued a civil certificate of airworthiness for each helicopter, there was no requirement for military QA. Only one officer was required to accept the product in order that payments could be authorized. The benefit was a sizeable reduction in personnel costs.

Prior to every aircraft acceptance, it was traditional to perform flight verification conducted by a qualified military test pilot(s). This requirement was not deemed warranted as the OEM test pilots followed the test procedures which would have been used by the military pilots. As initially the intent had been to conduct 100 check flights, subsequent arrangements were made for up to 10% sampling and in return, BHTC would deliver the helicopters to the unit location. This action saved the CF much time as the limited number of available CF test pilots were then able to fully dedicate efforts to more pressing certification activities.

CUSTOMIZATION

In support of specific mission requirements, the CFUTTH adopted the mandate of minimal customization and relies on one baseline configuration supplemented by mission kits. The tactical aviation squadrons and combat support squadrons (CSS) differ only in the mission kits normally employed. Although all aircraft share a common camouflaged, low infrared reflective paint scheme, six have been recently partially painted white for a United Nations deployment. In addition to the standard Bell Model 412HP features, all are equipped with dual controls, a wire strike protection system, a rotor brake, external/internal crew door jettison handles, a cargo hook, crew seats with integral lumbar support, transmission gearbox chip detecting system with fuzz burnoff and a heavy duty heater. All aircraft have a Flight Data Recorder and cockpit voice recorder (FDR/CVR) and rotor track and balance as the first step in a full Health and Usage Monitoring system (HUMS) implementation. All have modified landing gear and other support equipment to ensure air transportability via the CC130 Hercules aircraft. For the most part, the aircraft lighting, including instruments, interior and exterior lighting, as well as the interior paint scheme are Night Vision Imaging System (NVIS) compatible. In normal operations, the CH146 employs two pilots and a flight engineer leaving room for up to 12 passengers. CSS units employ a SAR technician and their aircraft are equipped with an external rescue hoist, Forward Looking Infrared (FLIR), a spotter window kit, a left hand auxiliary fuel tank and a survival kit located behind the pilots' seats.

Additionally, all aircraft have provisions to be equipped with the following mixture of military and commercial kits:

a. AN/ARC 217 and SELCAL Kit;

b. AN/ARC 164 Kit;

c. FLIR Kit consisting of a turret, sensor, electronics unit and a cockpit mounted hand controller and NVG compatible monitor;

d. Navigation Map Display Kit;

e. Pilot/Copilot Armoured Seats Kit;

f. Lightweight Armour Protection Kit;

g. Auxiliary Fuel Tank Kit;

h. Six-man Litter Kit;

i. External Rescue Hoist Kit;

j. Ski Kit;

k. Spotter Window Kit;

l. Inverter Kit;

m. Landing Light IR Band-pass Filter Kit;

n. Night Sun Installation Kit;

o. ASE equipment kit;

p. Water bucket kit; and

q. Special communications mission kit.

The approach taken to fit all aircraft for but not with the above equipment is viewed as a substantial cost avoidance opportunity as it offers employment flexibility and permits a reduction in the number of kits normally purchased.

AVIONICS MANAGEMENT SYSTEM

To address cockpit space and weight constraints, and to provide for future growth, it was necessary to deviate from the avionics suites typical in the commercial world. An Avionics Management System (AMS) integrates the navigation, communication, identification (IFF/SIF) and aircraft survivability (ASE) sub-systems. Two CMA-2082 Control and Display Units (CDU) are the core computers for the AMS and employ a dual-D MIL-STD-1553B data bus and ARINC 429/582 serial lines as the prime means of data exchange and control with the various sub-systems. A CMA-2060 Data Transfer System and an Emergency Control Panel also provide operator interface. The following equipment comprises the avionics equipment controlled by the AMS:

a. Dual AN/ARC-210 Multiband Radios;

b. Single AN/ARC-164 UHF(AM) Radio;

c. Triple KY-58 Vinson Voice Encoder;

d. Single AN/ARC-217HF Radio;

e. Single ANDVT TACTERM Voice Encoder;

f. AN/ARN-147 VOR/ILS/MKR;

g. AN/ARN-149 LF-ADF;

h. AN/APX-100 IFF;

i. KIT-1C Mode 4 Encoder;

j. CMA-2012 Doppler Velocity Sensor;

k. Collins MAGR Global Positioning Sensor (GPS);

l. Threat Warning System (type yet to be determined);

m. AN/ALE-39 Counter Measure Dispensing System;

n. AN/AAR-47 Missile Approach Warning System;

o. AR-335 Radar Altimeter (Dual Display); and

p. DM-442 Distance Measuring Equipment.

In addition to the above equipment the AMS is interfaced with:

a. Dual Sperry 7600 Digital Automatic Flight Control System (3 Axis combined Autopilot and Flight Director);

b. Dual Three-axis Reference System Directional Gyro and Vertical Gyro (TARSYN DG & VG);

c. Dual Electro-mechanical Vertical Situation Indicators (ie ADI's);

d. Dual Electro-mechanical Horizontal Situation Indicators; and

e. Map Display Unit.

As the above list reveals, the use of readily available military and commercial products eliminated development and support costs. The CDUs for example are based on the proven US Army Pavehawk program.

Another potential benefit is the reduction in workload thereby permitting single pilot operations. Cost benefits will only be achieved if the decision on aircraft usage reduces the current full crewing complement. Further time and effort are still required to achieve an AMS that fully satisfies the FAA and operational users. Resolution of CDU screen blanking, software anomalies and interface issues may reduce these cost benefits.

SUPPORT CONCEPT

In the past, the Department of National Defence (DND) policy concerning support to operations was for total self-sufficiency anywhere in the world and mandated use of its pre-established support structure and organization.

DND's traditional approach in providing supply support to a new piece of equipment had been to provide initially two years worth of consumables and a lifetime of repairables with often long procurement lead times forcing high stock levels and significant warehousing requirements at all levels. DND managed the inventory via the Canadian Forces Supply System (CFSS), coordinated transportation through the Central Movements Transportation and Traffic organization and provided shipment to deployed sites via military means, for example, Hercules aircraft and trucks. This traditional approach provides the autonomy and spares support required but at a cost.

From the start, this project acknowledged the Bell worldwide after-sale product support network and its existing commercial support structure when deciding how to best satisfy the various support elements.

CFUTTH initial sparing was reduced to meet anticipated current usage only and relies on Bell and other original equipment manufacturers to provide replacement stock as required. There is a concurrent reduction in administrative overhead as there are no personnel dedicated to CFSS inventory management nor are any required for cataloguing. The reduced initial provisioning provided immediate capital savings and eliminated the cataloguing activity for thousands of line items. Students of introductory finance understand that avoiding such up-front costs increases project feasibility.

In-service spares management uses the existing Bell Customer On-line Order Processing system or CO-OP for short. The CO-OP system includes modem access worldwide for deployed operations, real time access to Bell and CF inventory, demand capability at unit level, and a closed loop system for DND-owned repairables. The level of service for BHTC to ship parts is governed by three priority codes: 24 hours, 7 days or routine 30-days. Cost benefits in addition to reduced initial provisioning include reduced inventory levels and shortened procurement lead times. As inspection authority for spare parts is vested with civil authorities, minimal military personnel are needed for this function. The acquisition and management of parts acquired from other OEM approved suppliers in the CO-OP also provides tangible benefits. The ability to track usage and expenditures to individual helicopters and squadrons as well as locating critical serial numbered components allow for better fleet management decisions. Maximum benefits are being obtained from helicopter and spare parts warranty coverage as the CO-OP is used for warranty administration. Finally, contract provisions for the contractor to buy back both excess and obsolete parts will benefit the military.

The CFUTTH approach to transportation is direct shipment to and from squadrons with no base supply or base transport involvement, use of commercial shipping such as Purolator and Fedex. Cost benefits include the elimination of intermediate supply and transport organizations.

Having adopted the civil approach to parts procurement and management, DND also accepted the recommended OEM overhaul intervals for repairables as well as repair and overhaul administration by Bell. The following table provides a comparison of major components overhaul times between the CH135 Twin Huey lives in use at time of fleet retirement and the CH146 Griffon helicopter fleet.

COMPONENT	CH135	CH146
POWER SECTION	3500	4000
MAIN TRANSMISSION	1150	6000
MAST ASSEMBLY	1150	5000
DRIVESHAFT	1150	5000
TAIL ROTOR GEARBOX	2300	5000
COMBINING GEARBOX	2300	5000
HANGAR ASSEMBLY	1025	5000

Overhaul Interval Comparison

The reduction in overhaul intervals for the CH135 fleet is mainly attributable to DND calculations which provided added safety margins to that already accounted for by the OEM. It is fair to note that unique military requirements do necessitate the application of other life limits than those applied to the civil sector. While it is the intent to not depart from the civil standard, there is currently one example of variation from the norm. A reduction in life of the mast assembly from 10,000 hours to 5,000 hours had to be invoked for off slope landing. Over the 20-year life of the CH146 fleet at which time each aircraft will average around 8,000 to 10,000 flight hours, significant cost benefits will be realized.

The maintenance program for the CFUTTH is based on the OEM recommended maintenance requirements. Part of the commercial product support included assistance by BHTC Customer Service Representatives. All first and second level of maintenance is carried out by CF technicians and aircrew whereas third level is carried out by industry as a matter of Canadian Government policy. Only limited effort was involved in assignment of maintenance tasks to the appropriate CF level of maintenance and Military Occupation Code (MOC) in support of organization establishment requirements. It was also necessary to recognize the specialized military equipment maintenance and support requirements.

Another maintenance element is the previously introduced HUMS which permits rotor track and balance during a mission and will be expanded to support vibration diagnostics for engine and drive train trouble-shooting. The FDR/CVR also provides data for analysis and was critical to the investigation of our first accident in Northern Labrador in November 1996.

Single fleet acquisition resulted in savings and efficiencies for 1st and 2nd level maintenance by CF personnel. The 1991 study which compared the option of keeping the personnel structure utilized for previous fleets with that which would be adopted for the CH146 concluded that a decrease of

190 maintenance personnel would result. It is uncertain whether this figure was achieved as other rationalization activities have since complicated the issue. Nonetheless, it is safe to conclude that substantial maintenance personnel reductions have occurred and that cost benefits are being realized.

SUMMARY

An assessment of all available options and commitment by the political leadership assured that Canada would maintain a utility tactical helicopter capability well into the 21st century. Acknowledgement of civil expertise with the adoption of the civil helicopter certification as a basis for a military fleet, not only enabled the timely delivery of aircraft, it provided a number of cost benefits.

The number of personnel to define the requirement to industry, to perform QA functions, to conduct acceptance test flights, to manage inventory and to transport of equipment was kept at a minimum. The elimination of traditional OEM cost drivers, lower initial parts sparing, use of non-developmental avionics, the fitting of all aircraft for, but not with all mission kits, for the most part acceptance of OEM recommendations to repair and overhaul intervals, adherence to the OEM maintenance schedule and use of a proven world-wide inventory management system resulted in cost benefits.

In summation, for a relatively low cost of \$1.2B, one hundred CH146 Griffon helicopters will be delivered and infrastructure in place to support these assets in the achievement of operational commitments.

Affordable Structures Through Integrated Design

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Design for Affordability is the new paradigm for the 21st Century. Balancing the conflicting goals of systems superiority and systems affordability is the challenge of the integrated design environment on a larger scale than has ever been done before. This paper discusses the engineering processes and tools of Integrated Design which contribute to affordability of combat aircraft structures.

The objectives of integrated design are to ensure a balanced design so that no single performance parameter dominates the system and to manage the uncertainty of a major system development as it progresses through the acquisition cycle. A balanced system design achieves the optimum in system level performance and affordability. Analyses and simulations reduce the risk in the preliminary design phase, minimizing the amount of testing required for validation prior to production.

The Integrated Design Environment is a multidisciplinary concept, encompassing People, Processes, Tools. The culture of Integrated Product and Process Teams (IPPT), shown in Figure 1, facilitates design for affordability. Implementation of IPPT requires a radical change in Organizational Architecture, Business Practices and Tools. Organizational Architecture--The IPPT environment assures design for affordability by replacing the old vertical or functional

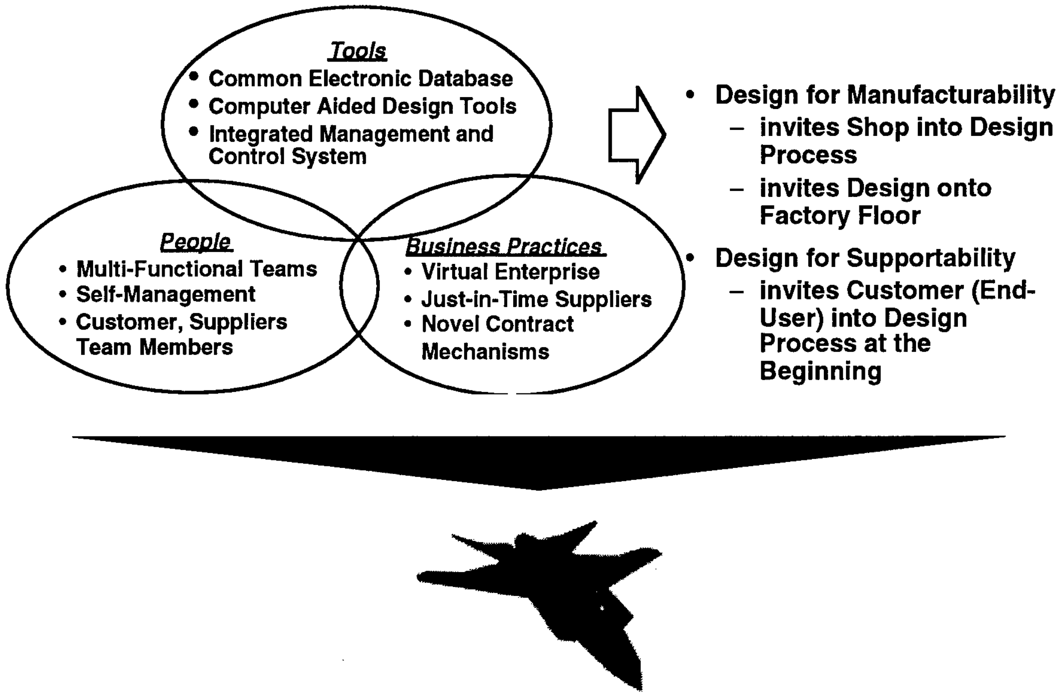


Figure 1 Integrated Product/Process Teams Assure Design for Affordability

Paper presented at the AGARD Symposium on "Future Aerospace Technology in the Service of the Alliance", held at the Ecole Polytechnique, Palaiseau, France, 14-17 April 1997, and published in CP-600 Vol. 1.

organizational hierarchy with a circular multi-functional process. It facilitates design for manufacturing by inviting the shop into the design process and the design team onto the factory floor. It addresses Design for Supportability by involving the end-user at the very outset of the design development. Business Practices--IPPT forces a radical departure from insular business practices by inviting suppliers and down stream functions to participate in the design and decision making process. This has spawned numerous new contracting mechanisms and business partnering scenarios, together with a new vocabulary. One such example is *virtual enterprise,* in which manufacturers, vendors, suppliers and integrators organize to operate as a single (virtual) company for the purpose of developing and delivering a particular product and then disband and formulate new partnerships for future products. A common feature of the virtual enterprise is electronic colocation of geographically separate business units, made possible by recent advances in rapid communication, high performance computing, and the protocols to transmit and manage massive amounts of complex data. Tools-- The principal tools in the Integrated Design Toolbox are the common 3-D electronic design database, computer aided design and analysis software, multidisciplinary design analysis and optimization methodologies, and accurate design to cost models.

The Integrated Design Environment is a computational environment that can quickly evaluate system performance, perform design tradeoffs, and provide an integrated and uniform environment to carry out analysis and simulation across disciplines from conceptual design through manufacturing. Figure 2 highlights a number of the commercially available design and analysis tools as they are applied to conceptual design, preliminary design, detail design and manufacturing, linked by a common 3-D parametric database. Effective use of these tools can reduce design cycle time, reduce the number of design iterations to hardware, and reduce dependence on hardware tests for design validation.

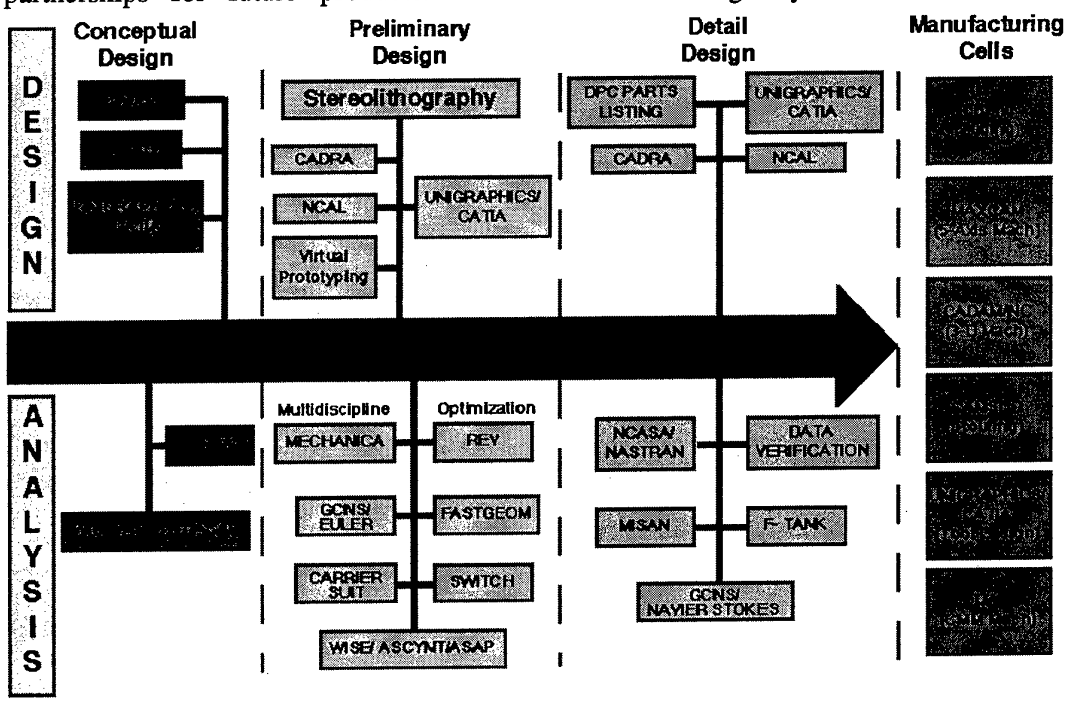


Figure 2 Integrated Design Process

Three major elements of the Integrated Design Environment are Structural Design, Aerodynamic Design and Signature Design. Recent computational advances have opened the design space to permit more complex structural configurations, more efficient aerodynamic shapes, and more sophisticated gaussian geometries for signature management.

Computer Aided Design Software is the backbone of the Structural Design Environment. Commercially available CAD systems (CATIA, Unigraphics, Computervision, PROEngr, etc.) support a paperless design environment, permitting design definition from the wire grid stage through full three-dimensional solid models, Figure 3. These computer aided design packages facilitate a seamless engineering environment by supporting complex engineering analysis and manufacturing simulation capability. In addition to supporting their own internal modules, these CAD systems recognize the realities of modern day business partnering and facilitate the virtual enterprise by maintaining interfaces to the major analysis (NASTRAN, LFINI, Mechanica) and manufacturing simulation packages (Deneb IGRIP, QUEST, Technomatix, Prosolvia) as well as to each other! The structural optimization process carries the design from conceptual through detailed design. Figure 4 shows the increasing levels of model fidelity required at each level of design.

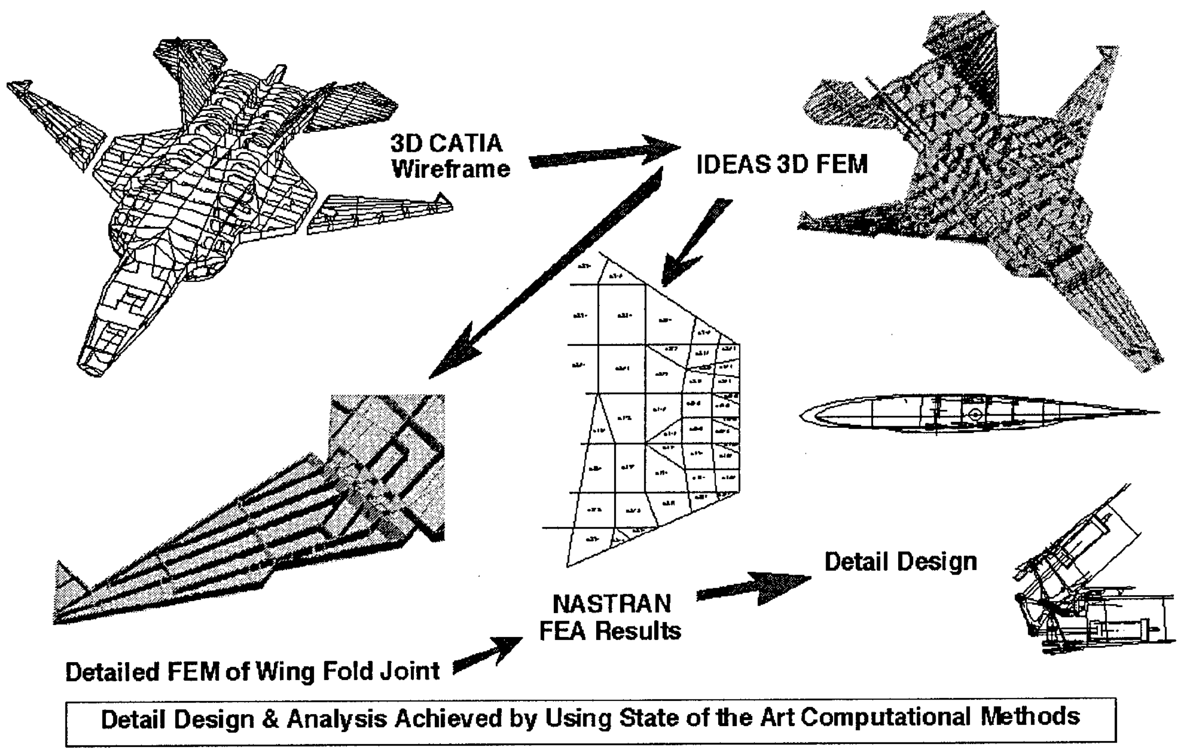


Figure 3 CAD is the Backbone of Integrated Design

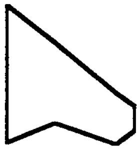
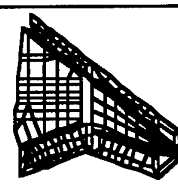
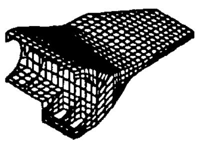
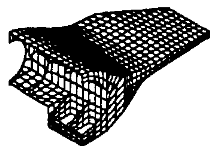
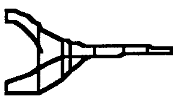
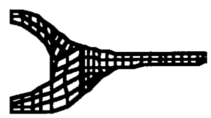
Method/Usage - Function	Inputs		Outputs	
• REV/Conceptual Design • Initial Wing Layout, Sizing		• Wing Planform Geom • Aircraft Weight, CG • Max Load Factor		• Initial Spar, Rib Layout and Sizing • Initial Skin Sizing • Course Finite Element Model • Wing Structural Weight Estimate
• ASTROS/Prelim. Design • Multidisciplinary Design Optimization		• Initial Structural Finite Element Model • Design Constraints (Strength, flutter, Buckling, aeroelastic Effectiveness • Aircraft Flight Envelope, Critical Maneuvers		• Optimal (Minimum Weight) Structural Sizing • Identification of Critical Load Paths • Structural Weight Estimate
• Mechanica/Detailed Design • Geometric Optimization		• Initial Structural Component Geometry • Geometric, Structural (Strength, Buckling) Constraints • Critical Static Loads		• Optimal Structural Element Placement, Geometry • Detailed Structural Sizing • Refined Finite Element Model

Figure 4 Structural Optimization Methods

The multidisciplinary structural sizing codes such as MBB Lagrange and ASTROS (illustrated in Figure 5) perform structural optimization under simultaneous static, dynamic and aeroelastic constraints.

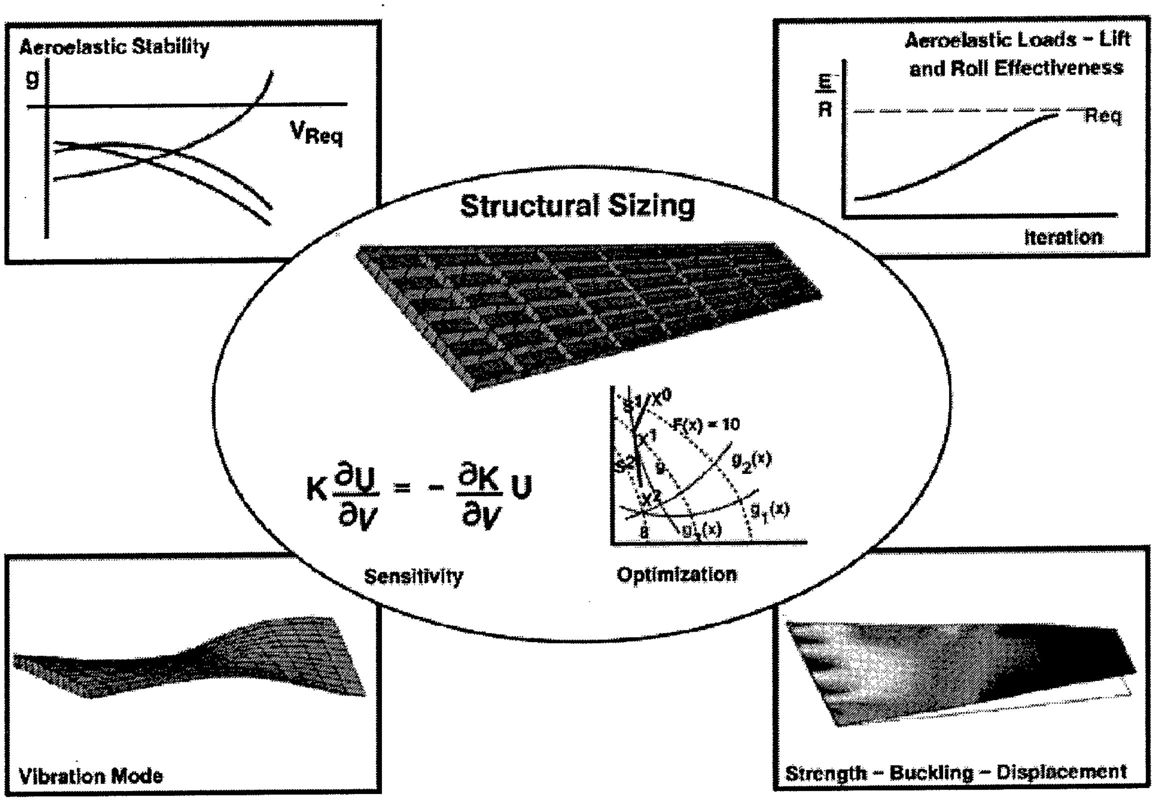


Figure 5 ASTROS Multidisciplinary Structural Sizing

A recent design study of the vertical fin for the Eurofighter EF2000 provides an example of combined aerostructural optimization. This example, using the same structural and aerodynamic model, is an approach to an integrated design analysis with not only structural sizing variables t, but also three additional aerodynamic design variables

- taper ratio λ
- aspect ratio Λ
- surface area S

Starting from an initial fin geometry (figure 6), the aerodynamic shape parameters and skin thickness were varied, subject to aeroelastic efficiency and strength constraints to achieve minimum structural weight with maximum lateral load capability. The optimized solution (figure 7) allowed a 7.5% reduction in structural weight and a slight increase in lateral load in exchange for a 10% reduction in fin aspect ratio.

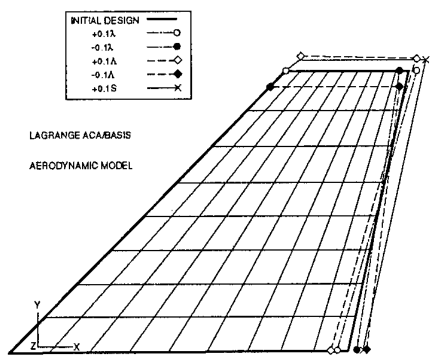


Figure 6 Aerodynamic Shape Study of EF2000 Vertical Fin

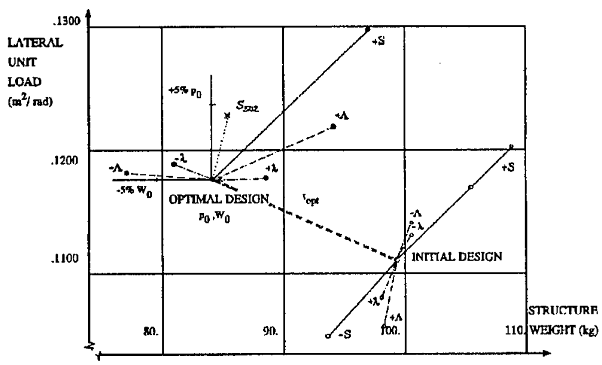


Figure 7 Aerostructural Optimized Solution of EF2000 Fin

Design to Cost is a recent concept which considers cost as an independent variable (along with the usual performance variables of range, payload, speed, signature, etc.) when balancing system characteristics. Design to Cost is required in the current US DoD Streamlined Systems Acquisition Specification, DOD5000. Design to Cost requires accurate cost models tied to rapid preliminary design tools in order to make timely design decisions for weapon system concept definition. Cost models may take either a "bottoms up" or a "top down" approach to cost estimating, using either discrete feature based models or parametric analysis of historical data. Consider a recent design trade study of a fighter composite fuselage skin, shown in Figure 8.

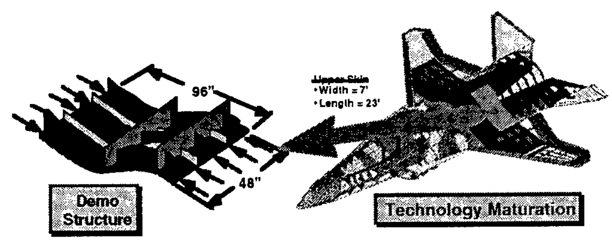


Figure 8 Fighter Fuselage Skin for Weight/Cost Trade Study

A structural sizing code used for preliminary design was integrated with a cost model for manufacturing of composites. The resulting parametric design carpet plots presented as a function of cost (figure 9) instead of the usual weight lead to heightened awareness of affordability in engineering design decision making.

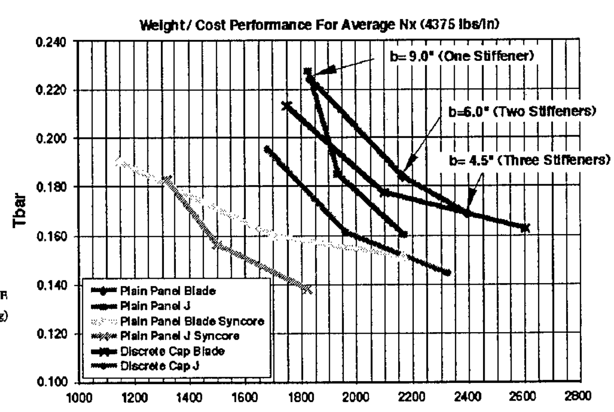


Figure 9 Weight Cost Performance

Computational Fluid Dynamics (CFD) is the analytical tool of Aerodynamic Design. CFD provides predictive capability of aerodynamic performance (forces and moments, pressure distributions) at reasonable cost and accuracy, particularly for attached or moderately separated flows. It is used routinely for steady, subsonic, transonic, and supersonic flow over and through complete vehicle configurations. Some flow phenomena not completely solved include aeroacoustics, laminar boundary layer transition, non-continuum and reacting flows at hypersonic speeds, and unsteady structural interactions. The types of CFD solution algorithms, in order of increasing accuracy are shown in Figure 10.

The challenge of CFD is the availability of computational resources, both memory and speed, shown in Figure 11, required to achieve these increasing levels of accuracy.

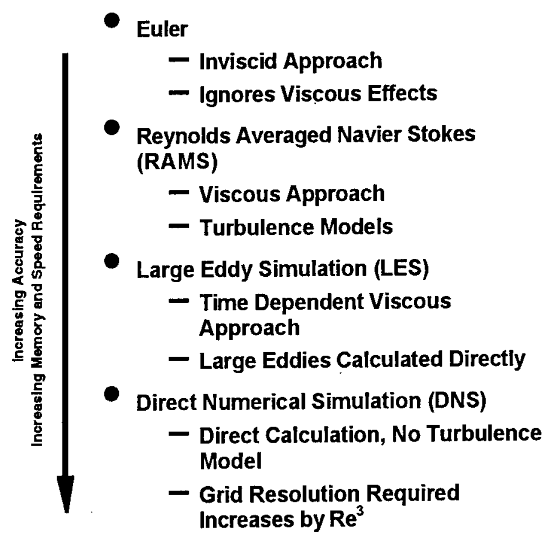


Figure 10 CFD Methodologies

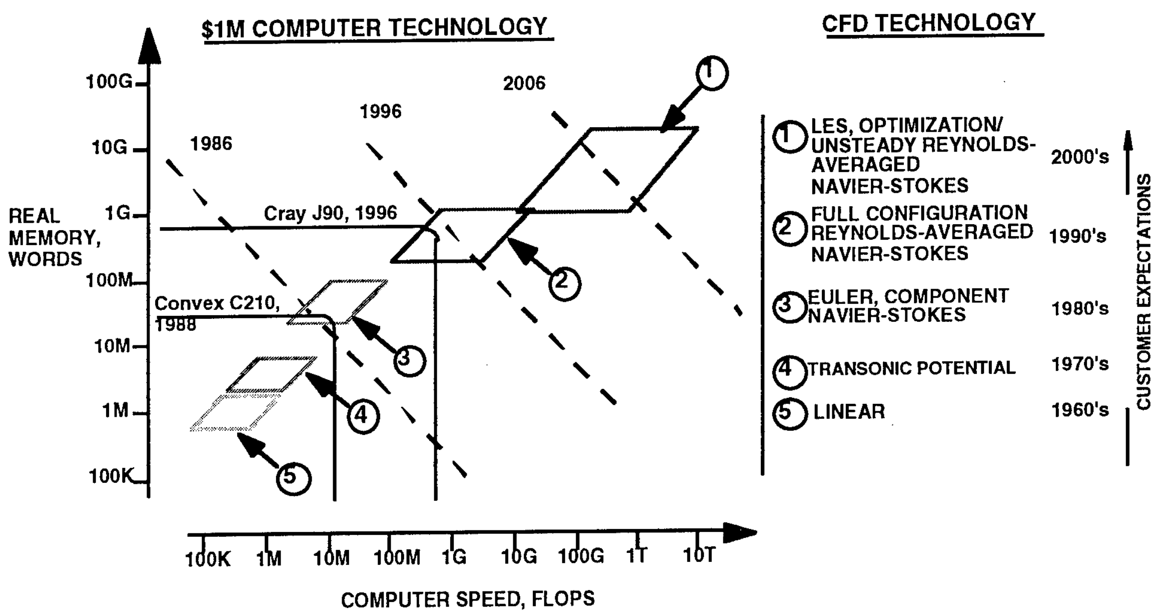


Figure 11 CFD Technology vs. Resource Trends

As a result, CFD is not yet cost-effective for database generation. Wind tunnel testing remains the most affordable method for generating the many datapoints required to characterize the performance, stability, control effectiveness and inlet compatibility of a maturing design. CFD has proved to be most effective as a design tool, analyzing critical design points, rapidly trading multiple design options, and refining configurations based on detailed wind tunnel data. CFD provides a complementary function to wind tunnel testing. It can be used to optimize the wind tunnel test matrix, reduce testing for and generally ensure that models perform as planned. One strategy to manage the computational affordability of CFD analysis is to selectively apply the solution algorithms, increasing model and solution fidelity as the design progresses from conceptual through detail design. Lower order solution schemes can be effectively used to develop trends, identify design critical features for detailed analysis with the more computationally intensive algorithms.

Currently, grid generation is a labor intensive item for CFD modeling. Surface geometry definition from CAD models remains difficult. Unstructured grids, which are useful for deforming and moving body cases, allow volume grid generation process to be accelerated; however, they pose difficulties for viscous flows (boundary layers and shear layers) and aeroacoustics.

Automation of hybrid methods for combined structured and unstructured grids will facilitate solution efficiency. Work will continue to develop more accurate turbulence models. In the future, multidisciplinary CFD analysis will include the effects of engine models, subsystems, structural interactions, and signature management. Application of CFD will continue to increase with improvements to computer speed and memory. RANS will be the dominant solution method of the foreseeable future. Based on historical experience of tenfold increases in computer capability every 5 to 7 years, full configuration analysis by LES is not anticipated for at least 20 years.

The low observable design process is a complementary, iterative process of analysis and test, as shown in Figure 12. The physics of radar cross section (RCS) is well understood. Recent advances in computing capability have enabled RCS design to progress from simple faceted structures to complex gaussian shapes. The prediction of RCS of real systems is often based on "Budget codes," which add the RCS contributions from different scatterers assumed to be non-interacting.

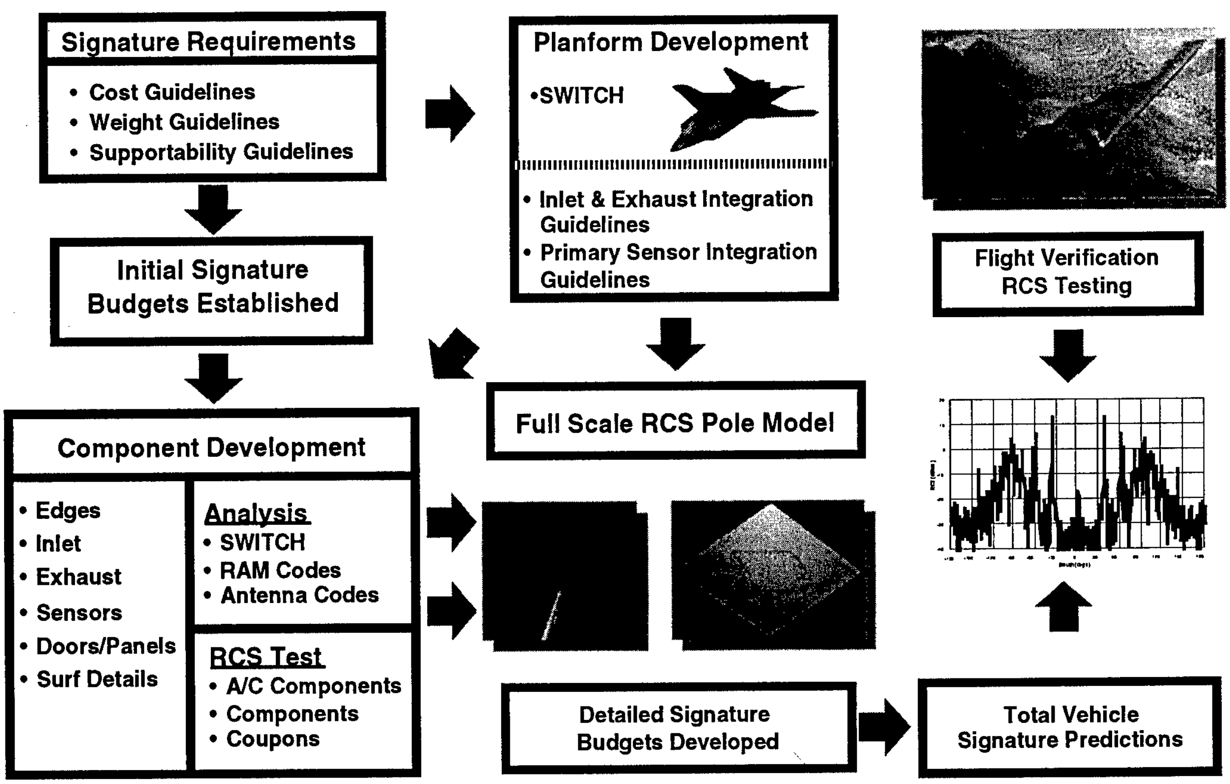
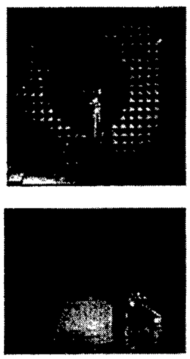


Figure 12 Low Observable Design Process

In the past a great deal of input to budget codes came from direct electromagnetic measurement, Figure 13.



- **Identify Key Areas to Focus Experimental Attention**
- **Reduce Number of Experiments Needed for Design of Real Systems**
- **Minimize Design Iterations**

Figure 13 Computational Electromagnetics Focuses Testing

Based on recent advances in RCS computation, the large number of experiments needed for design of real systems may be replaced by analytical predictions, and expensive range testing of full scale models and components, Figure 14, may be reserved for design validation only.

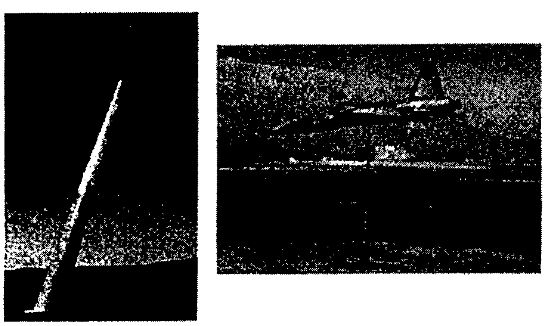


Figure 14 CEM Reduces Dependence on Full Scale Range Testing

One analytical tool which facilitates rapid RCS design is the "SWITCH" code. SWITCH is a hybrid code which captures the best features of the Surface Integral Equation (SIE) method (sometimes called Method of Moments) and the Finite Element (FE) method, as shown in Figure 15.

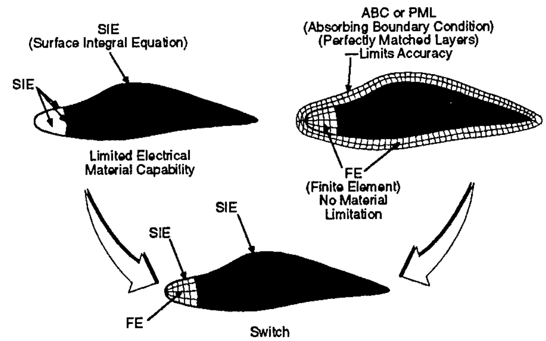


Figure 15 CEM Hybrid Solution Methodology

It provides the solution accuracy of the SIE and avoids volume truncation limitations of FE over the isotropic metallic regions of the body. By using finite elements over the radar absorbing material (RAM), it offers the capability to model thin layers of rapidly varying RAM material, without the piecewise homogeneous, isotropic approximations required by the SIE method. Coupled with a fully curvilinear geometry gridding routine and an anisotropic, inhomogeneous material model, the hybrid solution scheme achieves the objective of accurate, affordable solutions of relevant configurations with realistic geometries and materials. Figure 16 shows the comparison of the SWITCH code predictions with direct electromagnetic measurement for the VYF218 reference fighter model.

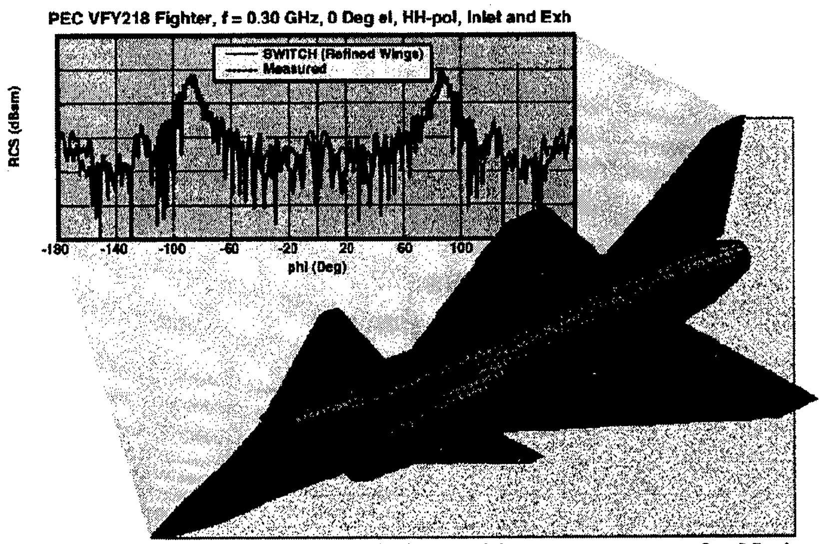


Figure 16 Comparison of SWITCH Predictions with Measurements for Notional Fighter

As shown above, the analytical tools of the integrated design environment contribute to systems affordability through reduction of design cycle time and cost conscious design decision making. They provide the ability to perform rapid trade studies of multiple design concepts, to optimize and reduce test programs, to refine configurations analytically, to monitor and manage system development uncertainty. Computing and communications capability have been the key pacing factors in the evolution of integrated design. Our vision for the future (Figure 17) is a fully multi-disciplinary design environment, which uses a master three-dimensional geometry database to ensure integrated product and process development. Artificial intelligence and knowledge based rules for adaptive meshing, automatic grid refinement, hybrid solution schemes and iterative error management will contribute to user friendly design tools. However, integrated design can never be a push-button process. Confidence in this next generation of integrated design tools will be derived from design validation testing and the continuing active involvement of the team of experienced engineers and technologists to guide the design process to success.

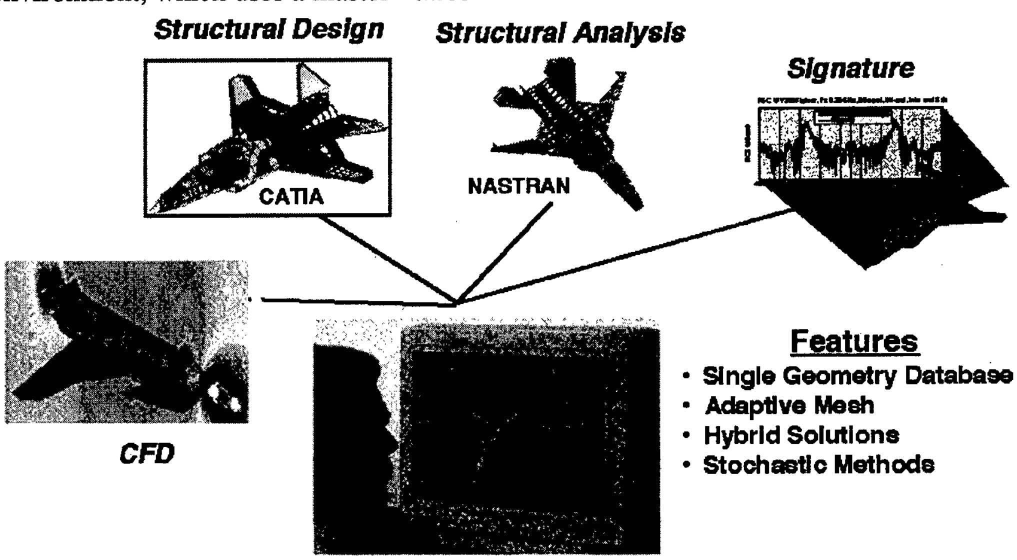


Figure 17 Vision of the Future - Integrated Multidisciplinary Design Optimization

VIRTUAL PRODUCT DEFINITION
THE KEY TO AFFORDABLE AND SUPPORTABLE PRODUCTS

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1.0 SUMMARY

Virtual product definition (VPD) is an emerging process which capitalizes on recent advances in computer hardware and software to enable a Paradyne shift in the way products are developed. Engineering, tooling, manufacturing and product support data that fully define the product is created and managed in a synthetic environment. All product definition geometry developed in the VPD process is defined as three dimensional solid digital models. This data is stored in an electronic medium with a common geometry database providing the primary linkage between the product design and a newly developed set of integrated design, analysis, manufacturing and supportability tools. The geometry related information that describes the product may be viewed and interacted with in a synthetic environment in the same way physical mockups were used in previous design processes. This geometric representation forms the most visible part of a Virtual Prototype.

Simulations of product fabrication, assembly, and the factory floor provide a synthetic environment for the manufacturing and tooling engineers to assess product producibility. These simulation tools, combined with process flow analysis and optimization, form the basic toolset for virtual manufacturing (VM). Similar simulations of the product support environment using the three-dimensional digital definition and virtual reality techniques allow the supportability engineers to assess various support concepts and suggest improvements. These earlier manufacturing and support inputs allow design and producibility changes to occur when they are most important to the product, but are the least costly. VPD has demonstrated the ability to generate higher fidelity product designs and redesigns and develop them in a shorter timespan, at significantly lower product costs.

2.0 VIRTUAL PRODUCT DEFINITION

Virtual product definition (VPD) is the product development process that creates engineering, tooling, manufacturing, and support data that fully defines the product and allow the interaction of this data to improve life cycle costs and shorten design and cycle time. The product and processes are exercised in a virtual environment to validate their form, fit, and function. The VPD data is stored electronically with a common geometry database providing the primary linkages between various analytical and simulation software tools.

The product of VPD is a virtual prototype. Virtual prototypes provide a superior means of visualizing any aspect of the product design, its fabrication and assembly, and the environment it will be used in. The virtual prototype is comparable to a physical mockup with some major advantages. Physical mockups are used to verify aspects of the design that are not easy to understand or demonstrate the total design once it is complete. Changes based on findings from physical prototypes are costly to implement since the design is mature. In contrast, the virtual prototype is built electronically in three-dimensional solid models and evolves throughout the design process. VPD is introduced in the Configuration Baseline phase of the Integrated Product Definition (IPD) process following completion of the of High Level Requirements and Initial Concepts phases. The virtual prototype rapidly matures throughout the Conceptual Layout (CLO), Assembly Layout (ALO), and Build-To-Package (BTP) phases as more product detail is added. As shown in Figure 1, the foundation of the VPD process is an integrated suite of software tools for design, analysis, manufacturing, and supportability. These tools are employed from the initial concept stage through the design evolution to a build-to-package release, and have resulted in higher fidelity and more supportable designs in a shorter period of time.

The virtual prototype (shown in Figure 2), is an integration of data from various sources that define the total product and its environments. Common geometry, feature based design of structures and subsystems, rapid loads and dynamics, and virtual manufacturing are some of the key areas required to effectively define a three-dimensional solid product. A common geometry digital database of three-dimensional CAD surfaces is essential in beginning the solid modeling, finite element modeling (FEM), and load generation process. Rapid modeling tools utilizing two-dimensional definitions of the structural arrangement and the common geometry database have significantly reduced the FEM modeling time. Designs can be quickly updated through the use of feature based design techniques.

The introduction of simulation tools in a virtual manufacturing environment enables proactive involvement by manufacturing and tooling engineers early in the design process, and the ability to provide inputs based on analysis. As shown in Figure 3, virtual manufacturing validates the product definition through realistic visualization of the tooling, assembly, and inspection processes. This early visualization allows for the manufacturing plan to be optimized and more efficient work instructions and training to be developed and implemented. This efficiency translates into reduced product cost and shorter schedules.

Paper presented at the AGARD Symposium on "Future Aerospace Technology in the Service of the Alliance", held at the Ecole Polytechnique, Palaiseau, France, 14-17 April 1997, and published in CP-600 Vol. 1.

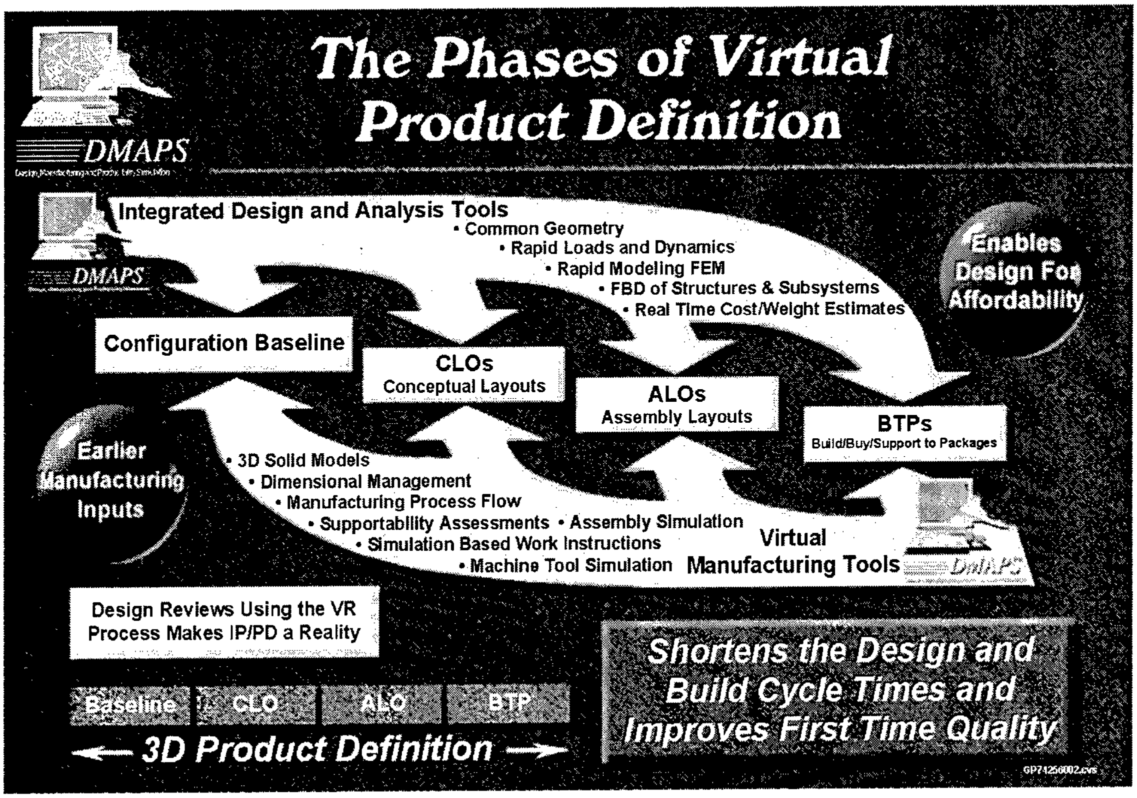

Figure 1. "The Phases of Virtual Product Definition (VPD)"

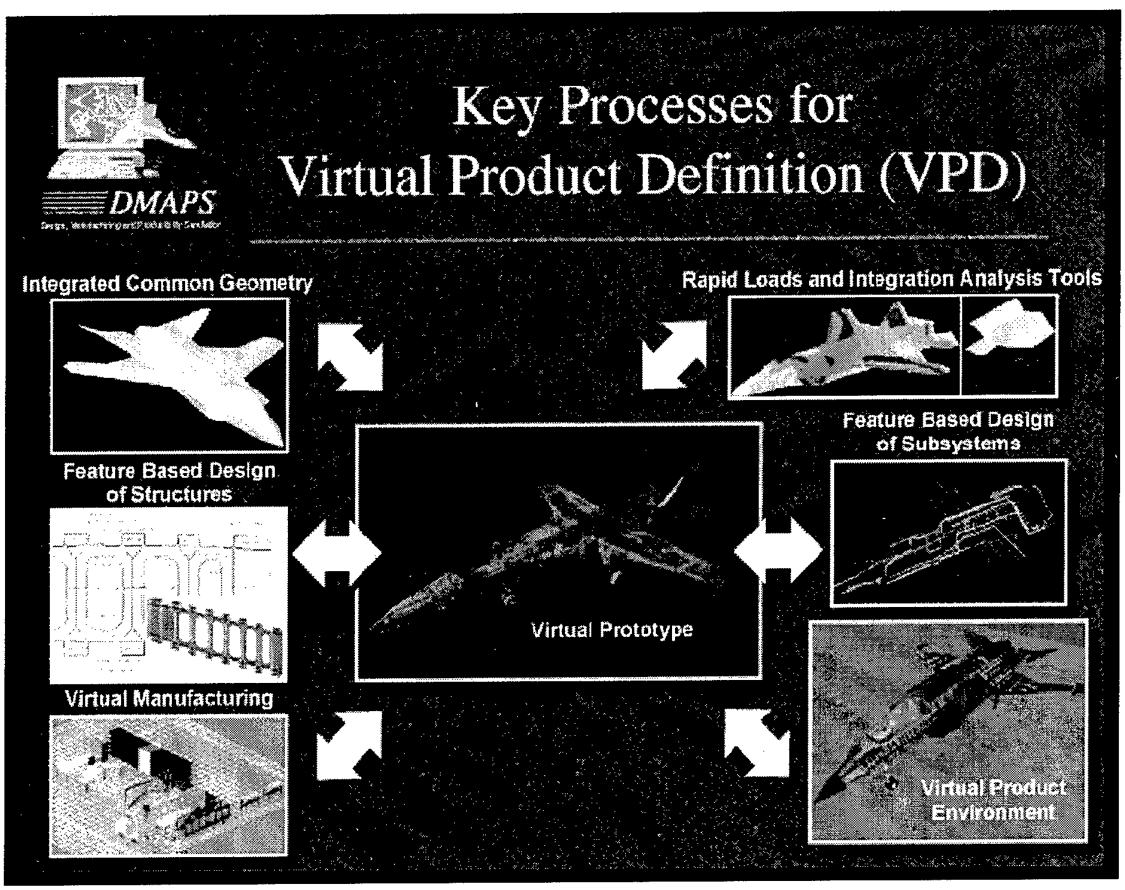

Figure 2. "Key Processes for Virtual Product Definition (VPD)"

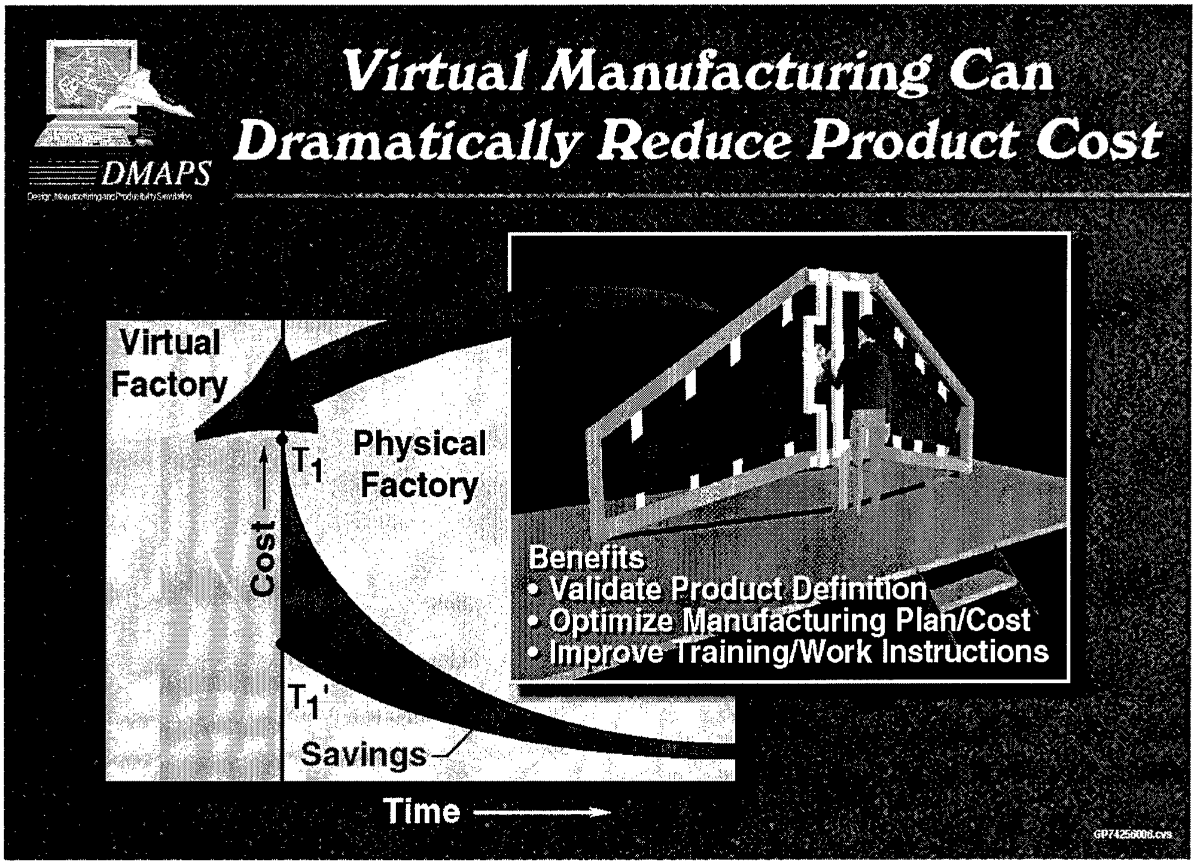

Figure 3. "Virtual Manufacturing Can Dramatically Reduce Product Cost"

Utilizing the VPD process leads to improved product definition and quality early in the design cycle (Configuration Baseline and CLO), which in turn results in more detailed product definition up front and less changes downstream. Problem areas can be detected earlier by the IPD team, and corrected while the design is still flexible. The VPD process has been employed on several new and existing product redesign projects within MDA. As indicated by Figure 4, staffing using the VPD process ramps up and peaks earlier than the typical program, but also ramps down earlier and peaks at a lower level. Data collected from pilot projects indicate a projected reduction in design cycle time and personnel of 33% and 25%; respectively, for a typical aircraft fighter program.

2.1 Design Process

The new design process of VPD uses an integrated approach consisting of personnel, process development, and simulation tools throughout the product design cycle. This provides a better communication mechanism for design integration resulting in a higher quality design while achieving cost and time reductions. Evolution of the new design process compared to a Traditional or Old Design process is shown in Figure 5. Note that the Old Design Process described here refers to the initial uses of an IPD design process in aerospace such as the design development of the F/A-18 E/F, F-22, or 777.

The two tiered, six phases of product design have common attributes in each of the design approaches. The Old Design process focuses on performing each design phase sequentially and often without the full IPD team multi-discipline interaction. The New Design process requires the IPD team to be fully and completely populated very early in the design process. This includes the traditional IPD design engineering team expanded by manufacturing, tooling, quality, supportability, etc. Configuration synthesis tools are used for integrating the High Level Requirements and Initial Concepts phases into the configuration baselines. In CLO, the configuration baseline is further defined to satisfy all the product flow down requirements. The full use of VPD early in CLO allows the design teams to make smarter decisions very early on during the product development where statistically 70% to 80% of the product cost gets locked in. The ALO phase finalizes the design and insures product form, fit and function. Build-to-Packages containing complete information and definition of the product are then prepared for release. The BTP is based on and must conform to the ALO definition. Traditional design used two-dimensional CAD wireframe, MIL-STD-100 drawings and physical mock-ups during these last three phases. VPD eliminates the need for MIL-STD-100 two-dimensional drawings and many of the physical mock-ups by using the three-dimensional solid master models and virtual prototypes. These simulation tools provide the design teams with insight and visualization into the development of the product never before available.

The three-dimensional product definition design process begins by creating a common digital geometry to be used by all disciplines to assure everyone is working to the same baseline integrated product database (shown in Figure 6).

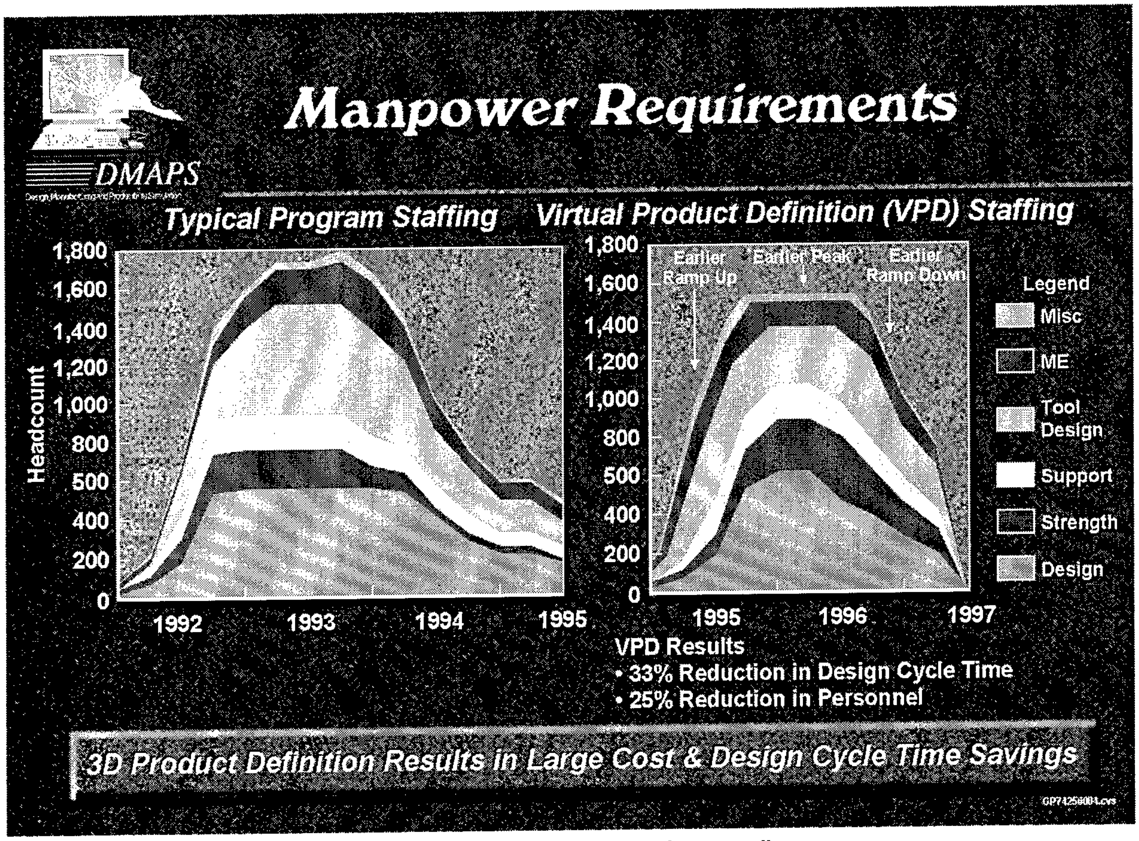

Figure 4. "Manpower Requirements"

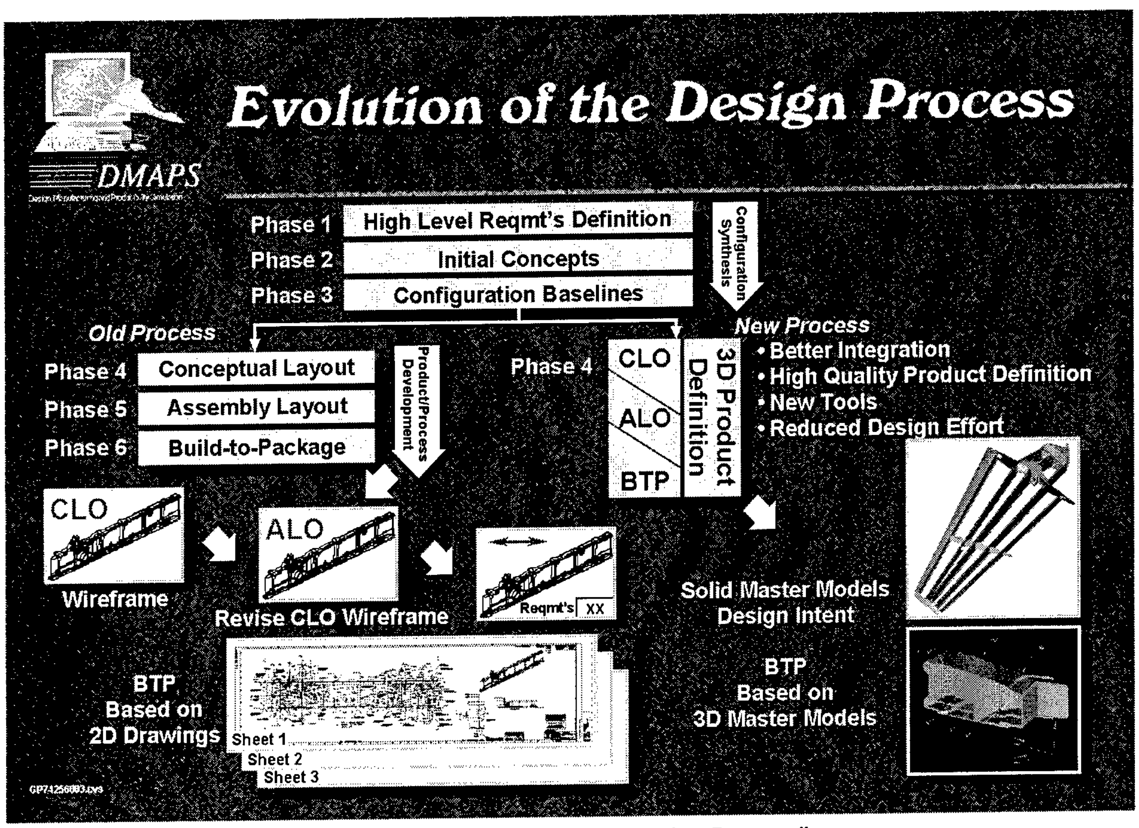

Figure 5. "Evolution of the Design Process"

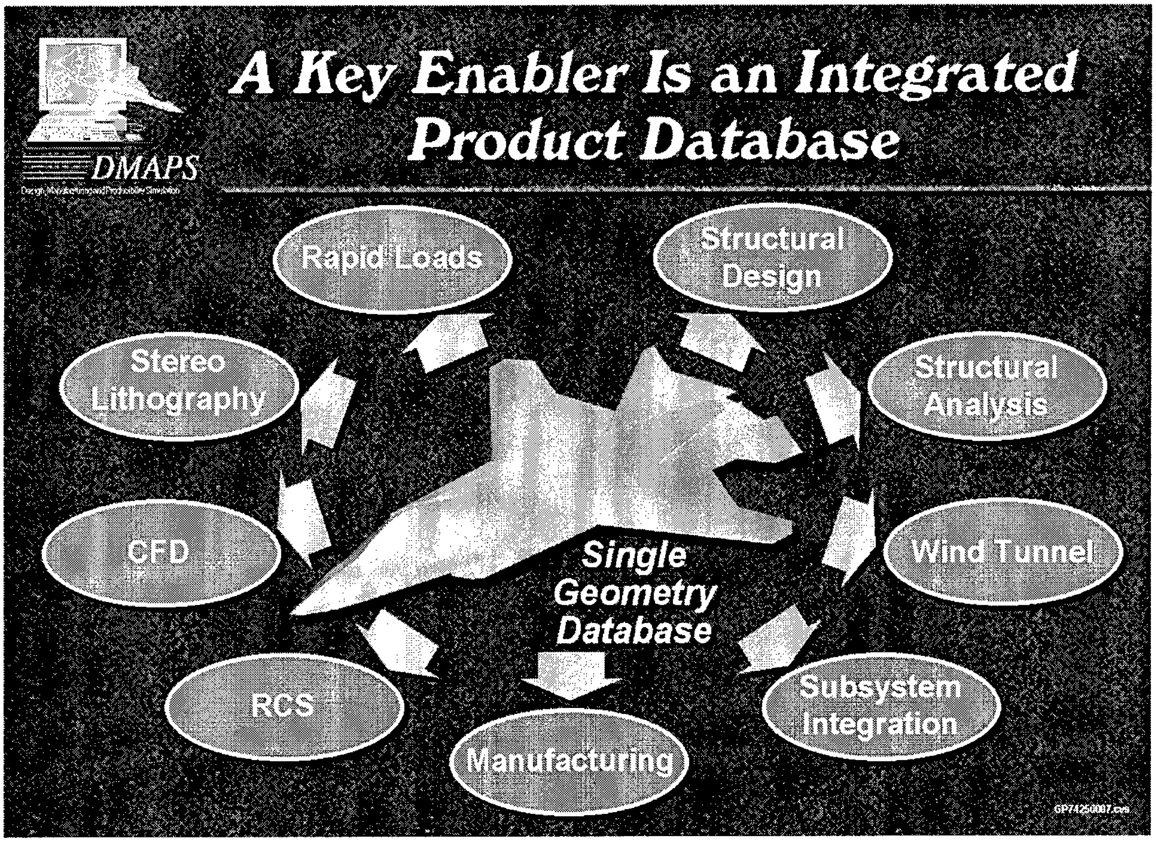

Figure 6. "A Key Enabler in the Integrated Product Database"

During CLO, basic design requirements are identified, parametric model(s) that control major structural locations are defined, datums for these structures are established, and the building block for subsequent detail part models are created. Parametric plate solid models are built from the integrated common geometry defining the vehicle envelope. These parametric models also serve as input to the integrated analysis tools for FEM development. The plate solids are the starting point for the virtual manufacturing environment, allowing tool development and assembly simulation studies to begin very early in the design process. Plate solids also allow subsystems engineers to study component locations and systems routing. Design evolution is monitored in the virtual product environment (VPE) where the IPD teams review structure, systems, tooling, manufacturing, and strength issues in a full three-dimensional digital environment (as shown by Figure 7). Results of these reviews are fed back into the design requirements and model and/or analysis are updated as required.

As the assembly layout phase begins, the vehicle geometry has been finalized, the structural arrangement is mature, detailed structural parts replace plate solids, sub-systems definition is maturing, tooling and manufacturing simulations reflect the assembly build sequence, FEMs are defined to a high level of detail, and vehicle loads have been finalized.

Part features are defined parametrically, with the ability to update rapidly as required based on geometric changes and strength sizing inputs (shown in Figure 8). In instances where parts are similar, a single parametric model can easily be recreated at a new location and rebuilt based on the surrounding geometry and design intent inherent to the part parametrics. This ability greatly reduces part creation time and insures uniformity of design. Dimensional management analysis allows the IPD team to analyze different fabrication, manufacturing, and tooling scenarios and identify unique geometric part requirements. As manufacturing simulations mature, dimensional management documentation is embedded into the solid part model. This information is used to identify datums, key characteristics and tolerances, thus ensuring producibility and a six-sigma fit. As the airframe structure matures, subsystems tools rapidly mature system component placement and line routing. Supportability assessments based on simulations of structures and subsystems are evaluated by the IPD team. These supportability assessments provide inputs to the final design that assure product viability. This also helps minimize or eliminate downstream product redesign.

In the build-to-package phase, the solid model of the product or tool is considered the master model. No longer is a two dimensional drawing the master product definition, that role is now filled by the solid model. Datum's, key characteristics tolerances, tooling provisions, as well as any other required product build, assembly, and installation data are embedded in the product solid model. The product BTP contains the product solid model and all information necessary for subsequent part fabrication, final tool design, fit-function checks, assembly and installation, and detailed strength analysis. Additional buy-to packages for subsystems equipment and support-to packages for final product field servicing are developed during this time and are based on the product solid models.

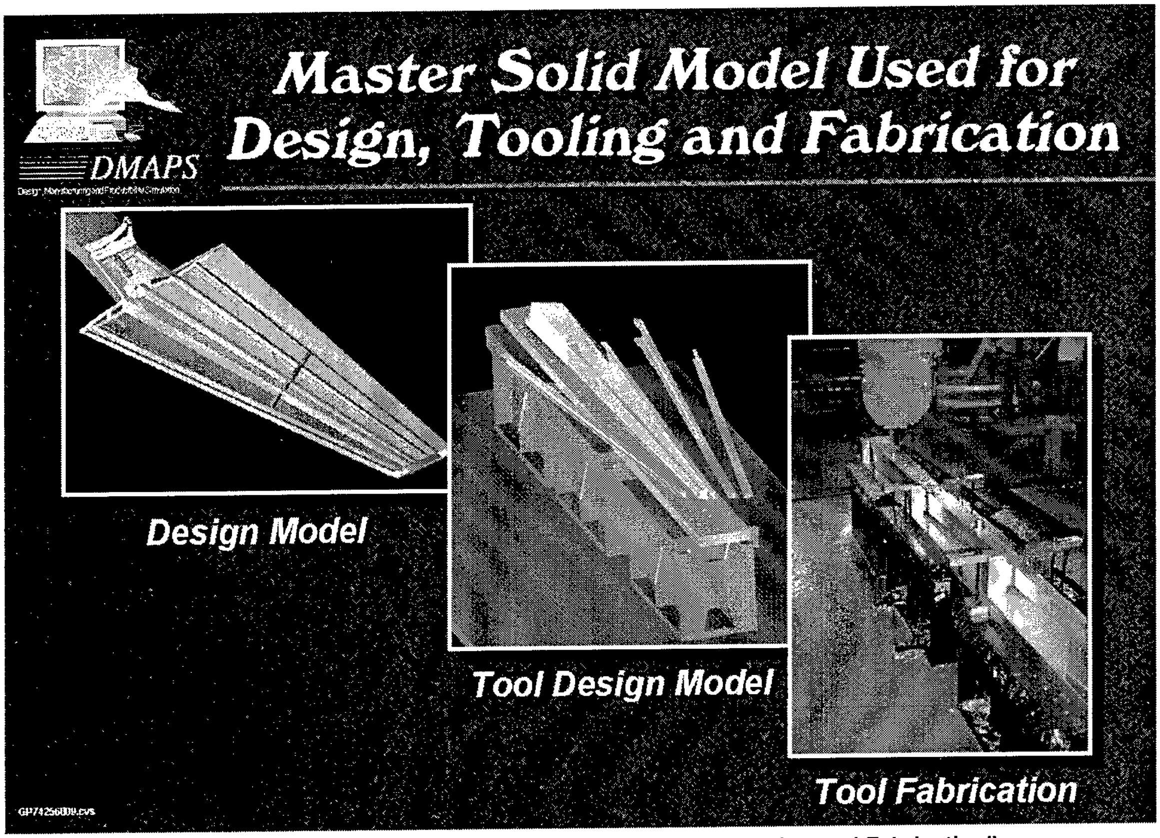

Figure 7. "Master Solid Model Used for Design, Tooling and Fabrication"

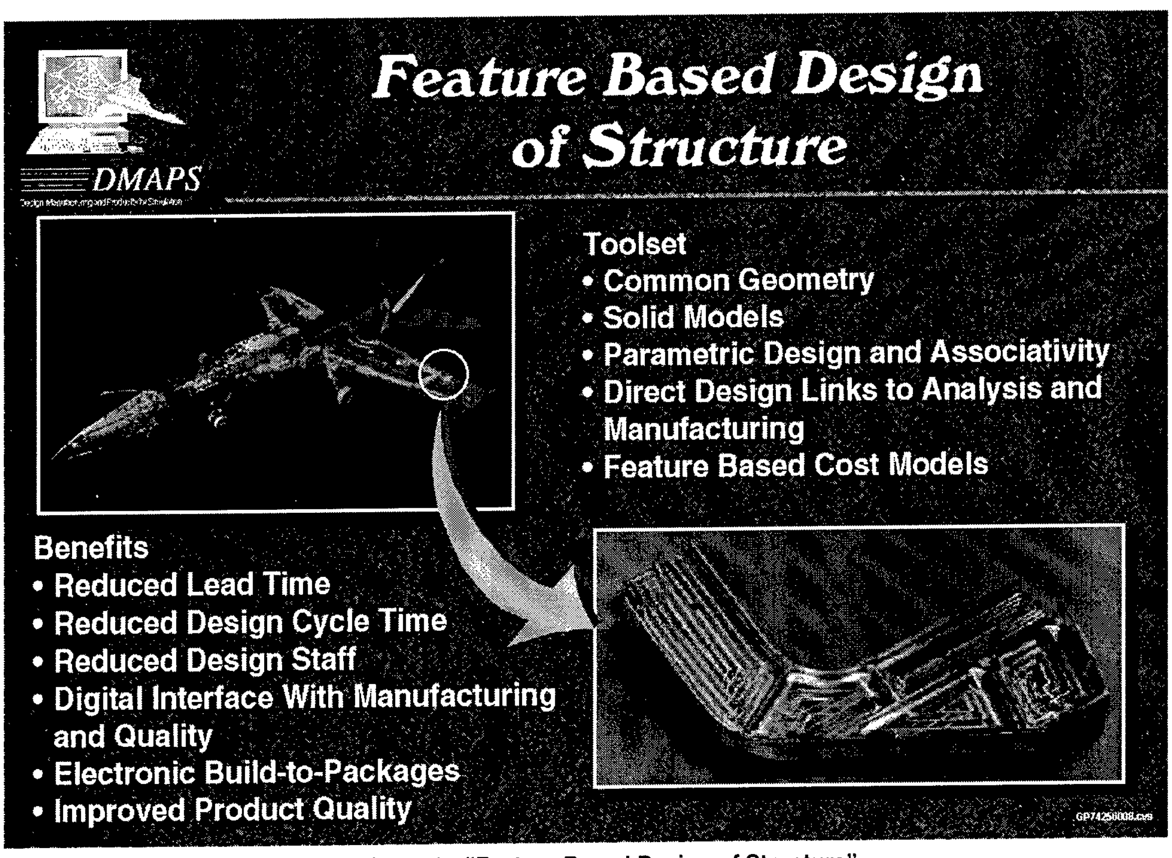

Figure 8. "Feature Based Design of Structure"

2.2 Dimensional Management

Dimensional management (DM) techniques are employed to ensure producibility as well as to predict and control the impact of variation on product form, fit, and function. DM should be used throughout the product development cycle with initial assessment of product requirements against the product and process being developed in the CLO phase. The majority of the DM activity occurs in the ALO phase, where variation analysis methods are employed to optimize tolerances, datums, and assembly approaches. This information is documented and released in the build-to-package. Coordination of tolerances, datums, and assembly sequences are facilitated by a multitude of VPD tools and products. These include the three-dimensional solid parts and tooling, the virtual assembly simulations, the three-dimensional tolerance analysis, and integration of process capability (shown in Figure 9).

Use of dimensional management tools ensure that the product's optimal set of tolerances, datums, and assembly sequences are defined, along with key characteristics. Key characteristics of the product are features whose variation greatly impacts the functionality of the design, and can be identified with three-dimensional tolerance analysis software (e.g., VSAÆ – Variation Simulation Analysis). This software predicts the percent contribution to variation of a specific design feature. Key characteristics are then embedded into the 3D solid definition and used in the integrated quality plan, and for subsequent statistical process control (SPC).

2.3 Virtual Manufacturing (VM)

Virtual manufacturing consists of simulating the fabrication process to assess producibility, modeling the assembly process to validate tooling, analyzing the assembly process to verify the rate production capability, developing an Electronic Build Plan (EBP) to accelerate shop learning and validating the numerically controlled (NC) programs to minimize or eliminate costly scrap and rework. Effective use of VM assures the ability of the product definition to achieve form, fit and function before significant investments are committed for production.

The approach to VM is centered on using the solid model digital geometry and 3D graphic simulation tools (shown in Figure 10). This toolset consist of modeling software for virtual assembly, process simulation, and NC/Automated Machine programming and simulation. As an example, ENVISIONÆ, a software package from Deneb Robotics, uses CAD solid model geometry created in Unigraphics to validate the proper design of tooling to ensure accessibility through the use of six degree of freedom motion, collision detection algorithms, CAD models of equipment, and human models in simulation. The introduction of ergonomic models results in designs of products, tools and processes that are consistent with the physical limitations of the operators. The development of preliminary labor standards directly from the simulation is another benefit of the process.

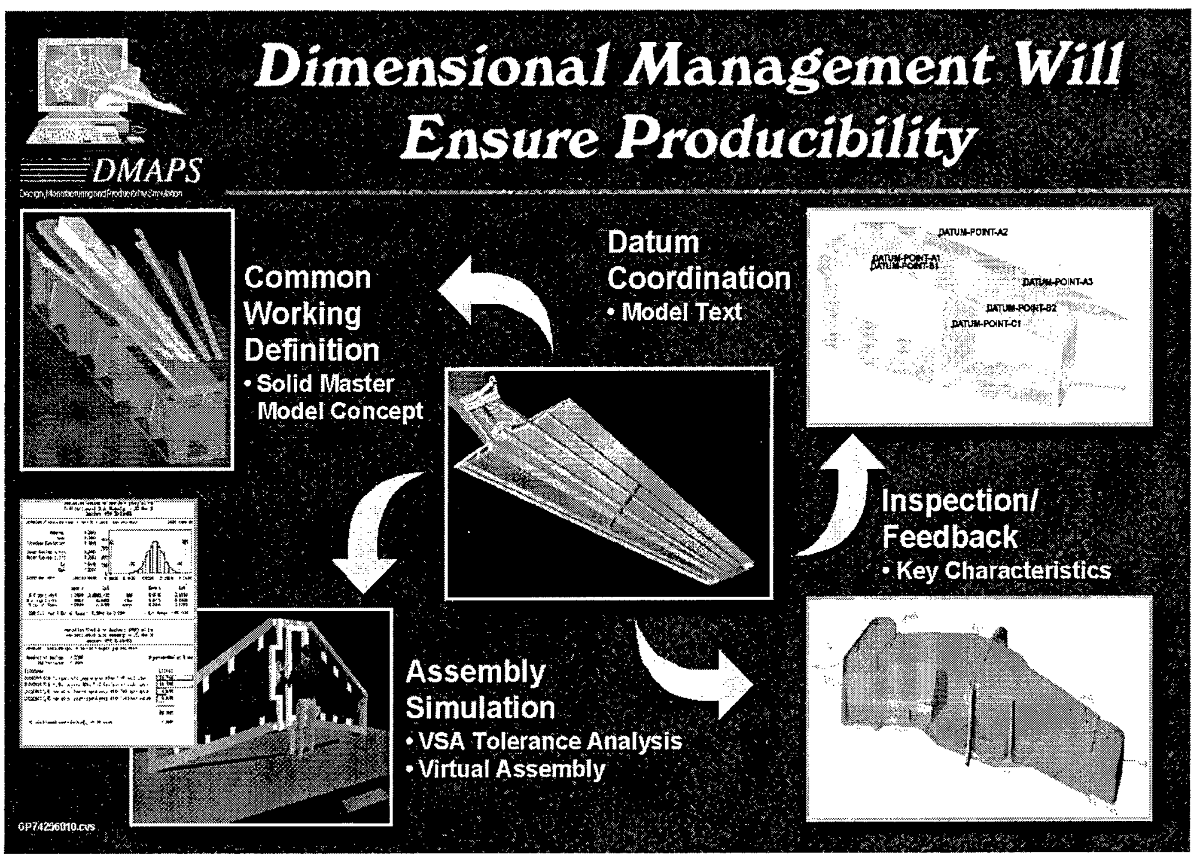

Figure 9. "Dimensional Management Will Ensure Producibility"

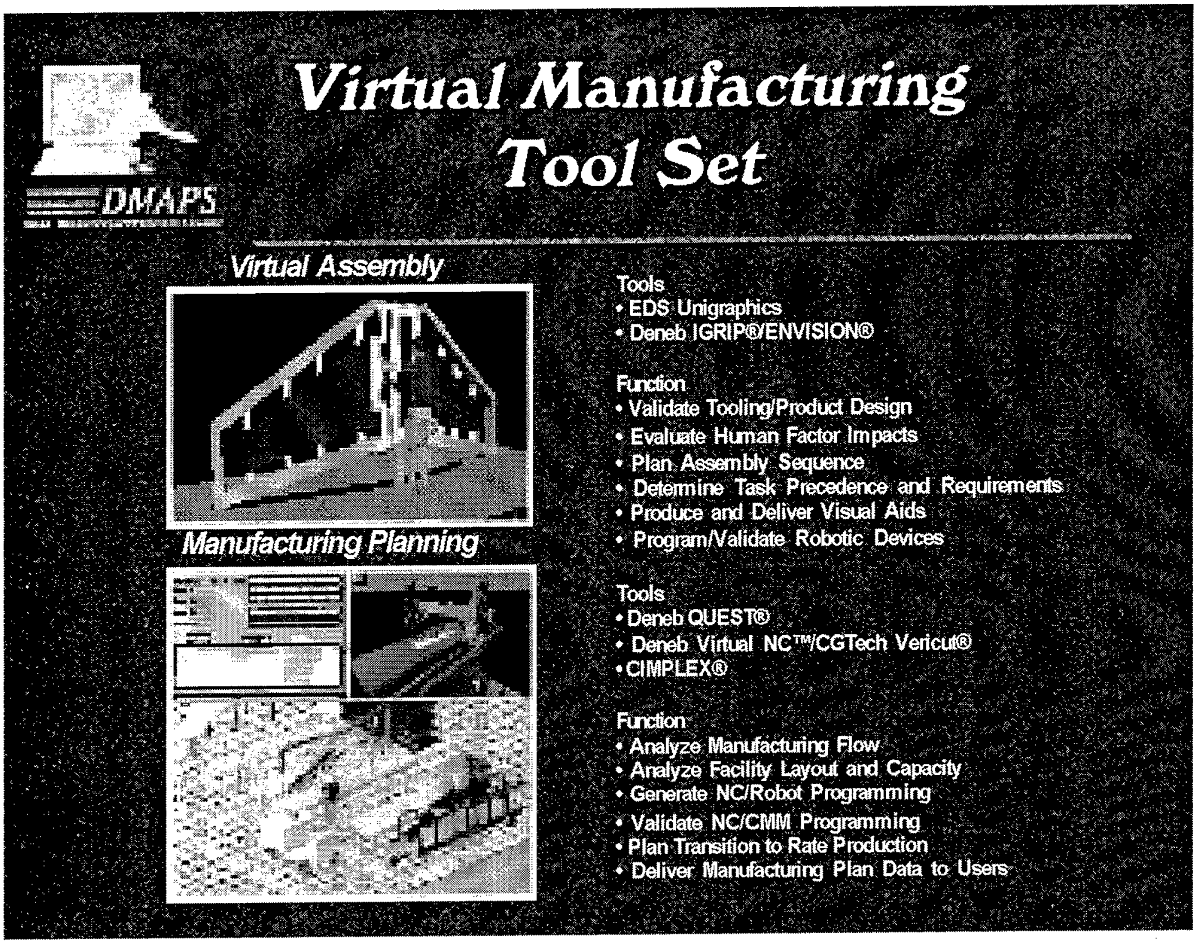

Figure 10. "Virtual Manufacturing Toolset"

The Virtual Manufacturing tool set, used in conjunction with design for manufacturing and assembly (DFMA) and variation simulation analysis (VSA) techniques, enables product and process improvements to be implemented in a virtual environment. This enables cost to be designed out of the production process making unit cost less sensitive to volume and rate.

Traditional NC program validation analyzes the material removal process, ignoring the machine tool. This is not adequate given the increasing complexity of NC machine tools and the difference between the cutter line source file and the post-processed data file that actually provides the instructions to the machine control unit. As an example, Virtual NC ™ from Deneb Robotics has been used to model a machine tool and its control unit logic. The resulting simulation is as close an emulation of the actual machining process as is technically possible today without physically cutting chips.

Use of assembly simulation tools like ENVISION® have enabled manufacturing engineers to prepare optimized assembly plans and sequences for release in the original build-to-package. Pilot projects have shown almost 90% of the tooling problems that are traditionally found during assembly of the first unit have been eliminated. By validating the product design concepts, tooling concepts and evaluating human factor requirements, assembly simulation is eliminating design, tooling, and planning rework as shown in Figure 11. This simulation/validation methodology assures constant build practices that contribute to higher quality products.

Aerospace assembly operations typically involve a large number of discrete tasks with numerous parallel paths. Three-dimensional process flow simulations (shown in Figure 12) are created using discrete event simulation software. The assembly process is defined using precedence diagram logic that is automatically converted into simulation control language. Resource utilization statistics are generated as outputs of the simulation run and interpreted by trained industrial engineers. These statistics provide the basis for informed decision-making, leading to an optimized manufacturing plan.

2.4 Electronic Build Plan (EBP)

The Electronic Build Plan provides an effective communication tool to define and validate the sequences and processes required to build the product before initial build (shown in Figure 13). The EBP is a major element of the Build-to-Package (BTP) which includes drawingless release and video work instructions.

As design intent is captured, a three-dimensional graphical simulation is developed to supplement or replace an operator's work instruction package. The manufacturing engineer determines the assembly sequence to be performed and then adds

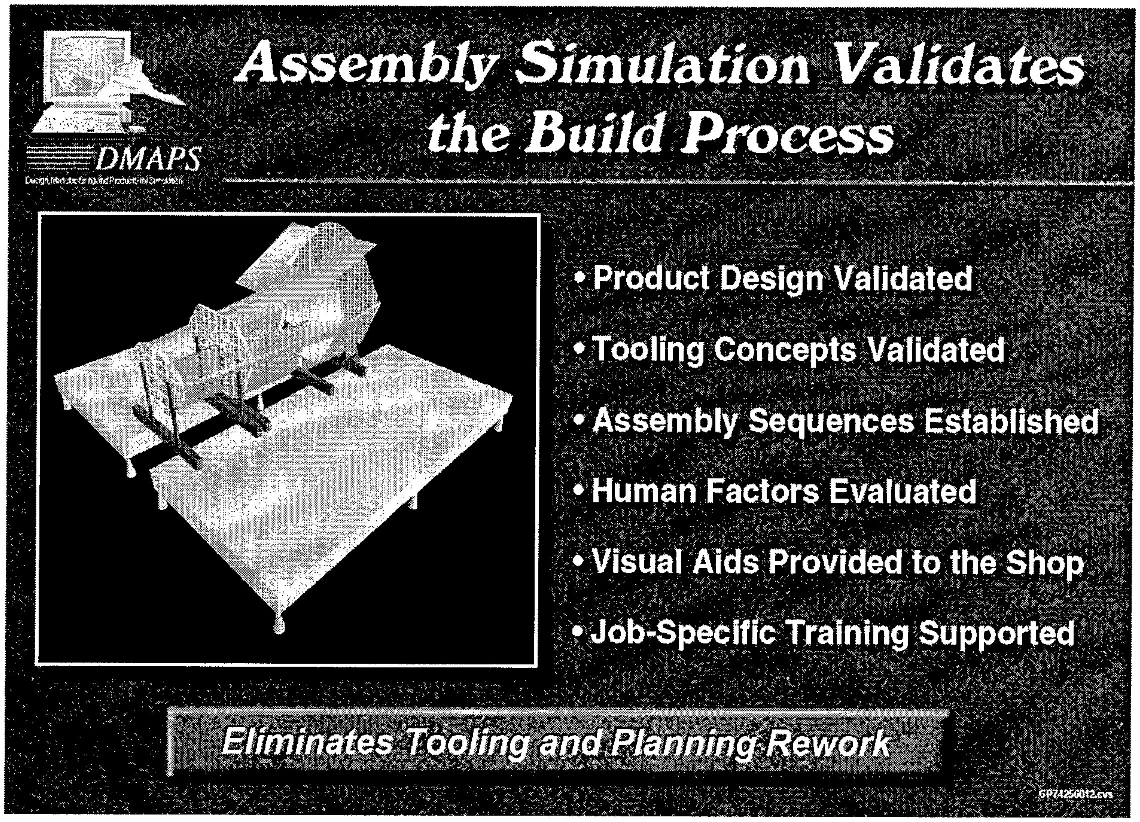

Figure 11 – "Assembly Simulation Validates the Build Process"

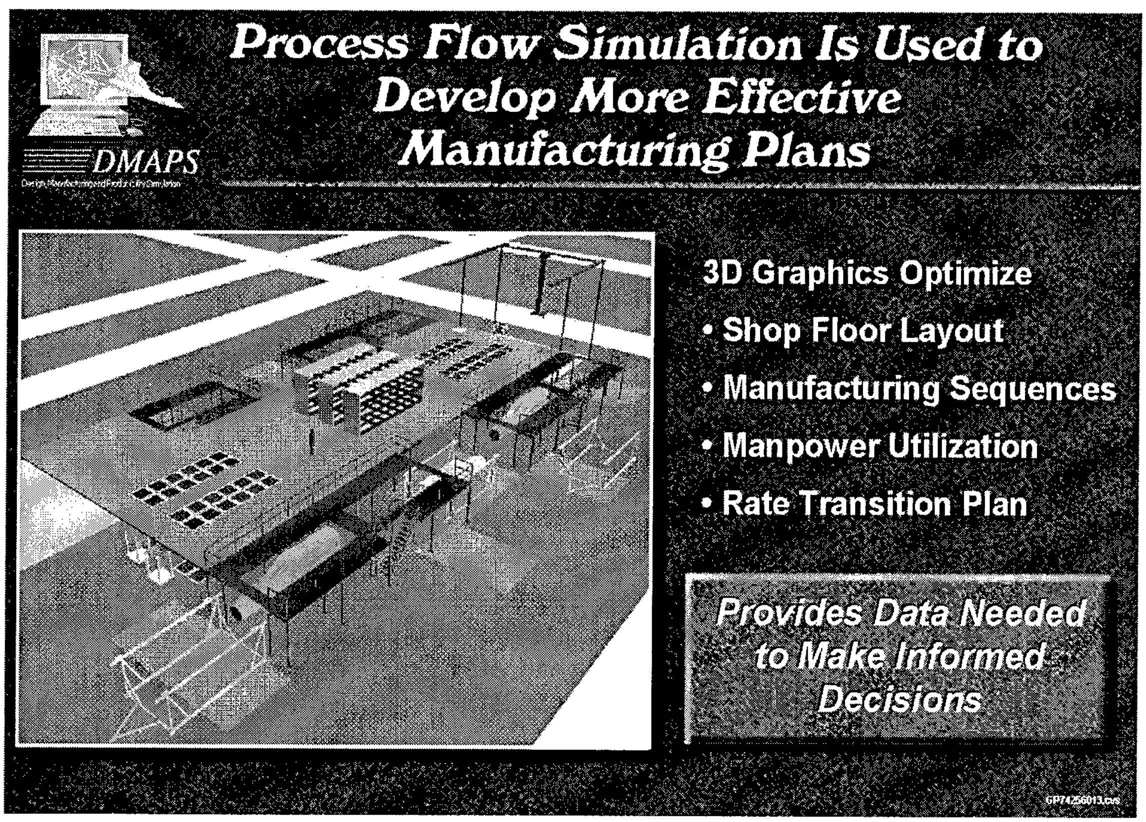

Figure 12. "Process Flow Simulation is Used to Develop More Effective Manufacturing Plans"

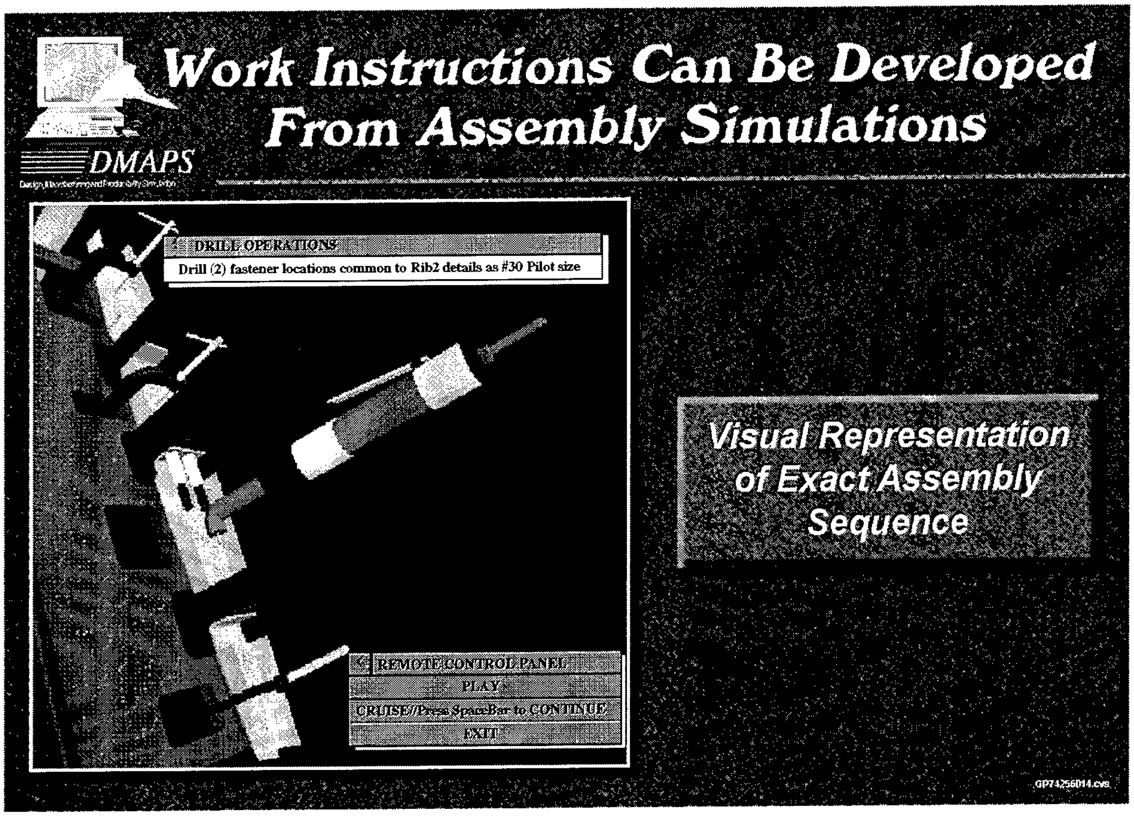

Figure 13. "Work Instructions Can be Developed from Assembly Simulations"

more detail, (i.e., hand tools, clamps, drill motors...) to the virtual assembly model along with the supporting text usually found in traditional written work instructions. The digital work instruction provides the operator a visual representation of the exact assembly sequence to the written text instructions, reducing human error in the assembly area (see Figure 14). The improved quality in the BTP and the use of an EBP is expected to result in 30%-50% reduction in assembly labor for the first three build units.

2.5 Supportability

The goal of successful product supportability requires an early supportability influence on the product design when changes have minimum impact to Life-Cycle-Cost (LCC) and schedule and can be easily incorporated into the product. The Virtual product definition and virtual reality (VR) technology are the tools that enable product supportability to meet their goals. Supportability assessments are performed using the same CAD three-dimensional solid model geometry created in VPD and converted into a virtual reality environment (shown in Figure 15). Product supportability issues and the impact to structures and subsystems are assessed in VR to generate optimum product support concepts and support equipment requirements. These become part of the released Support-To-Package.

Commercial virtual reality packages are being used on pilot programs to provide an immersive and interactive environment to assess equipment access and installation/removal clearances. VR can also be used to verify product support equipment integration and identify location for ground maintenance controls. Being immersed means the user or team better understands a sense of scale and position of the objects in VR that they are viewing. To interact with an object means the user/team has the ability to move, rotate, scale, or reposition objects within the VR environment. These assessments are completed early in the design process and are worked concurrently with design and manufacturing integration. Significant cost savings are realized by no longer requiring a supportability demonstrator and the associated redesign effort late in the product definition cycle. Significant LCC savings can be achieved through these early assessments to reduce downstream support manpower requirements. A typical aircraft engine installation assessment is shown in Figure 16.

3.0 CONCLUSIONS

Virtual Product Definition is a new process available to product design IPD teams but requires a significant investment in tools and training. Aerospace management as well as the customer community must demonstrate a strong commitment to these new processes and help the team members work through the cultural change required to implement the new processes. The benefits of using VPD for product design, from cradle-to-grave, is now being demonstrated resulting in better products, in less time and at lower cost.

3.1 Benefits

VPD is still very much in its infancy, but the demonstrated benefits and results of the application of the principles, processes, and tools have been dramatic. VPD has proven itself as an affordable and rapid design alternative through its deployment on pilot projects, new starts or redesign efforts of existing programs. The cost of early integration of manufacturing, tooling, industrial, logistics, product support and quality engineering into the product design team is more than offset by

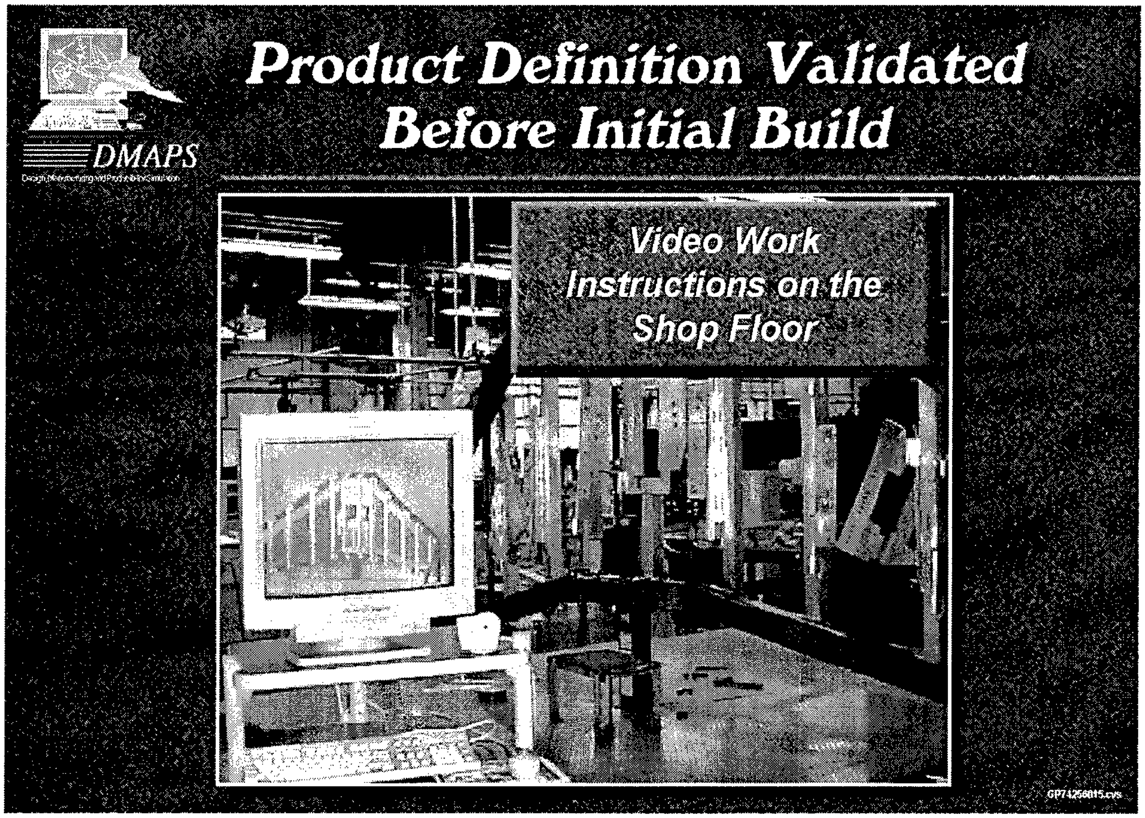

Figure 14. "Product Definition Validated Before Initial Build"

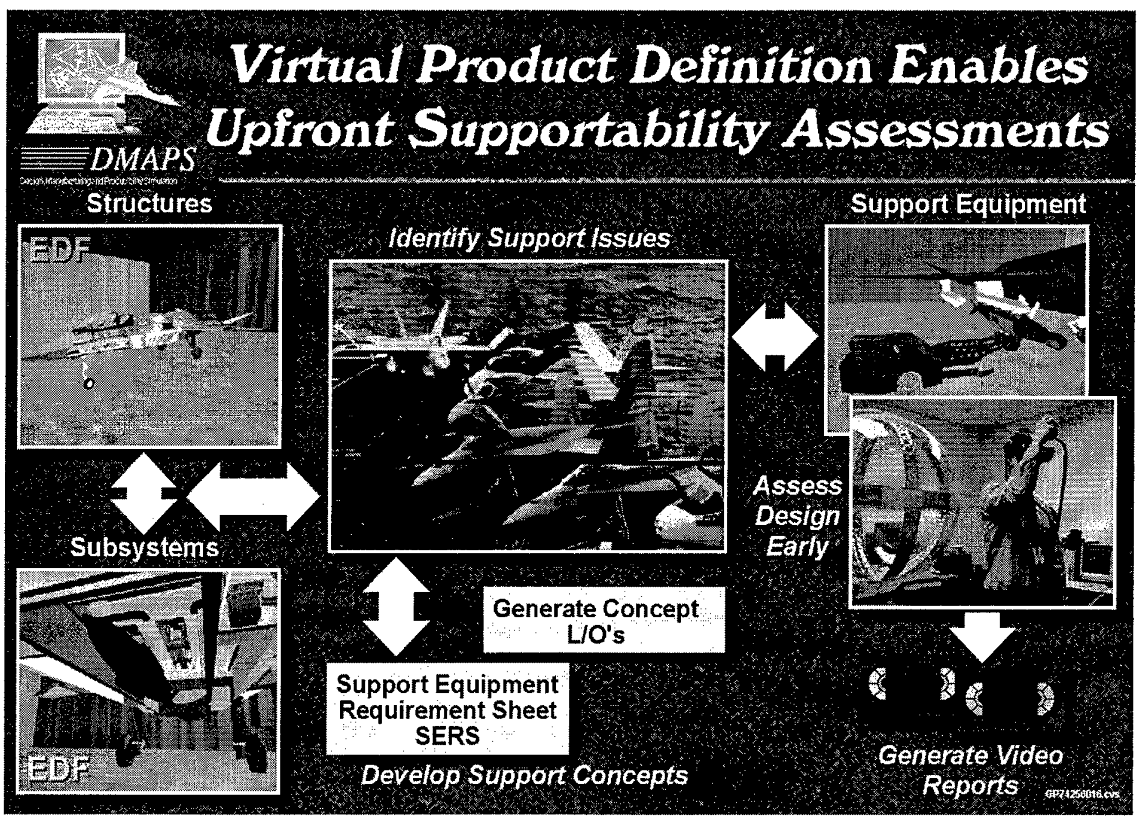

Figure 15. "Virtual Product Definition Enables Upfront Supportability Assessments"

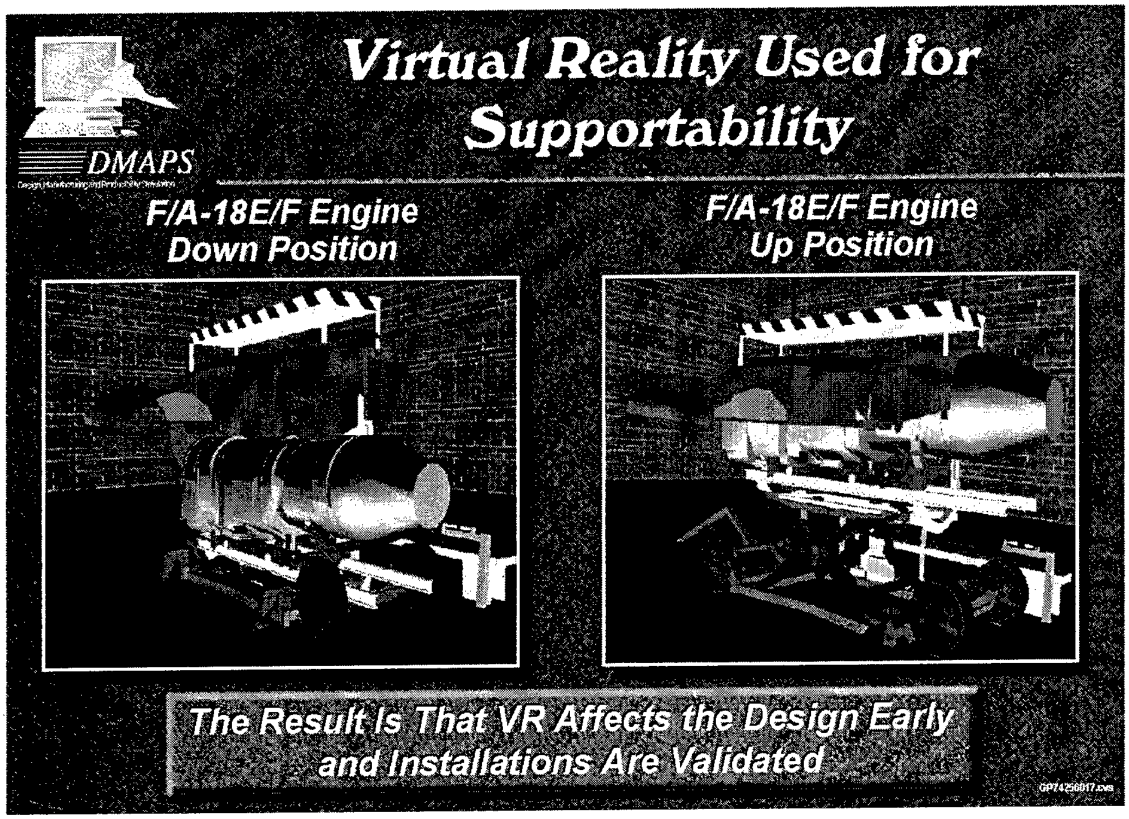

Figure 16. "Virtual Reality Used for Supportability"

reductions in redesign, replanning, and rework. These early measured benefits, as compared to previous best practices programs are:

- CLO cycle time reduced up to 50%
- CLO engineering labor reduced up to 70%
- ALO/BTP cycle time reduced up to 38%
- ALO/BTP design engineering labor reduced up to 50%
- ALO/BTP mfg engineering labor reduced up to 30%

The higher quality digital BTP has been used successfully for both fabrication and assembly and is expected to eliminate at least 80% of the engineering and tooling rework experienced using previous best practices. In addition, the use of the common geometry solid models by every discipline has been successful and is considered a "best practice".

3.2 The Vision

The technology to make it all possible is here, the challenge will be to surpass the cultural hurdles and institutionalize the process as a "best practice". There are further improvements that can be made. Figure 17 documents some of the improvements planned. Customer participation, acceptance, endorsement and commitment to use VPD tools and processes will be needed for the aerospace industry to meet the customer's mandate to "Provide Affordable and Supportable Products".

Besides the cultural change, some of the other changes that will be required to achieve even further product benefits, efficiencies and savings are shown in Figure 18. The VPD tool set requires further development. In particular, the integration of the tools needs to be improved and the interfaces made more user friendly. Integrating and linking quality assurance, a product data manager, a cost/LCC model and requirements flow down is still needed by the product team to achieve and accomplish their goal of an affordable and supportable designed product.

Definitions, Acronyms, Abbreviations

ALO	Assembly Layout
BTP	Built-To-Package
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
CLO	Conceptual Layout
DFMA	Design For Manufacturing and Assembly
DM	Dimensional Management
DMAPS	Design Manufacturing and Producibility Simulation
EBP	Electronic Build Plan
EDF	Electronic Development Fixture
EDS	Electronic Data System
FEM	Finite Element Model
IOC	Initial Operational Capability
IPD	Integrated Product Definition
LCC	Life Cycle Cost
MDA	McDonnell Douglas Aerospace
NC	Numerically Controlled
RCS	Radar Cross Section
SPC	Statistical Process Control
VM	Virtual Manufacturing
VP	Virtual Prototype
VPD	Virtual Product Definition
VPE	Virtual Product Environment
VSA	Variation Simulation Analysis

Figure 17. "The Vision"

Figure 18. "What's Need to Get There"

QUALIFICATION BY ANALYSIS - A FRAMEWORK FOR THE FUTURE

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SUMMARY

This paper provides a framework for exploring ways of reducing the amount of testing required in the process of structural qualification. From a review of the current process, it identifies five areas for particular consideration: structural analysis, design data, loading and environment, the structure, and qualification testing. For each, a brief description of the implications of reduced testing is given together with areas for improvement which are either ongoing or proposed.

1. INTRODUCTION

Today's aerospace market is extremely tough. Competition is fierce and customers are ever more knowledgeable and particular in their requirements. Even when a contract is won it is likely to be 'fixed price' with no scope for exploring options or error. If a manufacturing company is to remain in business in this environment, then there must be continual development to deliver the product quicker and cheaper, with enhanced performance and reliability, and right first time.

To achieve this, cost, time and uncertainty must be removed from every aspect of the company's operations. Focusing on the technical sector, all stages from initial concept, including R&D, through design, manufacture, qualification and onwards to in-service support, must be reviewed in order to remove unnecessary stages and increase efficiency, effectiveness and quality. The process of structural qualification is an important part of this and must therefore provide a contribution to the improvements.

Anything other than large scale change will not achieve the savings essential for survival. This will demand considerable 'lateral thinking' and inevitably lead to critical questioning of many long-standing 'truths'.

Current processes of structural qualification within the military aircraft industry usually include considerable testing which has to be accommodated within the timescales of the project and imposes a high financial commitment. Potentially, then, by reducing or removing test programmes significant savings could be made. This is not a new consideration - such steps have often been proposed in the past. However, each time, serious concerns were raised about the potential detrimental effects on airworthiness introduced by such significant rationalisation and, consequently, few changes made. In fact, in some areas the amount of testing stipulated in regulations has actually risen; an example of this is the requirement for two major airframe fatigue tests instead of one, now called up by the UK defence standards.

Even so, with the speed that technology is now developing, it is sensible to review the situation again. This paper does not aim to revisit old ground - and it certainly does not contain the answers. Instead it attempts to provide a framework for such a review which aims to encourage a logical, objective and careful approach, always mindful of quality and safety.

In order to allay the concerns noted above, three key aspects must be tackled. Firstly, the deliverables from structural qualification and their significance to the customer must be clearly recognised so that they are not compromised by any change. Secondly, the process by which the deliverables are currently achieved must be thoroughly understood so that the implications of any change can be predicted before implementation. Thirdly, the key factors

Paper presented at the AGARD Symposium on "Future Aerospace Technology in the Service of the Alliance", held at the Ecole Polytechnique, Palaiseau, France, 14-17 April 1997, and published in CP-600 Vol. 1.

influencing the process must be identified and then investigated in detail to reveal areas of uncertainty and discover means for potential improvement. These issues are explored in more depth in the following sections of the paper with particular reference to the aims of reducing testing.

2. STRUCTURAL QUALIFICATION

Structural qualification delivers a statement of assurance that the risk of the product suffering significant structural failure at any time during its design life, under the operating conditions specified in the design requirements, is acceptably small.

3. THE CURRENT PROCESS

The current process of structural qualification is based primarily on clearance by analysis. At its heart are a range of analytical techniques for predicting structural behaviour. These techniques generally require the following information: geometry, materials, manufacturing and assembly details for the structure under analysis; loading and environment representing the design usage; and suitable design data covering these situations from which to judge the capability of the structure.

Despite many advances in recent years, current analytical methods still include many areas of uncertainty and limitation such that their use alone involves too much risk.

Confidence is raised by testing structure which is representative of the product, either in total or in part, under loading which is both critical and as realistic as is practicably possible. This qualification testing, performed on the ground, provides evidence to assess the accuracy of results from the analytical models over a limited but critical number of load cases. From this, confidence may be gained in the subsequent utilisation of those models over the full operational envelope. Testing also provides primary evidence of the structural behaviour in areas where analysis is not possible and identifies critical features which have been overlooked in the analysis.

It should be noted that after 60 years of designing metallic structure and 20 of designing polymer composite structure, during which time major advances in analytical techniques have overcome many problems, tests still uncover a significant number of shortcomings, often the result of introducing ever more complex and novel structure.

In a few situations, neither analysis nor ground testing techniques currently available are sufficient. An example is the clearance of structure and attached equipment experiencing significant vibrational loading. In such cases, problems only come to light during flight trials which are a long way into the development programme and therefore are costly to overcome.

The current route to structural qualification has been developed through long experience over many years. It is based on extensive development test programmes to identify trends, formulate theories and derive design data, through to demonstration of the resultant understanding by accurately predicting the behaviour firstly of small elements and working upwards through complex structural assemblies to full scale airframes in a 'building block' approach.

4. A FRAMEWORK FOR CHANGE

From the previous section, it is evident that risk and, in particular, risk reduction is a major part of the process of structural qualification. Logically, changes to the qualification route which involve less testing, and hence less confidence, should be perfectly acceptable provided that improvements elsewhere - in what testing remains or in the analysis - counteract the greater risk, increasing confidence to such a degree that the overall risk is no greater.

Clearly, it is important to understand the risks involved in the current route. To do so, the individual elements making up the route must be scrutinised and the contributory risk associated with each assessed. In addition, risks dependent on the interaction of different elements must not be forgotten.

In this paper, the elements have been chosen to reflect the major parts of the qualification process:

- structural analysis;
- design data;

- loading and environment;
- the structure;
- qualification testing.

A survey of each below, briefly describes the general implications of reduced qualification testing, identifies some of the risks, and indicates areas of potential or ongoing improvements.

5. AREAS FOR IMPROVEMENT

When assessing the sources of risk in each element of the qualification process, it is essential that investigations do not concentrate on the engineering and physical aspects alone. Just as important are the human factors. Requirements of skill, expertise and training, lines of communication, management practices, ergonomics, the level of interest or tedium in the work, together with health and safety issues all influence to a greater or lesser extent the successful operation of each element in the qualification process. All have potentially enormous detrimental effects on process reliability through errors and omissions. Maintaining expertise is also becoming more difficult as aircraft projects become increasingly more complex and as a result the time between each becomes longer.

In this respect, automation is likely to play an important part in all stages of the process in that it reduces not only the cost of human labour but also, through embedded expertise, the cost of human unreliability. Even so, automation can only cover the expected; the benefits of human involvement lie in an ability to predict and detect the unexpected. Further, too much automation has a tendency to discourage engineering common sense, inducing instead a dangerous acceptance of the results without question.

5.1 Structural Analysis

Covered in this section are analytical techniques used to predict structural response to the various types of loading expected in service and how that relates to strength, stiffness and durability. If qualification testing is to be reduced significantly then they must become far more reliable. Less testing means less evidence of real behaviour with which to correlate analytical results and what limited correlation is possible is likely to cover a reduced range of conditions. Less testing also reduces the chance of identifying critical features overlooked in the analysis.

All analytical techniques require some degree of idealisation of the structure, inevitably involving assumptions and simplifications when reducing complex geometry to something which can be represented mathematically. Each assumption introduces an element of risk which is usually countered by introducing a level of conservatism in the approach provided the risk is recognised.

The level of complexity in finite element idealisation, at least in the past, has been dictated by the amount of computer storage needed and the time to run the analysis. To overcome this, super-elements have been developed but they require more complex techniques and if not expertly utilised can lead to errors in the analysis.

With increasing computer storage and speed, there is a growing view that simple elements should be used, to idealise small features which can then be assembled to form the complete model. Feature-based idealisation could indeed be automated to a great degree. Even so, idealisation of thin panels using simple solid elements could so easily result in a model just one element thick and, as such, incapable of identifying through-thickness effects. Instead, a plate element would be more appropriate and efficient.

It is clear then that expert analysts have an important role to play for the foreseeable future. For this reason, it is essential that analysts are competent, well trained, and with significant practical experience. However, even experts sometimes make mistakes or overlook things. With less testing, reduction of human errors has to be a major goal. There is great scope for embedding much of the expert knowledge into the analysis itself, provided that the knowledge can be suitably rationalised with clearly defined ranges and limits of applicability.

Independent of how good the modelling is, analytical results will not be correct if the underlying theory at the heart of the technique is wrong or not appropriate. In this respect, much still needs to be done to develop better methods of predicting non-linear behaviour generally and specifically dynamic response and durability under vibrational or impulsive loads.

Whether new approaches concern idealisation or theory, sufficient development testing must be carried out to ensure that they can be used reliably, efficiently and effectively. A little testing here may well save a lot of testing and re-testing at the qualification stage.

5.2 Design Data

Reduced qualification testing and a corresponding need for reliability improvements in the structural analysis place great demands on the availability, validity and accuracy of the design data which defines the structural behaviour and its limitations. Overall, the analytical qualification can only ever be as good as the design data utilised. Use of conservative data has been the reluctant answer in the past but the resulting over-design is now becoming increasingly untenable. At the same time, there is a drive to reduce the development test programmes from which most design theories and data are derived, with the risk that fewer conditions assessed and smaller numbers of samples tested under each will reduce the potential for identifying and quantifying the true behaviour.

Overall, a far better understanding of material and structural behaviour is required at a more fundamental level. Developments in physico-chemical analysis are aimed in this direction. Ideally, the behaviour of not only new variants of what already exists but also completely new forms should be predictable without enormous test programmes. Instead, testing should be limited to confirmatory checks at a few key points, together with derivation of any relational parameters to allow existing generalised design data to be utilised. Such an approach may well be valuable in detecting invalid data, whether caused by unsuitable or faulty testing, inappropriate or erroneous data analysis, or misunderstanding and inexperience of the behaviour being investigated.

There are still some aspects where more development is required. An example is the need to produce the rules and data to predict structural response to acoustic and impulsive excitation, including high strain rate data and how the rate influences failure mechanisms.

5.3 Loading and Environment

The validity of structural qualification depends ultimately on whether the loading and environment chosen for analysis and test is reasonably representative of what the structure will experience in service. If under-predicted then obviously the structure, once in service, will either not perform adequately or will sustain damage, possibly catastrophic. If over-predicted then the structure may well be over-designed or structural qualification will be difficult or impossible to achieve without significant compromises in performance. As with design data, uncertainty in the past has been countered by conservatism in the information but again this is now untenable if the structure is to be efficiently designed.

Similarly, there is a push to minimise the costs of wind tunnel testing from which much empirical data have been drawn in the past. What remains must be made cheaper, more accurate and more comprehensive. At the same time, analytical techniques for predicting loads must be improved, including the ability to deal with unsteady aerodynamics. Much work is now progressing in developing computational fluid dynamics in these directions.

Considerable effort still needs to be expended on developing an approach to acoustic and other vibrational spectra so that, firstly, realistic levels can be predicted and, secondly, a way of qualifying the structure under those loads can be devised which takes into account the likely variability whilst not imposing overly severe conservatism.

5.4 The Structure

A major difference between the analytical part of the qualification and the test part is that whereas the analysis works on the structure as idealised from the drawings, tests are performed on the structure as it is actually manufactured. Differences between the two can be significant. Examples include small detail differences introduced by the practicalities of milling, or variability of skin thicknesses greatly amplified by the super-plastic forming process. Even considering drawings alone, areas of stress concentration are notoriously difficult to find if the structure displayed is complex with, for example, interacting radii.

Greater visualisation, including virtual simulation, automated location of critical features, and the means to understand the implications of manufacturing all need to be developed further to produce an 'expert' system able to significantly reduce errors and omissions of this sort.

Tolerances are a practical necessity but they do introduce considerable potential for variability. Small changes in geometric dimensions can greatly alter the proportions of load taken, for example, by each element in multiple load path structure. Further, whatever proportional split is assumed for the analysis, a different split is likely to exist in the qualification test article and different splits again across the production articles in service. At present, variations are covered by factors included in both analysis and testing.

However, to complicate the issue, the customer is now very keen to see far greater interchangeability in the structure which tends to push for larger tolerance bands. If this problem is to be solved a fundamental review of how to design with tolerances should be considered.

5.5 Qualification Testing

Qualification testing has occasionally been thought of as the proof of the analysis. However, even though a real piece of structure is being loaded, the results still contain much uncertainty. For example, the larger structural tests are likely to involve just one test article for each, providing little useful information on whether the results are typical or extreme.

It is even questionable how representative a test article is of the production item. Although it may be manufactured on the same line at the same time, inclusion of test instrumentation and exclusion of non-structural items could introduce a slightly different build standard. A test article is also likely to have come from an early production batch. As such, it may not necessarily be representative of later batch standards where growing experience has smoothed the process of manufacture. Further, if there is a significant break in production, such that some experience is lost, or if production is moved from one site to another, involving new production personnel, the standard may well be different again.

Loading of the test article is usually, through practical necessity, a compromise on what is defined by the design specifications as service usage. Whether testing statically to flight envelope extremes or in fatigue to simulated flight spectra, loads are introduced at discrete points of the structure - very different from, say, the smoothly distributed aerodynamic loading seen in flight. For this reason, test loading can usually only be designed to be representative at a very limited although critical number of structural locations.

Overall then, a test article may be considered an example of the production item but certainly cannot be assumed to be typical or average; factors have to be used in the qualification to allow the tests to represent the fleet. In addition, the test results are the consequence of the test loading and not necessarily representative of what will happen in service.

Even so, if the test cannot be thought of as a proof of the design it still provides very valuable evidence which contributes to the overall level of confidence in the design and specifically in the analytical models. It is very important, therefore, that when correlating analysis results to test results that the analytical model is set up to be capable of representing each test accurately as well as in-service conditions.

If qualification testing is to be reduced, the confidence from what testing remains must be maximised. One option currently being explored is to use the same test rig and, importantly, the same test article for the main airframe static test and fatigue test. Proposals include reducing both the number and magnitude of static test cases to be investigated, which will be applied prior to the application of fatigue loading. Obviously, on the one hand, the reduced static test evidence must be shown to be sufficient to give confidence in the analytical models over the whole envelope and, on the other, the fatigue test must be shown not to have been compromised by the prior static loading.

Moisture and temperature are both important influences on the performance of polymer composite structures. They also impose significant cost and time penalties as well as practical difficulties if they have to be applied in the test programme. Significant steps are being taken to avoid this by understanding the basic behaviour through development testing of coupons and small elements. From this information, compensatory factors are derived for application to the qualification test loads imposed in ambient conditions. However, polymer composite materials now constitute a large proportion of the structure. In consequence, major airframe static tests, limited on practical grounds to ambient conditions, are becoming less representative environmentally and more reliant on factors.

A similar approach is being used to accelerate dynamic load tests where the normally high number of service loads would make the test duration unacceptably long if applied.

6. THE FUTURE

Each of the elements making up the process of structural qualification needs to be explored in depth to identify where improvements in efficiency, accuracy and confidence generally can be made. Sufficient time should be given to perform trials on the new approaches, using full scale demonstrators to test out the whole revised process, and then confirming its effectiveness through fewer unexpected failures occurring on subsequent qualification tests. This evidence, already beginning to appear in major static tests, is essential for the design authority, regulator and customer to gain sufficient confidence to accept the changes.

SYNTHETIC ENVIRONMENTS - A TOOL IN COMBAT AIRCRAFT DESIGN

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1. SUMMARY

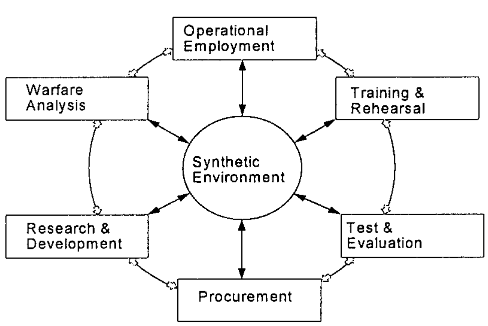
Combat aircraft design is a complex task requiring a balance to be struck between potentially conflicting requirements. Most recently the very practical consideration of affordability has come to dominate almost every phase of the process. However, the requirement for effectiveness remains.

This paper considers how the application of large scale simulation and modelling - dubbed 'Synthetic Environments' - can already assist in understanding the issues and trade-offs and goes on to suggest how the potential of the approach may in due course extend to a far wider range of applications.

The paper draws on examples of research into Synthetic Environments as an approach and will address some of the work on SEs and their applications in which the UK Defence Evaluation and Research Agency is involved.

2. INTRODUCTION

The task of designing combat aircraft is the responsibility of industry. However the design is both guided and constrained by the requirements placed on the complete aircraft system by the military customer. These requirements may relate to physical attributes like size and weight, will certainly relate to operational performance, and will also cover support, availability and, in various forms, cost. The complex task of generating the right requirement is therefore key to the successful completion of the rest of the equipment life cycle - and it is contended that Synthetic Environments can play an important role both in preparing the ground, and encapsulating the requirement.



Synthetic Environments in the UK are viewed as both a process and a collection of technologies which permit the construction of complex, large scale federations of simulations. Such large-scale simulations are already used in training applications in the US and there is a broad recognition world-wide of the need to consider this approach as an alternative or adjunct to live exercises on the grounds of affordability and practicality.

Synthetic Environments can, however, do more.

3. THE SCOPE OF SYNTHETIC ENVIRONMENTS

3.1 Definition

A definition of Synthetic Environments is likely to prove contentious as there are numerous variations. The definition coined by the UK MOD refers to:

> "Synthesised representations of a common world which permit interactions between players."

This brings out the key characteristic of an SE approach: the ability to represent the interactions, the interdependencies and the behaviours of disparate systems in a shared environment. It is an approach which supports integration at all levels.

An alternative way of looking at SE is to think of an SE as an interlinked set of models operated against a common timebase. It is important to remember here that models and simulations can be physical models (say cardboard cut-outs) as well as computer models and may usefully include instrumented real sub-systems, equipments or platforms.

A number of alternative definitions constrain SEs to involve geographically distributed simulations (perhaps using the distributed interactive simulation or DIS protocol);
other definitions constrain SEs to involve real people - alleviating some of the problems associated with representing human behaviours and decision making processes;

For the purposes of this paper it has been assumed that when any or all of these classes of component 'simulations' are involved the result is a Synthetic Environment.

3.2 Examples

A few examples of Synthetic Environments may help to reinforce or at least clarify the definition. Consider for example an aircraft design in which virtual representations of system components are integrated with representations of the other components with which they interact - in other words a virtual aircraft created by combining sub-system simulations. If some of the sub-system representations are actually prototypes of production hardware the result can be recognised as an 'iron bird' and the provenance of SE begins to become clearer. Stimulating a virtual or composite (iron

Paper presented at the AGARD Symposium on "Future Aerospace Technology in the Service of the Alliance", held at the Ecole Polytechnique, Palaiseau, France, 14-17 April 1997, and published in CP-600 Vol. 1.

bird) prototype becomes more and more complex as the aircraft designs themselves become more and more complex. Simple simulations may have sufficed in the past. Richer contexts for such development approaches will be needed in the future.

Perhaps the most common application of SE to date is as a context for training - providing the mission context for one or more manned simulators for instance.

At a higher level a wargame is a synthetic environment of sorts, notably a Synthetic Environment with real human decision makers. This is an application for Synthetic Environments which promises a great deal for the future but is unusually demanding in terms of robustness and rigour to the extent that there is some way to go before unsupported complex simulations can be brought to bear in high level decision support.

3.3 Defence application areas

In the military arena there are four principal application areas for synthetic environments:

- Equipment acquisition;
- Operational readiness;
- Operational support;
- Policy Formulation.

Equipment acquisition covers a number of uses of SE and is covered in more detail below. In brief it is under this label that concept development, requirement capture, design, manufacture and through-life support can be linked one with another through a common approach to modelling and simulation.

Operational readiness is another broad area which includes the development of doctrine and the support of training both in terms of longer terms skills and (through rehearsal) shorter term tactics. In this respect there is a potential link with operational support applications discussed below. In terms of training, the use of SE as a context for Computer Assisted Exercises has already been recognised. The US STOW-E exercise in 1994 for instance demonstrated how live (real people and equipment), virtual (real people in simulators) and constructive (simulated people and equipment) entities can be combined in a synthetic world. In individual training constructive SE is an ideal (and cheap) means of providing a rich context, stimulating the trainee as necessary to achieve the required level of training. The more complex SE configurations - linking man in the loop simulators with one another and with constructive models can also be applied to larger scale collective training. Again, this is a growth area in the US and an area of increasing interest in the rest of NATO. Indeed the newly formed NATO Steering Group on Modelling and Simulation is likely to take a keen interest in this application.

Operational support includes the use of SE as the basis for decision support. In the future integrated simulations may be used to carry out 'what if' analyses of real situations potentially providing an optimum solution but, perhaps more likely, assisting commanders at all levels to gain an insight into the sensitivity of a given situation to a range of factors.

The final category, policy formulation is at a much higher level but in many respects is a planning application similar to operational planning described above, albeit at a higher level.

4. INTEGRATING SIMULATIONS

4.1 Why integrate

The meshing together of real-world systems with their synthetic counterparts provides a means of looking at the relationships, interactions and dependencies between systems, other related systems and system components. For instance, within an Air weapons system there is the possibility of developing the platform's data architecture; modelling data flows and processing centres; assessing vulnerability and reconfigurability. Data Interface concepts can be tested against virtual sub-system models; physical interfaces, fits, tolerances, accessibility and maintainability can all be assessed in the context of the other (virtual) physical components in the vicinity (and those further away). At a higher level the effectiveness of the platform can be assessed with different sub-system fits taking the operational characteristics of the system into account, including those characteristics which depend upon other platforms, C2 interfaces, and both red and blue doctrine and tactics.

4.2 Technical issues

However, integrating simulations gives rise to a number of important considerations.

The examples given above are drawn from at least three different levels of information and interaction. Within themselves there may be a clear way ahead, however certain interactions and dependencies take place across interfaces between levels or between system components which may be represented to differing levels of abstraction, detail and fidelity. This poses some significant technical and methodological issues. Is it necessary to model always at the level of the lowest (most detailed) common denominator? Are there acceptable approaches to aggregating and/or disaggregating data? How application dependant is a given answer to such questions? How accurate must the registration be between the perceptions of the shared common world? What is the best approach to validation and verification of Synthetic Environments?

4.3 The opportunity for re-use

In creating this class of simulation, a considerable amount of information will have had to be amassed, analysed and encapsulated in the component models. The opportunity also arises, therefore, to make use of these data (and these models) for a range of applications. It is suggested that, although initially developed as a context for concept development, a data set and modelling environment can be retained or evolved into a form to support requirement capture, design, manufacture, training and support. The data, which might be carried from phase to phase through a procurement life cycle in this way, carries with it the assumptions constraints and possibly requirements, developed during preceding stages of the process. The opportunity therefore arises not just for re-use of the data but for maintenance of a common view of the 'world' (the system). The common assumptions encapsulated in the models and data might even, in due course, change the way in which requirements are communicated from customer to supplier at all levels.

5. AFFORDABILITY

5.1 The drivers

Although effectiveness remains the means by which a combat aircraft 'wins', if the design needed to achieve effectiveness is unaffordable the net result is 'lose'.

Affordability is inherently a difficult attribute to measure. It is influenced by a large range of factors and any one factor may influence it in a different manner depending on when in the life cycle of a system it is considered. In its simplest form affordability relates the availability of resources and the implications of expending those resources on particular options (or indeed the implications of not expending those resources). The complex interactions and influences of the components of the affordability equation may themselves become the subject of a Synthetic Environment (a financial environment) in due course but at present considering the main affordability driver - cost - is the more usual compromise.

In the design of a system, cost is incurred in a number of ways. There are costs associated with each phase of the process: Capture of requirements, option appraisal, trade studies, research, risk reduction exercises, design, development and manufacture. Once in service a system has to be supported and a raft of other costs dominate - spares, fuel, maintenance, manning. These again are interrelated and bear careful attention to detail. The in-service costs may exceed the initial procurement outlay but are spread over a longer period so the affordability consideration - matching the availability of funds - may be driven by the shorter term, but lower net cost, component.

The application of Synthetic Environments to the process has cost benefits but also requires investment. The possibility of modelling the process itself continues to be considered as a possible way ahead. To date this has met with only limited success and a piece-wise simulation approach - augmented by human judgement - remains the accepted method. However, this human judgement process has to be based upon as clear an understanding of the issues as possible - this is where an SE based approach first comes into its own.

5.2 A life cycle

At the start of the life cycle of a new aircraft comes the first identification of a need. Usually this is obvious - there are threats which continue to develop in capability and will ultimately become more capable than some in-service equipment so an update or replacement is needed. But should the replacement be similar to what is being replaced ? Operational analysis provides a means of considering potential concepts for equipments and operations. And surely SE can contribute in this field ?

In fact although SE is good at exercising concepts in a rich context, and drawing out many of the issues to be addressed, robust means of validation have yet to be fully developed and tested. This is discussed further below.

Before concepts can be put through their paces they have to be developed, taking an idea and developing possible concepts of operation, identifying dependencies and defining relationships with other systems in the process. The use of a Synthetic Environment as the context for concept development clearly has considerable potential.

At some, relatively early, stage of the process a military requirement begins to take shape. The requirement for a system like a combat aircraft cannot however be considered in isolation. When such a system enters service it must be capable of interoperating with all other relevant air, sea, land and CIS systems. It must be supportable. It must be effective.

In the past, reliance on a complex requirements document was something of an act of faith. In recent years the use of simulation and modelling to support the development of requirements has become the norm. It is suggested that the next step - the use of large scale simulation (SE) to support requirements capture - is just around the corner. *If SE can assist in the generation of a better, more robust requirement it will have contributed significantly to risk, and therefore cost, reduction.*

Once a firm requirement has been defined (more about the firmness of requirements later) it remains for systems designers to look at potential solutions. Traditionally there is a clean and simple interface at this stage of the process: The requirement or specification, as written, is taken to represent everything that is required of the design. But at the same time, it is left loose enough for suppliers to be able to offer a range of cost-effective options for the military customer to consider. The art of requirement specification lies in getting across a clear and common understanding of what is actually required. The military source, the author of the documents, the contracting authorities and the various suppliers should be left in no doubt as to where the fixed requirements stop and the scope for innovation starts.

At present, this is rarely achieved to everybody's satisfaction at the first pass, and an iterative cycle of query and clarification is frequently called for. *Here SE has the potential to provide what is perhaps its most valuable benefit: Commonality of understanding and assumptions.* This is a natural outcome from the use of common databases and a common / shared world within which concepts have been developed and exercised to develop the requirement.

6. SYNTHETIC ENVIRONMENTS RESEARCH

6.1 Programme aims

Many of the application areas identified above are recognised as having significant potential but few are sufficiently well-proven to be of immediate operational use. The focus of research is therefore to improve our understanding of the technology; to construct and prove methodologies for using the technology and, by demonstration, develop robust approaches for assessing not only the results of using SE but also the effectiveness of SE as an approach in its various application areas.

6.2 Representing live interactions

The incorporation of live aircraft entities into distributed simulations poses a different set of challenges from incorporating land vehicles. To begin with the speed of aircraft requires that basic state vector information is updated frequently and that prediction algorithms such as those used under DIS, are carefully optimised. Aircraft may be involved in distributed simulations for a wide variety of purposes. The most obvious perhaps is pilot training although using the aircraft as the essential component under scrutiny, or as a context for the analysis of another system (for instance a ground to air missile system) are equally possible.

DERA has carried out initial trials into the incorporation of a live aircraft into a virtual simulation, employing a piloted simulator to formate on imagery generated from the DERA VAAC Harrier trials aircraft in real time. Whilst only the first step towards fuller integration, the trials were nonetheless successful and demonstrated that the existing DIS standards provide a usable starting point for such simulations. In the other direction air traffic management trials have been conducted employing a scenario synthesised by computer and presented to the pilot and experimental systems of a live aircraft in real time.

6.3 Data sharing and re-use

A key benefit of an SE approach is the adoption of CALS-like ways of working such as data sharing and integration, multi-disciplinary workgroups and data re-use. These approaches have value within a research environment in the same way as they have value within a production environment.

Data which may be re-used can be of a wide variety of forms. For example, when system models are created they rely upon (or in fact embody) information including: physical configuration; logical architecture; boundary conditions; environmental assumptions; performance parameters and functionality. Through distributed simulation, direct use may be made of all of this data simply by inter-connecting the models and simulations. This simplicity is, however, somewhat compromised by the need to carry out a critical examination of the assumptions and data upon which each component simulation or model has been based to ensure that inherent conflicts are not built in to the overall simulation. The issue of validation of the overall simulation even then remains a separate issue: an issue which research is addressing but has yet to solved.

Never the less, access to the 'best' models maintained by those best qualified to maintain them, is an attractive and worthwhile objective.

6.4 Low cost man-in-the-loop simulation

Virtual design, development and manufacturing concepts ('virtual' here meaning synthetic rather than man-in-the-loop) have been in existence for some years and are beginning to show real benefits in industry. In the research community, modelling and simulation has long been a basic tool of the trade and now synthetic environments offers extended opportunities for 'virtual' analysis. The research community is frequently adept at devising cost-effective means of supporting such a new approach and the steady increases in the capability of commercial IT systems provides an ideal vehicle. An example resides at DERA Bedford where the latest Pentium Pro PCs have been found to provide sufficient capability to carry out detailed real-time modelling of flight control systems in the context of 'piloted' scenarios displayed either on monitors or on a low-cost 'all round' visual system. The system, which is DIS-compatible, provides the opportunity to examine the influence of system components upon one another and upon the controllability of modern aircraft configurations.

6.5 Tactics

Man in the loop simulation has the key advantage that human decision making is represented by a human decision maker - not by an abstracted model of the process. One occasion on which this is particularly important is when tactical decision making makes a significant difference to the outcome of an analysis.

People make decisions in the context of the information environment within which they are operating. It is therefore important to pay careful attention to the stimuli with which the 'man in the loop' is presented. If, as is often the case, certain stimuli are absent, allowances must be made.

Within DERA, the JOUST man in the loop simulation facility provides a means of assessing the performance of BVR weapons systems in simulated combats between up to 12 manned simulation stations and a number of computer-based aircraft. The manned stations have no motion environment and employ large desk top screens tailored to present the outside-world and cockpit information necessary for the evaluation in hand.

The strength of the system lies in the careful management and validation of data and in the construction of comparative trials of system options permitting any limitations of the simulated environment to be cancelled from the equation.

Although used predominantly as a self-contained evaluation facility, the system has recently been employed in a EUCLID CEPA 11 demonstration of distributed simulation technology with DIS connections to Thompson Training and Simulation in Crawley UK and TNO in the Netherlands. Scenarios were flown with up to 60 aircraft in the air at once, some virtual, some constructive. C2 communications were managed across the network simultaneously.

6.6 Issues of complexity

Synthetic Environments are inherently complex. They attempt to represent interactions on a scale which is representative of the real world. This poses a number of questions which remain to be answered but about which we may hypothesise.

Simulation has in the past been employed as a means of doing better than the real world - abstractions, aggregations and simplifications have traditionally been employed so that a complicated, difficult-to-observe process in the real world can be characterised and analysed in a model. With the advent of SE we have begun to replicate the real world. The complexities of the models, the lack of determinism in distributed real-time simulations and the non-linearity of many models all conspire to create a breeding ground for complex, perhaps chaotic or emergent behaviour. Real time constraints further limit the scope for taking stochastic measurements of performance or behaviour.

We may, therefore, need to revisit the way in which we capture and analyse simulation results. It may no longer be practical to carry out large scale data logging and analysis, instead it may be necessary to return to the expertise in live trials and bench experiments built up over many years to help us design experiments, instrument our SEs and observe the results. Perhaps there is a role here for some intelligent or KBS application capable of capturing just that expertise and employing it adaptively to on-line data logging and analysis ?

6.7 Fit for purpose

Perhaps the most hotly contested issue over any model or simulation is whether or not it is fit for the purpose for which it was constructed. There is a school of thought which says that it is not possible to validate SEs. The basis for this contention is that where an SE is concerned with entity level simulation with either real people or live components, the use of the SE is limited to real time experiments. The practical availability of manpower and time then limits the number of trials which can be performed to assess the SE and statistically significant doubts will tend to remain over aspects of the SEs performance.

Then is the time to resort to the concept of 'fitness for purpose'. Where a broad training context is called for, an SE may be judged fit for purpose with far fewer tests and a far less rigorous audit trail than an SE used for, say, decision support. Nonetheless, a coherent and systematic approach to making such judgements is necessary. Such an approach is under development in the UK.

7. CONCLUSION

SE has the potential to achieve cost savings by facilitating:

- better requirement capture;
- reuse rather than re-generation of data;
- greater commonality of understanding throughout the procurement chain;
- a common basis for assumptions throughout the life cycle.

The consequence is reduced risk to procurement, ownership and operation. Whilst the potential of SE is clear and the UK programme is making steady progress towards a greater understanding of the issues, there remain gaps in our understanding of criteria for judging the applicability and specifying the robustness of SEs for different application areas.

There is significant potential for changing the way in which participants in procurements - customers, suppliers, users, nations and decision makers - look at the options, judge the designs and develop and deploy the final product. Many separate communities are involved in these processes and a key area of continued research will be the relationships between the people involved with Synthetic Environments.

Rather like the computer being less than effective at giving rise to the paperless office, it is suggested that Synthetic Environments are destined to increase rather than decrease the need to understand relationships between real organisations and between real people. And at a technical level it is in the representation of human decision making and human behaviour that perhaps the greatest challenges remain.

Agility
in the context of Improved Operational Effectiveness

by

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1 Abstract

"The environment in which a fighter pilot operates is subject to continual change due to technology advances and the altering world situation. The only prediction which can be made with confidence is that profound change should continue to be expected.

The first air to air conflicts occurred in the Great War. Here, aircraft were, for the most part marginal with regard to performance, stability and controllability. Indeed, many combat losses could be attributed to these shortcomings rather than the action of the enemy. However, some of the aircraft were regarded, and still are, as models of the agile fighter, particularly in the hands of an expert pilot, or "ace". The basic skills required were the ability to remain in control and shoot accurately.

For subsequent conflicts, the same basic skills were required, although airframes were better stabilised and controlled and had increased power available, resulting in higher speeds. With radar and radio, it became possible to receive guidance towards the targets that the ground control perceived as the prime threat. Weapons remained visual range, however, but regardless of this, the increased speeds and the added information changed the difficulty of the pilot's task due to the implications on his situational awareness and choice of tactics. Increasingly, the combat results became more clouded by the interaction of the systems available to the pilot and his ability to assimilate the information provided.

The advent of jets, airborne radar capability, missiles and counter offensive equipment have all tended to complicate the picture whilst attempting to improve the ability to perform the same basic tasks, i.e. finding the opposition and shooting him down. Korea demonstrated the benefits of high performance combined with good handling, to the detriment of the Communist forces. However, some lessons were forgotten, only to be relearned in later conflicts."

These are the opening comments from the AGARD FMP Advisory Report on "Operational Agility", published in 1993. They set the scene for the issues to be discussed within this current paper.

2 The Overall Objective of Combat Aircraft Design

The primary objective of a combat pilot and his aircraft remains as it has always been, to find the enemy and destroy him without being destroyed. This was true in the very first aerial combats, remains true to this day, and is likely to remain so in whatever future theatre can be envisaged, whether air-air combat or air-ground. By implication, this quest for maximum effectiveness must be the prime driver for the design process.

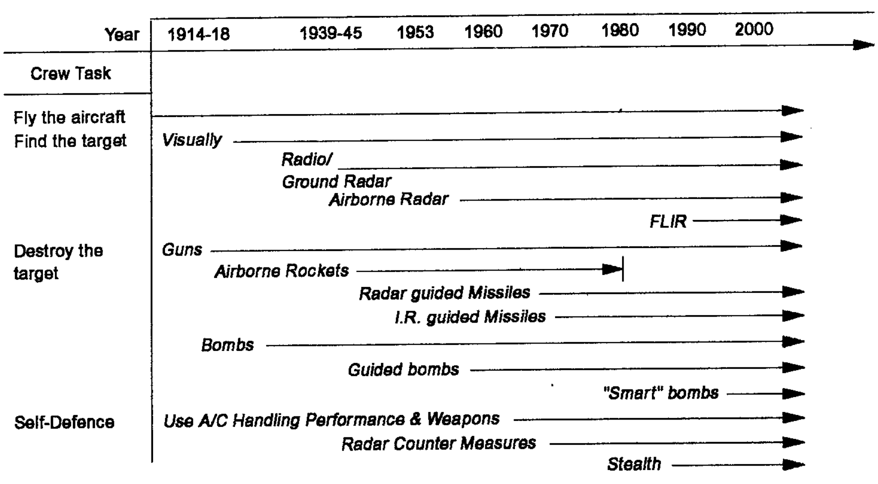
So what has changed from the earliest days of air combat?

The environment in which the crews operate has changed in a rapid and complex way, especially politically. Further, technology has added capability to both the opponents and ground defences, whilst some of the low technology items often employed in remote arenas remain potent and damaging. Each operational scenario will bring its own unique hazards, and the aircraft and crews have to be capable of adaptation to any circumstances.

To appreciate the overall changes that have occurred, it is worth considering the illustration of figure 1. The figure tries to illustrate how, in providing assistance to the aircrew by adding various systems to enhance the effectiveness, the task for the aircrew has actually grown in its complexity. There are many more aspects to be managed in a modern aircraft than in the earliest

Paper presented at the AGARD Symposium on "Future Aerospace Technology in the Service of the Alliance", held at the Ecole Polytechnique, Palaiseau, France, 14-17 April 1997, and published in CP-600 Vol. 1.

Figure 1: The Growth in Complexity of Crew Tasks in Combat



aircraft, where, all to often, the pilot was struggling to even maintain control, let alone fight effectively.

Intuitively, without some form of assistance, the crew of a modern combat aircraft face an immense task of organising their activities to ensure that they are effective in combat. Automation can and does assist. But, the real issue for the design team is the determination of what should and what should not be automated to enable the maximised efficiency of the crew and aircraft during combat. This requires studies of those technologies, which could possibly be employed, at an early design stage, such that the most appropriate, cost effective solution which meets the Customer's requirements is arrived at. Reference 2 provides an overview of the aerodynamic technology options which have to be considered.

Clearly, for this to succeed, it is imperative that the Design and Manufacturing organisation, Customer and Operator (where these are possibly different) are involved in this decision process at the early stages of concept and throughout the development of the design, up to its arrival in Service and subsequent Service life.

3 Agility Concepts and Definitions

The overall question for the design team is "what is it that we are trying to capture as a design requirement that will maximise the effectiveness of the vehicle?" In this context, the design team must be considered to include the Customer, the end user and the manufacturers, and each will have their own views.

Many people involved with combat aircraft design have their own views on what it is that makes an aircraft effective, whether it be pure performance, or the systems or the weapons.

Inherent in the "combat effectiveness" is agility, but this is also a subject where there have been many interpretations and arguments as to what constitutes agility. All of the definitions involve the use of a time based concept, but from an operational effectiveness aspect, the major concept that is worth considering is the preparedness for the next change or task, as well as the speed of response to a given set of stimuli.

Before proceeding, it is worth recalling a definition which the AGARD Working Group 19, which was set up to examine "Operational Agility" or "Functional Agility" as it has also been termed, as this sets the concepts which are required in context. Perhaps the title for the study should have been "Operational Effectiveness" as we rapidly arrived at the conclusion that it was the totality of the weapons system that we were dealing with.

Figure 2: Agility Definitions

- **Definition** ***Operational Agility***

  The ability to *adapt* and *respond, rapidly* and *precisely*, with *safety* and *poise*, to maximise mission effectiveness

- ***Operational Agility***

  =

  Σ Airframe Agility + Systems Agility + Weapons Agility

From the deliberations of the Group, the definition that was arrived at was as shown in figure 2.

Operational Agility conveys the "big picture", in that it relates the overall combat effectiveness of the airborne

Weapon System to the weapon system design and to maximisation of the performance of the system. The crucial aspect relates to the idea of poise as well as the precision and speed of response, i.e. it is the conveyance of the idea of always being prepared for the next event, step, or segment of the combat or mission.

To complete the scene, the Group expressed the view that the overall operational agility could be expressed as the sum of three major components, as shown in figure 2, each of which could be measured in some way. The components are the Airframe Agility, the Systems Agility and the Weapons Agility, and the definitions for these are as follows:

Airframe Agility is defined by the physical properties of the aircraft which relate to its ability to change, rapidly and precisely, its flight path or pointing axis and to its ease of completing that change. As such, airframe agility is comprised of manoeuvrability, the ability to change magnitude and direction of the velocity vector, and controllability, the ability to change the manoeuvre state through rotation about the centre of gravity, independent of the flight path vector. As such, airframe agility relates closely to, and may be regarded as an extension to, flying qualities and airframe performance.

Systems Agility is defined by the ability to perform and/or rapidly change mission functions of the individual systems which provide the pilot with his tactical awareness. It relates to his ability to direct and launch weapons both in response to, and to alter, the environment in which he is operating. Systems agility covers sensors for threat detection and acquisition, displays and cockpit controls, targeting systems, counter-measures, missile management systems and their ability to interact both with each other and with the pilot or weapons system operator.

Weapons Agility is defined by the ability to engage rapidly characteristics of the weapon and its associated onboard systems in response to hostile intent or counter measures. It addresses the weapons sensor and its interface to the aircraft sensors, the launch delays and release aspects, the weapons performance in terms of manoeuvrability and weapon airframe agility, range and duration and its lethality and ability to avoid counter-measures. As such the weapon mirrors the airframe that launched it in many respects.

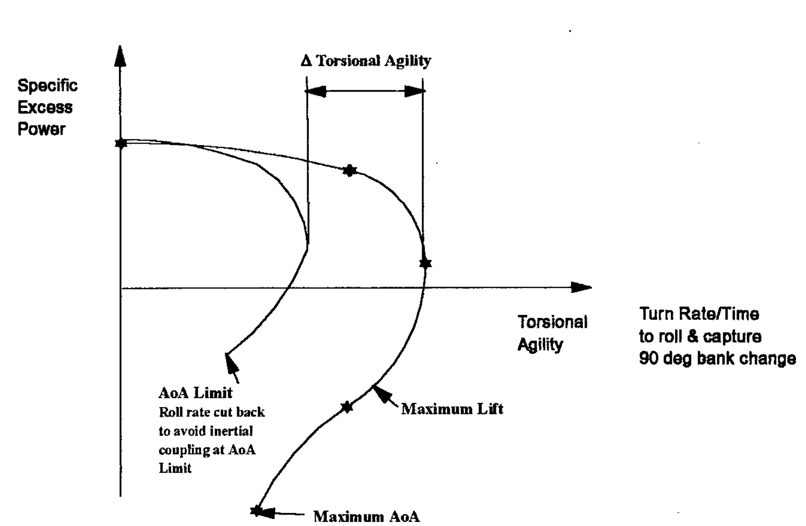
4 Use of Agility Related Metrics

Bound up in the agility concepts described by the Working Group are the respective merits of the airframe, the weapons, the sensors and airborne systems, all of which interact to provide the total weapon system package. It is to the difficulty of capturing the implications and to the evaluation the possible combinations of technologies that might be applied that the metric types proposed were targeted.

Whilst attempts have been made to derive agility metrics from a rigorous analysis of the flight mechanics equations or flight path equations, these have only addressed the airframe aspects of agility. Some metrics retain their essential usefulness as basic design parameters, e.g. sustained turn rate, attained turn rate and specific excess power, as these provide a fundamental sizing for the aircraft design, especially when combined with the flight performance requirements which give range, payload, etc. These metrics, which are totally conventional, may not even be thought of as being related to agility, but they do define a major portion of the airframe contribution to overall effectiveness.

However, most of the metrics proposed have a common theme running through them, which allows the concepts to be applied to any aspect of the Weapon System, singly or in combination.

Figure 3: The Torsional Agility Metric



Most agility metrics are derived from consideration of a task, however simple, combined with a time element. Some of the earliest metrics and simplest , such as time to 90° bank angle, represent open loop tasks. Whilst these are easy to evaluate and useful, they may not be fully effective in quantifying agility properly.

A better form of metric is obtained by defining a task to be performed, however simple, but with a specific accuracy to define the completion of the task, such as the torsional agility metric, illustrated in figure 3, taken from reference 3.

In terms of this example above, the task would then be to roll through 90° bank angle change and acquire the resultant bank angle to a specified accuracy, of say plus or minus 5°. In this case, an aircraft with a high roll acceleration or roll rate but poor control of either could take longer to complete the task than an aircraft with lower performance. This would tend to be reflected within the Handling Qualities ratings as well.

The most effective measures are those which define a task, the nature of the task which should itself be defined as a response to the environment to cause a desired mission outcome and change in that environment, and the accuracy required for the final outcome. It is this latter aspect which allows the precision and poise to be evaluated, since, if the task cannot be completed to the required accuracy, then time can be lost before being able to progress to the next stage.

One such study has been performed by DRA on helicopter agility (reported in reference 1) which attempts to define a metric relating the actual achievement to the absolute theoretical maximum, assuming instant changes and no lags. This metric, which has been termed the agility factor was then correlated with the handling qualities, as expressed by the Cooper-Harper rating, an example from reference 1 being shown in figure 4, for three aircraft configurations, A, B and C. Interestingly, as the pilot became more aggressive and the agility factor increased, there came a point at which the handling qualities deteriorated significantly, and in one case, aircraft C, this was sufficient to degrade the agility factor significantly.

A further more complex example which illustrates the systems aspects of agile response could be along the lines of examining the actions which have to occur in response to detection of an incoming missile threat. The question could be phrased in two different ways, with perhaps very different outcomes, viz.

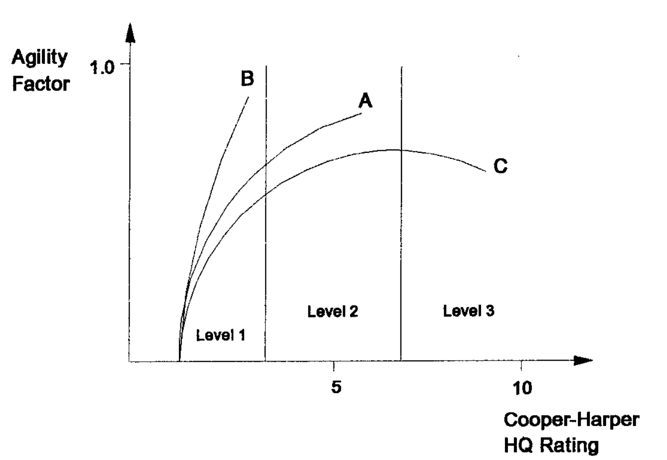
(i) to protect ones own ship, which could mean taking evasive action, selecting and employing counter-measures, etc.

as opposed to

(ii) launch flares or decoys in response to the incoming attack, which addresses only one aspect.

The first question has a number of answering options attached to it and requires the design to shape the specific actions to cause an outcome, whereas the second leads to the design of a cockpit switch to control a sub-system. The first approach allows a focus on the net effect of each aspect and allows comparisons of the effectiveness of the differing systems and solutions. It may result in the latter option, but only following a proper consideration.

Figure 4: Agility Factor and Relation to Handling Qualities



A further fundamental question regarding agility is "How much is enough?" and might be followed very rapidly by "How much can I stand?" and even "How much can I aford?" The answer to these is difficult to quantify; there are limits imposed, especially on the airframe, e.g. by loads or by handling qualities, on the pilot due to physiological effects but for the avionics and weapons systems, then the answer is less clear at present. When affordability is also added to this, then the question requires all aspects to be considered as being tradeable against each other.

It is suggested that the question is best answered for each individual project in its own right, as it will depend upon the roles which are intended and the specific mission tasks which are derived from these. Whatever, the key to successful determination of what is required in both terms of peformance and the technologies to be used, comes from defining the tasks and the criteria for completion of the tasks.

5 Design Trade-off Studies

Design of a combat aircraft to maximise its operational effectiveness requires the design synthesis process to take account of all of the aspects which will influence the vehicle performance as a weapon system.

Traditionally, this started by sizing the aircraft and establishing the required performance parameters, such as wing loading, sustained turn, attained turn and specific excess power levels. At the same time, the systems engineers would be establishing their systems design, such that they were compatible with the airframe, at least from an installation and power consumption viewpoint. This was usually accomplished by defining pre-set budgets for mass, volume and power consumption, whereafter, the design processes were essentially independent of each other, except for detail spot checks at appropriate stages of the system development.

A consequence of this approach was that sometimes, with more integrated designs, there would be a significant clash of priorities and a compromise would either have to be accepted or a redesign initiated, with consequent delay and expense. An example would be the compromise of a radar dish size to fit into the aircraft lines.

Modern combat aircraft are rather different in that they will tend to have the following features which will significantly influence the design and the design processes:

- A very long service life, from entry to final withdrawal, which has very significant implications for the airframe design and some of the systems as they will have to survive several upgrades to other systems. This requires that adequate capability and flexibility be built in from the start.
- An integrated design of the airframe and its propulsion system, flight control system and onboard avionics and other systems, especially defensive aids.
- The capability to have the avionics and weapon or weapons systems upgraded several times during the life of the aircraft, which again has implications for the design of the airframe and choice of powerplant, or secondary power systems.
- High levels of availability and maintainability, with significant use of onboard fault diagnosis and even repair.
- Adequate in-built flexibility to allow modification to meet changes in the perceived threats and advances in technology. It is this latter that is perhaps the most difficult of all to predict, given the pace of change which has occurred, especially in microprocessing power available with the latest techniques of chip manufacture and the change away from dedicated processors for aircraft use.

It is the high levels of integration of all of the aircraft attributes which leads to the complexity of the design process and the need to be able to apply various multi-disciplinary optimisation techniques. Examples of highly integrated modern combat aircraft are to be found in Eurofighter 2000 (reference 4), Rafale (reference 5), the F-22 (reference 6) and RAH-66 and the JAS-39.

Clearly, the use of a number of advanced technologies can be of great benefit in terms of the overall performance, and one of the key issues is the choice of which technologies should be employed to ensure the best effectiveness, whilst remaining within the inevitable affordability constraints.

The agility metrics concepts can be and have proved extremely powerful in helping the design decision process, even though the metrics are not yet well founded, and may have been applied without reference to agility specifically.

It is the asking of the questions that the metrics pose that is important in the process of understanding the available design trades.

Combined with these technical apects, there is a need to adopt a different way of working within the design teams, and these processes are still developing. The new ways feature multi-disciplined, multi-skilled, co-located teams utilising modern concurrent engineering processes and information systems and technologies.

6 Available Tools & Tool Development

6.1 Simulations

Traditionally, a range of tools has been available but one which has not really been harnessed the tools to represent the total weapon system. Instead the tools have been designed to concentrate on each individual system without regard for the impact that one system can have upon another. This was a reasonable approach, for traditional aircraft, before aircraft became so highly integrated.

Now, however, with highly integrated systems becoming the norm, there has been a need to develop tools which are capable of allowing the design teams to assess the various integrated design solutions. This approach starts with the Operational Analysis type tasks, where it is now commonplace to develop ever more sophisticated models of the aircraft, their various systems and their attributes, and the likely competitors to enable selection of the most likely combinations which will succeed against a given set of requirements or scenarios.

The result of this process has been the development of a set of simulations of ever increasing complexity which represent the aircraft and its systems with increasing levels of fidelity, culminating in full aircraft manned simulations in which all of the man machine interfaces are represented either by models or real equipment. Indeed, the trend is now to utilise virtual reality techniques and synthetic environments to capture the requirements and issues raised by operators in terms that can be readily understood within an engineering community and simulate the desired or expected performance before moving to final specification of the equipment for the aircraft. Within such environments it is possible to gradually replace the virtual components with the real hardware and software as it becomes available.

Certainly, experience has shown that the manned simulations are exceedingly powerful as communication tools between the design engineers, the aircrew and the Customer. When a complex man-machine interface has to be designed and evaluated, such tools are essential.

There is nothing quite so persuasive as being able to demonstrate via simulation a proposed solution to an issue in a realistic working environment, either to a programme manager or the Customer.

6.2 Demonstrator Programmes

In recent years, there has been a trend towards developing integrated technology demonstrations with a view to establishing how technologies should be combined. A number of these have resulted in flight demonstrators, such as the Jaguar FBW (figure 5), the HIDEC F-15, the SMTD F-15, the EAP (figure 6), the VAAC Harrier and the X-31 programmes. In each case, these have allowed the assessment of what the technology integration problems are, for a series of chosen technologies, and hence allowed the lessons to be accumulated for use in full production environments. Their value is that they represent the ultimate simulation tool and allow the turning of experimental models into real hardware with a view to seeing how it all works when combined.

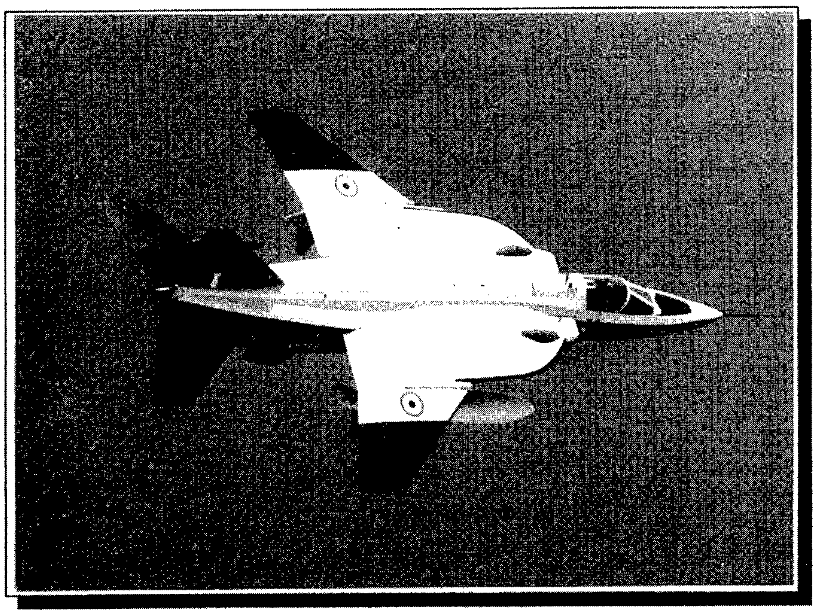


Figure 5: Jaguar FBW

For Eurofighter 2000, within the U.K., the EAP demonstrator aircraft was aimed at the demonstratioon of the integration of a number of advanced technologies, including FBW FCS applied to an advanced aerodynamic configuration, combined with new materials for a light weight, easily produced structure and the use of a digital databus architecture for the

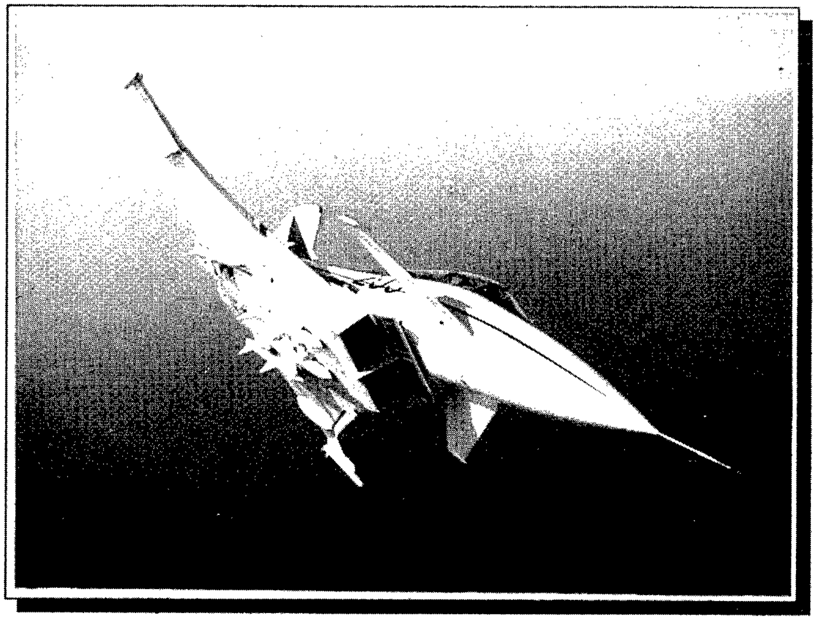


Figure 6: EAP

control of the aircraft avionics and utilities. This demonstration, which was supported by BAe and Alenia, provided a major risk reduction for the Eurofighter 2000 programme. Similarly, the X-31 programme has provided the industry within Germany with similar opportunities and the benefit of both demonstators is now being accrued on the Eurofighter programme.

6.3 Examples of the Design Trade Process

As an example of the design trade studies which can be undertaken is provided by Eurofighter 2000 (figure 7).

In the case of Eurofighter 2000, a number of simulations have been performed, both by the manufacturers and the Customer to determine the capabilities required and to establish the worth of the various technologies from an operational viewpoint, including evaluation of the integrated result against known opposition and the forecast developments which are anticipated over the next quarter of a century.

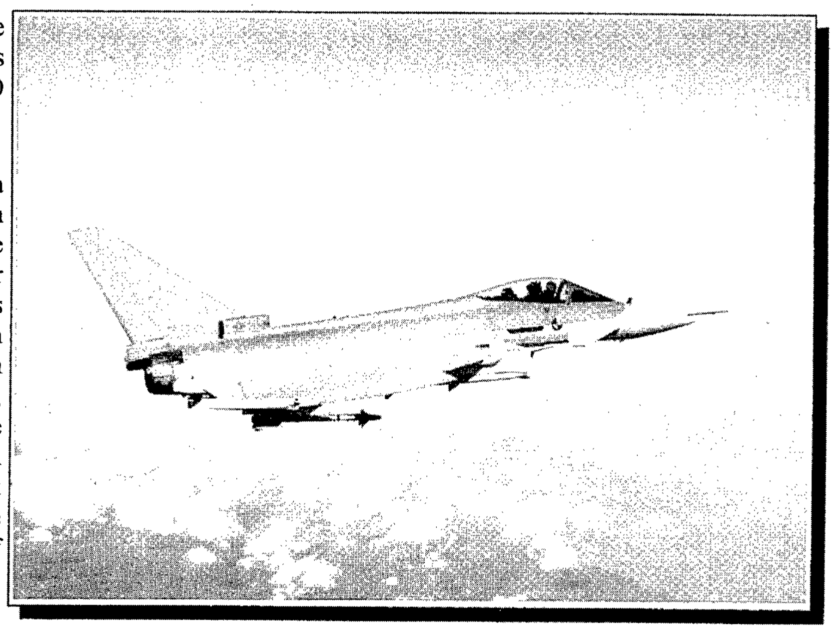


Figure 7: Eurofighter 2000

In the case of EF2000, the basic requirement calls for "an agile aircraft" without defining what this really implies. Clearly, the Customers are seeking a system with maximum overall effectiveness, whilst remaining within the very tight affordability constraints. There have been a number of examples in the design optimisation where the airframe, systems and weapons technologies interact.

The Eurofighter aircraft is designed to feature a very low wing loading and high SEP, giving exceptional turn peformance over a wide speed range. There has been a debate regarding whether or not the aircraft should be capable of Post-Stall manoeuvring. To put this into context, consideration has been given to the advantages that this confers, against possible penalties, such as cost, weight and maturity of the technology, but the debate also has to take into account the remainder of the systems, such as the impact on cockpit displays.

Eurofighter is being designed to be integrated with a weapon with a Helmet-mounted sight capability and with an improved seeker. The weapon has high thrust, so leaves the launch rail at high speeds, reducing its local AoA and when combined with its own neutral stability, this reduces the "tip-off" problem. The key trade is then between pointing the aircraft and being able to achieve a launch solution for the missile with the HMS.

The conclusion reached in a number of studies performed to date was that there was no driver at present for the thrust vector capability and that the current basic weapon system design was capable of dealing with the expected threats.

However, it is worth noting that the production airframe, by design choice, has the potential to add thrust vectoring as a mid-life update enhancement.

7 Implications for Future Specifications and Requirements

Many combat aircraft specifications and requirements are not really appropriate for the complex, integrated vehicles which have to result from attempting to meet the requirements.

The very complexity of the vehicles often means that decisions relating to the design options may not take into account all the influences, such as the potential changes in technology which may occur or the time for chosen technologies to mature to the point that they can be applied successfully. This may lead to engineering difficulties and expense later in the processes of development and procurement. It may even result in a debate as to what is the real requirement, meeting the specification or being fit for the intended purpose.

Recently, there has been a change to the way in which Weapon Systems are formulated which better accounts for the changes in technology which may occur during the design and subsequent life cycle of a combat aircraft.

The process, illustrated in figure 8.

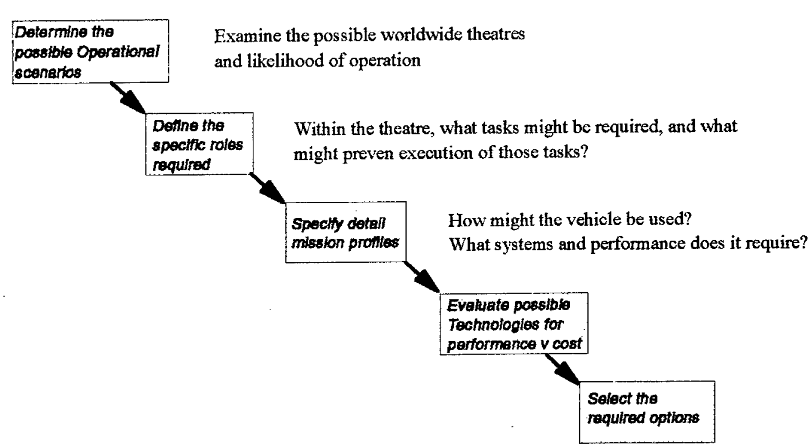
At a very top level, the need is to consider the operational scenarios, the wars or other conflict and policing roles, which may be encountered, from which the various roles and their relative importance can be derived. This level of activity will determine, for example, whether the primary role will be interdiction or air superiority with a secondary ground attack capability, at what range and against what particular threats.

The key is a method of defining the intended role of the vehicle, based upon the possible operational scenarios which can be foreseen, especially accounting for the perceived threats, and the concepts involved in Operational Agility can assist in this process, particularly if combined with the modern, powerful simulation methods which are now available.

Then, these roles can be broken down into a series of specific missions, then mission tasks, then mission task elements. From these, it should be possible to establish the interactions of the various technologies that can be applied to the aircraft and to determine which are the most cost effective technologies to employ, as all Customers will have an affordability issue which they have to work within.

In parallel with this activity, or possibly even preceding it, there has to be an activity to develop and start to examine which technologies are likely to be employed in the design. To do this, it is necessary to establish all of the options, but the process which follows is then crucial in determining which will actually be adopted.

Figure 8: Process for Determination of the Vehicle Roles and Technologies to be applied.



It is of note that the rotary wing requirements for handling qualities, as laid out in ADS33C, for example, already use the concepts of mission task elements in deriving their design parameters.

It is possible to write down a list of all of the technologies that you might wish to deploy, but an analysis is essential to determine which are the most cost effective technologies to use in a real aircraft project, especially taking into account the constraints on budgets which will inevitably occur and the level of maturity which can be expected at the time that the technologies are actually going to be applied.

Experience shows that this is a vital step, and that if it is not conducted carefully, the risks which emerge are sometimes too high to be managed effectively, often leading to cancellation and or financial problems for the manufacturers and customers alike.

8 Conclusions

The effectiveness of a combat aircraft and the agility of the aircraft are inextricably inter-related, especially if taking agility to mean much more than just the airframe related aspects which have been traditional, but including the weapons, sensors, avionics and man-machine interface.

Use of agility metrics and methodology, combined with the use of increasingly integrated modelling and simulation, including the application of virtual reality, synthetic environment techniques, can allow for the assessment of which aspects are best combined to produce the desired overall blend of capabilities, whilst recognising the bounds which are inevitably placed by affordability. Indeed, affordability has to become one of the parameters added to the modelling of the integrated system.

It is the successful blend of the various attributes of the integrated weapons system that will determine whether or not the vehicle is effective as a combat aircraft.

The key lies in defining the tasks which have to be undertaken together with the required accuracy of the result, rather than leaving the tasks open-ended. With this in mind, the metrics can then be tailored to any individual aircraft project.

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The Benefits of the Passive and Active Aeroelastic Design of Aircraft Structures

H. G. Hönlinger*, P.-M. Hutin**, E. W. Pendleton***

1. Introduction

The increasing performance requirements and the economical pressure to reduce Direct Operational Costs (DOC's) of new aircraft design can no longer be met by traditional and sequential design processes. This is especially true when considering aeroelasticity. The impact of aeroelastic effects on the design of new high-performance transport or fighter aircraft demands the use of multidisciplinary design concepts and optimization strategies in the preliminary design phase or earlier to develop flutter-free structures and to ensure excellent multipoint design characteristics.

This paper presents selected examples of a variety of aeroelastic design principles for passive primary aircraft structures and for active structures of advanced aircraft with highly sophisticated fly-by-wire flight control systems.

2. Aeroelastic phenomena

2.1. Definition and classification of the aeroelastic problems of aircraft structures

Aeroelastic problems of aircraft structures result in mutual interactions between static and dynamic deformations of the elastic aircraft structure which thereby induce steady and vibration-induced unsteady aerodynamic loads. In modern aircraft with fly-by-wire flight control systems as well as any other type of active control system, additional interactions between the airframe and control systems are possible. Thus, the flexibility of the aircraft structure is fundamentally responsible for a variety of aeroelastic phenomena and related problems. As long as the strength requirements are fulfilled, structural flexibility itself is not necessarily objectionable. The aeroelastic interactions resulting from structural deformations, however, may not only strongly influence the structural dynamics and dynamic flight stability, but also the overall performance and controllability of the aircraft; see Ref. [1]. Therefore, in the conceptual and preliminary design phase of a new aircraft, the application of aeroelastic design criteria becomes imperative for the structural design process.

The whole spectrum of aeroelastic phenomena to be considered during the design process can be clearly classified by means of Collar's well-known aeroelastic triangle of forces, Ref. [2], illustrated in Fig. (1). Three types of forces - aerodynamic, elastic,

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Paper presented at the AGARD Symposium on "Future Aerospace Technology in the Service of the Alliance", held at the Ecole Polytechnique, Palaiseau, France, 14-17 April 1997, and published in CP-600 Vol. 1.

and inertial - are involved in the aeroelastic process. Generally, aeroelastic phenomena can be divided in two main groups:

- static aeroelastic phenomena, which lie outside of the triangle, i.e. divergence of the structure, control effectiveness, and load distribution created by aerodynamic and elastic forces

- dynamic aeroelastic phenomena, which lie within the triangle since they involve all three types of forces, i.e. flutter, buffeting, and dynamic response or dynamic flight stability.

All of these aeroelastic phenomena have profound effects on the aircraft design and, e.g., the stiffness criteria based on aeroelastic requirements become increasingly important design criteria which govern the optimization processes of aircraft development.

2.2 General aeroelastic requirements for high-performance aircraft design

In this paper, only the most important aeroelastic design criteria applicable to high-performance aircraft ranging from glider to fighter to large transport aircraft is addressed. Due to the fact that aeroelastic phenomena like flutter and divergence can be of catastrophic nature and that other phenomena like static wing deformation can reduce control effectiveness or raise the drag and, in turn, fuel costs, the following design rules have, among others, become the standard for any aircraft design (e.g. Mil. Spec. and VAR/JAR regulations):

- the aircraft must be free of flutter, divergence, and aeroservoelastic instability within its flight envelope

- the control effectiveness of combinations of controls must be above a given minimum to assure safe flight performance within the envelope

- the flight shape of the wing should have minimum aerodynamic drag and sufficient effectiveness for all configurations

- the planform of a weight competitive wing should have maximum aerodynamic efficiency (aspect ratio) provided by advanced aeroelastic design.

The latter rules need to be established. This can be accomplished by updating conceptual sizing and layout processes to reflect the enhanced configuration freedom provided by advanced aeroelastic design.

The application of these rules during the design process will be demonstrated by selected examples in this paper.

3. Aeroelastic design of passive airframe structures

In this context, the passive structure is the load-carrying structure of an aircraft including all control surfaces. Special attention has to be paid to the attachment stiffness of the control surfaces from an aeroelastic point of view. If the controls are actuated manually, for example with push rods, the attachment stiffnesses of the control surfaces are considered as real springs (linear or non-linear). If the controls are actuated by hydraulic jacks, the attachment stiffness is considered as complex springs (with a certain bandwidth in its transfer functions).

3.1 Optimization strategies to increase the flutter stability of metallic wing structures

Modern transonic transport or fighter aircraft have swept-back wings which eliminate or prevent the phenomenon of torsion divergence. But from the preliminary design onwards, design strategies have to be applied in order to avoid bending-torsion flutter instabilities of these type of wings. To avoid flutter instabilities or to increase the flutter speed to speeds outside of the flight envelope, the stiffness and mass properties of flutter-prone components must be optimized. The physical optimization task is, e.g., to optimize the stiffness and mass distribution of the wing structure under the following constraints:

- fulfillment of all static requirements derived from design loads (strength strain and buckling, [3])
- no change in the outer geometric/aerodynamic profile
- additional minimum structural or balance weight to solve the flutter problem.

During the preliminary design process, when this type of optimization is normally required, the design is already frozen to a certain degree. This means that the design space is limited. Typical design variables in the preliminary design, as pointed out in Ref. [4], are:

- thickness or cross-section of structural elements
- geometry (coordinates of nodal points, key points of design elements)
- variable lumped masses (for flutter).

To enhance the optimization process, the aeroelastic design principles have to be defined in such a manner that they can be formulated as constraints with as much information as possible. These appropriate formulations can be easily found by means of the analysis of the envisaged flutter mechanisms. For the classical bending-torsion flutter of wings, the following two criteria which are beneficial for flutter prevention can be found, Fig. (2).

- The frequencies of the flutter-prone wing bending and wing torsion mode must be far apart. The further the two frequencies are separated, the more energy from the airstream becomes necessary to generate the flutter instability (e.g. flutter is shifted to higher speeds).

- When analyzing the shape of the flutter-critical wing torsion mode, lifting surfaces where torsion modes with nodal lines are situated rearward are found to be more prone to flutter than when nodal lines are shifted forward. This is additional information for the optimization of the stiffness or mass distribution to improve the flutter stability.

These aeroelastic principles applied in the optimization process of primary metallic structures usually lead to a local increase of the stiffness distribution of the initial design with a minimum of weight penalty. In most cases, the improvement of the flutter stability of a structure under the given constraints must be made with additional weight penalty. An example of the application of these aeroelastic principles is given in the following study of a transport aircraft wing structure. Figs.(3) and (4) show the result of a sensitivity analysis of the stiffness distribution in the forward and rear spars of the wing box. In this analysis, areas of reinforcement were identified which have a beneficial effect on the flutter stability of the wing design. After reinforcement of the structure a new flutter analysis was performed and compared with the initial (fully stressed) design; see also Ref. [5]. As can be seen from the figures with a reinforcement of only approx. 95 kg in structural weight, the flutter speed could be shifted to outside of the flight envelope, Fig. (5).

Manually controlled aircraft tend to be prone to control surface flutter instabilities. Based on the knowledge of this typical surface flutter mechanism, the problem can be countered with appropriate mass balance. With these additional balance masses, the inertial properties of a flutter-critical control surface can be manipulated so that the separation of natural frequencies is achieved again and flutter is shifted to higher speeds. The optimization task in this case is to again achieve the required flutter speed margins with optimal stiffness distributions, a light-weight surface structure, and a minimum of additional balance masses [6].

3.2 Strategies to improve the structural effectiveness of lifting surfaces

Lifting surfaces with aspect ratios of $\lambda \geq 5$, in the first approximation, have a beam-like structural behavior and deformation. For unswept wings like sail planes, static aeroelastic phenomena are entirely dependent on wing twist stiffness around the elastic axis, and wing bending stiffness is not a factor. Swept wings of modern transonic transport or fighter aircraft, however, have an important and complicated effect on the aeroelastic behavior. Due to geometric coupling for a swept wing, any bending will cause a reduction in the wing twist (wash-out twist), i.e. of the local angle of attack distribution as can be seen in Fig. (6). The drag and lift distribution of the wing, in turn, is dependent on the angle of attack distribution. For large transport aircraft the wing contributes to 60-65% of the total drag and therefore the structural behaviour (efficiency) of the wing has a significant impact on the fuel consumption. The streamwise incidence reduction resulting from bending can also drastically reduce the control effectiveness of ailerons even with the possibility of aeroelastic control surface reversal. To counter this problem, the stiffness distribution of the wing structure (wing box) has to be optimized. In this case, the aeroelastic optimization task is to produce a required flight shape (local angle of attack distribution) and control effectiveness of the aileron with a minimum of structural weight penalty with regard to other constraints (e.g. flutter stability, minimum drag, or limited root bending moment). Here again, the aeroelastic means of achieving an aerodynamic and flight control benefit is to manipulate the stiffness distribution of the metallic wing box based on the knowledge of the aeroelastic bending-twist coupling mechanism of swept wings [7].

3.3 Aeroelastic tailoring strategies for composite structures

From an aeroelastic point of view, the major advantage of composite material is its anisotropic stiffness behavior which offers more freedom in the stiffness design (additional design variables are the fiber directions of the composite material). Aeroelastic tailoring is the embodiment of the directional stiffness of composite material into an aircraft structural design to control aeroelastic deformation, static or dynamic, in such a fashion as to affect the aerodynamic and structural performance of that aircraft in a beneficial way.[8], [9], [10].

Static and dynamic aeroelastic phenomena can be "treated" with this technique. In this presentation, only two typical examples for optimizing the aeroelastic deformation (wing twist) under steady aerodynamic loading are given. Fig. (7) shows the result of a design study for a generic swept wing transport aircraft. This generic wing consists of a metallic inner wing and a composite outer wing starting at a 60% wing span. The subject of the study was to assess the potential of aeroelastic tailoring for the outer wing. The reference for this study was a metallic wing design. The comparison of the three investigated cases clearly shows the potential for drag reduction of the aeroelastically tailored wing.

The relative wing twist between flight and jig shape is nearly half compared with the metallic reference wing. In addition, the aeroelastically tailored wing is less sensitive to wing fuel conditions which, in turn, also improves the drag. Also, aeroelastic tailoring can be applied as well to shift the nodal line of a flutter-critical mode to achieve higher flutter margins or even to realize forward-swept wing configurations.

The Grumman X-29 technology demonstrator is another example of aeroelastic tailoring applied to wing design [11]. The X-29 wing had a forward leading edge sweep angle of 29.3 degrees, as shown in Fig. (8). The wing skins consisted of graphite epoxy composite laminates with an orthotropic 0 / 90 /+- 45 degree ply orientation. The -45 degree plies were located 9 degrees forward of the 40% chord to provide the bending-torsion coupling in the wing to sufficiently reduce the wash-in tendency. The reduced wash-in also precluded the occurrence of divergence within the aircraft envelope. The result is a weight competitive forward swept wing design.

3.4 Benefits of passive design principles

The presented examples demonstrate that knowledge of the mechanisms of aeroelastic phenomena combined with optimization strategies and modern composite structures technology lead to aeroelastically efficient and stable structures with minimum structural weight penalties when applied from the beginning of the design process. If aeroelastic problems are discovered late, i.e. during flight testing, only ineffective repair solutions with high structural weight penalty can be applied or, in the worst case, can result in costly redesign.

However, much work remains to be done, particularly for the integration of controls and performance into aeroelastic configuration design and optimization processes. Full modelling of aircraft control aspects is needed to establish critical load cases, evaluate control authority, determine hinge moment requirements, simulate maneuver, etc. Also, aeroelastic benefits which typically require more structural weight, such as wash-out twist, must be fully evaluated from the point of view of aircraft performance before the benefits of aeroelastic tailoring can be fully activated.

4. Aeroelastic design principles of active aircraft structures

In this context, an active aircraft structure is any aircraft structure with active elements like computer-controlled, hydraulically activated flight control surfaces which can be used to introduce energy into the structure in order to improve its performance. A general scheme of active aircraft structures is given in Fig. (9). Sensors integrated at designated locations of the structure measure the behaviour of the passive airframe structure (e.g. rigid-body motions and elastic deformations). The signals of the sensors are fed into the computer (controller) which, in turn, processes via control laws the input signals for the control surface actuators for any other active system.

4.1 Active control functions

The integration of modern electronic flight control systems (EFCS) in combination with fly-by-wire technology offer design engineers a chance to implement additional active control functions in order to gain benefits for airframe performance as outlined in Ref. [12], [13].

Active Functions	Benefits
care-free handling	reduction in structural weight
maneuver load control (MLC)	reduction in structural weight
gust load alleviation (GLA)	reduction in structural weight
Fatigue Life Enhancement	reduced maintenance costs
deformation and elastic mode control	reduction of aerodynamic drag
flutter suppression	improvement of dynamic stability
ride comfort improvement	passenger comfort

The optimal implementation of these active control functions into the passive airframe leads to active aircraft structures which enable the aircraft to function beyond the performance of the classical passive structure. Gust load alleviation (GLA) systems, for example, reduce the additional loading produced by gust by means of lift generated by control surface deflections on the wing, Fig. (10). Usually, the design driver for transport aircraft wings is the bending load and, consequently, applied GLA leads to less structural weight in the wing fuselage attachment section. In a similar manner, fatigue life enhancement functions lead to less structural weight by means of the damping (reducing the peak values) of the fatigue life consuming vibration modes. Depending on the control laws, the main part of the active functions mentioned ahead can be used to change the external forces, i.e., aerodynamic load distribution acting on the lifting surfaces with the aim to reduce internal loads (stress) in the structure which, in turn, lead to less structural weight. In this case, the optimization task is to optimize the control laws according to stress constraints together with other constraints like minimum control energy or controller robustness, etc. which are relevant to the control systems.

Another application of active functions involves changing properties of the structure itself to improve the modal damping and dynamic stability of the "active structure". Here, the optimization task is to generate control laws which process the measured signals in a way that energy from the airflow around the lifting surface is extracted by the control surface and introduced into the "flying aircraft system" so that the frequency, mode shape, and damping of selected modes are positively manipulated to increase the flutter margine (active flutter suppression).

4.2 Dynamic stability of active aircraft structures

In all of these control law optimization procedures, the dynamic stability of the "flying active aircraft" system is mandatory. The interaction between the aircraft's structural dynamics, unsteady aerodynamics, automatic flight control, and active functions has emerged as an important design consideration. This field of merging dynamic flight disciplines is called aeroservoelasticity, as illustrated by Fig. (11). In this aeroservoelastic triangle, the left leg represents the classical dynamic aeroelastic interaction which does not include inputs from an active system. Similarly, the lower leg of the triangle represents a classical aeroservodynamic control system synthesis. Finally, the right leg represents the important dynamic servoelastic coupling between the elastic modes of the aircraft and the active control system. This coupling, together with the unsteady aerodynamic feedback inputs from servo-actuated active control surfaces, then results in an aeroservoelastic interaction which is generally known as structural coupling.

Active functions are, in many cases, high-gain control systems. As mentioned ahead, the control surface areas generally used for active functions are small fractions of the wing area to be aerodynamically influenced. Therefore, to achieve efficiency, high-gain systems are required. High-gain systems, however, bear the risk of instability problems for higher vibration modes. Dangerous aeroservoelastic instabilities may occur if the sensor signals with an information content, which are broader than necessary, are not processed and fed back correctly by the control laws. Aeroservoelastic instabilities can be as dangerous as classical flutter instabilities.

4.3 Integrated flight control design and optimization with respect to flight dynamics and aeroservoelastic stability requirements

As outlined ahead and in Ref. [14], the development of advanced digital flight control systems for modern civil and military aircraft are strongly influenced by aeroservoelastic effects. The implementation of active functions, in addition to the electronic flight control system (EFCS), increases the complexity and the risks of aeroservoelastic instabilities. To counter this problem, an integrated design process of the EFCS and all active functions is necessary. This design procedure includes the derivation of the EFCS gains, phase advance filters and notch filters to minimize structural coupling in one combined optimization process. The EFCS shall be designed to cover full rigid, flexible aircraft frequency ranges with respect to the aircraft rigid mode and structural mode coupling stability requirements for each control system loop. The structural coupling influences will be minimized by notch filters or other measures and the EFCS must be as robust as possible with regard to all aircraft configurations and to all kinds of non-linearities of the complete system "flying aircraft with active controls". This integrated design for a flexible aircraft is possible with the assumption that the aircraft characteristics are predictable with the necessary accuracy. This means that the architecture of the mathematical model of the "flying aircraft with active controls" system must be structured in such a way that optimization procedures can be applied (design variables and constraints).

To enhance the integrated optimization process of EFCS and its additional active functions, it is practical for it to be carried out in two stages as outlined in Ref. [14]. In a first step, the active components of the control system should be optimized with respect to aeroservoelastic criteria which are

- optimization of the sensor locations and sensor attachments (e.g., the gyro platform should be put into the antimode of the first fuselage bending mode, the elastic pitch-yaw angle/pitch-yaw rate is at a minimum; see Fig. (12)

- optimization of the actuator transfer functions (a strong decay in the actuator transfer function at medium to high frequencies would minimize the coupling effects)

- minimization of weight / inertia of control surfaces (high-frequency structural coupling effects are small when using light-weight controls).

The second step is the optimization process of the filters in the control loops. There could be two types of filters which are interdependent and which should be optimized together. Phase advance filters correct the low-frequency phase shift of notch filters and other delays. But the major tool for decoupling the aircraft control system from aeroservoelastic influences is notch filter optimization. An outline of the optimization procedure is given in Ref. [14]. In the optimization procedure the transfer functions of the filters are the design variables, and aeroservoelastic stability, control power, control authority, etc. are the constraints.

4.4. Potential of active control technology for aircraft structural design

When using active control technology (ACT) in the preliminary design stages as a design tool for active structures, its full potential to reduce structural weight for the improvement of the dynamic stability and handling qualities can be explored. The implementation after the design freeze, however, results in a so-called repair solution which, by definition, cannot be optimal. The block diagram in Fig. (13) describes the scheme of the active control feedback path of a modern fighter flight control system. It consists of measured rate signals which are filtered by phase advance filters and notch filters which are designed and optimized to provide sufficient stability margins for the elastic aircraft vibration modes. When applying the design philosophy for active structures, these notch filters can also be used as filters to provide an alleviation of elastic mode vibration (integrated active function). The requirements to which the gain and phase margins have to be optimized are depicted in Fig. (14). When evaluating the behaviour of the open loop frequency response function with and without the control system, the required principles of the concept are as follows:

- minimization of the phase lag from the elastic mode control for the "rigid" aircraft
- phase shift of the 1st elastic mode to the left with respect to the given requirements (design variable is the transfer function)
- system robustness for all flight conditions and aircraft configurations. This is achieved by use of open-loop frequency envelope response functions for all worst-case configurations (constraints).

Additional requirements to be met within the design process are:

- minimization of actuator fatigue life by limiting the additional actuator loads (constraint)
- no degradation of flutter speeds for aircraft with active structural functions (e.g. elastic mode control) (constraint).

The benefits of the integrated concept are:

- the improvement of aircraft handling qualities by use of the flight control systems
- the reduction of elastic aircraft vibration modes through the elastic mode feedback via rate signals
- improvement of flutter margins
- no additional redundancy concept necessary when using flight control system feedback paths.

This example is only a demonstration of the potential of an advanced control system design with the consequent application of aeroelastic design principles.

5. Active Aeroelastic Wing technology

5.1 Principle and potential of this technology

Active Aeroelastic Wing technology (AAW) is a multidisciplinary, synergetic technology which integrates aircraft aerodynamics, active controls, and structures to maximize aircraft performance as described in Ref. [15] to [18]. The difference of this concept, in comparison to active control technology and its improvement, is that AAW uses wing flexibility for a net benefit and thus enables the use of weight competitive high-aspect ratio and thin swept wings which are aeroelastically deformed into shapes for optimum performance. This makes it possible to achieve the multi-point aerodynamic performance required of future fighter aircraft. This is a new design approach in contrast to traditional air vehicle design approaches which treat wings and control surfaces as rigid components. These traditional approaches also see aeroelastic response as a negative aspect which must be overcome. Wing flexibility in high-performance aircraft usually causes adverse aeroelastic twist which, in turn, degrades the control effectiveness at high aerodynamic pressures. Traditionally designed high-performance aircraft wings are therefore stiffer than necessary in order to reduce adverse twist. This, however, adds significant structural weight and drag penalties.

Active aeroelastic wing technology turns aeroelastic wing flexibility into a benefit through the use of multiple loading and trailing edge control surfaces activated by a digital flight control system, Fig. (15). At higher dynamic pressures the AAW control surfaces are used as "tabs" which promote wing twist instead of trying to reduce it. The energy of the airstream is employed to twist the wing with very little control surface motion. In AAW, the flexible wing creates the control forces. This is the "revolutionary" idea of this concept. Optimization procedures are mandatory for the realization of this revolutionary concept.

5.2. Benefits of the AAW technology

At present, the benefits of the AAW technology are best attained for fighter aircraft when the design strategy requires a higher aspect ratio wing (λ >3.5). The wing skins and spars as well as the rib stiffness are optimized using only strength, buckling, and flutter constraints. Neither stiffness nor the corresponding weight penalty is addressed to increase static aeroelastic control effectiveness. Trailing edge control surfaces are even permitted to lose control effectiveness. The AAW control laws generate for all wing control surfaces (leading and trailing edge controls as a set) an optimal set of control surface deflection to provide large amounts of control power while still optimizing aerodynamic drag at low wing strain conditions across the subsonic, transonic, and supersonic aircraft flight envelope. AAW technology has already been demonstrated in wind tunnel tests and the next step will be flight testing, Fig. (16).

6. Smart Structures Technology and possible application in aircraft

6.1. Realization of Active Control Technology with smart materials

Historically seen, the Active Control Technology (ACT) was initiated as a repair solution for solving stability problems as a means of providing weight reduction measures to existing aircraft structures, as already outlined. With the development of the fly-by-wire technology, ACT became a design element. The new generation of smart materials now offer the potential for a higher grade of integration of the ACT into passive structures. Smart materials like piezo electric materials can be simultaneously used as a sensor and actuator, and can be directly integrated into load carrying passive structures, Fig. (17). These properties of the smart structure allow not only the realization of ACT goals, e.g., Gust Load Alleviation, Flutter Suppression, Ride Comfort, but also the principles of the active aeroelastic wing technology as integrated solutions. However, it must be clearly stated that smart materials will not replace the material used for primary, i.e. load-carrying structures, nor will it replace the need for optimizing passive structures in the future.

6.2 An application of Smart Structures technology

In the area of smart structures, the concept of active damping has already received considerable attention in the past years [19]. The modal damping inherent in metallic structures is low and is even lower in composite structures. Low damped structures, however, respond to excitation with high peak amplitudes which, in turn, are detrimental to the fatigue life of a structure. Therefore, the improvement of the modal damping of airframe structures is of general interest.

The basic idea of active damping is to use piezoelectric material to introduce extra damping in a structure, hence reducing vibration levels in the various modes of vibration of a structure. The extra damping can be generated in a structure by a number of methods. The traditional method is to introduce damping forces which are 90° out of phase with the structural motion. A more advanced technology is to actively enhance the damping of a passive element in the structure. This can be done easily by using constrained layer damping. The constraining layer is bonded to the structure using viscous material which acts as a passive damping element. The constraining layer effectively induces shear in the damping material while improving the damping properties of the structure. The increase in damping, however, has to be made with an additional weight penalty.

One way of introducing additional shear into the damping material is to actively control the motion of the constraining layer. There are two possibilities for achieving this. One method is to use piezoelectric polymers as a constraining layer to control its motion by applying the appropriate voltage. The second technique is to use piezoelectric material in addition to the constraining layer.

As an example of this technology, the following investigation using a cantilever beam shows a piezo-ceramic pad bonded to the constraining layer of a beam element. The visco-elastic material between the beam and the constraining layer is subjected to extra shear as a result of the constraining layer, hence to the amount of the shear in the visco elastic material. Several investigations were carried out for various combinations of the passive and active elements. The results are shown in Fig. (18). Four cases are depicted to demonstrate the effects of Constrained Layer Damping (CLD). These included: 1) a beam with CLD in the passive mode with no feedback, 2) a beam with active control only, 3) a beam with CLD, and 4) active control in comparison to a passive beam.

As expected, the passive beam has the highest peak in both excited vibration modes. The beam with CLD treatment had its second mode significantly attenuated. This result is not surprising because passive damping elements tend to perform better at higher frequencies. Case 4 shows the best result as the combination of passive and active damping methods.

The full potential of this technology has yet to be explored. But one may assume that the application of the optimization procedures will be essential for the success of this technology. Similar to the aeroelastic tailoring of composite structures, optimization strategies have to be developed to "tailor" the damping properties of structures by introducing the damping as a design variable. This example, however, already shows that smart structures technology enables the design engineer to "tailor" not only the stiffness properties in various directions but also to "tailor" the modal damping behaviour of a structure with a minimum weight penalty.

Another example of smart structures involves the application of piezoelectric material to the vertical tails of the F/A-18 to alleviate buffeting. Unsteady vortices emanating from the forebody during high angles-of-attack maneuvering can often excite the vertical tails of twin tail aircraft at their fundamental resonant frequencies. These vertical tails' responses over prolonged exposure to the flow field result in fatigue damage and high maintenance costs.

One potential solution to this problem lies with smart structures. Small piezoelectric packages are developed and distributed along the surfaces of vertical tails. A buffet alleviation control system is employed to activate the piezoelectric packages which, in turn, add energy to the structure so as to suppress the resonant responses of the tails due to the buffet. Fig. (19) shows a picture of the F/A-18 undergoing high angle of attack testing. Similar testing at high angles of attack is planned utilizing this buffet suppression concept.

7. Conclusions

For the design of high-performance aircraft, aeroelastic design criteria will become increasingly important and will need to be considered in the conceptual design phase. Multidisciplinary design and optimization procedures are essential for the efficient application of aeroelastic design criteria and to ensure minimum drag, the control effectiveness of metallic and composite structures, as well as dynamic stability.

Active control technology must be applied to extend structural aircraft performance beyond the structural limits of the passive airframe. The AAW is an advanced example of consequent application of this technology. The combination of active controls and smart structures technology enables the design engineer to tailor structural properties like stiffness and structural damping to achieve optimal performance. In order to explore the full potential, optimization procedures will play an essential role in the multidisciplinary design process of future aircraft. But much work still remains to be done, starting with the appropriate modelling of the "flying aircraft with EFCS and Active Functions" before the benefits of this fascinating technology can be fully exploited.

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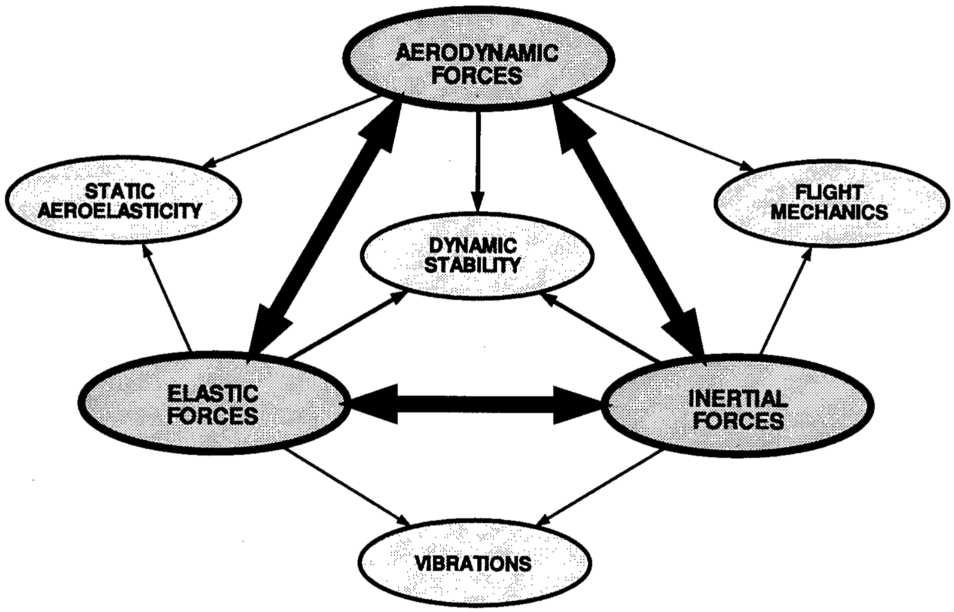


Fig. 1: COLLAR'S AEROELASTIC TRIANGLE

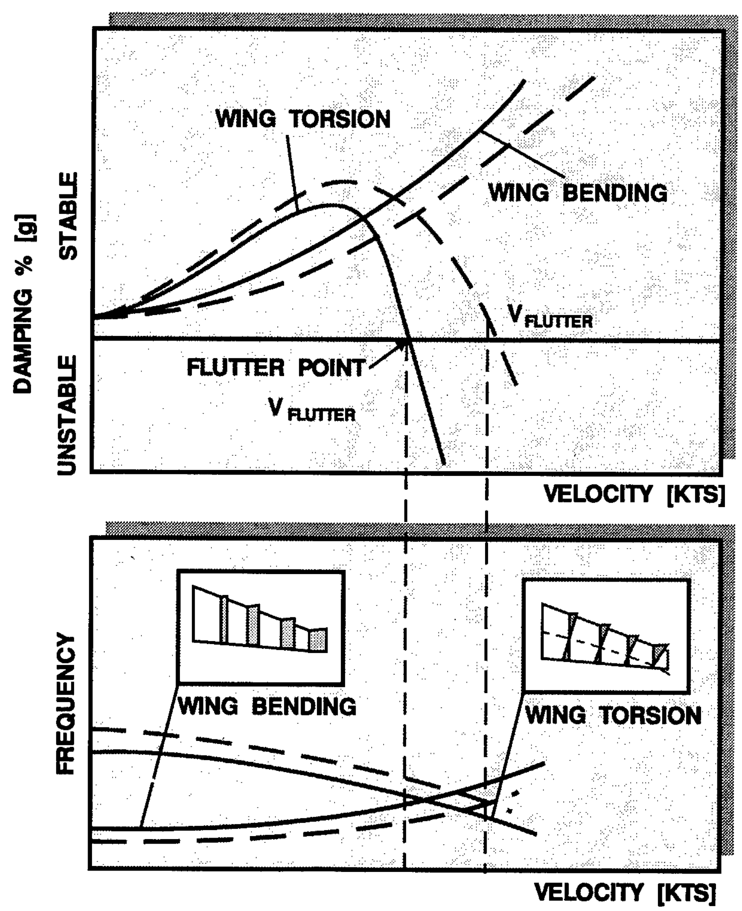


Fig. 2: WING TORSION FLUTTER MECHANISME

Daimler-Benz Aerospace Airbus

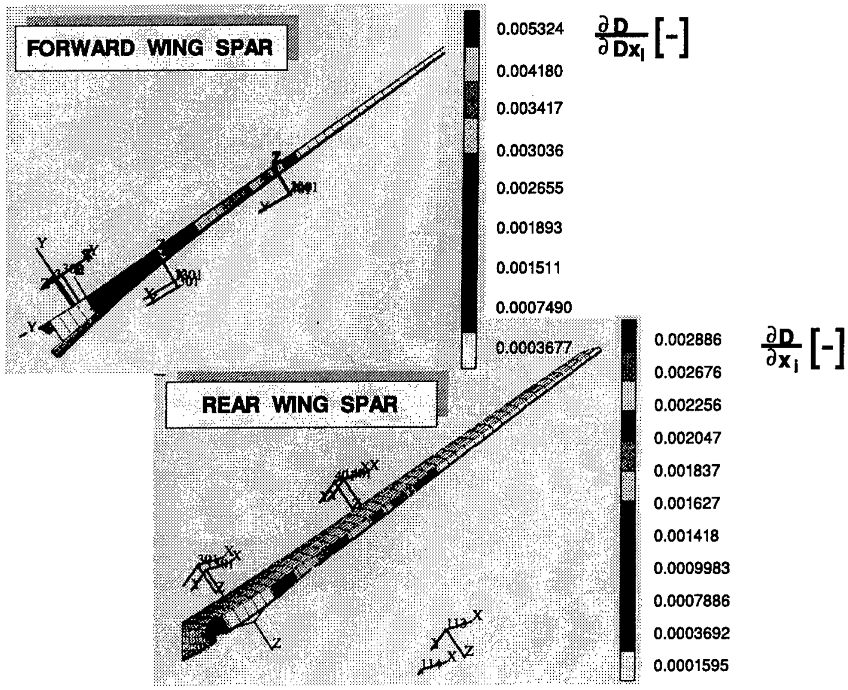


Fig. 3-4: RESULTS OF SENSITIVITY ANALYSIS

Daimler-Benz Aerospace Airbus

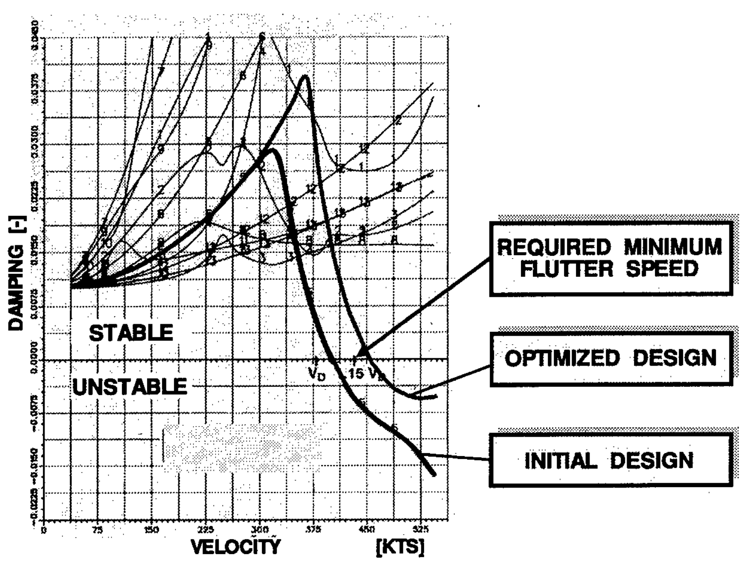


Fig. 5: RESULT OF FLUTTER SPEED OPTIMIZATION
(WEIGHT IMPACT 92.8 KG)

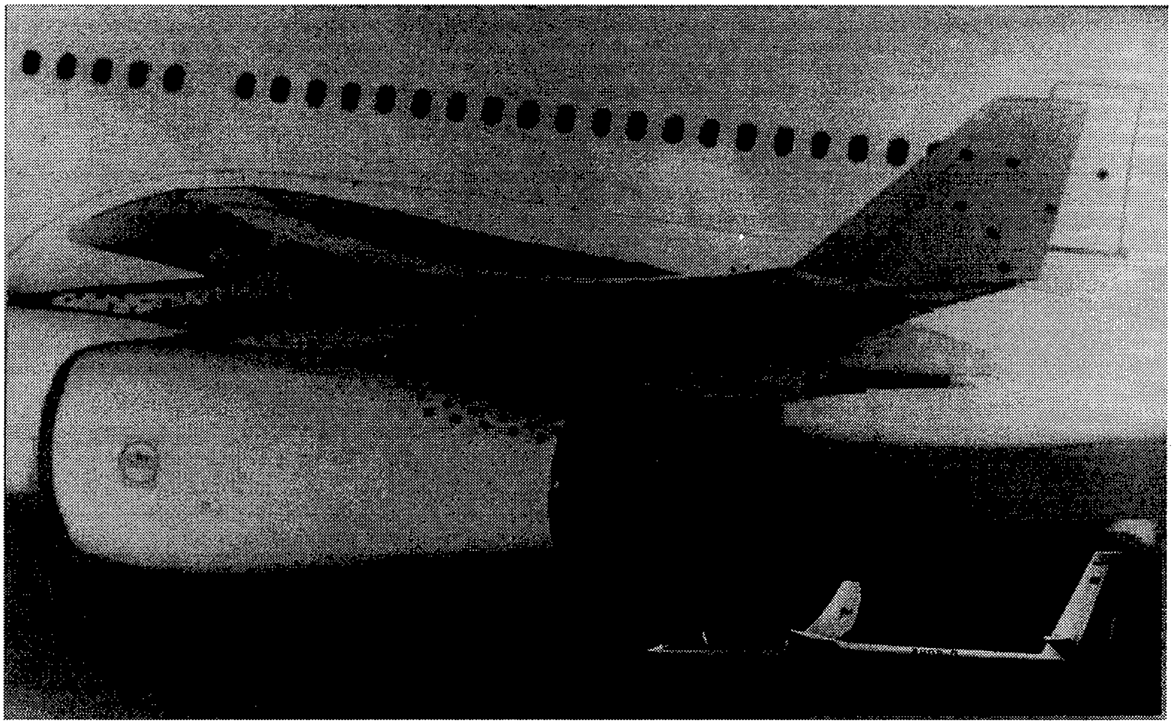


Fig. 6: WINGS UNDER AIRLOAD

Daimler-Benz Aerospace
Airbus

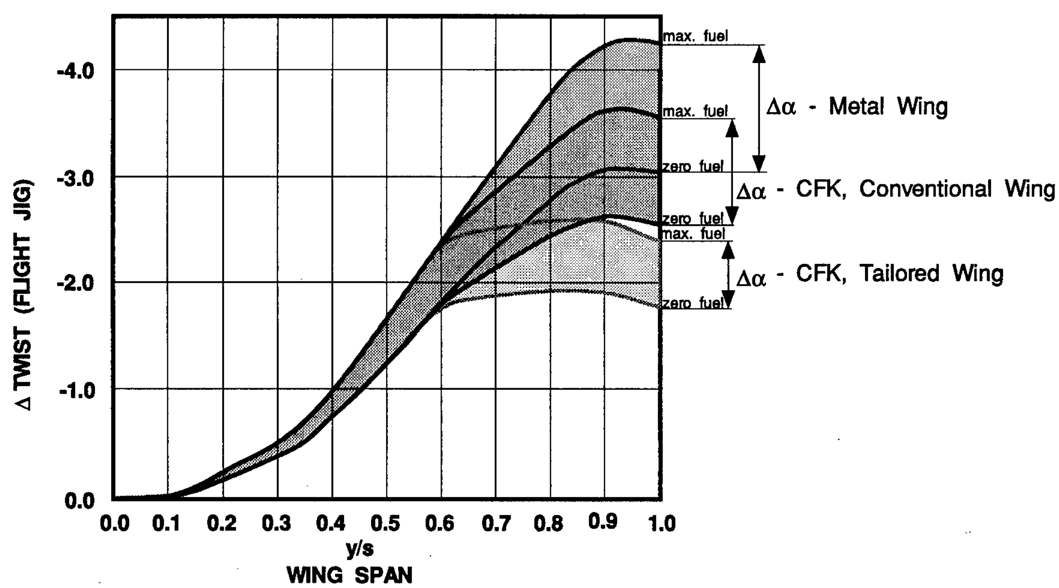


Fig. 7: EXAMPLE OF AEROELASTIC WING TWIST TAILORING

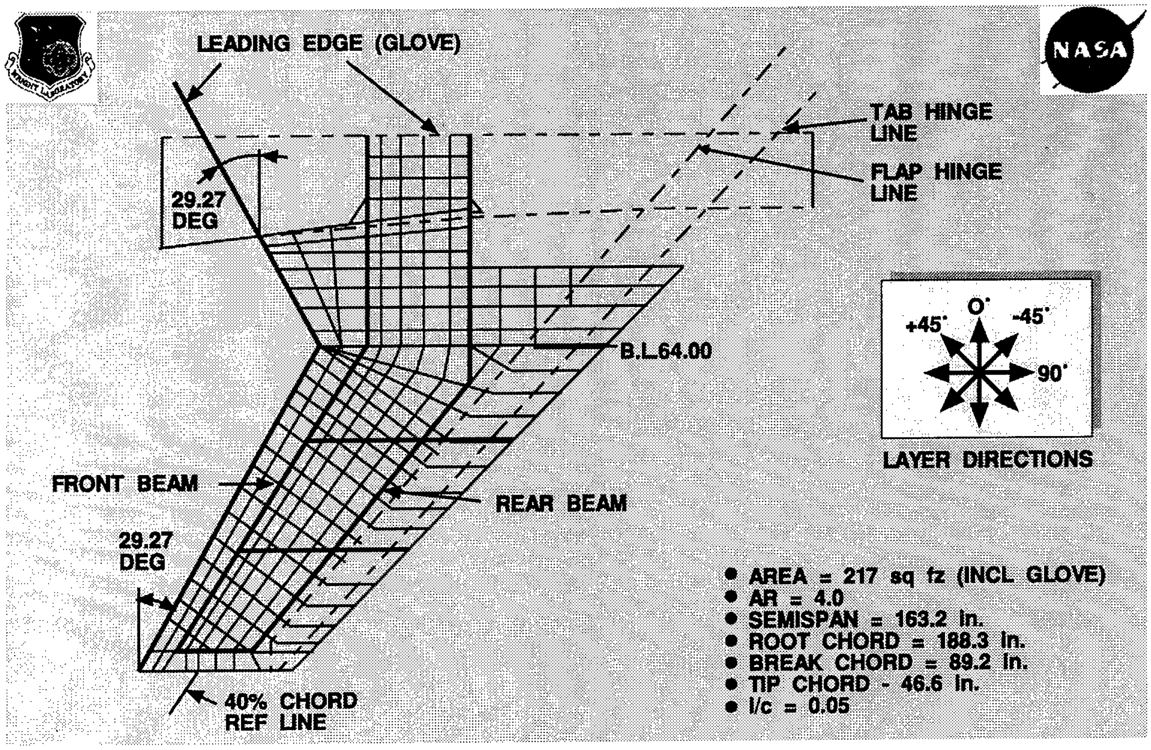


Fig. 8: X-29 FORWARD SWEPT WING PLANFORM & GEOMETRY OF STRUCTURAL GRID IN PRELIMINARY DESIGN

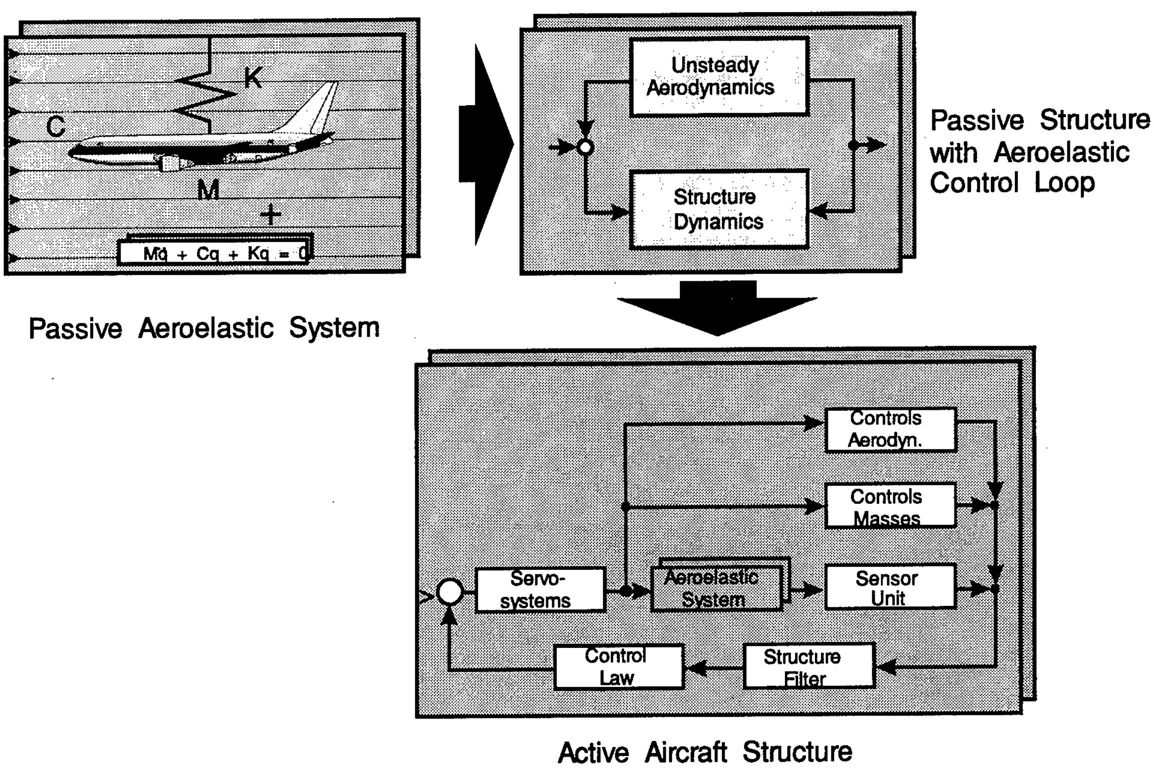


Fig. 9: ACTIVE STRUCTURE

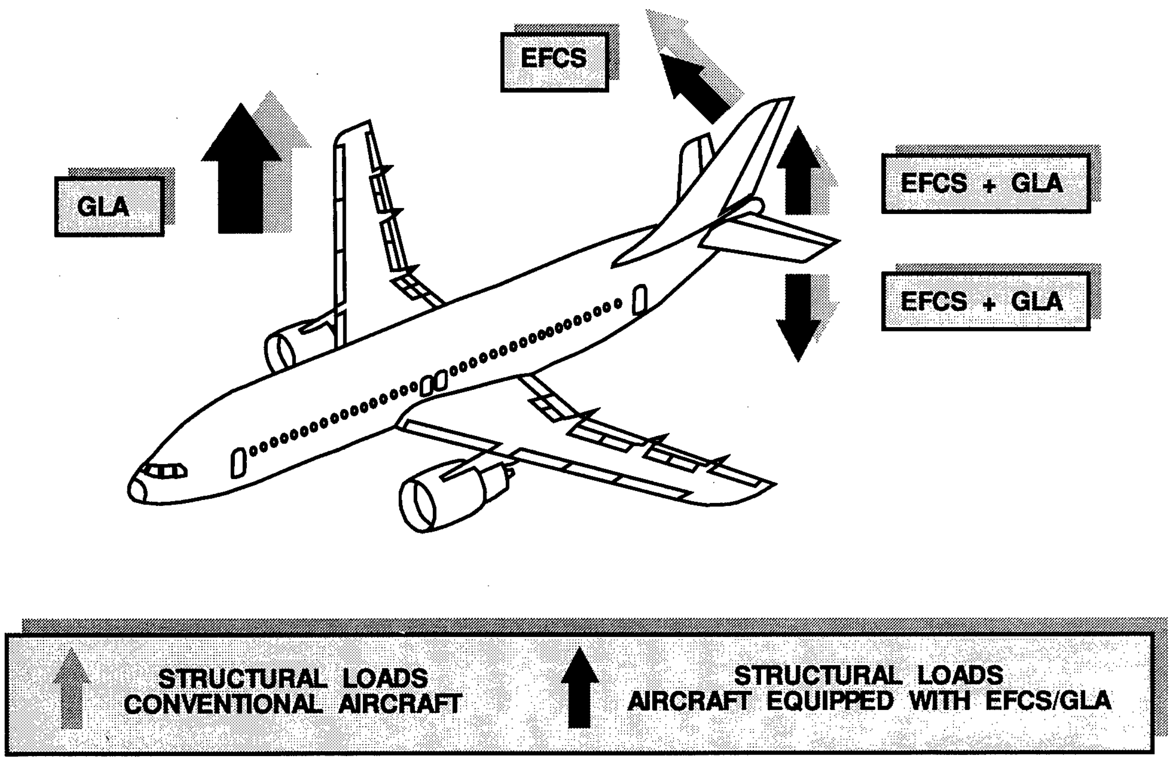


Fig. 10: BENEFITS OF GUST LOAD ALLEVIATION (GLA)

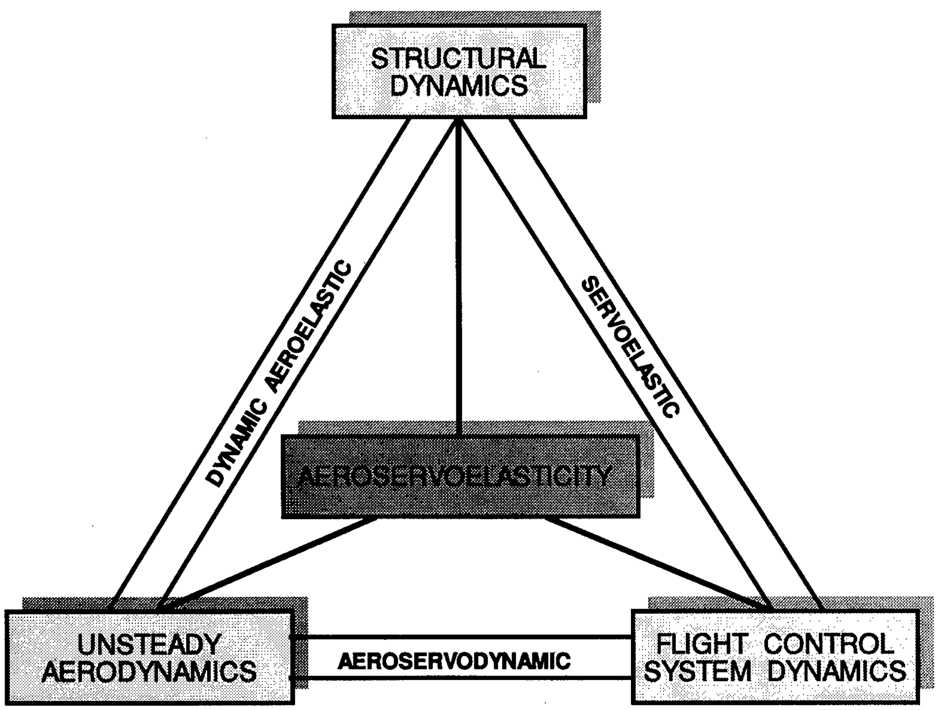


Fig. 11: AEROSERVOELASTIC TRIANGLE

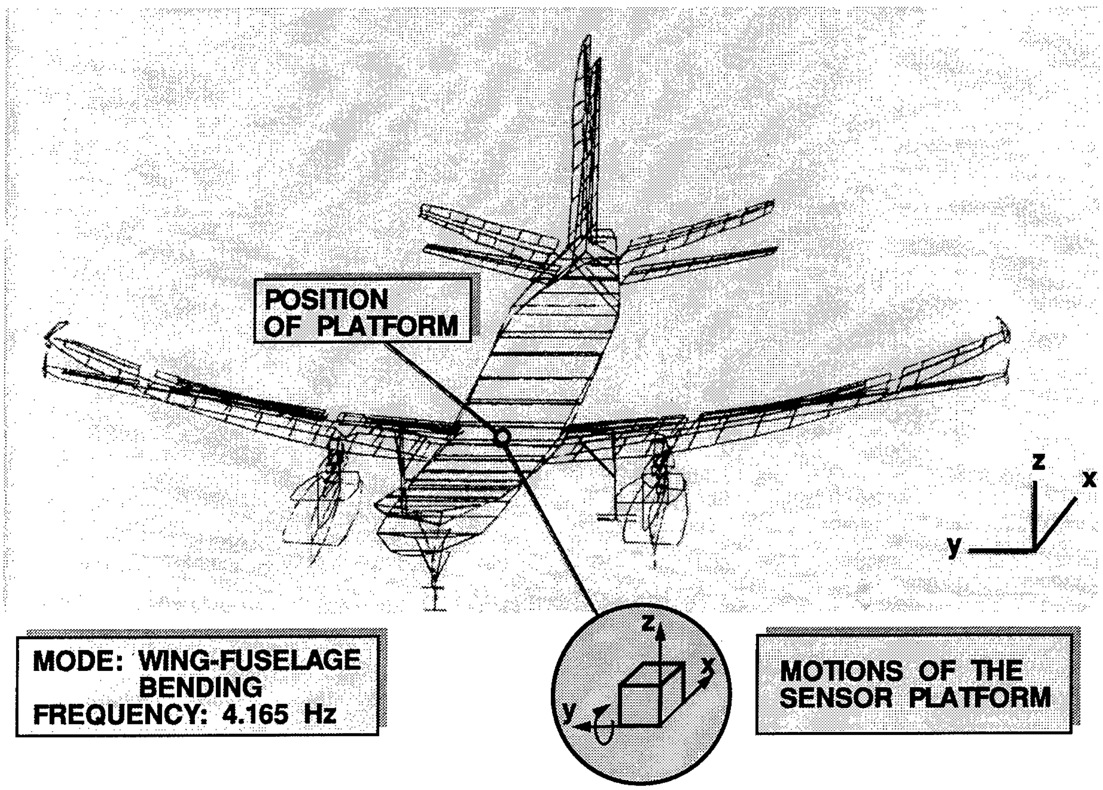


Fig. 12: INFLUENCE OF VIBRATION MODES ON AIRCRAFT SENSOR PLATFORM

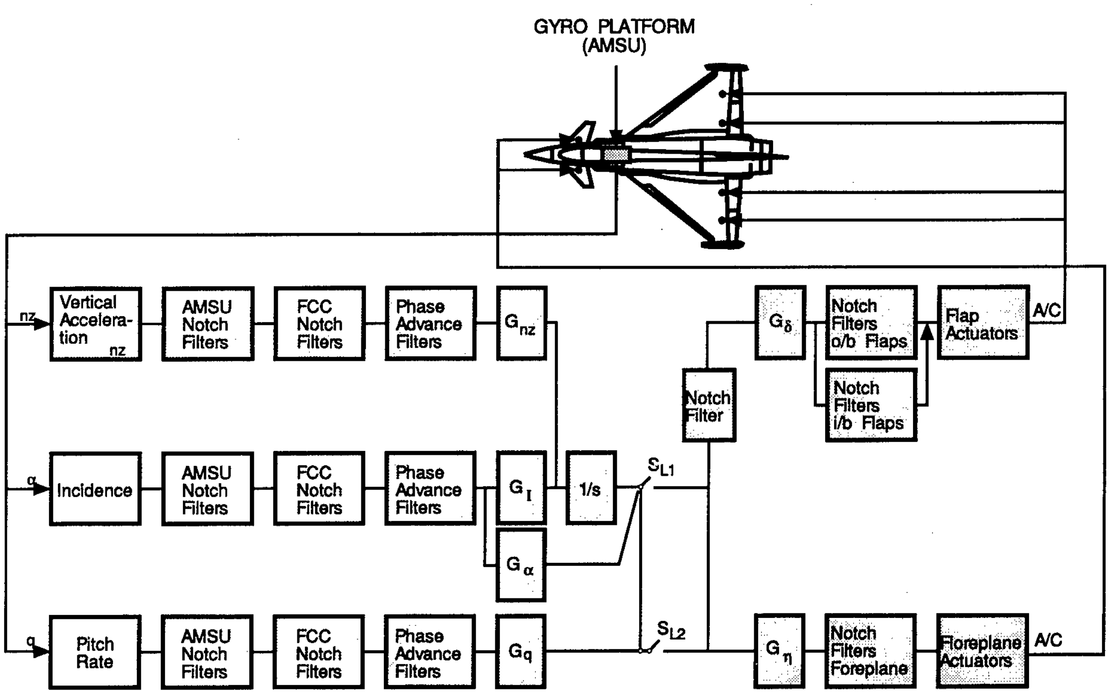


Fig. 13: FLOW CHART OF LONGITUDINAL CONTROL

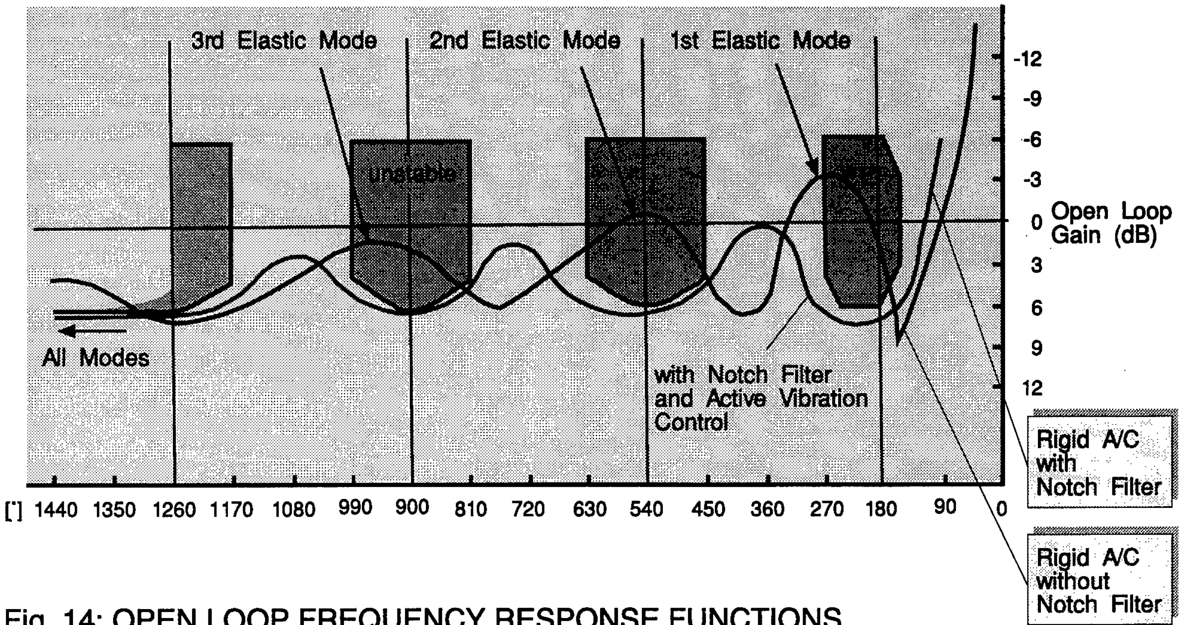


Fig. 14: OPEN LOOP FREQUENCY RESPONSE FUNCTIONS FOR INTEGRATED DESIGN

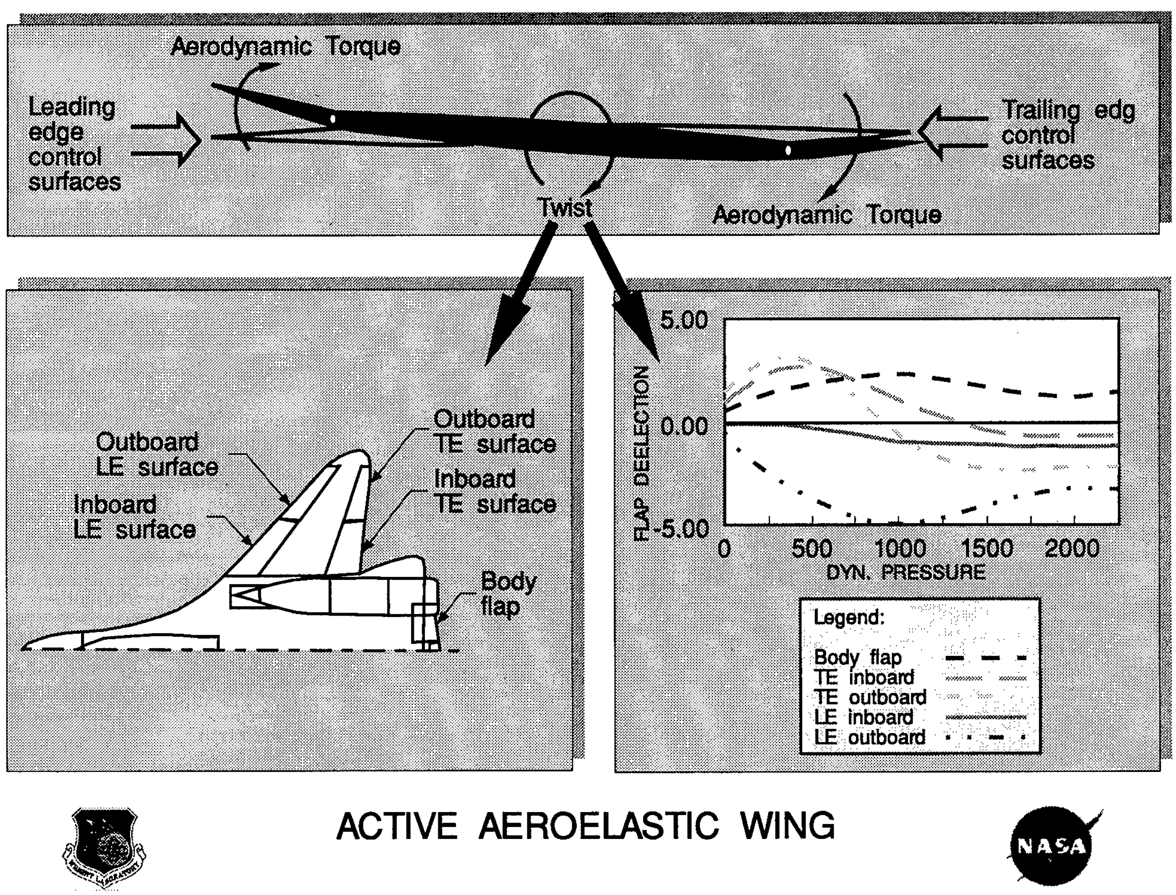


Fig. 15: PRINCIPLE OF ACTIVE AEROELASTIC WING

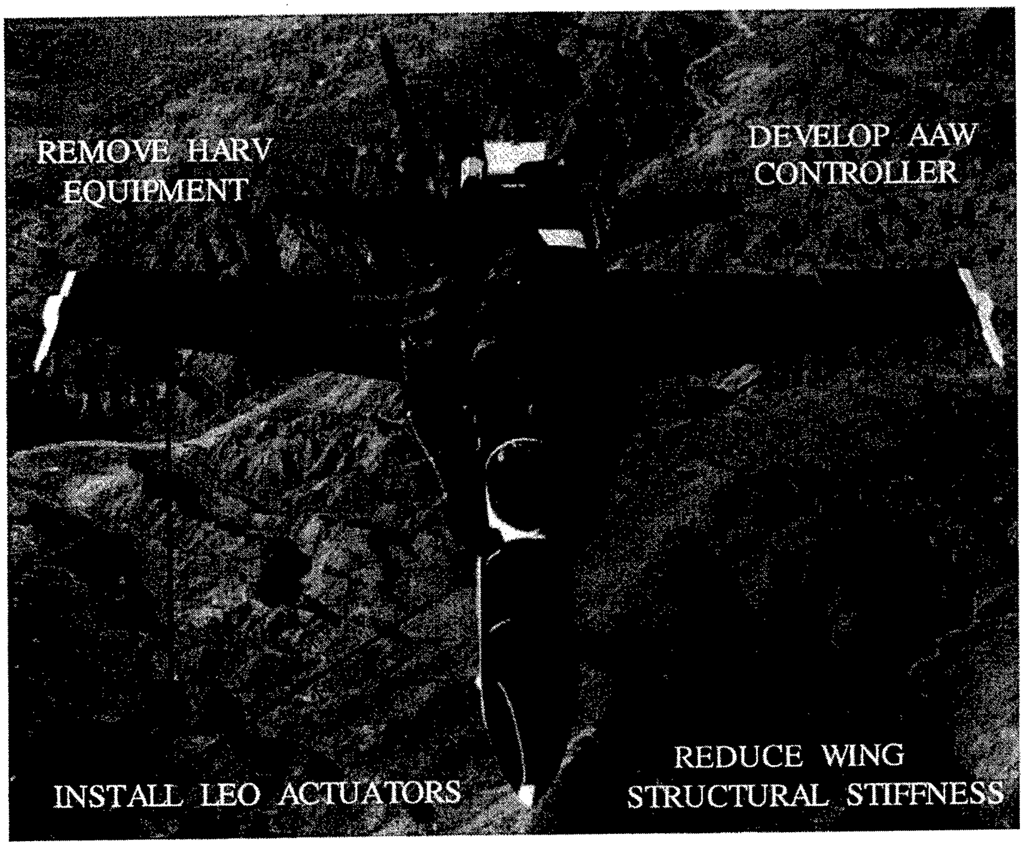


Fig. 16: AAW TEST BED

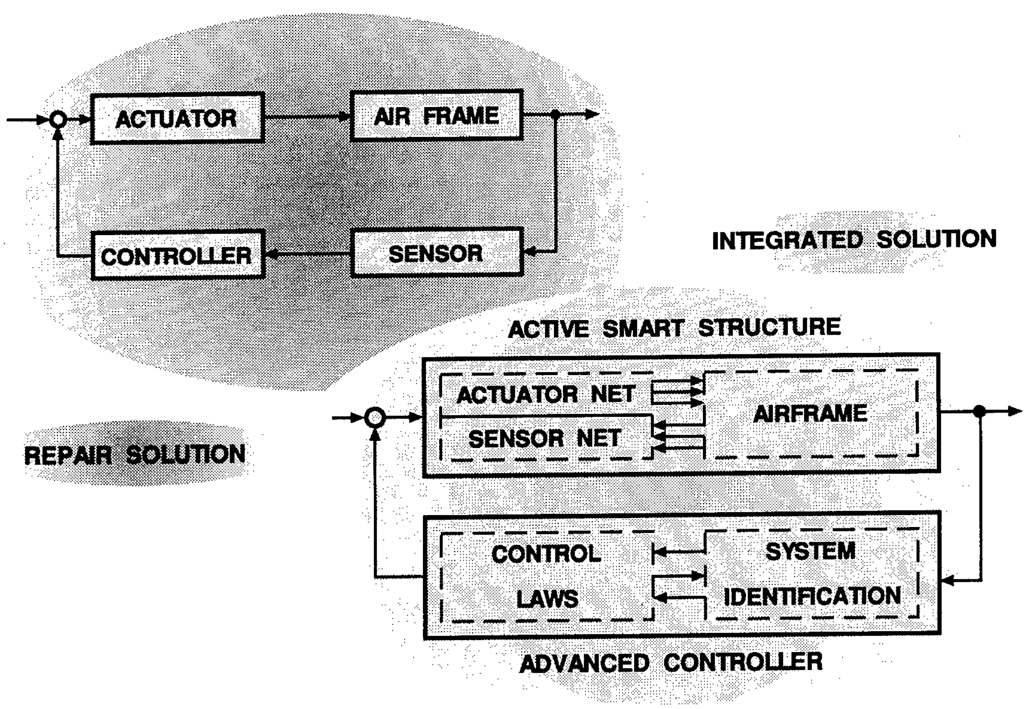
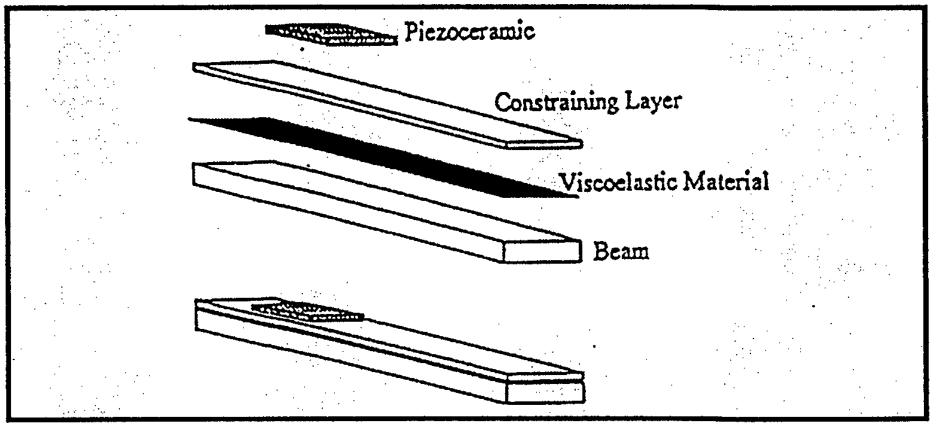


Fig. 17: PRINCIPLE OF SMART STRUCTURES



Principle of test specimen

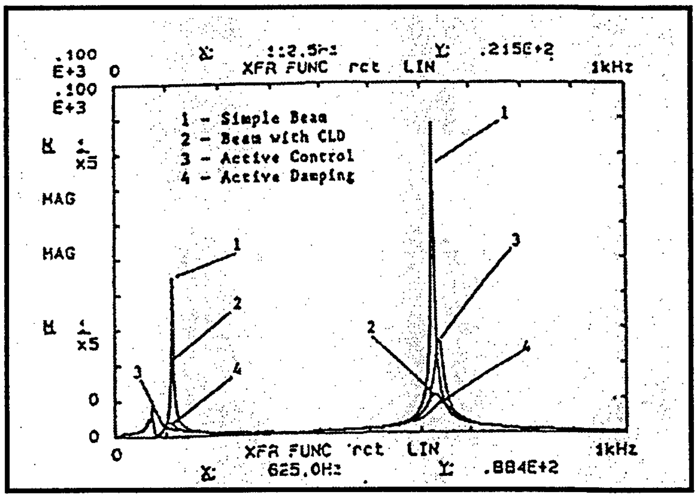


Fig. 18: RESULTS OF CONSTRAINT LAYER DAMPING TESTS

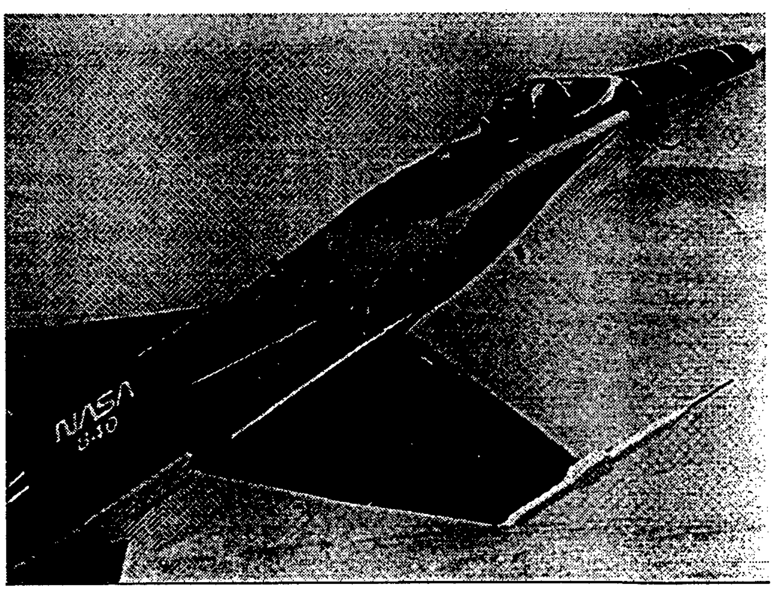


Fig. 19: F18 AT BUFFET CONDITIONS

Balancing Affordability and Performance in Aircraft Engines

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INTRODUCTION

The historical measure of performance of an aircraft gas turbine engine has been simply the thrust it produces divided by its weight (T/W). While this measure is still appropriate, as the aircraft engine has matured, the rate of change of thrust to weight has begun to decrease and other factors such as costs have become increasingly important relative to performance. Therefore, it can be argued today that performance should have a broader, more comprehensive definition that includes other factors such as durability and reliability. Further, most modern military aircraft have some degree of "signature" treatment incorporated into the system. "Signature" is the radar (RF) or infra-red (IR) signal that either emanates from or is created by an aircraft that allows its detection. The F-117 and B-2 systems are well known examples of low signature or "stealthy" systems. It is neither appropriate nor relevant to discuss signature control technology in detail here, but it is important to mention several points in connection with this subject. First, signature control is accomplished through a combination of the use of special design methods and materials with special physical properties. Second, any form of signature treatment adds weight and cost to the system. Third, the engine inlet and exhaust structures are a significant source of signature (both RF and IR) and require special attention if a given level is to be achieved. These areas of a system also represent the interface between the engine and the airframe and the responsibility for them typically is shared between the airframe and the engine manufacturers. Finally, retention of low signature usually requires additional maintenance and this also affects the affordability of a system.

The military budget pressures worldwide have changed the role of cost because it affects both the rate and the total quantity of a new system that can be acquired. Cost and the ability (or inability) to acquire new equipment also affects the total size of the force. There is a growing interest in a new term, affordability, but there also is an ongoing debate about what affordability truly means. For example, to some affordability means the acquisition costs, whereas to others it means life cycle costs which includes the cost of fuel, the cost of maintenance, and the cost of acquisition. Irrespective of the detailed definition of affordability, there clearly is an evolving need to balance affordability and performance in aircraft engines. As military budgets around the world continue to contract, systems acquired today will be required to remain serviceable for longer times. It is easier and more efficient to design to longer lives than to engage in *post facto* life extension as is being done with many systems today. This additional requirement should sharpen the focus on affordability and most likely will lead to a better definition related to total cost of ownership. Today, the challenge in the development and manufacture of aircraft engines is to balance affordability and performance in such a way that continued improvement in system capability is realized.

This paper will discuss a variety of the cost elements for developing and producing an aircraft engine and will offer some suggestions for reducing these costs. It also will describe the current state-of-the-art with regard to performance and will discuss the implications of the increasing importance of cost on the prospect for realizing further improvement in the performance of aircraft engines. Additional factors, which are not exclusive to aircraft engines, but which currently play a significant role, such as limited lot size, low rate production, and development programs whose progress is constrained by budget rather than technology and the impact of these constraints on product costs also will be mentioned. Some suggestions for reducing development costs will be made and some predictions about the changing ways in which development will be done in the industry over the next twenty-five years will be offered.

PERFORMANCE

There are several parameters in addition to thrust to weight that are important in any discussion of performance. Two of these are related to the engine cycle which has a significant effect on thrust. These are the compressor exit temperature (T_3) and the turbine inlet temperature (T_{41}). Another parameter is simply whether the engine is augmented (that is, whether it has an after burner). There also are a series of reliability and durability measures which relate to the broader definition of performance. The latter category would include mean time between overhaul (MTBO) and the frequency of unscheduled engine removals (UER). Both of these are related to operating costs in terms of maintenance and spare engine inventory and to reliability which translates directly into availability.

The compressor exit temperature, T_3, is related to the engine pressure ratio and this in turn is influenced by component efficiency and materials capability. Component efficiency has improved over the years as the result of improved aerodynamic and aero-elastic design codes. Turbine inlet temperature, T_{41}, is mainly related to materials capability and higher T_{41} values usually create durability penalties. Major improvements in engine performance have been realized from higher operating temperatures whereas weight reductions have been achieved by introduction of lighter weight, higher temperature, stronger materials. Higher operating temperatures also translate into reduced fuel consumption, which is desirable, provided it can be achieved with accept-

Paper presented at the AGARD Symposium on "Future Aerospace Technology in the Service of the Alliance", held at the Ecole Polytechnique, Palaiseau, France, 14-17 April 1997, and published in CP-600 Vol. 1.

able reliability, durability and at affordable initial product cost.

Two of the more critical components that enable higher operating temperatures (T_3 and T_{41}) are higher temperature capability disks and airfoils. In the compressor section, where the compressor discharge temperature (T_3) is the major limitation, the most significant challenge continues to be the temperature capability of the rotor materials. This is because there is no provision for cooling the compressor components, in contrast to the turbine section. Therefore, the compressor discharge temperature T_3 equates identically to the maximum material operating temperatures for components at the rear of the compressor. In the high pressure turbine section, the airfoils and disks are cooled by air bled from an intermediate stage of the compressor. This cooling allows the creation of the significant temperature differential between gas temperature (measured as T_{41}) and the material operating temperature. It still is important, however, to have high temperature capability materials in the turbine because the cooling air used to create this temperature differential is air that is pumped by the engine which does not contribute to the propulsive force. Therefore, the cooling air detracts from T/W and specific fuel consumption (SFC), but is necessary to allow acceptable turbine section performance and durability.

Major advances over the years have been made in both nickel base alloys for disks and for turbine airfoils. In the latter case, the advances have been made both through improved alloys with higher temperature capability and through the use of specialized solidification processing of the airfoil castings to either create directionally solidified (DS) airfoils or monocrystalline (MX) airfoils. In the case of disks, increasing operating temperatures have prompted the transition from cast and wrought or ingot metallurgy materials such as Waspalloy and IN718 to nickel base powder metallurgy alloys such as IN100, Rene 95, and Rene 88. Introduction of powder metallurgy alloys has successfully increased the creep strength of disk materials so long term disk growth at the higher operating temperatures is not a problem. Additional improvements in disk alloy temperature capability are obtainable through special processing methods, but these add cost. Two examples are coarse grained processing and dual heat treatment as have been described in detail elsewhere.

The principal life limiting characteristic of disks today is fatigue. For military engines which operate under the Engine Structural Integrity Program (ENSIP), the fatigue characteristic that is more limiting is crack growth. The ENSIP approach assumes a pre-existing crack and the inspection interval is determined by crack growth. In transport engines, achieving a useful balance between crack growth and low cycle fatigue is a challenge because of higher utilization rates and less frequent inspections. Balancing these two characteristics is still a principal consideration when selecting and developing new disk alloys.

Nickel base superalloys exhibit a transition in elevated temperature fatigue crack growth mode if the load is sustained at its peak value. This transition is from a transgranular to an intergranular crack path and is accompanied by a significant acceleration in crack growth rate. This crack growth transition effect is known as hold time crack growth. The propensity for the hold time crack growth transition to occur and the extent of crack growth acceleration when it does is strongly temperature dependent (approximately an exponential dependence). If the crack growth rates under hold time crack growth conditions are universally incorporated into lifing models, the time between inspections or the life time of disks becomes quite short. This is not consistent with field experience that has provided a large volume of data collected from thousands of engines in service. The current issue and focus of discussion, therefore, is: "When should hold time crack growth be considered in calculating the life of components such as high pressure compressor and high pressure turbine rotors or disks?". To date, there have been very few incidents of disk cracking that have exhibited the characteristics associated with hold time crack growth. On occasion, very hot portions of disks can develop intergranular fatigue cracks and these cracks may be related to hold time crack growth. In such situations, hold time crack growth rates must be considered in life calculations. The current discussion is focused on what is the appropriate data to use for life calculations. The aim is to obtain representative lifetimes that are realistic and include some margin. but are not so overly conservative that the serviceability and availability of the product is compromised. While this discussion will certainly continue, it appears at present that the incorporation of hold time crack growth rates in all life method calculations or disks is inappropriate. Use of hold time crack growth rates to calculate the life of the hottest features such as disk posts may make sense, however. The key is to balance field experience with laboratory test data and arrive at a representative practice that is very low risk but not so conservative that unnecessary weight is added to the engine or unreasonably short inspection intervals are required.

AFFORDABILITY

Having discussed some of the factors that affect the performance of aircraft engines, it is appropriate to turn our attention to the question of affordability. As mentioned in the introduction, affordability is becoming a critical consideration in the procurement, operation and maintenance of aircraft engines both for military and for commercial use. Affordability has a number of dimensions and presently there is no broad agreement on the definition of this term. Therefore, to establish a common frame of reference it is suggested that affordability should include acquisition costs, fuel cost, and maintenance costs as the primary variables. It also would be appropriate to include a parameter related to reliability since this affects system availability. Availability becomes a cost issue because it affects the number of aircraft required to sustain the required fleet size at any given time. Conceptual recognition of availability as an affordability element clearly is appropriate. Developing a quantitative method for quantifying the cost of availability and including it into the affordability index seems "beyond the pale" at present. Availability should be considered qualitatively, but quantification of it for detailed incorporation into any affordability index must be postponed.

Let us first turn our attention to acquisition costs as a main component of affordability. Acquisition costs have two principle elements, product development costs and production costs. In military engine programs, product development often is treated contractually as a discrete activity and reimbursed as such. This isolates product costs from development and creates an accounting system that tends not to include the non-recurring product development cost into unit acquisition cost. This complicates the creation of a realistic working defintion of affordability.

Several discrete elements comprise engine product development costs: the engineering effort required for design, first article development, and test. Today, extensive effort is required to demonstrate that an engine meets specifications both in terms of performance (T/W and SFC, etc.) and in terms of reliability. Once the product is designed and test articles are produced, testing begins to assure reliability and to develop an adequate database to qualify it for service.. This is a major activity and represents a significant portion of the overall product development costs. There are a number of new approaches and evolving methods that, when incorporated into product development, will reduce these testing costs and at the same time reduce both the product development cycle time and cost. Included here are improved design methods using three dimensional modeling and geometry modeling with computer-aided design (CAD) packages such as Unigraphics or Catia. Rapid prototyping is an important way to get first articles onto test quickly and the use of electronic data transfer (EDT) to get the geometry files from the CAD system into the tooling and production hardware manufacturing phase is becoming common. The use of EDT has a major impact on reducing the cycle time for product development. It also reduces translation errors that were common when working from a drawing. Another activity that is growing in use and gaining in maturity is the use of modeling and simulation to either augment or replace some of the component testing. This reduces the amount of repetitive "build and test" effort associated with the qualification and test phase of product development. As computing power continues to increase, become less expensive and more widely available, modeling and simulation will become the norm. The tremendous benefit of this approach is widely recognized and it should receive necessary support to undergo sustained development. While it is unrealistic to forecast the replacement of testing with modeling and simulation, it is argued here that modeling and simulation can significantly accelerate the product test and qualification activity by reducing the number of iterations and by preventing unwanted early failures in a test program.

The term product cost contains a number of sub-elements including purchased materials and component costs, shop labor and fixed costs related to plant and equipment. Producing the product at a low rate and, therefore, at an undercapacity situation increases the fixed cost contribution per unit. For military products today, low rate production is becoming a way of life. Therefore, it is important for manufacturers, including engine producers, to begin to adopt new production methods that allow them to operate efficiently at sustained low production rates. This minimizes product cost increases due to disproportionate fixed cost contributions. Here, the notion of flexible manufacturing and "lean production" is relevant but this concept has been discussed for a long time and still is not truly a reality in the aerospace industry. Flexible manufacturing that utilizes re-configurable tooling or allows production of several components in one machining center or machine tool would be a significant benefit in cost reduction under low rate production circumstances. Another source of production cost reduction is realized from the improvement in process capability of all production processes. Using processes of known capability reduces product variation and improves the first time yield of components, which reduces the amount of rework and scrap. Improved first time yields also reduce cost by minimizing materials review board (MRB) dispositions and extra inventory required to support the diversion of components from the production stream due to deviations and irregularities. There is growing recognition among aircraft engine producers that improved first time yields are an essential part of cost reduction and affordability. First time yields are not only associated with the original equipment manufacturers operations but also with all the operations in the supplier "food chain" that produces raw materials and components for use in the end product. There are broad based efforts under way in the supplier plants and in the original equipment manufacturers (OEMs) plants to understand, characterize, and improve the process capability of all manufacturing processes used in production. Once these processes are understood and characterized, then improving them to reach a process capability (C_{PK}) of ≥ 1.5 will be possible. C_{PK} is defined as the the specification range divided by six standard deviations and corrected for long term process drift. Achieving C_{PK} of 1.5 corresponds to a defect rate of 3.4 per million opportunities. Clearly improved process capability helps achieve larger C_{PK} values.

Concurrent with this process improvement activity must come the discipline in the design of products to only commit to mature materials and to processes where the process capability is known and is acceptable. It is argued here that improving process capability and product quality will allow design minimums and typical values of material properties to be increased with attendant and component performance improvement. This will permit performance improvement at no increase or even a possible a decrease in cost. Acceleration of the effort to understand, characterize, and improve manufacturing processes in all phases of product realization, therefore, has become a top priority for engine companies and their suppliers.

IMPROVED PERFORMANCE, NEXT GENERATION ENGINES

Notwithstanding the increased pressure on cost, there is keen interest in improving the performance of aircraft engines. Based on the earlier discussion of performance metrics, this translates to higher operating temperatures to improve thrust and SFC, lower weight to enhance T/W, at constant or better durability and with lower signatures, both RF and IR. The challenge will be to introduce improvements that address these constraints in an affordable manner.

It is clear that a very important contribution to improved performance of next generation aircraft engines will be continued introduction of higher temperature capability, lighter weight, and, in some cases, higher specific stiffness materials. As has been mentioned previously, considerable advances already have been realized in conventional materials such as Ni base superalloys and Ti alloys. While there is further opportunity to improve these classes of materials, it is becoming increasingly obvious that the rate of progress is beginning to slow as the remaining opportunities for improvement become fewer. At some point, the cost of introducing additional incremental improvements will not be consistent with the benefit realized. Accordingly, the high temperature materials researchers and the engine company engineers have been working together for a considerable period of time on several new classes of materials. Included are intermetallic compounds (IMCs), metal matrix composites (MMCs), ceramic matrix composites (CMCs), and polymer composites (PMCs). This section will describe the current state of development, at least as perceived by the author, of each of these classes of advanced materials.

Intermetallic Compounds: Intermetallic compounds have been recognized for many years to have the potential for improved high temperature strength:density ratios. Historically, intermetallic compounds have been limited in application by their low temperature brittleness. After a number of years of research, there are a few compounds that appear attractive. These have sufficient balance between improved high temperature properties and the potential for mitigating the low temperature brittleness to make them candidates for structural applications in aircraft engines. These compounds belong to two classes: Titanium Aluminides and Nickel Aluminides. Many other intermetallic compounds such as Molybdenum Disilicide ($MoSi_2$) and Niobium Aluminide ($NbAl_3$) have been discussed and studied but, today, there is no evidence that the low temperature brittleness of these materials can be mitigated to an acceptable degree. There are two Titanium Aluminides of general interest, Ti_3Al and TiAl. Between these, TiAl is the more attractive because it has the highest stiffness, lowest density, best oxidation resistance and highest temperature capability. It also poses the greatest challenge for improving low temperature ductility. In the last ten to fifteen years, considerable effort has been devoted to alloying TiAl to improve its low temperature ductility and significant progress has been made. As a result, there now are a number of first generation materials with compositions based on TiAl. These are currently being pursued by engineers at the engine companies and by researchers interested in light weight, high temperature materials. Today one of the more mature of these first generation alloys would appear to be Ti-48Al-2Cr-2Nb (Ti-48-2-2). This alloy has been studied extensively by GE and by a number of government and academic researchers.

In addition, a considerable effort has been devoted to improved processing of TiAl, particularly casting technology. Today, relatively large, near net shape castings with complex geometries can be successfully produced. Demonstrating the capability to investment cast TiAl is very important because the limited ductility of this material class makes shaping it by conventional metal working processes (e.g., forging and rolling) difficult due to the incidence of cracking. The intent here is not to provide a detailed exposition of this alloy or even of Gamma Titanium Aluminides but rather to make it clear that considerable progress has been made in readying this material class for introduction into real products. As the state of development stands today, it appears that Ti-48-2-2 components likely will be introduced for production applications before the end of this century.

The initial applications for this material will be low, to moderate, risk components such as stiffness limited parts which replace conventionally cast nickel based alloys and low pressure turbine (LPT) blades which also replace conventionally cast nickel base alloys. Replacing Ni base static parts results in ≈50% weight reduction whereas replacing rotating parts such as LPT blades allow >50% weight reduction when the disk modification is considered. Clearly, the latter of these two applications is higher risk, but considerable factory engine testing with Ti-48-2-2 LPT blades already has been done and technical feasibility has been demonstrated. The alloy Ti-48-2-2 appears to have the capability to function acceptably at temperatures as high as approximately 750°C, making it a suitable replacement for all but the strongest conventionally cast Ni base alloys. As with all new materials, the remaining issues that will pace the introduction into real products are cost, producibility, and reliability. There currently is a large effort underway to address all of these facets of the introduction. Each of these activities is showing very promising results. Perhaps the most impressive area of progress has been in casting technology where one to two mil (≈50μm) overstock components are now being cast regularly. This creates the potential for cost reducing cast Ti-48-2-2 near net shape blades which is attractive because this will allow the introduction of TiAl components such as low pressure turbine blades that are cost competitive with conventionally cast nickel based alloys, but with a weight reduction at the same time. Longer term, as applications for this material continue to evolve, revert and scrap such as turnings will become available from manufacturing operations and this will further reduce the cost of castings made from this material.

The challenge today, however, is to reduce the cost of castings made without the benefit of revert use to a level acceptable for product introduction. Recent progress suggests that this will be accomplished, but there is further work to do over the next twelve to eighteen months.

Titanium Matrix Composites: The second class of promising new materials are Titanium Matrix Composites (TMCs). TMCs have been investigated for the past twenty to twenty-five years. The early versions were reinforced with boron fibers, but in the early eighties it became apparent that boron fiber costs were going to remain so high as to make TMCs unaffordable. After a several year hiatus, silicon carbide reinforced TMCs came into the picture. These materials have been under extensive investigation since the late seventies or early eighties and, today, have been proven to be technically feasible. Silicon carbide fiber reinforced TMCs have strengths about twice that of conventional titanium, stiffness also about twice that of conventional titanium at a comparable density. These TMCs clearly are attractive from a technical standpoint. The issue today, however, is cost and these materials currently have a cost structure that makes their introduction unattractive. Over the past several years, a consortium of engine companies and TMC producers have been working together to reduce the cost of silicon carbide reinforced TMCs and considerable progress has been made. The situation today is that these materials can be affordable if the production volume is sufficient to dilute the capital costs of producing them. (This is the low rate production problem as it pertains to an advanced material.) This represents the classic "Catch 22" in the introduction of any advanced material that requires new capital investment for its production. That is, the cost does not come down until the market emerges and the market does not emerge until there is a clear prospect of a lower cost. Cooperation between users and producers and the temporary infusion of government money in the form of a large onetime purchase of material to create a temporary market is a good way to break this gridlock. It appears that this is imminent in the case of TMCs. If so, it is realistic to expect that these materials will be introduced into limited high value applications within the next two to three years. In cases such as this, timing is of the essence. If real applications, and therefore real markets, do not develop in a timely fashion, the one time government purchase will not be sufficient to sustain the production capability and these materials will disappear back into the laboratory.

Polymer Matrix Composites (PMC): Of the three classes of materials being discussed here PMCs are significantly the most mature. The application of Polymer Matrix Composites for large aircraft structures already is in production but these PMCs have very limited temperature capability. For engine applications, higher temperature PMCs and PMCs with higher toughness than is required for aircraft structural applications are needed. Today polyimide matrix, carbon fiber composites are being used in production applications for the outer bypass duct for the F404 and F414 engine. For this application the PMCs replace titanium ducts at a significant weight reduction and at cost parity or cost reduction dependent on the current market prices of the composites and titanium. Extending the use of PMCs in aircraft engines to a significant degree will require materials with higher temperature capability than those being used today. There are a number of new, higher temperature capability resins for use in PMCs, but the production of these in quantity and is still under development and production processing methods are still being defined. Perhaps the most advanced composition is AF700B which can operate for very short periods of time up to 375° C. As with TMCs, one of the main issues here for introduction into products is the cost/volume relationship. However, in the case of high temperature PMCs processing costs also are an issue. Numerous new methods of processing PMCs are under evaluation at present. Included are automated fiber or towpreg replacement and fiber braiding followed by matrix infusion by techniques such as resin transfer molding (RTM). In principle, each of these methods has attractive features and would appear to allow cost reduction to be achieved. In practice, however, each process requires expensive new facilities to practice the method on a production scale. Further, each is sensitive to the detailed nature of the matrix and the fiber so successful use may be very materials systems specific. This will complicate estimating the cost/volume relationship used in payback analysis for capital investment. Today, the promise for cost reduced processing methods for advanced PMCs is significant but this has yet to be realized in practice.

Ceramics and Ceramic Matrix Composites (CMC): As engine operating temperatures continue to increase, ceramics is the most obvious material class capable of defeating the temperature limitations of metals. Monolithic ceramics have considerable temperature capability but have very little damage tolerance. There have been repeated attempts to use monolithic ceramics in applications such as turbine blades but these have achieved limited success due to the incidence of unanticipated and premature fracture. More recently, Allied Signal has been running small auxiliary power turbines (APU) with ceramic turbine blades in commercial service as a field demonstration. For very small blades, such as those in an APU, ceramics may well be an attractive proposition. However, the brittle failure characteristics of ceramics suggests that, as the stressed volume of the component increases, the probability of fracture also increases substantially. Therefore, it is unclear whether the monolithic ceramics will be applicable to large hot components such as turbine blades in large engines.

A proven way of mitigating the brittleness problem of ceramics is to toughen them by the introduction of ceramic fibers into the ceramic matrix, creating Ceramic Matrix Composites (CMC). CMCs have been demonstrated to have considerably better toughness than monolithic ceramics. The toughening mechanisms in these materials now are reasonably well understood as a result of extensive elegant fundamental research. The technical feasibility of using CMCs in hot static structures such as afterburner parts and exhaust nozzle flaps for fighter engines has already been satisfactorily demonstrated.

Components made from these materials not only appear to have longer lifetimes than their metallic counterparts, but also are lighter in weight. Here again, the issue of cost becomes a major barrier to extensive use. For CMCs as with other advanced materials, a major contribution to cost is the cost/volume relationship. This can be overcome if a significant application base develops. Processing costs also are expensive but the competitive metallic parts also are relatively expensive to fabricate. Thus the emergence of CMC static parts in the afterburner section of military engines appears very promising and it may be only a matter of time until complete acceptance is realized.

From the standpoint of improved engine performance, however, the use of CMCs in turbine blades and in combustor liners is a more challenging proposition. Here the question of adequacy of damage tolerance of CMCs and long-term retention of this damage tolerance is the central issue. Further, the most attractive class of materials due to their enhanced thermal conductivity are systems based on carbides and nitrides with silicon carbide being the front running candidate. Fabrication methods for silicon carbide reinforced silicon carbide matrix (SiC-SiC) composites have been the subject of intense study over the past several years. This effort has led to significant progress using both chemical vapor infiltration (CVI) and melt infiltration (MI). Each of these two processes have unique limitations but, at present, melt infiltration appears to be the more promising, in the judgment of the author. Further, rig tests and laboratory tests suggest that the damage tolerance concerns may be overstated and that cooled CMC turbine blades with cooling hole configurations similar to Ni base alloy blades may be a viable concept. While there are many issues left to be resolved regarding introduction of CMC turbine blades, the prospect is more promising than might have been estimated by inspection. It is too early to forecast introduction of CMC turbine blades in real products, but it is clear today that this concept is a front running candidate for defeating the intrinsic metallic temperature limits.

SUMMARY

This paper has attempted to describe in general terms the emerging competition between improved performance and affordability in aircraft engines. This competition has been driven by the recent change in the cost sensitivity of the market place. This in turn is a result of the changing structure in the world military budgets and the reduced willingness to pay for performance in the face of perceived diminished threats. The absence of a clear definition of affordability complicates analyzing performance - affordability trade-offs. This creates confusion about the various elements of costs and their importance to the military customer. The paper discusses affordability and offers a strawman definition. It is hoped that a broader discussion will ensue as a means of achieving some agreement on this subject. More discussion is needed and a common definition must emerge in order for the producers and users to have a consistent view of which possibilities for performance improvement are considered affordable.

It also has been argued that the standard definition of performance (thrust/weight) should have additional dimensions. Today, where reliability, durability and signature are all parts of the overall operating environment for an aircraft engine. It has been suggested that these characteristics need to be incorporated into a better, more comprehensive definition of performance. It is important that this discussion not be dismissed as only a semantic argument because some real energy and creativity should be applied to achieving some standardization in definition of terms. Without this, it will be very difficult for users and producers to reason together to make optimum use of available resources to achieve continuous, affordable improvement in product performance. Improved performance must be realized in real, fielded systems and this is a challenging proposition.

Finally, the prospect for improved performance through the use of advanced materials has been discussed. Several of the more promising classes of advanced materials have been identified and their current state of development have been briefly assessed. An important point that emerges from this discussion of advanced materials is identification of the barriers and difficulties associated with their introduction into real products. An attempt has been made to outline some of the underlying issues responsible for these barriers. The economics of new material introduction is a many faceted puzzle but solving it is necessary if advanced materials are to become available in the quantities required for real products. The producer, user, and customer must all come together to create an environment that allows these materials to be available. Traditional concepts of competition may have to be modified in favor of improved cooperation if an adequate market for these materials is to be created. This truly represents a change in approach and will require cooperation of unprecedented proportions between users, producers, and customers. There are limited signs that this cooperation is beginning to emerge and this should be encouraging to all interested parties. Working together in new ways to offset the reduced volume of product requirements in the aircraft engine industry will be necessary for survival and continued progress. There is some basis for optimism that this can be accomplished if working together becomes the norm. Achieving this makes the future bright, while failure to achieve this makes the future very uncertain. This provides a major incentive for changing the way we work and should be viewed as a high priority challenge for the next decade.

Reducing Costs for Aircraft Gas Turbine Engines

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Introduction

Current military budget constraints are highlighting the cost issues in procuring and maintaining adequate defense forces. Aircraft and their engines are typical examples where costs are more and more expensive from one generation to the other. However, at the same time, it is recognized that the correlated increase in performance is necessary to keep the pace with the potential of adverse weaponry.

Due to the historic and dramatic changes in recent global events, the United States military services have been undergoing a drawdown in size. Since 1989, our military forces have been reduced by 30%. Over this period of declining budgets the DoD has slowed down the modernization of our forces in order to concentrate on maintaining force readiness and quality of life. However, by the year 2010, more than half of the US Air Force fighter fleet will consist of existing F-15's, F-16's and F-117A's -- well beyond the expected service life of these systems.

DoD and other defense departments must address the modernization of their forces to ensure readiness into the next century. This modernization will only be possible within the era of reduced defense budgets when the S&T community begins to focus on increasing the effectiveness of a user-identified capability while decreasing the costs of the necessary technology, and improving material through planned upgrades.

Recognizing the importance of this challenge, the Aero Propulsion and Power Directorate of Wright Laboratory began to investigate the issues of affordability and cost of future aircraft turbine engine propulsion systems being developed under the DoD/NASA/Industry Integrated, High Performance Turbine Engine Technology (IHPTET) Initiative. Similar activities are being addressed by the Franco-British AMET (Advanced Military Engine Technology) program. The goal of the IHPTET program is to demonstrate technology by the turn of the century that will double the propulsion capability for a wide range of aircraft and missile applications. The IHPTET program has added cost reduction to it's list of program goals. The two (2) principal aspects of engine life cycle cost that are being addressed within IHPTET are engine acquisition cost (unit sell price) and operating and support (O&S) costs. This paper will describe the efforts that have been made to identify the cost of future, advanced turbine engine powerplants, identify the cost reduction potential for these engines, and define the technology developments required to lower the cost of future engines.

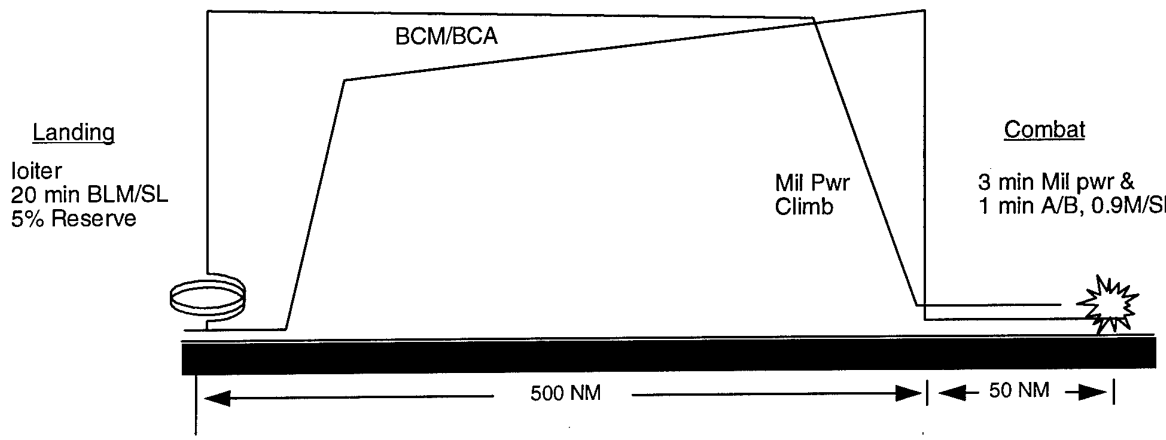
Weapon System Affordability

A unique aspect of the aircraft powerplant is it's positive influence on the size and weight of the aircraft. The application of high performance propulsion systems results in a smaller, lighter and lower cost aircraft. Traditional thinking dictates that high performance also implies high cost. This cost versus performance issue does not necessarily have to be a trade-off or compromise. Both high performance and low cost can be achieved at the same time.

One of the first issues to be addressed was to determine the influence of propulsion system performance and cost on the overall cost of an aircraft. In an earlier in-house Air Force study conducted by WL/PO, the impact of engine performance, defined as thrust-to-weight ratio (T/W), on aircraft take-off-gross-weight (TOGW) was investigated. A battlefield air interdiction (BAI) mission was selected as the mission that would size the aircraft and engine. Figure 1. shows a schematic of the

Paper presented at the AGARD Symposium on "Future Aerospace Technology in the Service of the Alliance", held at the Ecole Polytechnique, Palaiseau, France, 14-17 April 1997, and published in CP-600 Vol. 1.

Battlefield Air Interdiction



GENERAL NOTES

MISSION

- Warm up: 5 min T/W=.2
- Short Take-off: 1/2 min Max A/B
- Short Landing: 1/2 Min Mil Pwr
- 5% Reserve Fuel at Landing
- 5%Fuel flow conservatism
- No Range/Fuel Credit for Descent
- External Fuel: 3500lbs
- Payload: 2xTDM
  - 2xASRAAM
  - 500 Rds 20mm Ammo

ECONOMIC

- FY 1990 $'s
- Fuel Cost: $0.551/Gal
- 750 Aircraft over 10 Years
- Single Engine Aircraft
- 750 Engines + 25% Spares
- 20 Year Life Cylce
- Engine is Two Level Maintenance
- Costs quoted for 250th Unit

Figure 1 : BAI Mission Schematic

BAI mission and also lists the groundrules and assumptions that were used for the mission and for the cost analysis.

The initial study task focused on identifying the aircraft TOGW and engine weight required to satisfy the mission. Figure 2. shows a plot of aircraft weight and engine weight as a function of engine T/W. As shown in the figure, the size and weight of the aircraft shrinks as the engine T/W increases. The base engine identified in figure 2. is similar in performance to the Pratt & Whitney F119. This engine results in an aircraft that weighs a little over 41,000 pounds. Conversely, the aircraft powered by an engine whose performance is characterized by levels that will be demonstrated in Phase III of the IHPTET program weighs a little over 29,000 pounds. In the aircraft weight analysis, all mechanical components were considered. To arrive at aircraft TOGW, most components of the aircraft were scaled by weight. Some components, such at the cockpit and weapons are not scaleable and therefore their weights remained constant. The final aircraft weight was the sum of the scaled and unscaled component weights.

Two interesting phenomena occur. As the aircraft gets smaller, the engine thrust required to accomplish the same mission also gets smaller. This, coupled with the fact that the IHPTET initiative, will result in a smaller engine for a given thrust size. The dashed line in figure 2. shows how the engine weight is impacted by these two phenomena.

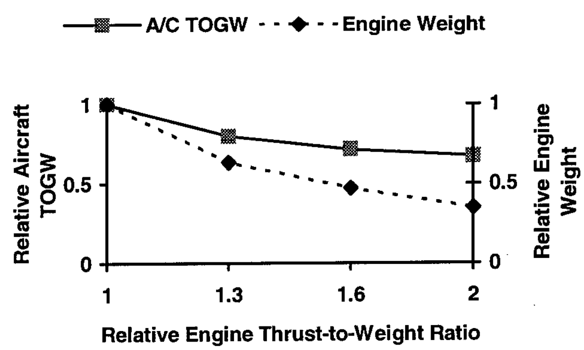


Figure 2.

Acquisition costs were determined for the aircraft and engine combinations. For the aircraft, a simple conversion of $775 per pound of weight is used to arrive at the aircraft cost. The primary purpose of the study was to determine the engine impact on aircraft structural weight. In the analysis, avionics weight and costs were not considered. From a weight viewpoint, the avionics is not a significant factor. However, from a cost perspective, avionics is one of the

ENGINE GOALS/PAYOFF	PHASE I	PHASE II	PHASE III
• THRUST/WEIGHT	+ 30%	+ 60%	+ 100%
• FUEL BURN (1)	- 20%	- 30%	- 40%
		PAYOFF (1)	
• AIRCRAFT ACQ COST (FY90)	- 19%	- 25%	- 30%
• ENGINE ACQ COST (FY90)			
- AT CONSTANT $/lb Fn	- 15%	- 25%	- 30%

(1) Based on typical mission/system

Table 1. Cost Analysis Results: Historical $/lb Fn

most significant contributors to the cost of a modern fighter aircraft.

An estimate of engine cost was determined by examining the historical costs of modern fighter engines. The subset of

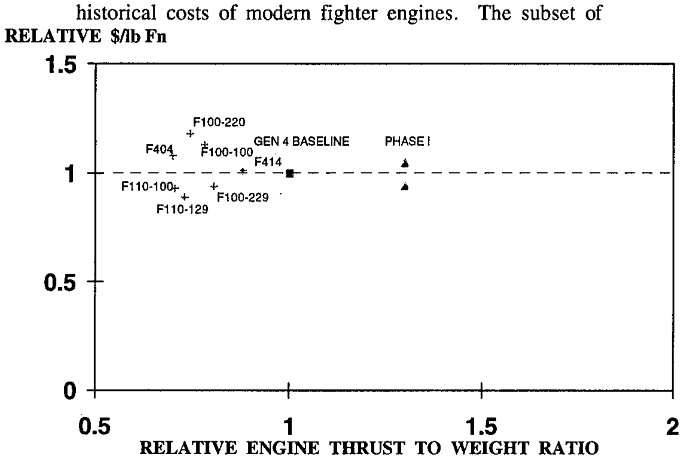


Figure 3. Historical Trend of Engine Acquisition Cost

modern aircraft investigated included the Air Force F-15 and F-16 and the Navy F-18. Figure 3 shows a normalized plot of engine cost expressed in terms of dollars per pound of thrust ($/lb Fn) versus relative engine thrust-to-weight ratio.

In addition to the fielded engines described above, the data base also includes cost estimates for the IHPTET Generation 4 and Generation 5 engines. The cost data for the fielded engines represented the unit sell price negotiated as of the last engine buy. All costs were then converted to constant FY90 dollars. Figure 3 indicates that the cost ($/lb Fn) of modern fighter engines is relatively constant. Using this relationship, the engine costs were derived for our study configuration. Table 1 shows the results of the cost analysis for both the airframe and the engine. The only factor influencing engine cost is the engine size, which is a function of technology level. The engine and aircraft cost payoff due solely to advanced technology, high performance propulsion systems is quite significant -- illustrating the importance of advanced technology from a system point of view.

ENGINE GOALS/PAYOFF	PHASE I	PHASE II	PHASE III
• THRUST/WEIGHT	+ 30%	+ 60%	+
• FUEL BURN (1)	- 20%	- 30%	- 40%
		PAYOFF (1)	
• AIRCRAFT ACQ COST (FY90)	-	- 25%	- 30%
• ENGINE ACQ COST (FY90)			
- AT CONSTANT $/lb Fn	-	- 25%	- 30%
- AT "GOAL" $/lb Fn (2)	----	- 40%	-

(1) Based on typical mission/system
(2) Integrated IHPTET innovative design and adv manufacturing technology

Table 2. Cost Analysis Results: Goal $/lb Fn

Cost Reduction

Having investigated the affordability aspect of advanced propulsion systems, the next issue to address was to identify what could be done to lower the manufacturing cost of advanced technology engines. The engines of the future will achieve their incredible performance primarily through improvements in aerodynamics and materials technology. The materials used in these engine cycles will have higher temperature capability, improved strength and will be lighter in weight than the materials used in today's aircraft engines. Advanced technology engines of the future will be characterized by the application of high temperature organic matrix composites (OMC) for the fan, front frame, ducts and cases.

Advanced titanium metal matrix composites (MMC) will be used in the compressor rotor. Compressor blades and vanes will be made of advanced intermetallic titanium offering high strength and temperature capability. Advanced intermetallics will also be used extensively in the diffuser, combustor and in the exhaust nozzle. Advanced ceramic matrix composites (CMC) will be required for the combustor, low pressure turbine (LPT), turbine rear frame and in the exhaust nozzle. High pressure turbine blades will be designed to require less cooling air through the application of advanced integral convective cooling methods. Multi-alloy turbine discs will provide localized creep and fatigue resistance at the rim and hub, respectively.

Compared to the mostly monolithic materials of present day engines, the high temperature, high strength composite materials for future engines present significant processing and manufacturing challenges. Developing cost effective methods to fabricate and manufacture engine components with these advanced materials is the key to future engine cost reduction. In the IHPTET program, cost reduction goals have been established. The goals were defined based on an evaluation of cost reduction potential, and an assessment of the technology development programs required. The assessment of programs included an evaluation of technical and schedule risk. Accomplishing these goals requires an integrated emphasis on innovative design and improved material processes and manufacturing science.

Figure 4 illustrates the impact of the IHPTET cost reduction goals relative to the historical trend shown previously in figure 3. As indicated in the figure, a significant shift in the state-of-the-art is required to attain these goals. Table 1 described the cost payoff associated with higher engine performance. Recall that these payoffs were due solely to the reduction in engine size needed to accomplish the mission. Cost was assumed to follow the historical trend. Table 2 shows the total cost benefit (in terms of the unit price of the engine) when cost reduction technologies are applied.

Engine Manufacturing Cost

Once the impact of cost reduction and advanced performance had been determined, the next step in the analysis involved an investigation of the impact of cost reduction on the manufacturing cost of an engine. In the previous analysis, propulsion technology to perform a given mission was examined.

Required thrust levels changed as technology improvements were made. These changes in required thrust, in turn, had an impact on both the aircraft and the engine size, and subsequently, cost.

In order to focus only on manufacturing costs, a cost comparison was made for two engines whose thrust levels were held constant. In this way, mission requirements would not be an influence on engine size and cost. The level of technology for the two engines, however, did change. The engines chosen for comparison were a current engine and an advanced IHPTET Phase II engine scaled to produce the same level of thrust. The current engine represents an engine whose manufacturing methods are mature, well established and in place.

Figure 5. shows a cost comparison between these two (2) engines. The engine schematics illustrate the impact of advanced technology on size and cost. The Phase II advanced technology engine requires less airflow to produce the same thrust as the current engine, so it is smaller in diameter. In addition, improvements in aerodynamic and aeromechanical technology dramatically reduce the number of fan and compressor stages in the Phase II engine, resulting in a shorter engine. The principal factors contributing to lower manufacturing cost for the advanced technology engine are its smaller size (as a result of advanced turbine engine cycle design), reduced parts count and the development of cost effective manufacturing methods. Figure 5 also shows the cost breakout for the two (2) engines by major sub-module. The numbers in parenthesis represent the percentage contribution of each sub-module to the total engine cost.

It is interesting to note the change in the cost distribution between the cold section and the hot section for the two engines. The most dramatic parts count reduction is in the fan and compressor, hence, the highest cost reduction potential lies in that area. In the hot section area, the cost is expected to rise slightly despite the fact that the engine is smaller. This is due to the application of advanced materials and cooling schemes necessitated by higher turbine inlet temperatures. Parts count reduction is also a small, but not significant factor in the hot section.

The augmentor/nozzle and externals areas are also expected to show a reduction in cost. The cost reductions for these two areas are driven by design innovation, such as fixed A8/A9 exhaust nozzles and integral fuel/hydraulic pumps, as well as the smaller engine size. Table 3 highlights some of the significant differences in materials and/or configuration between the current engine and the advanced technology IHPTET Phase II engine by major component area.

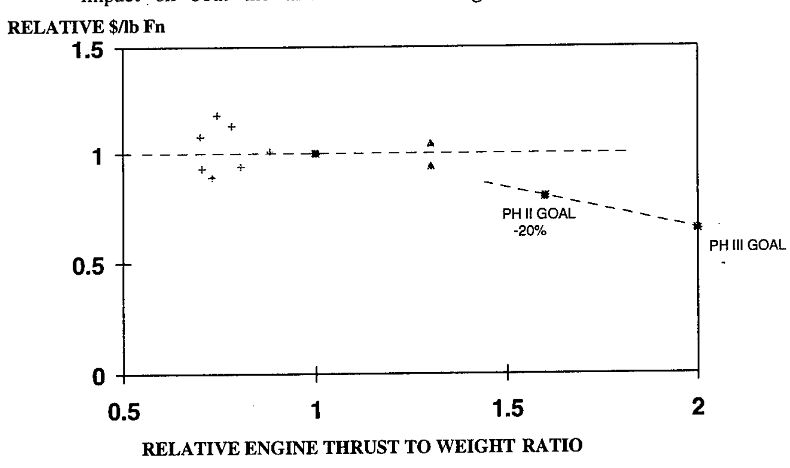
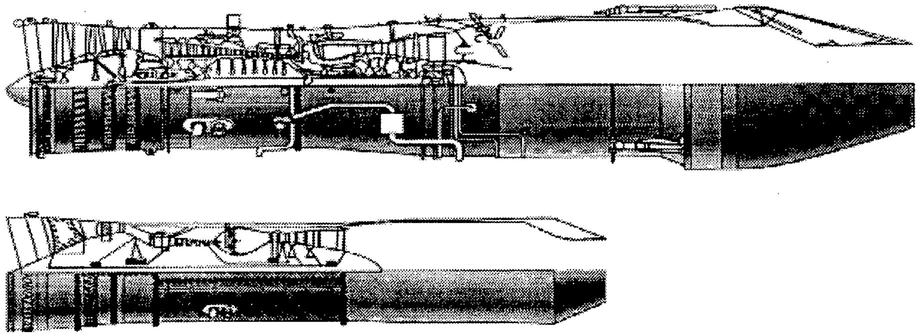


Figure 4. IHPTET Engine Acquisition Cost Goal



COST	COLD SECTION	HOT SECTION	AUG/NOZZLE	EXTERNALS	TOTAL
Current Engine	$1,257,000 (36%)	$887,000 (25%)	$444,000 (13%)	$924,000 (26%)	$3,500,000
IHPTET PHASE II	$821,000 (29%)	$936,000 (34%)	$282,000 (10%)	$755,000 (27%)	$2,794,000

Figure 5. Cost Comparison between a current engine and Equivalent Thrust IHPTET Engine

Implications of Cost Reduction on Manufacturing Cost

The previous example comparing the current engine to an equivalent thrust IHPTET Phase II engine offers some interesting insights into the manufacturing cost area. A closer examination of the cold section was made by breaking down the cost for the high pressure compressor into the costs for the rotating and non- rotating components.

The high pressure compressor blades and disks for the current engine are made of conventional monolithic titanium material. For the IHPTET Phase II engine, the blades will be made of gamma titanium and the disks will be made of a monolithic titanium incorporating titanium metal matrix composite ring inserts. The manufacture of MMC reinforced compressor disks involves more processing steps than for a monolithic disk. Consequently, the manufacturing cost for a MMC disk would be expected to be higher.

This brings up an interesting issue. How can this higher expected manufacturing cost be conducive to cost reduction -- especially in the cold section? The answer to this question is presented in table 4. Table 4 shows a comparison of cold section costs for the current engine and the IHPTET Phase II engine. When analyzing the cost of the fan and compressor rotor stages, the cost per stage for the IHPTET engine can be up to forty percent (40%) greater than for a conventional forged monolithic rotor and still meet the targeted cost reduction goal.

Similarly, for static components in the cold section the cost per pound for the IHPTET engine can be up to eighty-five percent (85%) higher than for the conventional engine and still achieve the cost reduction goal. In some respects, the old adage that higher technology costs more holds true. However, the allowable growth of the manufacturing cost must be controlled through the development of improved manufacturing methods.

	Current Engine	IHPTET Phase II
Inlet/Fan	Ti replaceable blades	OMC/IBR
Compressor	monolithic rotor replaceable blades	Ti MMC IBR
Combustor/Diffuser	fabricated, multi-piece	cast gamma Ti
Hi Pressure Turbine	monolithic disk	multi-alloy disk
Low Pressure Turbine	monolithic disk, turbine inlet nozzle	vaneless, counter rotating
Augmentor	fabricated, multi-piece	bonded Ortho Ti, CMC liner
Exhaust Nozzle	variable A8/A9	fixed A8/A9
Controls & Accessories	dual-redundant FADEC	model-based logic, lightweight components

Table 3. Material/Configuration Comparison

	Current Engine	IHPTET Phase II
Rotor Cost	$520,000	$342,000
Cost/Stage	$40,000	$57,000
Static Structure Cost	$737,000	$479,000
Cost/lb Structure	$1,100	$2,050

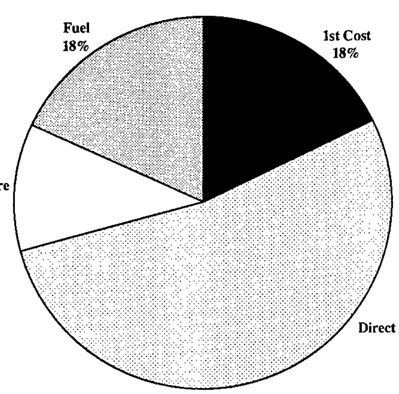
Table 4. Manufacturing Cost Comparison: Cold Section

Maintenance Costs

The preceding sections have focused on engine acquisition costs, but these of course contribute only one part of the total cost of ownership. It is equally important to achieve reductions in other elements of the cost, the maintenance component in particular. The issues of high engine maintenance cost and unsatisfactory reliability have been given considerable attention in recent years, the UK experience and views of possible solutions, for example, being detailed in Reference 7. The scale of the problem can be typified by British Royal Air Force experience, as illustrated in Fig 6. This shows how the overall cost of owning and operating the RAF's RB199 afterburning turbofan engines is split between production engine purchase price, maintenance costs over a typical service life of 6000 operational flight hours, and fuel costs over the same time span (which is equivalent to 20 to 25 years).

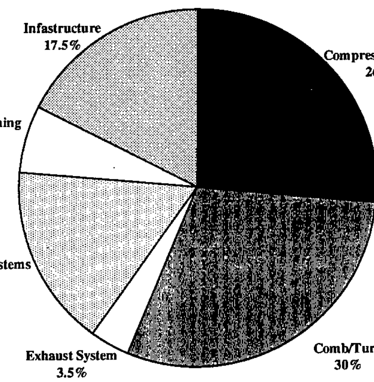
The RB199 is of comparable vintage and technology standard to the F100-229 and the RAF currently operates some 500 of them in various versions of the twin-engine Tornado, its main combat aircraft, which makes up 70% of its total combat force. To support the engine, the RAF operates a four-tiered maintenance structure, ranging from front line servicing at squadron level (1st line), through area maintenance units (2nd and 3rd lines), to contractor repair (4th line). As well as direct engine repair costs (spare parts and manpower), there is a significant 'infrastructure' cost associated with these arrangements. This is separately identified in Fig 6. Strictly speaking 'Infrastructure' means such things as the fabric and tooling of the repair workshops and engine pass-off test beds, the logistics network, and other overhead items. For convenience here it is broadened to include minor maintenance costs that cannot clearly be assigned to specific engine components.

Figure 6: Current Generation Engine (RB 199) - Cost of Ownership



It can be seen that the cumulative costs of maintenance, including infrastructure, over the 20 to 25 year life cycle considered here amount to some 3.5 times the initial purchase cost. This represents a major cost burden and one that will be far from acceptable in future engine generations. However, on the positive side, such high figures suggest that there should be ample scope for substantial reductions in future engine designs. Reducing component manufacture cost, along the lines discussed earlier, will clearly have a direct effect on maintenance by reducing the costs of replacement parts. Design for ease of maintenance will also play a part. But the key factor will be major improvements in component life and reliability. The influence of these aspects is considered further in the next section.

Figure 7: Current Generation Engine (RB 199) - Maintenance Cost Split



Before leaving Fig 6, it may be noted that fuel costs, although important in absolute terms, contribute less than 20% to the overall engine cost of ownership. Fuel consumption depends heavily on operational or performance-related factors such as aircraft role, mission characteristics and engine cycle optimization. The continued emphasis on reduced fuel burn in future engine generations tends to have more to do with mission endurance and operational effectiveness than with cost. Analysis of these issues is a major topic in itself and falls outside the scope of the present paper. Fuel burn will therefore not be considered further here.

Current Engine Maintenance Costs

Fig 7 breaks out RB199 maintenance costs into the four engine component groups identified in Fig 5, i.e. compression system, combustor and turbines, exhaust system including afterburner and nozzle, and external or ancillary systems (fuel and controls, gearbox, instrumentation, etc.). In the figure these segments represent direct engine repair, including spares and labor, and are effectively the costs incurred at 2nd, 3rd and 4th lines. Immediate on-aircraft support at 1st line is identified separately as this will be required for routine servicing, whatever the maintenance needs. Infrastructure and miscellaneous non-attributable maintenance costs are also identified as a separate item.

It can be seen that compression system and hot section maintenance costs are of roughly similar magnitude, with ancillary system costs also being substantial; the RB199 exhaust system appears to be relatively trouble-free. The detailed statistics behind Fig 7 indicate that for the compression system, the mean time between module (i.e. main component) rejections tends to be in the 400 to 600 hour range, with around 50% of the total number of compressor modules being rejected for repair action in any single year. Fortunately the repairs generally fall well short of complete replacement, the annual repair cost being around 10% of the cost of a fleet-wide refit with new compression systems. For the turbines, the mean time between rejections tends to be 300 to 500 hours, with two-thirds of the total modules being rejected in any single year and annual repair costs amounting to 20% of a fleet-wide fit with all-new turbine modules.

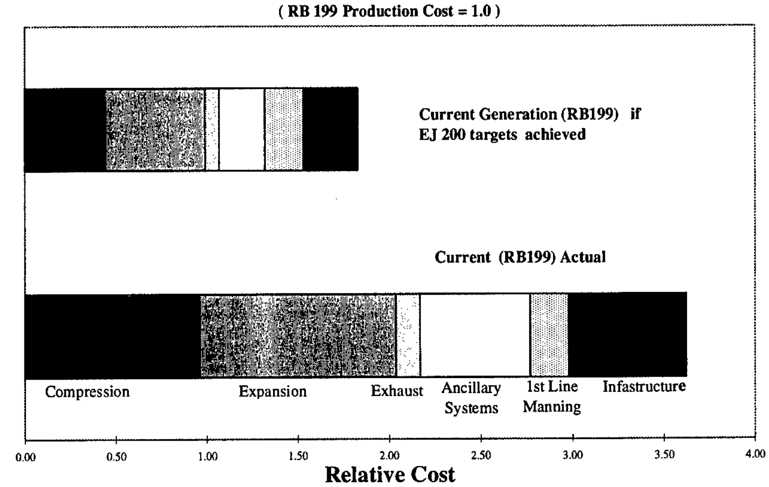
Even though the rejected components require only partial refurbishment, maintenance actions are being demanded at much more frequent intervals than the theoretical lives of the components would indicate (Ref. 7) The reasons for rejection in practice are varied, but for the compression system bearing and seal wear and foreign object damage (FOD) or bird strike are among the common causes, although disc or bearing life expiration is also a factor. FOD in particular accounts for up to 50% of RB199 compressor repairs.

In the hot section, component cracking, due for example to local overheating or thermal fatigue, together with seal wear, are the most frequent problems, rather than straightforward and predictable life expiration. In the ancillary systems area, fuel system wear and electric or electronic problems are the common culprits.

The RB199 is a 1970s design, whose specification was governed predominantly by performance requirements, like most combat engines of that vintage. Rigid life requirements were not set, not only because of the stress on performance, but also because the science of realistic component in-service life prediction for combat engines was in its infancy.

The new engines being developed for entry into service during the next three years are being specified with at least equal weight being given to cost of ownership, notwithstanding their substantially higher thrust/weight ratio and the higher engine pressures and temperatures that go with that. Typical of this new generation are the Pratt and Whitney F119 engine, the SNECMA M88 and the Eurojet EJ200. The latter engine, targeted for the RAF to power the EF2000 fighter, is specified to have 6000 hour (i.e. full service) lives for most cold section components - an order of magnitude greater than the average compressor mean time between rejections in the RB199. Hot section lives are to be typically 1500 hours or more, again much greater than present RB199 achievement.

Figure 8: Maintenance Cost Distribution - Current Generation
(RB 199 Production Cost = 1.0)



If the EJ200 life standards could be applied to the RB199 and it is further assumed that maintenance action could be restricted largely to component replacement on life expiration, massive cost savings would be achieved. The results of a component by component analysis on this basis are shown in Fig 8. Recent studies have indicated that some improvement in FOD occurrences and the associated repair costs should be achievable through better airfield 'housekeeping', changes to operational practices and other measures to reduce foreign object ingestion, although without changes to the engine/aircraft geometry there are limits to how far this can be taken.

It is assumed that 1st line manning remains unchanged, but that infrastructure and miscellaneous costs will reduce in proportion to direct repair costs. The costs have been normalized in terms of first cost (initial purchase cost of 500 engines = 1.0). It is seen that, given these somewhat idealized assumptions, through life maintenance costs for the engine would be cut by 50%.

Future Engine Maintenance Costs

The above example is purely hypothetical but serves to illustrate the potential for cost reductions. Turning to the engines of the future, as pointed out earlier higher thrust/weight designs embodying more advanced component

Fig 9: Production Cost by Subsystem - Current v New Generation
(RB 199 = 1.0)

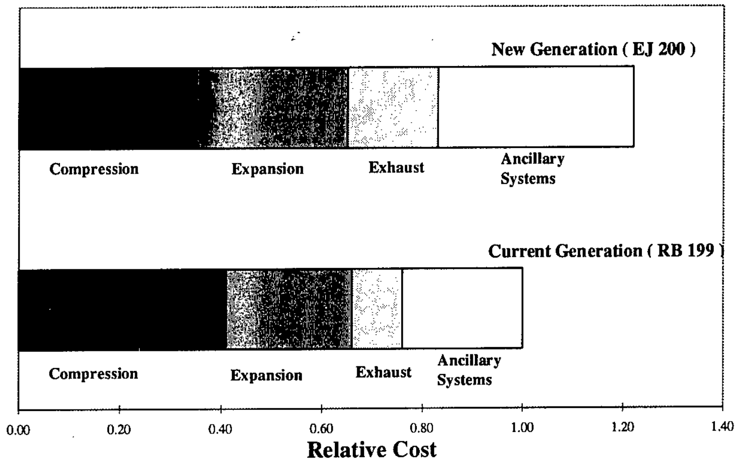
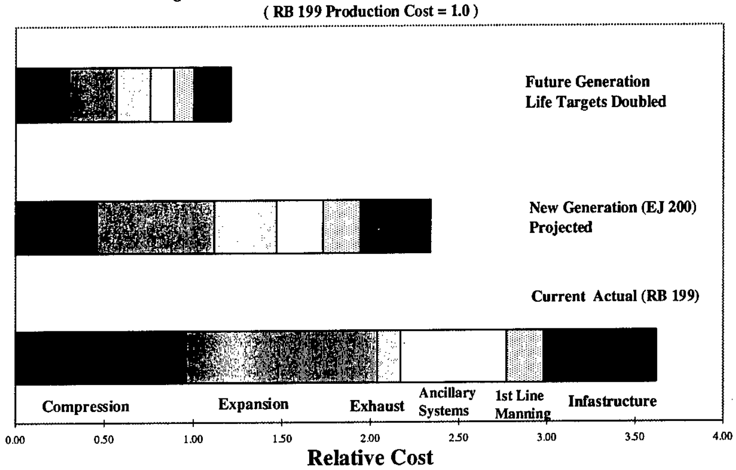


Figure 10: Maintenance Cost Projection - Future Trends
(RB 199 Production Cost = 1.0)



technologies generally cost more to manufacture per lbf of thrust. The EJ200 will be no exception to this rule. Actual production prices have yet to be negotiated and agreed, but it is expected that unit first costs will be around 20% higher than for the RB199 at constant economic conditions, as shown in Fig 9. The two engines are of similar size, unlike the F100/IHPTET comparison shown in Fig 5, but the EJ200 delivers 25% more combat thrust, broadly reflecting the constant $/lbf trend. The new engine has many fewer components (10 turbomachinery stages instead of 16) and this is particularly reflected in lower costs for the compression system. On the other hand, more complex hot section and exhaust systems and the need for more expensive high temperature materials and processing routes, will push up the cost of these parts of the engine - trends which are also consistent with those shown in Fig 5.

High manufacture costs for hot section components will have an adverse effect on maintenance costs, especially as these life-limited parts are planned for replacement perhaps three times during the life span of the engine. The component by component analysis, again assuming that maintenance can largely be confined to repair for life expiration reasons, is shown in Fig 10. The current generation (RB199) actual maintenance burden over 6000 hours is represented by the bottom bar. The projected maintenance cost for a new generation (EJ200) engine over the same time span and assuming the same size fleet is shown in the middle bar. It is assumed that FOD will continue to require unscheduled compressor repairs and that the 1st line manning requirement will be unchanged from present levels; infrastructure costs are assumed to reduce in proportion to direct repair costs. The costs have again been normalized in terms of RB199 acquisition cost for ease of comparison.

The net result of the analysis is that despite high manufacture costs for the critical hot section components, achievement of the planned EJ200 service lives would offer around 35% maintenance savings compared with the RB199 baseline, under constant economic and fleet-size conditions. It should be noted that the planned service lives take account of differences in mission type and hence throttle usage on the engines. While the higher manufacture costs of the new engine reduce the potential saving, a 35% reduction over the 20 to 25 year period equivalent to 6000 hours remains substantial, representing a cumulative saving of up to $2B for a fleet of 250 twin-engine aircraft.

Like the other engines of its generation the EJ200 is near the end of its main development cycle and will shortly go into full-scale production. As in the US, advanced engine research and technology programs in Europe are focusing on the next engine generation. Further gains in maintenance cost will be a key goal for such future projects. Moreover there is an increasing tendency for combat aircraft and engines to remain in service for longer, while improved maintainability and reliability will lead to higher availability, so that annual utilization may also tend to rise. The nominal engine service life of 6000 hours may therefore need to be increased.

The upper bar in Fig 10 represents a future generation engine of EJ200/RB199 size, designed for an overall service life of 9000 hours (cold section components), with hot section components designed for at least 3000 hours, i.e. double the planned hot component lives of the EJ200 engine. However to provide a back-to-back comparison, the figure presents the cost analysis over the same 6000 time span as before. Further reductions in component count and developments in advanced manufacturing technology are expected to deliver an engine of higher thrust, at a production cost no greater than EJ200 levels, reflecting the downward trend in cost/lbf thrust predicted in Fig 4. To support the lower maintenance requirements the engine would also be designed and have an intake concept intended to minimize FOD and bird strike. Extensive use of on-board diagnostics and simpler, more highly integrated, "fit and forget" ancillary systems (including the reduction or elimination of hydraulics and mechanically driven fuel system components) will allow 1st line maintenance requirements and manning to be reduced, in line with the concept of the maintenance-free operating period (Ref. 7). This reduction in the front line servicing 'tail' will be of particular value operationally, especially during remote area deployments. More importantly from the cost standpoint, intermediate servicing levels at 2nd and 3rd line will be combined and greatly reduced, or even eliminated.

The increased hot section lives and inherently very high reliability of this future style of engine may require a small compromise in ultimate performance capability, but in cost and affordability terms the potential gains will amply repay this. Fig 10 indicates that overall engine maintenance costs over 6000 flight hours could be reduced by a further 50%, bringing them for the first time down to a similar magnitude to the initial acquisition cost.

Summary

Analysis has shown that advanced technology turbopropulsion systems being developed under the DoD/NASA IHPTET program will offer a significant payoff with respect to the size, weight and cost of future aircraft. Cost reduction goals have been incorporated into the IHPTET program. The goals address engine unit acquisition cost and maintenance costs. The cost reduction goals are compatible with IHPTET performance goals and both are designed to be met concurrently.

Satisfying the engine cost reduction goals requires the development of innovative designs and improved, cost effective manufacturing methodologies for advanced material systems. In some cases, the advanced engine material systems are incompatible with conventional manufacturing methods. A good example of this incompatibility is investment casting of high temperature materials such as gamma TiAl. Conventional core and shell materials adversely react with the gamma TiAl causing poor quality castings and low yields. In this case, a new core or shell material must be developed.

An analysis of advanced technology turbopropulsion systems has shown a promising consensus between the benefits of higher performance and the reduced cost goals of the IHPTET program. This analysis indicates that manufacturing cost targets are compatible with the advanced material systems and lower engine cost.

The impact on overall cost of ownership of the maintenance trends discussed in the preceding sections is summarized in Fig 11. Here first cost is added to direct maintenance (hardware plus labor) and maintenance infrastructure. Building on the EJ200/RB199 comparison, all engines are assumed to be of similar size on a mass flow and physical diameter basis. Extending component design lives and improving the quality of design to the point where unscheduled engine or module rejections are largely eliminated will have a highly beneficial effect on cost of ownership. In the near term, the higher cost of advanced hot end technology will off-set the gain to some extent, as illustrated by the EJ200-standard case. But for the following generation of engines, design for longer lives and fullest exploitation of cost reducing and low maintenance technologies will counteract this and continue the downward trend, opening up the prospect of halving the overall cost of ownership engines entering service in the 2010 to 2020 period. Compared to the present, this would represent a saving of over $3B over 20 years, for a moderately sized aircraft fleet typical of those operated by the UK and other European nations.

It is however necessary to interject one final cautionary note. Restricting major maintenance to planned, well-spaced overhauls of life-limited components, with little or no action in-between is an ideal which even commercial airlines, whose engines operate to a relatively benign and predictable schedule, find difficult to attain. The combat engines currently in service were not intended to have the levels and costs of maintenance envisaged for the future, but even so reality has fallen well short of intent. It is likely that future combat engines will suffer from unscheduled maintenance needs in the same way, even after several years in-service maturity. The much greater attention being paid to life and reliability in new designs and the capabilities of modern engine health monitoring and diagnostic systems should however ensure that the gap between aim and reality will be much narrower. New engine projects will only be affordable if this is the case.

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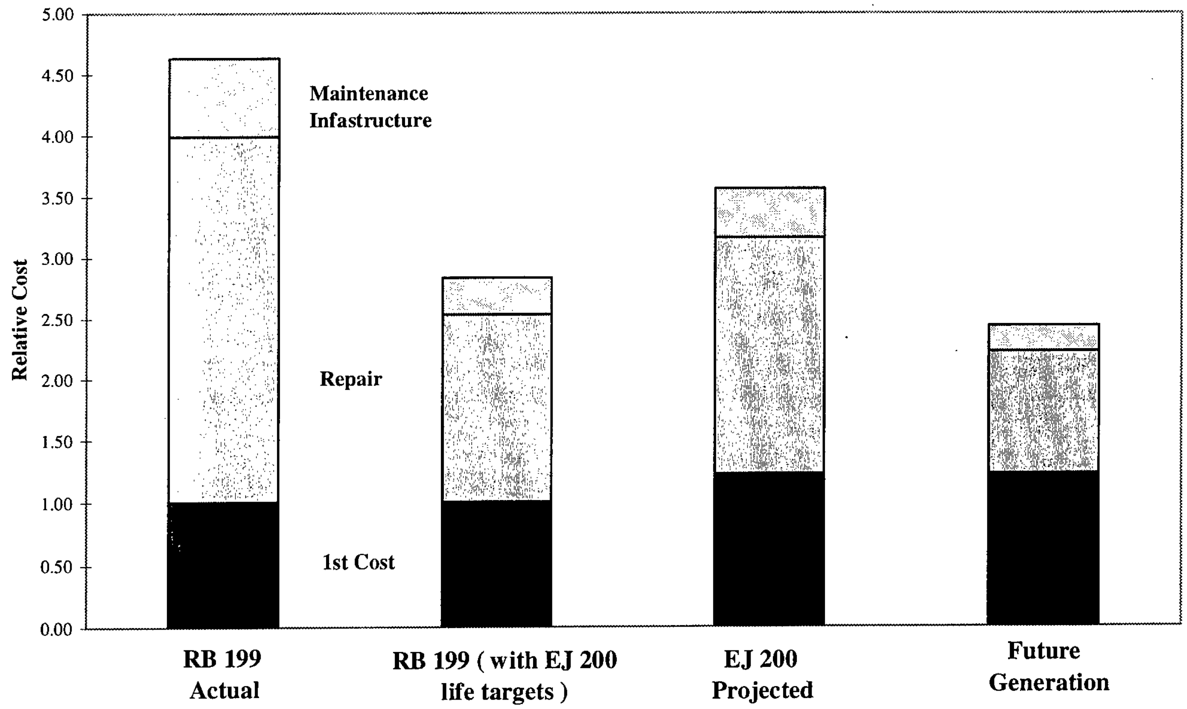
Figure 11: Cost of Ownership - Future Potential
(Engines sized to same mass flow and physical diameter)



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V/STOL & STOVL DESIGN CONSIDERATIONS

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1. Introduction

As has been noted in many studies of this class of aircraft (cf "Aircraft Design Integration" L.M.D.C. Campos, Aerospace 2020) full vertical take off and landing of attack type aircraft (non-rotor powered) has been shown to be an unwise design option. This is due primarily to the substantial amount of thrust which must be provided for vertical lift severely limiting gross weight and therefore either payload or range.

However, if even a limited amount of forward motion is provided, so that a conventional lifting wing augments the vertical thrust of the propulsion system the situation changes considerably. This combination of wing and propulsion produced lift has been shown to provide both useful payload/range combinations and significantly shortened take-off roll. Upon completion of the mission, with either payload expended or fuel load consumed, the system is now sufficiently lighter so that vertical landing does become possible. This gives rise to a class of aircraft known as "STOVL" or Short Take Off/Vertical Landing. Obviously one could also design the aircraft with shortened landing distances but not truly vertical. However, an interesting systems trade comes to bear on the problem.

"Short" vs "Vertical" landing capability manifests itself in a trade off in system weight. The results of this trade off quite literally depend on "how short is short?" Studies conducted by both the USAF Wright Laboratory and USN (Naval Air Warfare Center Warminster) both indicate that around 1000 ft seems to be a transition point. If one expects to operate with either take off or landing distances under 1000' ft the additional weight of the propulsion lift devices (lift engines, fans, etc...) is about the same as those devices (blown flaps, slats, leading edge devices, etc) which would have to be added to the wing in order to produce an equivalent effect. This means that landing distances from zero to about 1000' seem to result in approximately the same system weight impact. Beyond 1000 ft say up to 3000 ft (still fairly short) results in measurable weight savings.

This trade study does not address the operational advantages of vertical recovery. The ability to recover on small ships or remote roadways without arresting gear offers significant military advantages for many missions.

Therefore, we have a category of very useful system designs having short take off and vertical landing capability. The question now arises as to how one can integrate needed fuel, payload, and mission systems in order to create a viable combat capability. The most successful example of an existing system of this type is the Harrier.

The category of STOVL attack aircraft represents a substantial platform integration challenge to the design team. The interplay of propulsion, weight, range, payload, and equipment is sharply focused because of the vertical flight requirement (like a helicopter). Yet once into conventional flight the speed, maneuverability, survivability, and lethality trade offs predominate. Design success depends on achieving an operationally useful balance in both regimes.

2. Mission Need

As was stated in the previous paragraphs, STOVL provides the design team with a finite but limited design window. The addition of further requirements (longer ranges, internal store stations, supersonic flight) serve to reduce the design space even further. However in all but the most extreme circumstances, given the ability to make reasonable engineering trade offs, technically feasible solutions exist.

However, in any given design, the application of technology which enables a useful STOVL machine also enables a class of CTOL machines. Except for lacking the STOVL's unique take-off/landing characteristics these CTOL machines usually have higher performance (or longer range, greater payload, etc) than their STOVL counterparts. This illustrates the classic systems engineering aspect of platform integration. STOVL capability has a price (both in money and performance) and that price must be justified by

Paper presented at the AGARD Symposium on "Future Aerospace Technology in the Service of the Alliance", held at the Ecole Polytechnique, Palaiseau, France, 14-17 April 1997, and published in CP-600 Vol. 1.

the mission need of the customer. The advantages of vertical or near vertical capability, esp in regard to operating in confined spaces (small ships, remote landing sites or unprepared landing zones) makes STOVL desirable. The mission of the military customer must be enhanced by this capability in order that the system price is justified. In aircraft system design there is never any "free lunch;" STOVL merely illustrates that fact more quickly than do more conventional designs. As I will discuss later, STOVL also demands more diligent attention to systems engineering discipline (ie weight control and requirements growth) than does a conventional aircraft.

The reward for working in such a confined design space and then sustained diligence in protecting that design from negative influence can be a uniquely useful military capability not easily obtained any other way. The ability to project air power and/or protect ground operations from either small, readily available ships or landing sites near the front lines is a powerful incentive for solving STOVL's technical challenges.

3. Propulsion

The successful STOVL attack aircraft depends on advanced propulsion. In a sense high thrust to weight propulsion systems represent the fundamental enabling technology for this class of platform. The ability of the system to produce substantial amounts of thrust in dry (non-afterburning) operation at very light weight simply makes operationally useful STOVL possible. Earlier attempts at this class of aircraft either failed or were operationally limited by the propulsion system.

From the propulsion cycle perspective, thrust to weight is a direct function of maximum cycle temperature. This means designing turbine blades (both from a materials and cooling circuit design standpoint) to withstand substantial temperatures (at the edge of current state of the art). Yet, temperatures in modern engines are already nearing values which require significant technology just to produce. Temperature rise per unit length of combustor with hydrocarbon fuels represents a limitation to what we can produce (in a reasonable length) even if we can find blades to withstand these temperatures. This situation leads one to believe the next series of advances in thrust to weight will come more from reducing weight than raising cycle temperatures.

Propulsion weight reduction manifests itself in two ways. First by making existing components lighter and second by eliminating or reducing those components. Part of this results from the incorporation of new technologies - for example digital fuel controls are not only smarter and more reliable than hydromechanical, they are lighter (and cheaper by the way). The most significant weight reduction however comes from the application of new materials and process's. Increased use of composites for cases and shrouds. Possible use of metal matrix composites and advanced alloys in rotating parts. Higher strength materials allow greater rotational speeds which when combined with advanced aerodynamics, can eliminate some compressor stages. Reducing the number of stages required to produce a given pressure ratio not only dramatically reduces weight but also enhances reliability.

It is very difficult to over emphasize the contribution of high thrust to weight propulsion to this class of aircraft. The above technologies must be applied to the entire propulsion system, of course, not simply the engine. Nozzles, valves, shafts, lift fans, etc all constitute part of the thrust to weight equation.

4. Airframe

Overall system integration in any fighter or attack aircraft represents a design challenge. STOVL simply provides the design team with another system (the system for producing vertical lift) to integrate. Two integration concerns immediately dominate our design space.

First, we have the obvious requirement to package a vertical lift system (including ducting, fans, nozzles, louvers, etc) inside a fuselage or wing, centered about the aircraft center of gravity (cg). This displaces more traditional components such as fuel tanks and avionics. In addition, the size of some of these components (fans or lift engines) limits or tends to size the diameter of the fuselage, thus impacting fineness ratio. This in turn tends to set transonic drag rise which then drives the necessary thrust to obtain supersonic flight. Utilizing volumetrically efficient lift thrusters (like rocket engines for example) would be severely limited because of their negative impact on the ground environment. Likewise, adjusting the fineness ratio by extending the fuselage is rarely a viable solution because structural weight increases rapidly. This tends to give us a rather short coupled, large diameter fuselage which utilizes a superior thrust to weight propulsion system to drive it through transonic drag rise. It remains, however, for the designer to find room elsewhere for tanks, avionics, etc...and carrying such things externally aggravates the problem.

The second platform integration problem can actually be assisted by the need to accommodate the lift system. This problem is the trade off between stealth and aero performance. Due to the signature constraints of modern weapons it is very difficult to carry them in plain view and sustain a low value of signature. The most obvious solution to this problem for a multi-role aircraft is to suspend the weapons internally in some sort of bay. Designing a "bomb-bay" aircraft presents the designer with several problems. First a bomb bay requires significant structural modification over a more conventional fuselage. The structural load paths can no longer flow from fore to aft through the skin and stringers of the fuselage but are interrupted by the design breaks caused by the bay. In addition the bay structure must be rigid and strong enough to allow proper operation of store suspension and release equipment and door opening mechanism under both maneuver and aero loads. The weapons bay, as well as the propulsive lift system, all take up volume inside the aircraft. This reduces the volume available for other systems and/or fuel. Accommodating these negative impacts often results in a broader fuselage, esp in the wing carry through area than would be the case in a non-bay aircraft. Such a design, however, can more easily accommodate lift systems. The thickness of the shoulder area also tends to allow for an inner structure which can more easily accommodate the longitudinal keels common to catapult/ arrestment aircraft. This allows the design team to evaluate the potential of so called "soft" cat/trap operations. The "soft" term refers to the fact that the lift at the end of the catapult or the engagement speed of the arrestment can be reduced through partial application of propulsive lift. Another factor favoring internal bay designs is that the weapons bay wants to be on the cg, whereas the lift system wants to be fore and aft (two post) for effective pitch control. Thus internal weapons carriage and vertical lift system placement is often quite compatible.

Aside from the structural lay-out, advanced airframe materials and processes also play a large role in successful STOVL designs. The design and construction of lightweight yet stiff and strong structure pays large dividends in reducing system weight. Advanced composite designs are anticipated to reduce airframe weight by up to 25% over conventional all metal designs. Utilization of advanced materials, integrated sensors, and non-parasitic signature treatment may improve that number even further.

5. Mission Systems

In modern attack aircraft, mission systems constitute an ever increasing share of both cost and weight. Modern weapons systems are ever increasing their electronic content and the "information battlefield" of the future is likely to continue that trend. Avionics and the necessary systems for creating electrical power and cooling are costly, heavy, and difficult to package. In a highly weight constrained environment, these systems can become a significant portion of the systems "payload."

Several factors must be considered with respect to these systems. First, functions must be integrated wherever possible. The aircraft no longer has a radar, it has radar functions. These functions are processed through common support electronics and radiated through multi-functional antennas. Central processors perform the processing function for many systems on a time shared basis. A software based "resource manager" schedules the utilization of common hardware to perform multiple functions.

Next, functions available from sources outside the platform must be incorporated to the maximum extent possible. Data, sensors, intelligence, imagery available from other sources must be incorporated in the system reducing on-board weight, lowering cost, and increasing effectiveness due to the utilization of sensors which could not be packaged in a small aircraft.

Advanced technology must be applied to everything from the basic electronic component to the full up sensor array. Utilization of advanced digital signal processing techniques for example can eliminate multiple stages of heavy and expensive custom built analog circuits. Smaller devices run cooler and require less environmental conditioning and power. This effect cascades into the ECS and secondary power system making them smaller, lighter, and more reliable. Integrating these mechanical systems through multi-functional devices also allows considerable weight savings over conventional sub-systems.

6. Weapons

The customer for an attack aircraft wants lethality. This constitutes the "chain" of finding, hitting, and destroying a given target. The less likely you are to find or hit a given target the larger the power of the weapon you need to achieve the same probability of target destruction. (In some sense, nuclear weapons are one extreme of this argument). Accurate targeting and timely intelligence coupled with precision guidance means smaller weapons can provide the same lethality to a given class of targets. To some degree, simple tactical judgment that a small STOVL platform is an unsuitable delivery mechanism for the largest class of targets can be used to set realistic upper bounds on payload. This payload limitation has a direct (1000# bombs weigh less than 2000# bombs) and an indirect (lower structural weight due to smaller bays or even aircraft) impact on weight.

7. Weight

The above paragraphs all emphasize weight. In any vertical machine weight takes on an importance far greater than in a conventional aircraft. Simply put STOVL machines are extremely weight critical. In conventional aircraft adding to the empty weight means that either the wing must be sized up or the takeoff and landing distances must be increased. In STOVL aircraft not only must the wing size be increased but the propulsion system size must increase to meet the vertical landing requirement. Thus typical growth factors of between 2:1 or 3:1 for conventional aircraft can increase as high as 4:1 for STOVL. Operationally, increased landing weight at the same thrust level means decreased "bring-back." This means jettisoning either fuel or stores. Since at mission completion we rarely have much excess fuel the stores would have to go. In reality, since today's precision weapons are far too costly to throw away, the only choice would be to limit load out, thereby lowering potential mission effectiveness.

8. Systems Engineering Discipline

Typical aircraft development programs grow almost 1 lb per day from the beginning of development to operational capability. The normal solution to such a situation is to observe the growth, then institute a "weight control" program - often with limited success. Such lack of control can (in fact has) destroyed V/STOL or STOVL programs rendering the eventual designs or prototypes either outright or operational failures (ie some couldn't fly at all - some could fly but carry little but their own weight). Weight discipline must be initiated with the signing of the contract and weight must be as tightly managed, controlled, and budgeted as cost and schedule. Along with weight is the phenomena of "requirements creep." This tendency occurs as the potential customer begins to expect ever increasing capability as the development process continues. Since each new capability comes with both a weight and cost penalty, this tendency must be rigidly controlled. System trade-offs must be utilized to identify only the essential set of mission capabilities - else again weight growth will threaten success.

Aspects of the Crew Interface for Mission Systems

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SUMMARY

The challenge for future mission systems is to produce affordable solutions that provide the desired levels of operational effectiveness. This will be achieved by a system that enables the operator to be in ultimate control of the mission system through a manageable workload and an appropriate level of situational awareness. The crew interface is therefore vital to exploiting the full capabilities of the platform under control.

The crew interface can be enhanced by the thoughtful application of technology. To be affordable however, the technology must be carefully matched with requirements. At all stages of the design, including research phases, consideration has to be given to a careful harmonisation of the capabilities of the human, the hardware and the software. To be effective, the design must evolve from the beginning through co-operation between the designers, the implementors and the users.

Recognising the benefits of extending this approach into the research phase, a collaboration has been established between British Aerospace Military Aircraft and Smiths Industries Aerospace to explore aspects of the crew interface for mission systems.

This paper discusses the goals for an affordable and effective future mission system and the approach being taken to achieve these goals.

1 INTRODUCTION AND OVERVIEW

Affordability is driving us away from dedicated role aircraft and to platforms that cope with a wider range of roles - this will lead to mission systems that potentially contain a high volume of information and data. Whilst it will not necessarily all be used on a single mission, the cockpit/interface must be designed so that none of the information can be confused and so that it is mutually exclusive.

At the 3rd International Workshop on Human-Computer teamwork in September 1992, Group Captain G.A.Miller of MoD OR(Air) stated: "With the ever-increasing sophistication of avionic systems, we are fast approaching the situation in which the aeronautical industry can offer systems that are technically capable of meeting our operational requirements but which the aircrew cannot fully exploit; perhaps we are already there." [Ref. 1].

The following sections discuss what is meant by an effective weapon system and identifies the contribution of the crew interface. Enabling technologies that support the future crew interface are then, considered, followed by a discussion of how they might be affected by the human factors requirements. The paper concludes with a discussion of the collaborative approach being adopted to support distinct but related research activities.

2 WHAT IS AN EFFECTIVE WEAPON SYSTEM

2.1 Measures of Effectiveness

Measures of effectiveness (MoEs) can be defined in whatever top-level terms or abilities seem important to the priorities the day. For example in wartime in an offensive rôle lethality might be the highest priority, whilst in peacetime affordability might be considered more important.

Examples of measures of effectiveness might include:

* Affordability;
* Flexibility;
* Lethality;
* etc.

Assessment of MoEs tends towards the subjective. Clearly, depending on the standpoint of an analyst, different priorities will be set for each of them in attempting to calculate a total MoE for the complete weapon system.

In considering affordability, it is necessary to address the ability to carry out missions in terms of, for example:

* Cost of mission;
* Risk of failure (e.g. value of target defences);
* Value of target;
* Condition of the weapon system.

At the very least for affordability, it is necessary to minimise the cost of the mission as well as the risk of failure.

The airborne weapon system can be partitioned into two distinct sub-systems: a vehicle system which enables the aircraft to be controlled and manoeuvred, and a mission system which enables the aircraft to carry out missions.

An effective weapon system is therefore an effective vehicle system combined with an effective mission system.

2.2 Mission System

The vehicle and mission systems of the aircraft share a crew interface, but the remainder of this paper will discuss aspects of the crew interface for the mission system, with a view towards affordability.

Paper presented at the AGARD Symposium on "Future Aerospace Technology in the Service of the Alliance", held at the Ecole Polytechnique, Palaiseau, France, 14-17 April 1997, and published in CP-600 Vol. 1.

Mission system functions are provided in the aircraft to support affordability in terms of for example:

* minimising the cost of the mission;
* maximising the effect of co-operation;
* maximising the probability of mission success.

Such functions as navigation, communications, threat avoidance and target attack all are included in the mission system to support the crew in their mission management activities such as situation assessment, planning and routing.

2.3 Crew Interface

As mission managers on the aircraft, the crew must have ultimate control of the mission system. In order to exercise this level of control properly, adequate situation awareness must be made available primarily through the crew interface. An effective crew interface will not only provide awareness of the emerging situation, but will also assist in making correct mission decisions and responses. However, interaction between the crew and the mission system clearly can be a complex activity, and can greatly affect the affordability of the mission if it is not performed, implemented and engineered effectively.

The crew interface therefore has a crucial role in maximising mission effectiveness. As a result its design must be carefully considered. It needs to be both easy to use and intuitive, rather than requiring effort to decode/read/assimilate and the crew workload associated with driving it must be optimal.

3 WHAT ARE THE CHALLENGES TO AN EFFECTIVE CREW INTERFACE?

The challenge to an effective crew interface is principally the ability to handle the complexity and quantity of data that modern avionics equipment can provide.

The numbers, capabilities and modes of use of avionic sensors continue to increase; recent arrivals include millimetre-wave radar, infra-red trackers, and laser obstacle warners. This proliferation can greatly enhance situation awareness. However, if mishandled or incorrectly processed, it can add problems and lead to unproductive work at the crew interface. Further, with more sensors and more modes, there is scope for more control of the machine which in turn creates more data available to be assimilated; hence more workload.

Evolving capabilities in communication related technologies, such as data link, and the desire to undertake more coordinated operations continues to increase the amount of information entering the cockpit. At the same time, evolution of the cockpit display systems and underlying avionics imposes fewer limits upon what can be physically displayed/engineered due to more capable and generic processing, data storage and display technologies.

However, the diverse means of presenting information via ad hoc channels (i.e. visual, aural, information-on-request) requires the crew to integrate and memorise the total situation. For example it is possible to display moving map data providing the crew with information about terrain; it is possible to present information regarding threats . The crew must integrate this information to enable them to minimise the threat while avoiding terrain.

As a consequence it is difficult for the crew to monitor the situation continuously [Ref. 3], and so, when there are changes, they may be unaware or uncertain of what has changed and its impact upon their mission. This is a particular difficulty in the rapidly changing situations encountered by fast jet aircraft in a battlefield.

A key design driver for the crew interface is then to find appropriate ways to display this plethora of information to the crew which enables them to maintain the requisite level of situation awareness for the tasks they are to undertake.

4 RESOURCES

In recent years, enabling technologies have been explored to find a means of handling this complexity and quantity of information.

Broadly, enabling technologies are required in support of:

* Information sources;
* Information handling;
* Information processing;
* Display and Control.

4.1 Information Sources

The processing capability now exists to automate the management of the sensors in quite sophisticated ways. Algorithms exist for the effective fusion of conflicting, noisy and uncertain data. Consequently, the amount of data which it is necessary to present at the crew interface is growing much more slowly than the amount that is available.

With advanced processing, the quality of information from the machine can be increased, and so, in some senses, can the quality of the information which the machine requires from the crew. For example, one might envisage a sensor manager being instructed to maintain search only on those sectors from which a threat might disrupt a specific mission plan, rather than maintain search with respect to specific co-ordinates.

In the modern aircraft, there are additional sensors, modes and automatic functions which can complete or enhance a picture that formerly would have been incomplete or deficient. So in the modern aircraft, there is less need for remedial or supplementary action by the crew, such as varying the transmitter characteristics, correlating with datalink reports, or following kinematic ranging manoeuvres.

Many of these actions can now be entrusted, at least in part, to a Mission Management function in the Mission System, with little or no interface transaction.

This more 'robust' sensing is also a pre-requisite for the machine to take on much of the general situation monitoring, reporting only significant or anomalous data or events to the crew.

4.2 Information Handling

The spectacular growth in Information Technology (IT) in the everyday world is plainly visible, and its impact is starting to be felt. In the more demanding environment of the fast jet, with more stringent robustness criteria, special HMI constraints, and exacting response times required of the software, and with long lead times to market, the IT revolution is reaching the mission system some years later than it is reaching the home, the office or the factory, but the impact is potentially as great.

Until recently, on-line storage was at a premium. Semiconductor memory was bulky and was either fragile or expensive; large capacity is now available in physically small and inexpensive modules. Similarly, laser disc store was unsuited to fast jets but can now be used, with enormous potential for storing mission data and map data in pictorial, tabular or iconic form. This can be displayed on demand - albeit with increased interface loading, but potentially great benefit to mission effectiveness - or it can be used within the machine, allowing some processing loops to avoid the crew interface altogether.

The arrival of optical fibre data networks enables practically unlimited transmission bandwidth for many applications. For example, it allows the presentation of highly detailed imagery, from optical or infra red sources, in the cockpit.

Although demanding of the machine, image handling is not unreasonably expensive, and it allows some types of situation data to be presented to the crew in the most easily assimilable way.

The large volumes of Information to be handled within a Mission System can be enhanced through sophisticated Information Processing technologies. [Ref. 2]

4.3 Information Processing

Perhaps the most spectacular growth of all is in the processors themselves. Together with the new capabilities in data memory and transfer, this opens up new territory of man-machine co-operation which is only just beginning to be explored and exploited.

Returning to the example of integrating terrain and threat data, consider a map overlay of the threat to a low-level penetrator posed by ground defences. Any one threat might be at a pre-briefed location, or it might be notified or detected in real time. A simple but informative display would indicate missile or tracker range and terrain shadow - that is, the zones where, at a given height above the ground, the intruder would be screened from the tracking sensor. Such a calculation would have been unthinkable a few years ago; now the shadow heights can be calculated, complete with atmospheric refraction of the radar beam including beam slope and vertical air density gradients, at rates exceeding a million pixels per second on 'ordinary' processors that are being fitted in office workstations. Having calculated this per-pixel height table, once, a display mask, for any specified height above ground, can be generated so that the crew can see 'what if' they were to fly higher or lower.

As such tools become available, consideration must be given as to how they are best used in a confined space and time. A binary mask overlay can be displayed on a map easily enough, but this raises other questions - is it necessary to provide an input channel for 'what if' heights, or simply to display the mask for current height? Might the crew forget which is being displayed - how should the display be tagged? Is an estimate of the threat intensity required, rather than just a binary indication of 'in sight and range'? If so, how should the map be de-cluttered, or is a strong but temporary threat overlay display acceptable? The machine may be allowed some discretion to select the display, but how it does this might need to be controllable by the crew.

It has been indicated that the new technology is not just producing more or better data - with 'smart' processes the machine can be made to communicate in 'information' rather than 'data' much more than in the past. Possible examples range from graphical fuel management, in which both state and trend - and significance - can be 'perceived' in a simple line display, to recognition of tactical formations, by hypothesis and investigation. The former takes advantage of the number-crunching resource being available inexpensively, the latter moves, cautiously, into the developing domains of neural networks and sensor management.

In the context of the affordable aircraft, the main characteristics of IT are (a) that it is potentially inexpensive (assuming that current progress in reducing the cost of software production is sustained) and, (b) it consistently impacts the crew interface, by increasing, decreasing or changing the interface traffic.

4.4 Displays and Controls

Just as IT is giving us unprecedented choice of input and output data, developments in HMI devices are giving unprecedented choice in how the data is input and output.

Programmable displays now make it possible to separate displays hardware requirements from information presentation requirements. The task of selecting a hardware fit - display screens, HUD, helmet displays, etc. - remains, but the functionality embedded in these equipments can now be separated from the hardware design.

It is thus possible in principle for the system to evolve, changing and developing its sensors, weapons, navigation equipment and software functions, with only occasional or minor impact on the hardware of the crew interface.

The revolution has already begun with graphics processors, colour multifunction screens, programmable bezels, helmet mounted displays, low-displacement sticks and voice I/O. The interactive voice system in the Eurofighter 2000 has proved so successful with the aircrew, both as an intuitive interface and a perceived workload reducer, that the use of such systems will be extended for the future.

This control interface could be further refined by the use of eye tracking and virtual reality techniques, so that the crew only needs to 'look and touch'. Demonstrators have been working on the ground for several years, and low resolution airworthy systems could be available in the short term. A higher resolution system is more uncertain and is a more a long term goal.

5 NEW DESIGN CHALLENGES FOR THE CREW INTERFACE.

The use of these new techniques and technologies introduces new design challenges. For an effective crew interface these challenges fall into three major categories:

* The requirement for trustworthy information;
* The ability of the crew to assimilate the information;
* The ability of the system to present the information.

In turn, the quality of the provision of these major factors depends on several issues.

* Integrity, fidelity, quality and stability of information;
* Completeness of information;
* Aircrew trust in the system;
* Human limitations.

5.1 Integrity, Fidelity, Quality and Stability of Information.

Increasing the level of sophistication in the technology, for example through degrees of automation, to mask the functional complexity, is often viewed with apprehension. The impression that automation is not sufficiently capable or knowledgable may be founded on experiences of ill-considered implementations of automated functions. In order to preserve their situation awareness and minimise any ill effects upon workload, the crew need to be sure that any information that is presented in the cockpit:

* is telling the operator what he thinks it is telling him - if he is to attack a data link track is it still at the location that his displays are telling him it is at, or is the information stale and it has now 'moved on'?
* contains sufficient information and data to allow them to perform their tasks;
* contains sufficient data/information to enable him to identify the tasks which have to be performed.

It is necessary therefore that the interface to the mission system contains sufficient accurate information in one form or another for the crew to identify and perform their tasks.

5.2 Completeness of Information.

The requirement for complete information will be determined by the set of concerns currently being resolved by the crew, and making up the situational whole. If the information that can be provided is incomplete, it may be preferable not to use it if its presentation will lead to questions in the crew's mind and possible incorrect interpretation and extrapolation. On the other hand, in some cases some information may be better than none, e.g. memorised radar tracks, providing that the crew are aware of the status of the data.

It must be remembered, however that complete information is an aim rather than an achievable reality; there will always be, and always has been, uncertainty.

A key factor then is to design the display of certain types of information to include a qualitative representation which enables the representation of uncertainty.

5.3 Aircrew Trust.

Understandably, aircrew can be suspicious of untried technology and concepts and prejudiced by previous 'bad' experiences. The potential areas for mistrust can be better understood by involving aircrew in the design process from the inception - it must, however, be borne in mind that where a crew of today may not trust a system due to its immaturity or lack of familiarity, the crew of tomorrow may have been brought up with such systems/technology.

A key factor then is to build aircrew trust through the provision of, for example, sufficient information to allow them to understand why the system is doing or saying what it is. This is particularly applicable to concepts surrounding automation. [Ref. 1]

5.4 Human Limitations.

Basic human capabilities will not change in the future, but what can change is how those capabilities are utilised. This will require careful consideration of the benefits of the technology to support the crew of a manned aircraft and not replace them.

A key factor for the crew interface system is to design an information system which takes account of the best attributes of both the human and the machine.

5.5 Summary of Crew Interface Design Challenges.

The crew interface must therefore be able to present large amounts of information in a form that enables the crew to retain their situational awareness by:

* understanding what the interface is telling them;
* providing sufficient information to enable them to identify and perform their task;
* identifying any uncertainty in the data;
* understand what the system is recommending and why;
* allowing the crew to use their abilities to best advantage while supporting them in those tasks which they are less capable of performing.

Where a mission system is generating a solution, then the solution and the problem should be presented together in a convincing way. A key systems design factor for the crew interface is the presentation of integrated information, 'image making', so that information is presented in such a manner that the solution is, as far as possible, self-evident.

6 APPROACH

In considering the above resources and design challenges together, the design process is revealed as complicated. Therefore it becomes increasingly important that the functions of distinct parts of the system, including the crew interface, are viewed together as components of a total system capability.

In the light of this interdependence it is clear that the various organisations involved must work together closely to integrate an avionic system. But it is increasingly becoming necessary that they work together at the research stage, not to share research of their proprietary technologies, but to share the concept of what these technologies will do and how they will end up interacting.

Ultimately, the choices to be made in defining a best system solution will be based on a balanced consideration of top-level measures of effectiveness (i.e. Affordability, Flexibility, Lethality, etc.) as discussed earlier.

The development of a mission capable simulation provides a process to support this approach and will help to focus research and development onto those issues and elements that are ultimately important. As a result, resources will be more effectively used, thereby contributing to the affordability of the development process.

7 THE WAY FORWARD: COLLABORATIVE MISSION SIMULATION

Mission capable simulation provides a facility where mission system functionality can be modelled in a realistic simulator environment with a realistic crew interface in its cockpit. Such a facility offers:

* the ultimate customer early access to the mission capabilities of the eventual product aircraft;
* the system integrator the opportunity to demonstrate a fully integrated mission system prior to committing to full scale development;
* the system manufacturer a means of demonstrating, verifying and validating the correct functioning of a particular system at the design stage.

As a systems integrator British Aerospace has such a facility as a resource for testing mission systems functions both developed in house, and by systems suppliers such as Smiths Industries. Both companies require such a tool to support research into distinct mission system functions; BAe for their Tactical Situation Assessment (T.S.A.) programme, and SIA for their Intelligent Crew Interface programme. Because of the core nature of the Intelligent Crew Interface to any future mission management functionality, both companies require the distinct work of the other at the outset to achieve early mission simulation; i.e. there are two distinct objectives which require both a common toolset and each other.

8 CONCLUSION

By employing a mission simulation approach to a total system design, an affordable integrated crew interface can be examined and developed concurrently with novel mission system functions. Such an approach brings the system user, system designer and system integrator into contact early and throughout the development cycle.

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Modern Fighter Mission Avionics
The Joint Strike Fighter Avionics Architecture

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Summary

The Joint Strike Fighter (JSF) program is potentially the largest new military aircraft program in the world today. A preliminary avionics architecture has been defined and published. Several efforts are underway to prototype and demonstrate various aspects of that architecture. The architecture will be refined and updated between now and the beginning of Engineering and Manufacturing Development (EMD)—expected to begin in 2001. This paper describes the avionics architecture in its current state, discusses the motivation behind the various areas of the architecture, presents the issues involved, and discusses the results of some of the demonstration efforts.

The JSF program is based on the four pillars: affordability, lethality, survivability, and supportability. First and foremost among the pillars is affordability. In order to field a lethal, supportable, survivable aircraft, affordability tradeoffs will be conducted by the prime contractors. Historically, 30-40 percent of weapons system life cycle costs have been attributed to avionics, hence reduction in avionics systems costs are essential in satisfying JSF pillar requirements. An F-22 technology point-of-departure has been used to baseline the avionics architecture planning. The JSF is leveraging that significant technology investment, conducting maturation of new contributing technologies, and implementing, where appropriate, COTS components, standards, and processes to enhance affordability of the next generation strike fighter.

Also discussed in this paper are the implementing standards for the JSF open avionics architecture. The preliminary set of standardization areas, along with candidate standards and leading alternatives, from the Joint Advanced Strike Technology Program Avionics Architecture Definition (JAAD) Version 1.0 is presented.

Introduction

This paper describes an approach to modern fighter mission avionics, in particular that taken by the Joint Strike Fighter (JSF) program. The paper concentrates on the avionics architecture and the rationale behind it, with an emphasis on affordability. The JSF avionics architecture was initially developed by an integrated product team (IPT) of government and industry personnel. The purpose of the architecture is to provide a framework for the evolution of a fully developed and validated avionics system for a next generation of strike weapons systems for the U. S. Air Force, Navy, Marine Corps, and our allies. Demonstrations of various aspects of the avionics are being done to provide a low risk transition to Engineering and Manufacturing Development (EMD) in 2001. As the various demonstrations progress we expect that the architecture will evolve with lessons learned. We expect to update the architecture periodically during the concept development phase (CDP) of JSF and into EMD.

Cost Saving Opportunities

We identified cost saving opportunities by analysis of recent avionics systems and by examining technology developments taking place. The primary technology programs examined are discussed in the next section. We took a broad view of cost saving so we included alternatives like improving the weapon accuracy (fewer weapons are needed). Listed below are the primary cost saving opportunities considered:

- Leveraging existing aircraft avionics (F-22, F-18, etc.),
- Exploiting the newest technology to make avionics cheaper, not better,
- Omitting expensive subsystems by relying on off-board systems, or other on-board subsystems, to take up the slack,
- Substituting software for hardware,
- Substituting processing for expensive sensor components,

Paper presented at the AGARD Symposium on "Future Aerospace Technology in the Service of the Alliance", held at the Ecole Polytechnique, Palaiseau, France, 14-17 April 1997, and published in CP-600 Vol. 1.

- Sharing resources across subsystems through super-integration
- Using commercial (COTS) based components,
- Employing open architectures, and common components across the aircraft, to reduce numbers of module types, to attain competition, and attain economies of scale—both hardware and software
- Using advanced packaging and other techniques to reduce weight, volume, and power and hence aircraft size and cost
- Improving the avionics capability so fewer aircraft and/or weapons are needed
- Improving avionics reliability to the point where support costs can be dramatically reduced, and availability much improved so fewer aircraft are needed; and
- Improving software processes and software reuse to make software cheaper and more flexible.

Point of Departure

The F-22 avionics system was the point of departure for the JSF avionics architecture definition. We picked F-22 because it is the most recent, and highest performance, avionics system designed to this point. Potential updates to the F-22 point of departure were taken from a variety of sources as described in the following paragraphs.

Commercial developments were the first upgrade sources to be considered, since in recent times commercial electronics has had explosive technological advances, and since there is a concentrated high level management push to seek cost savings through use of commercial off-the-shelf technology (COTS). As an example of how far COTS has come, consider that in 1987 we were doing advanced development with 30Mhz processors and having trouble making them perform at that clock speed. Today one can buy a variety of 300Mhz plus processors off the shelf with forecasts of 1Ghz processors by year 2000. Interconnect speeds have similarly multiplied. In 1987 we were researching 50 mega-bits per second (Mbps) fiber optic links. In March of last year the JSF Scalable Multi-Processor System (SMPS) demonstrated 50 meter fiber optic links running, in a distributed shared memory computer, at 4Gbps. Since then commercial chips have become available to run that same link at 8Gbps. A company named Sequent just began shipping commercial "server" computers which use those 8Gbps chips.

While many of the advances in commercial electronics have been in the computer area, there have also been COTS communications technology advances (such as satellite direct television), potential high volume COTS radar applications (such as automobile collision avoidance systems) and COTS use of head-up display (HUD) technology in automobiles. Tapping into any of these potentially high volume applications could lead to reduced costs for JSF avionics.

Other potential updates to the F-22 avionics for JSF came from various Air Force, Navy, Army and DARPA programs. The AF PAVE PACE program had recently studied entire avionics systems and had ranked the various parts according to cost. This work led to the initiation of the Integrated Sensor Subsystem (ISS) program to seek commonality among RF support electronics and to define an open architecture in this area. The AF Very High Speed Optical Network (VHSON) program and the Navy Next Generation Computer Resources (NGCR) programs together provided a basis for the use of commercial based interconnects in avionics and the idea of a unified avionics interconnect. The AF functionally integrated resource management (FIRM) program was exploring the concept of a real time data management system while the Navy PowerScene system was developing a "virtual reality" like information system showing the pilot important information he could not see by looking out the cockpit window. The Navy's Advanced Shared Aperture (ASAP) program was pushing the use of wideband multi-purpose phased array technology and provided an opportunity for sharing phased array apertures among multiple functions. The Navy/ AF Special Airborne Antenna System (SAAS) and Structurally Embedded Reconfigurable Antenna Technology (SERAT) programs were working to develop shared multi-frequency low band antenna and provided a basis for integration and sharing of functions across low band antennas. The Navy Shared Aperture Sensor System (SASSY) program was working to further integrate electro-optic (EO) sub-systems and to demonstrate the use of staring EO arrays. This work provided a path to cost and weight saving in the EO arena.

Cost of Avionics

Figure 1 shows a breakdown of aircraft life cycle cost (LCC) along several lines. For this chart LCC is defined as the cost of the program from inception to the end of its useful life. It includes the operating cost, such as for fuel and for people to operate and maintain it. It does not include a factor for disposal. I must emphasize that the percentages shown here depend on the avionics subsystem installed, are estimates taken at one point in time, and certainly should not be taken as the last word in costing. For this issue of the chart (there have been several others) an inclusive definition of avionics was used along with a robust avionics system. The chart has been updated several times in the past and will be further updated in the future.

In the first level breakdown the chart shows the split among production, research and development

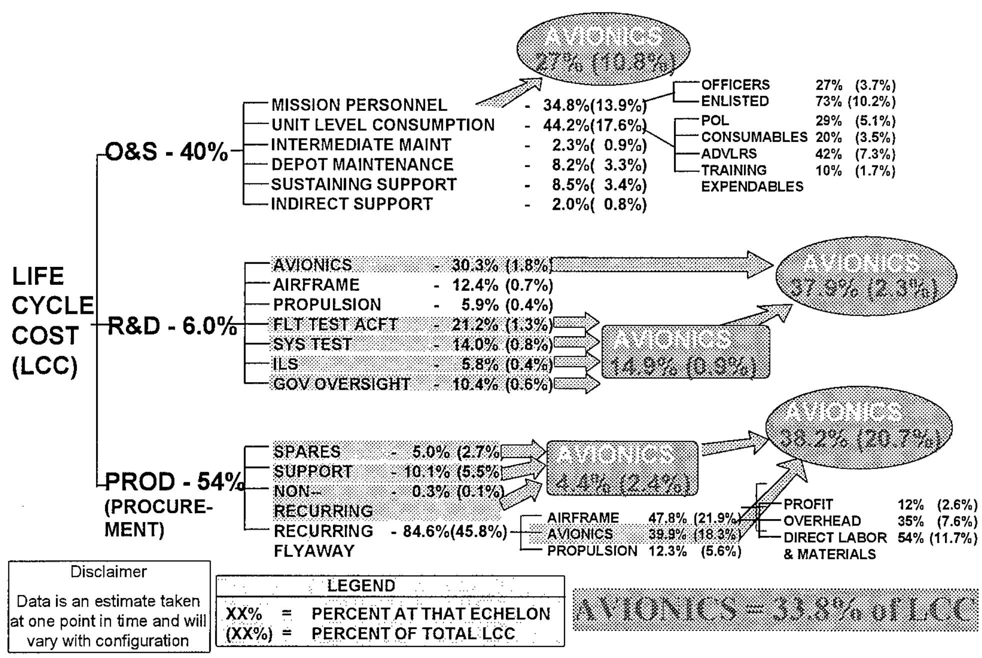

Figure 1. Avionics as a Percentage of Life Cycle Costs

(R&D), and operations and support (O&S). At the second level avionics O&S is 27% of 40% for a total of 10.8%. The number in parenthesis is the percentage of total LCC at that level, and is generally the most useful number. In the R&D area avionics is directly 30.3%, but also contributes to flight test, system test, ILS, and government oversight for a total of 37.9% of the R&D costs. In the production area avionics is over half of the non-fly-away costs at 4.4%. When the non-fly-away is added to the fly-away, avionics becomes 38.2% of the production costs, or 20.7% of the total LCC. The grand total avionics cost, including O&S, R&D, and production is shown in the lower right of Figure 1 and is 33.8%. This tends to confirm the common rule-of-thumb that avionics is about one-third the cost of the aircraft.

Figure 2 shows avionics costs broken down by major groupings. Note that the costs are not broken down in the traditional manner—by subsystem (radar, EW, etc.). As will be seen later, the integrated architecture attempts to share components, such as apertures across subsystems so that costs of traditional subsystems become less meaningful. The cost percentages shown are an amalgamation of information from a number of sources. One source of information was the AF Pave Pace program. A second source was conversations with various sensor and processor engineers at the Naval Air Warfare Center, and at subsystem equipment vendors. Like other cost estimates given in this paper, they change with the equipment included on the aircraft, and with time, and should not be taken as the last word in cost estimation.

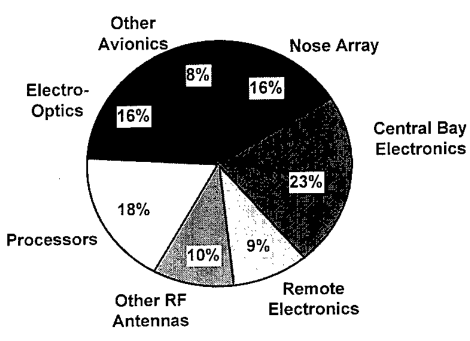

Figure 2. Avionics Production Costs by Major Sub-System

As can be seen in Figure 2 central bay RF electronics, at 23%, are the most costly area in this breakdown. Central bay RF electronics are a conglomeration of pieces from a variety of RF functions (radar, electronic warfare (EW), communications (COMM)), with a large percentage made up of RF receivers. As mentioned before the AF ISS program is seeking to reduce costs in this area.

Processors are the next most expensive item at 18%. The cost of processors has caused the JSF program to initiate the Integrated Core Processing program to reduce the cost of processing while still providing the increased processing necessary for a high performance robust avionics system.

Tied for third in this cost estimation are the nose array and the EO sub-system. While the nose array shows up in only third place in this cost breakdown, it is the single most expensive item in the avionics. All other equipment groups shown have multiple components. Because the nose array is such an expensive component, and because it is also heavy, the JSF office has initiated the Multi-Function Integrated RF System (MIRFS) program. While the study aspect of MIRFS is considering all aspects of the RF subsystem, the development part of the program is concentrating on the expensive nose array.

Although the overall EO subsystem is potentially as expensive as the nose array, JSF has done only limited technology maturation work in this area. A small study effort has been done and a staring array has been flown, but no major demonstration has been undertaken. The reason that we haven't done more is mainly limitation of funds. In fact we have outlined an EO technology maturation program, but have not had the funding to implement it. The other reason that we haven't initiated a major program in the EO area is that we are not certain that we need an EO targeting system. This is discussed later.

The antenna category in Figure 2 shows up next at 10%. JSF started some technology maturation work in this area, but did not proceed forward, because of funding limitations and because this area was a relatively small percentage of the total avionics cost. However, the low cost of antenna may be somewhat misleading, since the cost of aircraft and structure to accommodate the antenna sometimes far out weighs the cost of the actual antenna. Reducing the number of antenna by sharing them across functions and frequencies could still have payoffs in the future. processor types could perform functions to support the multiple RF functions, and possibly EO as well.

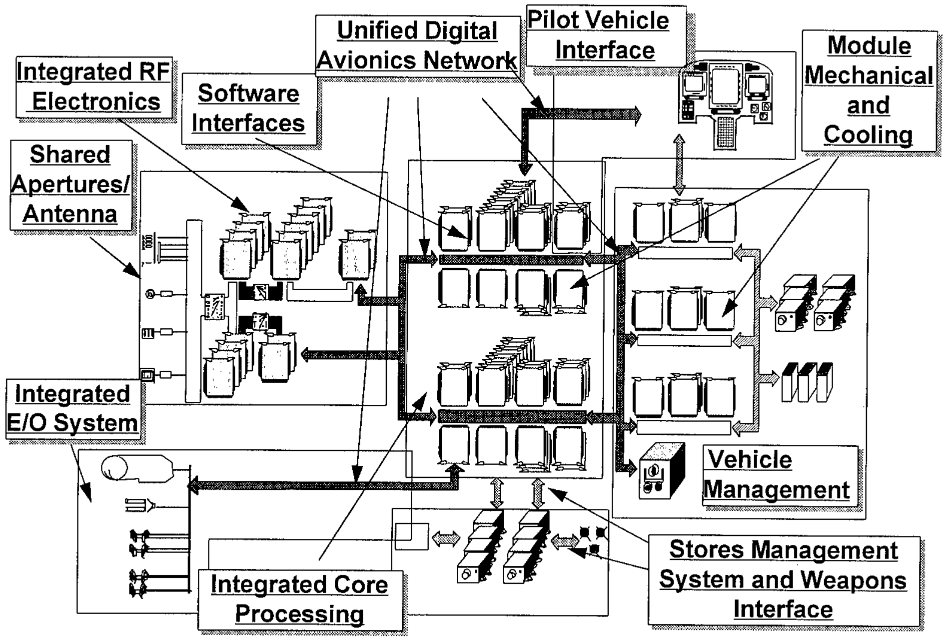

Figure 3. Diagram of JSF Open Architecture

Key Features of the JSF Open Architecture

Figure 3 shows the JSF open architecture diagram. This diagram is taken from the JAAD, Version 1.0 dated 9 August, 1994. Since that time contracts have been let to industry and the final design of the avionics architecture is in the hands of the contractors. However, this diagram still serves as a guide to the architecture goals and to the location of important interfaces where standardization could provide many benefits. This section discusses the key features of the open architecture and how they contribute to affordability.

First, as mentioned previously the JSF avionics architecture breaks down the avionics system into component groups, rather than traditional subsystems, with the goal of sharing the components across functional subsystems. This leads to the concept of super integration—that is integrating across the traditional subsystems. For example, the nose array being matured under MIRFS is designed to (as its name implies) be capable of performing multiple functions such as radar, electronic support measures (ESM), electronics countermeasures (ECM), and COMM. As another example, the processing architecture is such that the same processor types could perform functions to support the multiple RF functions, and possibly EO as well. We may also be able to integrate low band antenna in such a way that they can be shared across functions.

Second, the JAAD defines an open architecture. The purpose of the open architecture is to reduce both development and life cycle update and maintenance costs. The open architecture seeks to segment the system such that components from different vendors can be plugged together in creating the overall system. Key interfaces are identified and standards are proposed for those interfaces. We intend that interfaces be defined sufficiently well that we will achieve cost savings through competition for developing and building the components making up the avionics system. We also intend that piecemeal upgrades using new technology be easily and cheaply done during development and throughout the life of the aircraft. Because of the rapid changes in commercial digital technology, we anticipate that new processing hardware will be inserted into even the prototype avionics more than once during the development phase of the aircraft. A key factor in allowing this is independence of hardware from the software, so that the software will have only minor changes when ported to next generation hardware.

Another important feature of the open architecture is scalability to add new functions to the avionics system over time. Obviously this will be difficult if new apertures are needed, but adding functions to the processing area should be accomplished fairly easily and cheaply by plugging in new processor modules and by adding new software. Key to being able to add processing power over time is initial installation of interconnects having sufficient performance and the needed features to accommodate the new hardware and software. Thus advanced interconnects are being explored to achieve the highest performance practical and also to predict what features will be needed to support future computing paradigms.

To allow easy addition of new software, particularly third party software, we are exploring open architectures at the application software level. The use of standard interfaces to the operating system and to the graphics system is good first step, but more is needed. As a supplementary approach we are considering alternatives such as providing a standard program interface through a data base manager, or using object oriented programs which access data through a standard public interface while maintaining data internally through a private interface. We are also following the development of the Common Object Request Broker Architecture (CORBA). Further discussion of the standards are given in the Building Codes section.

In the EO area the architecture anticipates two integrated subsystems. The first is a targeting forward looking infra-red (FLIR) camera, perhaps also performing long range infra-red search and track (IRST), integrated with a laser ranger designator behind a single window. The second EO subsystem is a multi-function advanced distributed aperture system (ADAS). Instead of employing separate apertures for different functions the ADAS, consisting of low cost staring arrays distributed around the aircraft, seeks to save costs by integrating the functions of short range situational awareness, missile warning and navigation.

While the baseline avionics architecture sensor suite includes radar, EW, and EO subsystems, studies are being conducted to determine if some of the on-board sensor suite could be replaced with information from off-board sensor systems such as from the JSTARS aircraft. For example, it may be possible to eliminate (and save the cost of) one or the other of the major on-board targeting systems (radar and EO) by substituting off-board sensor information. If the radar and off-board sensors could substitute for the EO targeting subsystem we would attain considerable savings. Alternatively it may be possible to reduce the range (and hence the cost) of the on-board sensors by using off-board sensor information. Both approaches are being pursued in seeking to hold down avionics costs.

Integration and sharing are also being pursued in the RF support electronics area. As mentioned earlier the ISS program seeks to reduce costs in this area by creating an open architecture of multi-function time-shared plug-and-play components for RF support electronics. Along with the recent development of very high speed analog to digital (A/D) converters and digital receivers, this program has high potential for achieving dramatic cost reductions. The ISS system has standard RF and intermediate frequency (IF) interconnects. These interconnects include switches to allow redirecting of the signal for time sharing of components. The interface standards needed to support this open architecture are under development (by ISS) and are candidates for incorporation into a future version of the JAAD. They include RF, IF, and digital interfaces and are expected to be available in the 1998, 1999 time frame. Of course the final decision for use of these standards (like all JSF standards) rests in the hands of the JSF prime contractors.

In the core processing area integration and sharing of the processing resources across multiple sensors and functions provides the opportunity for further reduction in the number of module types and also provides a form of redundancy, which can be used to provide fault tolerance. For example, if both radar and EO use the same type processing system, one processing system could act as backup for the other. If the radar processing system failed, the EO could be shut down and its processing resources used for the radar. Alternatively a single spare module could provide backup for both radar and EO. The use of redundant systems can save money by reducing the requirement for immediate maintenance thus making the aircraft more available. Redundant systems can also save maintenance cost as well by eliminating the need for much of the costly immediate maintenance and allowing instead deferred scheduled maintenance.

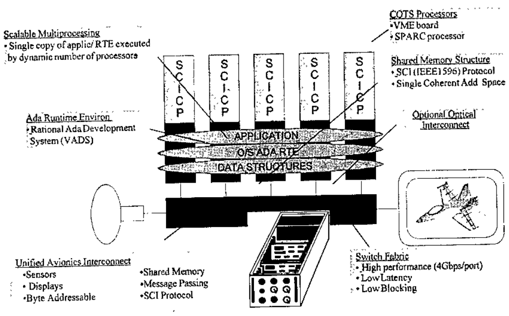

Figure 4. The JSF Scalable Multi-Processor System (SMPS)

Another potential feature of the JSF architecture is parallel processing. With the combination of high speed processors and high speed interconnects now available, there is the potential of replacing special purpose processors with multiple parallel general purpose processors. In a sense this is substitution of cheap (in the sense that there is no recurring cost) software for hardware. Toward this end the JSF program initiated the Scalable Multi-Processor System (SMPS) program. This program demonstrated the use of multiple parallel general purpose processors, in a shared memory environment, doing a compute intensive task that might also have been done by a special purpose processor. It also developed an Ada based "threads" system for supporting software automatically scalable to any number of processors. Figure 4 shows a diagram of the SMPS.

These processors also make it possible to substitute cheaper processing for more expensive sensor components. For example, super-resolution processing techniques might be applied to less expensive radar front-ends to yield an equivalent image.

With the emergence of digital receivers, digital processing has moved into what previously was an all analog domain. This presents integration cost saving opportunities and challenges. For example, it might be possible to use some of the same type processing elements across multiple digital receivers, as well as in the traditional signal and data processing areas. This could reduce maintenance cost by having fewer module types to spare and repair. It could also provide redundancy of components, as described above, thereby increasing aircraft availability and deferring maintenance. Another possible area of commonality across digital receivers and core processing is interconnects. A single digital interconnect type could be used in both areas. However, providing a digital interconnect with sufficient speed to move the very high speed raw digital data out of the analog racks is a substantial challenge. An alternative is installing digital processing in the analog rack, but this presents the challenge of controlling the resulting digital noise.

JSF Avionics Architecture Building Codes

Figure 5 shows the building codes along with leading and tracked candidate standards. Work is underway to gain experience with the building codes in preparation for EMD. Commercial based standards are proposed for use wherever feasible in both the hardware and software areas such as for the interconnect standard, the application-to-operating-system standard, and the graphics interface standard.

However, in other areas military standards may be a better solution. For example, the leading mechanical/ packaging alternative is the liquid flow-through SEM-E module taken from the F-22. Because liquid flow-through technology will likely be needed to provide a very controlled environment for using commercial integrated circuits, and because no commercial liquid flow-through module is available, the existing F-22 module was chosen. There is also an IEEE standard for it.

In the electrical area the 270 volt prime power is taken from the F-22. However, the leading alternative for the backplane power is a single intermediate 48 volts. This was selected because the low consumption voltage of emerging commercial chips makes it difficult to feed enough amperage, at those voltages, down the backplane. With an intermediate voltage final conversion to the consumption voltage would take place on the individual module.

A unified avionics interconnect is the goal for the interconnect area. The unified interconnect would act as an intra-rack backplane interconnect, a rack to rack interconnect, and a sensor to processor interconnect. It would perform the functions of a traditional backplane bus, a signal processor switched network, a test maintenance bus, a command and control bus, and a local area network (LAN). There is controversy over whether or not the unified interconnect should support byte addressability and shared memory. The byte addressable shared memory proponents claim a speed latency advantage of up to three orders of magnitude and that any unified interconnect should support all computing paradigms (particularly high performance ones) which might be needed in the future. The message passing only proponents claim that traditional LANs, of the Ethernet type, are more popular and therefore less costly.

No standards are specified for the processor area, although the goal is fewer processor types. The reason for not specifying standards is that the technology is moving too fast to standardize on any one set of processors. Rather we are striving to make the software independent of the hardware so that we can be free to use any processor set in the future.

F-22 (JIAWG)	JSF	
Point of Departure	**Leading Alternative**	**Tracked Alternative**
MECHANICAL • SEM-E Format • Liquid flow thru cooling • Conduct. cooling (VMS) • Bristle brush connector	**MECHANICAL** • SEM-E Format • Liquid flow thru cooling • Conduct. cooling (VMS) • Bristle brush connector	• Larger, ease of manufac. • Conduct., air flow thru • Liquid flow thru • Smaller connectors
ELECTRICAL • 270V prime power • 5V power thru backplane	**ELECTRICAL** • 270V prime power • 48V power thru backplane	• 115/230V, 400/800-1600 Hz • 28/270V, (5V, 3.3V, ±15V)
INTERCONNECTS (N/W) • Interconnects/ buses • (Pi, TM, DFN, HSDB) & FOTR	**INTERCONNECTS (N/W)** • Unified network protocol	• Multiple interconnects (SCI, F-22, Fiber Chan., ATM)
PROCESSORS • Many processor types	**PROCESSORS** • Few processor types	• App. specific processors
SENSORS • Dedicated apertures • Dedicated RF electronics	**SENSORS** • Integrated apertures • Time-share RF mod.	• Wideband Rx, narrow Tx • F-22 RF electronics
SOFTWARE • Op Sys, sys mgr (Propr.) • Ada 83 • Graphics I/F (custom)	**SOFTWARE** • POSIX (commercial) • Ada 95 • X-11, Motif,Open GL	• F-22, commercial dev • C / C++ • PHIGS, GKS, F-22

Figure 5. JSF Avionics Architecture "Building Codes"

In the sensor area the ISS program is developing open architecture standards for support electronics as was discussed earlier. While other integration (such as is being done by MIRFS) is taking place, no other standards have been proposed.

In the software area Ada 95 is the DoD preferred programming language, although we expect that any existing commercial software, which we might use, would be programmed in another language such as C++. POSIX is the leading candidate for an operating system interface. Although it was not listed in the JAAD Ver. 1.0, OpenGL appears to be gaining popularity as a graphics interface and will likely be used. As was mentioned previously more work is being done to attain an open architecture in the applications software arena and may result in additional standards.

Conclusion

The JSF program is working toward an avionics system for the 21st century which supports its four pillars of lethality, survivability, supportability, and most of all, affordability. We must control costs or the JSF aircraft will become unaffordable. Toward this end we are examining a wide variety of cost saving opportunities. We are seeking to mature new technologies which hold the most promise for cost reduction, although we have funding limitations which prevent us from exploring every avenue we would like to explore. Our contractors are also separately exploring cost saving opportunities which they feel are important. Our published avionics architecture serves as a guide to our goals, but final implementation is left to our contractors. We are confident that we will substantially reduce the costs of avionics over previous generations, while still providing a very robust and capable avionics system.

A Discussion of a Modular Unmanned Demonstration Air Vehicle

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1. SUMMARY

The idea of an unmanned combat vehicle has existed for many years. We now have the opportunity to capitalize on numerous technologies under development to make an unmanned combat vehicle a viable option for military commanders. The key problems are the issues dealing with the integration of these technologies into a synergistic aeroform, and the human control problems that arise due to these technologies. A modular demonstration platform that can capitalize on new technologies as they mature is a key way to demonstrate the viability of an unmanned combat vehicle, as well as answer some of the questions, and technology challenges, that may arise due to off-board control of a lethal air vehicle. A modular airframe is required in a demonstration platform to flight test and demonstrate various technology sets as they mature. Modularity is important because it provides greater system flexibility and should reduce the life cycle costs of the air vehicles. The demonstration platform must be capable of performing a notional mission similar to what may be envisioned for a combat UAV, in order to show that demonstrated technologies are applicable to production vehicles. The challenges and payoffs of this aggressive vision will be discussed.

2. INTRODUCTION

There is undeniable promise in the use of unmanned vehicles for various military applications. These vehicles are best suited for those flight scenarios which are determined to be dull, dirty, or dangerous by pilots. Dull scenarios require an extended length of time on station flying in a set pattern, reconnaissance vehicles come to mind as an example. Dirty missions include flight in environmentally hazardous conditions, exposure to chemical, or biological, agents. Dangerous missions require flight in a high threat environment where the probability of survival is low, for example the active Suppression of Enemy Air Defenses (SEAD) mission.

The obvious benefit of the UAV is the protection of the vehicle operator by removing the pilot from harm's way. However, it would be wrong to assume that a pilots brain is not needed anywhere in the vehicle control loop. The functions of the pilot must still be performed. In fact the degree of autonomy placed in the air vehicle is a key parameter that must be determined dependent on the mission and role of the UAV. "Keep the pilot's head in the cockpit but leave the rest of him at home" is a key idea that has been supported throughout the UAV community. When the unexpected occurs, it is the human who possesses the natural flexibility to adapt to the changing situation. Although this concept is pervasive for most flight regimes, it is especially necessary in a test, or demonstration vehicle. If a demonstration vehicle is to be unmanned, it must be able to communicate to the controller the

Paper presented at the AGARD Symposium on "Future Aerospace Technology in the Service of the Alliance", held at the Ecole Polytechnique, Palaiseau, France, 14-17 April 1997, and published in CP-600 Vol. 1.

necessary information for the pilot to make a correct decision, or must possess the necessary algorithms to be able to solve unforeseen problems on its own. This is one of the many key challenges that must be addressed in any unmanned vehicle.

The removal of the operator from the air vehicle is a benefit for many reasons. With today's high technology, the pilot has become more of a systems monitor instead of responsible for purely controlling the vehicle. The limitations of humans in an aircraft cannot be ignored as a potential benefit of UAV's. High acceleration, and rate of acceleration maneuvers may be necessary in a flight test vehicle and certainly in a combat vehicle to avoid threats or to stress system components. Now is the time that the technological flight envelope constraints can be explored as opposed to the flight envelope limitations imposed by an air vehicles human cargo. The opportunity now exists to truly identify and explore flights technological bounds through the use of UAV's.

The technology has existed for many years to construct air vehicles that can out perform their human pilots. The idea of tail sitting aircraft being launched and recovered in an upright position was discounted mainly because of the strain imposed on the pilot of such a vehicle. This launch and recovery option may now need to be reexamined along with other innovative flight operation ideas. Past UAV's were limited mainly due to their lack of on board processing of information, and the fact that line of sight communications were necessary for their control. The BQM-34 Firebee target drone was fitted with munitions decades ago as a possible strike platform in the late Vietnam era. Although the concept was successfully demonstrated, the vehicle management system proved to be a problem. Today the US Air Force uses old F-4 Phantom aircraft flown remotely as targets for various exercises. However, these planes are slaved to their airfield and cannot operate autonomously. The communication, and information processing developments of recent years now allow us to remove the human limitation on air vehicles without a high penalty in loss of vehicle control. Demonstration and test vehicles usually have a high degree of uncertainty and risk that accompanies each test flight and therefore demands a human at the controls in the cockpit. However, as previously mentioned, a human may limit the degree to which a demonstration vehicle can truly explore its envelope and determine the real promise of the tested technologies. The UAV in the testing environment fulfills one of the stated flight areas for which UAV's offer so much promise, the dangerous flight mission. UAV's offer us an opportunity to rethink how we employ aircraft in the future.

The potential financial benefits of UAV's offer another reason for their inclusion into the force structure. The major high cost driver on the life cycle cost of an operational vehicle is its operations and support cost. Any developments that may cause a dramatic decrease in the maintenance and flight cost of an operational system would be welcomed by most nations. UAV's may be stored until they are actually needed similar to cruise missiles. Operational UAV's may be able to be kept in dehumidified storable containers until they are required in a conflict. If they are maintained by reserve personnel, the only day to day cost would be simulator costs for UAV controllers. After a conflict, the UAV's could be placed back into storage there by dramatically reducing operations and support cost of these aircraft. Some UAV's could be kept flying to be used in peace time exercises as needed, and for the training of reserve maintenance personnel.

An unmanned demonstrator vehicle also offers a great opportunity to lower the life cycle cost of a test vehicle. An unmanned demonstration vehicle can be a lower weight vehicle, and require less turnaround time, and maintenance than its inhabited counterpart. Unmanned vehicles open up the design space for the configuration of the air vehicle. Engines may be placed on the vehicle centerline and receive unrestricted air flow without a crew compartment to design around. UAV's offer the engineer a free hand to improve the maintenance requirements for an aircraft, as well as produce innovative ideas in the integration of flight systems. Due to these design freedoms, the need for stringent test design reviews prior to each flight test may be eliminated. Therefore the time, and money required for a flight test program can be greatly reduced.

The use of an unmanned vehicle as a technology demonstrator has been recommended by several studies as a first step towards developing an Unmanned Combat Air Vehicle (UCAV). A technology demonstration platform should be envisioned by the science and technology community as a way to explore the technology benefits, and disclose the potential operational problems with employing an unmanned combat vehicle. A technology demonstration platform should seek to integrate maturing technologies in a revolutionary aeroform. The prime objective of the demonstration platform should be to show that by integrating technologies in a new aeroform high payoffs may be ascertained in increased performance and reduced cost of air vehicles.

3. REQUIREMENTS

A technology demonstration platform is defined in different ways to different people. Some imagine a vehicle designed to meet some predetermined performance goals. Some imagine that the aircraft should be a platform to carry various maturing technologies cheaply and quickly. While still others feel that a technology demonstration platform must be capable of showing that maturing technologies are ready for production aircraft, by flight in a given flight scenario. A combination of all these definitions is required to be implemented in a successful flight demonstration vehicle. The degree to which a demonstrator meets these requirements is determined by the needs of the science and technology, and warfighter community.

An unmanned demonstration platform should be designed to excel in three major areas, which will directly affect the technologies that may be demonstrated in the platform. First, high but achievable cost and performance goals should be established by the science and technology community for different classes of UAV's. The unmanned demonstrator should be designed to demonstrate the achievement of an established goal set. This necessitates agreement by the sponsoring agencies on what vehicle performance or cost parameters have the highest need for improvement, which of course is not a simple task. Once goals are established they need to be given some degree of prioritization, because inevitably, the achievement of one goal will come at the expense of another goal, for instance reduced vehicle weight may need to be traded against vehicle agility. We must be cognizant that like manned aircraft, there are various classes of UAV's. Goals should be established for a certain set of UAV's for flight demonstration. Most likely a fighter attack class of UAV's would provide the potential for the highest degree of technological payoff, due to its usual stressing flight regime. Other possible classes for possible demonstration mirror the divisions within manned aircraft, special operations, airlift, or reconnaissance. It is important to note that both cost and performance goals for a UAV must be demonstrated. The great potential payoff of operational UAV's is the ability to perform a mission with both reliabily, and at low cost. If cost is not included as a goal along with increased performance, the benefits of UAV investment could be lost, or at a minimum clouded. The established goals should be set high to force engineers to stretch the bounds of technology, and exercise their new design freedoms due to the void of the human operator.

The idea of demonstrating goals as a first factor in a demonstration program is important. The established goals must have a baseline from which to compare the advances. It may be difficult to determine a baseline aircraft. For a UAV demonstration it may make sense to use a technology year as a baseline instead of an actual aircraft. We may establish 1990 as the baseline technology year for a fighter attack class of UAV's. Therefore we would use a notional aircraft with technologies similar to F-22, or F-18E/F as a measure of comparison with the goals that can be achieved by our UAV demonstrator. A reconnaissance UAV may use the current Tier 2+ Global Hawk, or Tier 3- Dark Star as a baseline. An airlift, or special operations UAV would likely use a technology year baseline like a fighter attack UAV. The demonstration vehicle will strive to meet established goals by integrating maturing technologies from air vehicle technology thrust areas. The achievement of cost and performance goals will prove that UAV's hold great promise for employment in an operational flight scenario. More importantly a UAV demonstrator shows how technologies can be integrated to achieve a payoff for dollar investment. The technologies that are used to achieve goals is the second area which would shape the development of the UAV demonstration platform.

The second area which should shape the development of a demonstration platform is the ability of the platform to flight test technologies fast and cheaply. The unmanned flight demonstrator may be designed to flight test one specific suite of technologies, or it may be designed such that maturing technologies may be easily added to the vehicle configuration. The first option of designing a demonstrator for a certain technology set requires a high initial cost with a designated high expected payoff due to the fact that the platform may be optimized for that set of technologies. The second option of designing a modular vehicle also requires a high initial cost but the expected payoff for any one suite of technologies will likely be lower. However, the modular demonstrator will be capable of demonstrating more technologies over a longer period of time. An analysis must be made as to whether the need for a high payoff due to a specific set of technologies justifies the cost of developing a designated UAV demonstration platform. It is more likely that a modular UAV demonstration platform is warranted so that a host of technologies may be tested singularly or in combination thereby taking advantage of the sunk cost in the platform. If a UAV demonstrator is developed with modular modifications in mind, maturing technologies will be easily implemented into the test vehicle. The new found design freedoms will allow the modular UAV demonstrator to be developed around a payload, engine and avionics core, instead of a core that includes a crew station. Again this fact may aid the test engineer in incorporating new technologies into the test vehicle.

The question arises for a supposed fast, cheap flight demonstrator, what technologies can be tested? That question really depends on the degree of modularity that is envisioned for the flight demonstrator. The price for the type and number of maturing technologies to be demonstrated is the amount of risk in the flight demonstration program. It would likely be prudent to only implement maturing air vehicle technologies, subsystems, flight control, structures, aeromechanics for the initial flight of the UAV demonstrator. Later the vehicle may take advantage of its modularity to flight test and demonstrate various avionics suites, and possible new propulsion systems. The goals that are developed for a demonstrator may necessitate the implementation of maturing technologies from various aircraft fields. However, to mitigate risk it would be wise to keep as many aircraft technology systems constant as possible. The UAV demonstrator should initially use a production control station and engine, with modifications to fit a flight test vehicle in order to lower risk.

A streamlined review process is a necessity for any flight test or demonstration program that advertises itself as being fast and cheap. The review process that is necessary before flight test needs to be greatly simplified. Manned aircraft must go through an Executive Independent Review Team (EIRT) before flight test after large modifications have been made to an aircraft's systems. This review requires many hours of preparation and analysis and hence a high cost to ensure the flight worthiness of the air vehicle. An unmanned demonstrator may allow the stringency of the flight review process to be greatly reduced. If the unmanned demonstrator is operating in a test range the threat to life and property will be minimized. It is important to keep in mind, however, that because of the cost of these demonstration vehicles it is likely that the vehicle developers would not be able to stand their loss. Therefore, the review process cannot be completely eliminated, just reduced.

The third and final area which should shape a UAV demonstration program is the amount of mission concepts that the vehicle can demonstrate. There are several reasons why the demonstration vehicle must be closely correlated to some type of operational concept or scenario. The first reason is relevance of the technologies. The technology suite that is flight demonstrated must be stressed in a manner similar to what they would be subjected to in an operational environment. This must be accomplished to ensure that the technology set is applicable to production aircraft. The second reason is that the goals that have been established for the demonstrator have to be shown to have been met. This means that the demonstrator must have a flight regime that is similar to the baseline aircraft which is used to measure goals. In the event that a technology year was used as a baseline, the demonstrator must be capable of stressing the technologies in a vain similar to the class of vehicles the technologies represent. If we look at a fighter attack class of unmanned demonstrator that would be a precursor to a unmanned combat aircraft a likely baseline would be a F-22, or F-18E/F. Therefore an unmanned demonstration platform must be capable of completing a flight regime that would be commensurate of a fighter attack mission to ensure that the measured payoffs can be adequately compared to the baseline aircraft. Some performance goals that may be selected to demonstrate may be scaleable. We know how to scale weight and payload requirements for example relatively easily. However, other performance goals like agility, may be more difficult to scale, and therefore necessitate a full scale demonstrator capable of fighter attack performance. The technologies employed in the demonstration program must be transitionable to the next generation of aircraft. The unmanned demonstrator should show the viability and payoffs of maturing technologies.

During the period 1979 to 1983 the HiMat program was a successful yet costly UAV program run by the National Aeronautics and Space Administration (NASA) designed to show high maneuverability possibilities of fighter aircraft. The demonstration vehicle was a one half size of standard manned fighter with a taskeoff gross weight of 3370 lbs. The main criticism of the program was that the technologies demonstrated on the test vehicle were not readily transitionable to a production aircraft. The benefits realized were not scaleable to an aircraft that could perform a mission and therefore there impact was diminished.

An unmanned demonstration vehicle should be capable of flying an aggressive flight scenario that may be typical of a production UAV. In the case of the demonstration of technologies which may be applicable to a fighter attack class of vehicle, the demonstration UAV should be capable of achieving performance criteria that would be typical of a selected operational mission. A concept of operations is usually necessary to determine how an operational vehicle may be employed in a conflict. If this information is not known it may not be clear how demonstrated technologies may be employed in an operational environment. In such cases the UAV demonstrator developer must make an educated determination of likely performance criteria. In a fighter/attack class of UAV demonstrator, an active Suppression of Enemy Air Defense (SEAD) flight profile may posses the necessary flight characteristics to ensure that demonstrated technologies are applicable. Notional performance criteria which may follow from requirements for this profile include a 1000 lb payload, a maneuvering capability of 7g at 500psf, and a 500 mile mission radius. The mission radius will equate to increased test time capability for the demonstration vehicle. These payload and performance requirements will ensure that the demonstrated integrated technologies are applicable to the next generation of fighter attack aircraft. It will also ensure that any cost and performance goals that are met can be justifiably compared to the goal baseline. It is important to keep in mind that the impetus for "mission" performance criteria is to ensure the relevance of technologies and the relation to a goal baseline. Trades must likely be made between the stringency of the performance criteria and the added cost to the demonstration vehicle due to the criteria.

The added benefit of ensuring that a UAV demonstrator is capable of definite performance criteria is that the UAV can start to answer questions pertaining to the use of an Unmanned Combat Aircraft (UCAV) in an operational environment. There is currently a high degree of interest in the use of unmanned aircraft in combat roles. The projected cost saving of UAV's warrant consideration of a UCAV as an operational vehicle. Before UCAV's can be used operationally there are several questions that must be answered concerning the required vehicle management system, human system interface, concept of operations, and exploitation of design freedoms. A UAV demonstrator designed to high performance criteria can begin to answer some of these questions. The UAV demonstration platform should be able to explore some of the critical enabling, or enhancing technologies of the combat UAV.

A UAV demonstrator will allow researchers to explore suggested improvement directions in various technology areas. However, ensuring that a demonstrator is capable achieving high performance concepts will allow research in specific technology areas that must be explored before a UCAV is a viable operational capability. A UAV demonstrator will allow engineers to explore the overriding technology enablers for combat UAV's. Guidelines must be developed for allocating mission and vehicle functions to be controlled on-board UAV's. Research is needed to establish these guidelines for vehicle management functions.

4. AFFORDABILITY

The cost of a new military system has increasingly become the number one driver in the determination of a systems survival through the development process. A UAV demonstration vehicle should be able to decrease the development costs of new aircraft, by revealing potential problems with maturing technologies before they arise in a demonstration validation phase of the aircraft development. As previously suggested, low cost should be another goal that a demonstration vehicle strives to achieve.

During these times of reduced military expenditure, it is increasingly difficult to begin new programs even if the potential cost and performance benefits are high. A flight demonstration and flight test asset may not be available to prove cost saving technologies, if the demonstration asset's development costs are too high. A UAV demonstrator program should be lower cost than a comparable manned demonstration platform.

When we think of UAV's in terms of affordability we usually think of the high operations and support cost savings. As previously mentioned the UAV can be placed in dehumidified storage, and not pulled out until needed. The UAV operators can do the majority of their training on simulators, eliminating the need for proficiency flights. The number of required maintainers can be greatly reduced. These reasons make the operational UAV very attractive from a life cycle cost perspective. A UAV demonstrator however, will need to fly just as much as a manned demonstrator. The payoff is in the flight test of integrated technologies. Therefore, although some operations and support cost savings may be achieved through ease of maintenance, modification and reduced fuel consumption, the big cost savings should come in reduced demonstrator acquisition cost.

In terms of acquisition cost the fielding of a smaller, less complex demonstration vehicle in the key cost driver. The reduction in size and weight directly attributable to the cockpit and related subsystems is conservatively 5%. Extensive use of 'more electric aircraft' technologies, reduced levels of avionics and sensory payloads made possible by the exploitation of off-board information will also contribute to weight and cost savings. The added requirement of high computing technology for autonomous operation should be offset by the revolution in computing and processing speed.

Structurally, the design freedoms ascertained by the elimination of the cockpit allows new configurations. Subsystems may now be able to be placed in more optimized locations affecting balance and stability, thereby reducing vehicle power requirements. The X-29 had a empty weight of 15 klb, and was developed at a Research Development Test and Evaluation (RDT&E) cost of $140M. The F16A had a empty weight of 16 klb and developed at a RDT&E cost of $250M. Conservatively speaking, an unmanned modular demonstration platform can have an empty weight of 10 klb and have an RDT&E cost of $80M while still flight demonstrating a host of technologies. The use of an unmanned platform is more attractive for not just safety reasons, but also for reduced cost and test time. Certainly the use of cheaper materials, and revolutionary manufacturing processes can be used in the development of the UAV demonstrator. Thereby, the cost can be expected to be further reduced.

The point has been made in recent literature that unmanned aircraft can be lower cost because they do not have to be made to last. Redundancy and reliability do not have to be stressed as much as a manned aircraft. While it is true that some relaxation of safety factors can be made, if the unmanned aircraft will operate in an environment with manned aircraft, a certain degree of reliability must be employed. The developers of a UAV demonstration vehicle must be able to capitalize on the lessons learned from past flight test program, while at the same time relaxing criteria which relate to the fact that there is not a human in the vehicle. A flight demonstration asset may be designed such that it can prove a host of technologies. Therefore, the test asset should be developed to demonstrate technologies for a long service life. Consequently the vehicle must be designed to last.

5. TECHNOLOGY CHALLENGES

The use of an unmanned vehicle to flight demonstrate maturing technologies is not without its challenges. Criteria must be developed to decide whether sufficient levels of response have been achieved in controlled functions to include interactions among off-board and on-board controllers in a mission oriented system-of-systems. A reliable generic control system should be developed and tailored for an unmanned demonstration vehicle. This control system must have a high degree of performance reliability. During landing and takeoff the vehicle may need inputs from ground controllers. A less than robust control system may allow the vehicle to get in a pilot induced oscillation situation relatively easily. The UAV demonstrator should use existing control stations to the highest degree possible, and make modifications to support a test vehicle. The relative high cost of vehicle development necessitates the use of existing control systems at the highest degree possible.

Command and control presents another challenge that must be addressed in an unmanned demonstrator. The amount of bandwith required and the type of link should be analysed. The optimum antenna placement is usually on the bottom of the vehicle, except in the critical phases of takeoff and landing. Some type of antenna switching would be required. Flight termination systems codes should be selected to minimize the chance of uncommanded termination due to other transmitters that may be in the testing area.

Guidelines must also be developed to fully employ aeronautical, propulsion and structures control technologies to achieve envelope expansion beyond human capability. The optimal locations for various subsystems must be studied. Aircraft developers have always had to design around the man in the machine paradigm so subsystems have traditionally been placed in certain areas as a matter of course. The miniaturization of various subsystems is now necessitated to support the reduced size of the test vehicle. Consequently the problems with the dissipation of thermal energy are still present, as in manned aircraft.

A unmanned demonstrator will allow other specific UCAV technology challenges to be answered. Especially if the UAV demonstrator is designed to achieve high performance flight characteristics which may be expected of a UCAV. The unmanned demonstrator should be designed to use existing engine technology if it is to demonstrate air vehicle technologies. However, improvements in engine specific fuel consumption and cost can be implemented on the platform. There is an inherent high degree of risk in a demonstration platform. Therefore, the highest number of systems that can be kept constant mitigates that risk. This is not to say that commercial off the shelf systems (COTS) are always the correct course of action. The integration of COTS is sometimes more costly and risky than the development of new systems. The trade between COTS and new equipment needs to be analyzed by development engineers.

6. CONCLUSIONS

A modular unmanned demonstration vehicle offers researchers a new opportunity to analyze maturing technologies. The unmanned demonstrator should be developed with certain performance and cost goals in mind to ensure that the demonstrated technologies are relevant to the next generation of operational aircraft. The fact that the UAV demonstrator can be developed under new design freedoms means that it can be cheaper and require less support cost than a comparable manned demonstrator.

Cost savings are due mainly to the reduced weight of the UAV demonstrator. However, the streamlined test review process, and decreased maintenance and reconfiguration time may also have cost impacts. In order to achieve cost goals and reduce vehicle risk, as many systems as possible should be held constant within the demonstrator. This includes as a suggestion, propulsion and control station technology.

Many technical challenges remain in the development of an unmanned demonstrator. The potential payoffs of low cost, high performance, and relatively cheap flight testing make a UAV demonstrator a very attractive to flight test maturing technologies.

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AGING AIRFRAMES AND ENGINES

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SUMMARY

The presence of aging aircraft fleets has been increasing throughout the world due to the global, financial, and political environment. The reduction in the defense budget of many countries has forced them to use their military aircraft well beyond their original design lives. Also, the demand on the performance of these aircraft has been increasing due to increased payload and severe usage. Maintaining the airworthiness of these aircraft and their propulsion systems while at the same time keeping the maintenance costs low is of prime concern to the operators and regulatory authorities. The flight safety requirements and the performance demands are likely to result in higher maintenance costs. However, the unique opportunities provided by the research and development in the areas of new and improved materials, structures, manufacturing, repairs, and Non-Destructive Inspection (NDI) technologies have made it possible to keep the increase in costs to a minimum and in many cases reduced the overall maintenance costs. This paper discusses the contributions made by research and technology towards lowering the maintenance cost and improving the flight safety of aging airframes and engines.

1 INTRODUCTION

The majority of aircraft currently in service and many of their propulsion systems were designed using the technologies that were state-of-the-art 20 to 30 years ago. When these aircraft were designed the analysis methods such as finite element, durability and damage tolerance were in their infancy with the result that the analyses could not be performed with a great degree of confidence. Many deficiencies of the materials used in the original design of older airframes and engines have been eliminated and new materials, currently available, offer significant improvements in stress corrosion resistance, oxidation resistance, ambient and high temperature strength, and fatigue life. The improved durability, damage tolerance and environmental resistance of new materials offer great potential for enhanced reliability and low maintenance and support requirements. The applications of advanced technologies such as materials, structures, manufacturing, repair, and NDI to in-service aircraft are discussed in this paper. Significant savings obtained with the use of these technologies are shown. The application of new improved materials to replace old parts is also discussed.

2. AGING AIRFRAMES - PROBLEMS AND SOLUTIONS

2.1 ADVANCED ANALYSIS METHODS

The techniques for stress, durability, and damage tolerance analyses were rather limited when the current aircraft were designed. Significant advancements have taken place in analysis methods which can give more accurate information on the global and local stresses with the result that the behavior of a structure or structural component can be predicted with good accuracy. Some of the commonly used techniques and computer codes available for stress, durability and damage tolerance analyses, and for designing repairs are shown in Figure 1. The repair codes provide very efficient tools for designing repairs for in-service aircraft.

Using the stress analysis and loads data, it is possible to predict the life of a structural component with the durability and damage tolerance analysis techniques. From the crack growth analysis of a critical area of a structural component under actual spectrum, experienced by a structural component, it is possible to identify initial inspection and subsequent inspection requirements as shown in Figure 2. The crack growth curve for a critical location is obtained over a period of N_f flight hours from the assumed initial flaw a_0, based on damage tolerance requirements, to the critical size a_c at which point the flaw can cause catastrophic failure. If the inspection capability of the Non-Destructive Inspection (NDI) equipment to be used in field or depot is a_i, then the cycles to grow the crack from a_0 to a_i are determined to be N_i. The initial inspection requirement is given by $N_i/2$ and subsequent inspection requirements are given by $(N_f - N_i)/2$.

The inspection requirements for aircraft structures in the past have been primarily based on in-service experience with the result that critical inspection areas are sometimes missed and at times severe inspections are imposed, resulting in excessive support requirements and cost. The procedure outlined in Figure 2 can be used to zone an aircraft structure for inspections depending on the severity of loads and structural details such as thickness, presence of substructure, fastener diameter and type, etc. A typical zoning of a wing structure for Air Training Command (ATC) usage is shown in Figure 3. The wing in the figure has been divided into 5 zones, namely A, B, C, D, and E. The fasteners in each zone have different inspection requirements depending on the structural details and stress levels. The fasteners in zones D and E are in an area where the stresses are rather small and crack growth life is very large. The zoning and inspection requirements, of course, depend on the usage of an aircraft as the loads spectrum will change with the usage. For usage other than ATC the inspection requirements will be different from those shown in Figure 3, however, the inspection zones may still be the same. Thus, the analytical techniques provide opportunity to define inspection requirements based on usage and structural details and reduce the inspection cost.

Paper presented at the AGARD Symposium on "Future Aerospace Technology in the Service of the Alliance", held at the Ecole Polytechnique, Palaiseau, France, 14-17 April 1997, and published in CP-600 Vol. 1.

ANALYSIS TYPE	ANALYSIS TECHNIQUES/CODES
GLOBAL	FINITE ELEMENT- NASTRAN, PATRAN, ASTROS, FRANC2D, FRANC3D
OPTIMIZATION	FINITE ELEMENT- ASTROS
DETAILED	FINITE ELEMENT, BOUNDARY ELEMENT, BONDED JOINT, BOLTED JOINT
DURABILITY	STRAIN LIFE APPROACH
DAMAGE TOLERANCE	CRACK GROWTH - PARIS AND FORMAN EQUATIONS FLIGHT BY FLIGHT- WHEELER, WILLENBORG AND CRACK CLOSURE MODELS FOR RETARDATION RESIDUAL STRENGTH- FRACTURE TOUGHNESS, R-CURVE, J INTEGRAL COMPUTER CODES- AFGROW, NASA FLAWGRO, NASGROW
REPAIR	METALLIC STRUCTURES- RAPID COMPOSITE STRUCTURES- CREPAIR, COMPAIR COMPOSITE REPAIR OF METAL - AFGGROW, CalcuRep, COMPACT 3D

Figure 1. Analysis techniques and computer codes

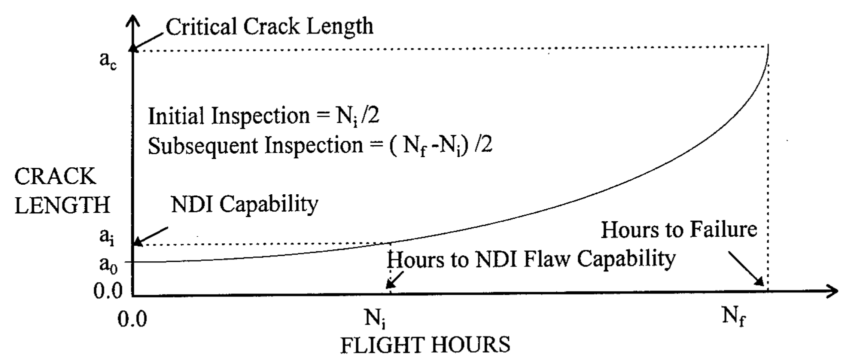


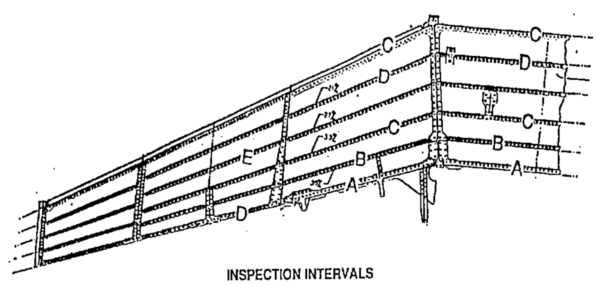
Figure 2. Initial and subsequent inspection requirements from crack growth life

2.2 STRUCTURAL LIFE ENHANCEMENT TECHNIQUES

A number of structural life enhancement techniques [1] have been developed to enhance the life of an aircraft structure. Figure 4 shows the application of various life extension techniques to in-service and new aircraft. The figure also shows the locations where these techniques can be applied (e.g. whether the technique can be used at the manufacturing line, depot, or field). The analytical methods that can be used for life prediction and the level of verification testing required for implementing a technique are also shown in the figure. The techniques which require a minimum amount of testing are well established and have been extensively used.

2.3 ADVANCED REPAIR METHODS

Improved structural efficiency of bonded composites has provided an excellent opportunity to repair metal structures with composites [1-6]. In this repair concept a composite patch is bonded to the damaged metallic part instead of using a conventional mechanically fastened patch. Bonded composite repair has many advantages over conventional mechanically fastened repairs. These repairs are best suited at places where stress levels are high and mechanically fastened repairs will adversely affect the structural integrity due to the drilling of additional holes or where there is no place to drill holes for



INSPECTION INTERVALS

ZONE	ATC
A	2450/1200
B	8500/5500
C	11500/6000
D	>20000/>12500
E	>20000/>12500

Figure 3. Zoning of metallic aircraft structure or inspection

repairs. The applications of these repairs to in-service aircraft in the USA are found in C141 lower wing skin at weep hole, T38 lower wing skin near 'D' panel door, F16 lower wing skin at fuel access hole, and C5 fuselage. The T-38 aircraft -29 lower wing skin, near the 44% spar between WS 72.25 and WS 76.70 at Panel 'D' attachment holes, has developed cracks as shown in Figure 5. Conventional mechanically fastened repairs are not

PRE-STRESSING TECHNIQUE	IN-SERVICE APPLICATIONS	LOCATION WHERE PREFORMED	ANALYSIS METHODS	REQUIRED TESTING
COLD WORKING	T-38, F-5, F-16, JSTARS, F-18, F-111, C-141, 747	MANUFACTURING LINE, DEPOT AND FEILD	EQUIVALENT INITIAL FLAW (EIF), FATIGUE LIFE FACTOR (FLF)	MINIMUM
SHOT PEENING	T-38, F-5, F-18, F-14, 737, 747, C-13, B-1	MANUFACTURING LINE, DEPOT AND FEILD	EIF, FLF	MINIMUM
INTERFERENCE FIT FASTENERS	T-38, F-5, F-18, 747	MANUFACTURING LINE, DEPOT AND FEILD	EIF, FLF	MEDIUM
LASER SHOCK PROCESSING	NONE KNOW,	MANUFACTURING LINE	DEVELOPMENT REQUIRED	SUBSTANTIAL
RIVETLESS NUTPLATES	F-14, A6E	MANUFACTURING LINE, DEPOT AND FEILD	EIF, FLF	MEDIUM
STRESS WAVE RIVETING	F-14, A6E	MANUFACTURING LINE, DEPOT AND FEILD	EMPIRICAL	MEDIUM
STRESS COINING	F-18, DC-8, DC-9, DC-10	MANUFACTURING LINE, DEPOT AND FEILD	EMPIRICAL	MEDIUM

Figure 4. Life enhancement techniques applications

possible due to the limited space available for drilling the fastener holes. Bonding of an aluminum doubler will provide only limited doubler stiffness and will not result in an efficient repair. A bonded boron repair is ideal for this location. An external boron patch could not be applied as the door has to fit in the area and has to be flush with the outer mold line. Hence, an internal repair patch was designed as shown in Figure 5. A pre-cured boron repair patch was secondary bonded through the 'D' panel door.

Cost analysis was carried out to show the benefit of using composite repair technology to T-38 lower wing skin repair shown in Figure 5. A mechanically fastened repair was not feasible at this location, hence, cost comparisons between mechanically fastened repairs and composite patch repairs were not realistic. The cost of composite patch repair was compared with the cost of acquiring a new wing as shown in Figure 6. The figure shows significant savings in the operation cost with the repair.

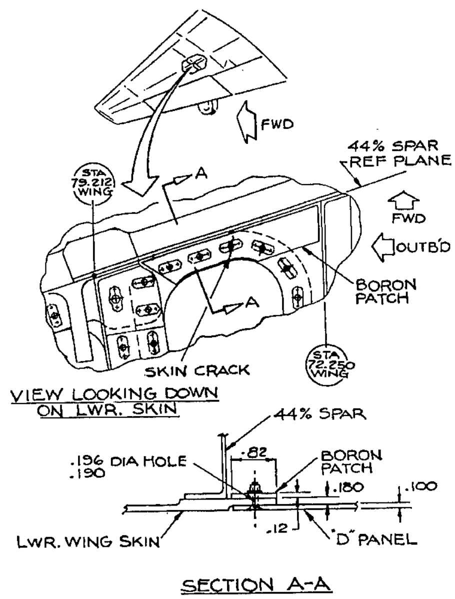


Figure 5. T-38 Lower wing skin composite patch repair

2.4 LOW COST PRODUCTION

Advanced manufacturing techniques such as Super Plastic Forming (SPF) provide a unique opportunity to reduce production cost by redesigning parts, particularly sheet metal parts, so as to reduce the piece count. The reduced piece count results in tooling cost and fabrication cost savings. An additional advantage of SPF is the potential weight savings as the reduced piece count is associated with reduced assembly details and fasteners. A typical application of the SPF manufacturing process is illustrated in Figure 7 where a sheet metal bulkhead is redesigned using the SPF process and mechanically fastened web stiffening is replaced by SPF stiffeners which are weld bonded [7] to the bulkhead web. Cost and weight savings potential of the SPF bulkhead concept is shown in Figure 8 where different bulkhead concepts, made with advanced materials, are compared. The SPF concept shows significant cost and weight savings.

ASSUMPTIONS IN COST ANALYSIS

1. Cost of new wing = $ 800,000
2. Average life of wing = 20 years
3. Average labor cost for repairs = $ 80/hour
4. Inspection requirements for the repair are twice a year based on damage tolerance analysis
5. Labor hours to repair left and right wing = 40 Hours
6. Repair design and analysis hours per aircraft (assuming 100 aircraft need repairs) = 4 Hours
7. Non-Destructive Inspection (NDI) per aircraft per year = 1 Hour
8. At least 4 aircraft are at one given location for repairs so that travel cost can be spread over 4 aircraft
9. Aircraft will be in service for at least for one year and wings are not scrapped due to other problems

COST OF OPERATING A NEW WING PER YEAR

Cost per year = Cost of new wing/ average life of wing =800,000/2 = $ 40,000

COST OF COMPOSITE PATCH REPAIR

Total labor cost including inspection = 40 + 4 + 1 = 45

Labor cost per aircraft = 45*80 = $ 3,600

Travel cost per aircraft = $1,500

Total repair cost per aircraft = 3,600+1,500 = $ 5,100

COST SAVINGS

Savings = 40,000 - 5,100 = $ 34,900

Figure 6. Composite patch repair cost savings analysis

2.5 ADVANCED MATRIALS APPLICATION

The primary materials related problems occurring in in-service aircraft are exfoliation corrosion, stress corrosion cracking, and fatigue. A common practice is to overcome the deficiency of the older T6 aluminum alloy by replacing it with T7 alloy. This substitution is not always feasible as the T7 alloy has lower mechanical properties compared to the T6 alloy as shown in Figure 9, and the structural parts need to be beefed up (increase in thickness) to meet the design requirements. This is especially the case in fighter/trainer types of structures where the performance is the governing design requirement and the aircraft structures are designed with a minimum margin of safety. Also, in some cases the thickness of a redesigned structural part with T7 material cannot be increased due to the restrictions on the dimensions dictated by the mating surfaces. Figure 9 shows the properties of conventional aluminum alloys along with the properties of advanced aluminum Powder Metallurgy (PM) alloy 7093 which has higher ultimate and yield strength compared to the T6 alloy.

2.5.1 In-Service Evaluation of 7093-T7 PM Alloy

The in-service evaluation of the PM alloy has been carried out [1, 7] by selecting problem structural components from a T-38 trainer and investigating the potential benefit offered by the material. The T-38 engine mount support shown in Figure 10 was one of the selected components. The original material is 7075-T6 and the component has shown in-service corrosion problems. Replacing the material with 7075-T7 results in a negative margin of safety and any redesign by increasing the dimensions could not be done due to restrictions imposed by mating structures. The use of 7093-T7 PM material results in a positive margin of safety. A number of engine mount supports were manufactured by using the PM alloy and have been flying without any known problems.

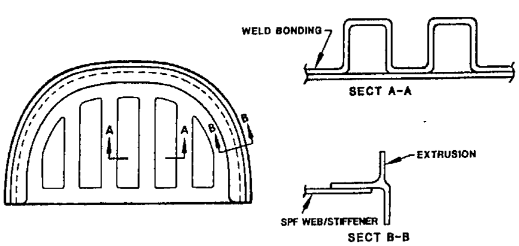


Figure 7. Superplastic formed bulkhead concept

BULKHEAD CONCEPT	COST ($)	PERCENT COST SAVINGS	WEIGHT (LBS)	PERCENT WEIGHT SAVING
Baseline Aluminum Sheet Metal	11,395	-	43.6	-
SPF Aluminum Lithium	4,134	64	37.2	15
Machined Aluminum Lithium Forging	17,462	-53	35.0	20
Machined Aluminum Lithium Billet	17,561	-54	35.0	20

Figure 8. Cost comparisons of various bulkhead concepts

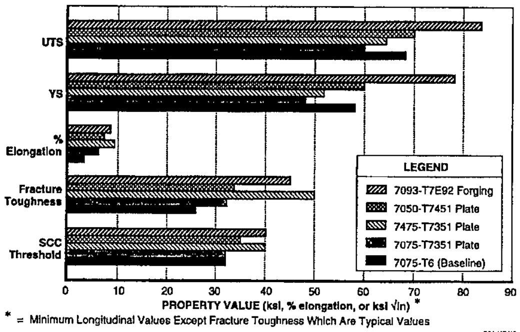


Figure 9. Mechanical properties of aluminum alloys

2.5.2 Cost Savings With Advanced Materials

An application of a combination of advanced technologies to achieve life cycle savings is seen in T-38 66% spar [8]. In-service cracking has been observed in the spar (Figure 11) due to a number of factors related to severe lead-in-fighter spectrum and high stresses at critical locations. The analytical tools, available at the time the T-38 aircraft was designed in late 1950, were not adequate to identify the magnitude of the stresses at critical locations. Present analytical tools such as finite element analysis along with proper modeling of fastener flexibility can predict stresses well and show good correlation with inflight data.

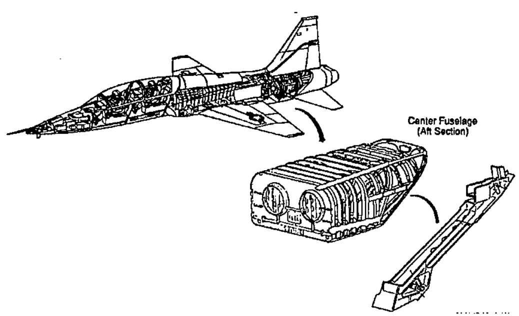


Figure 10. Engine mount support

The projected use of the T-38 aircraft to beyond the year 2020 would require that the spar be replaced at least twice or even three times in some aircraft with the present design. Hence, a redesign of the spar is likely to result in significant cost savings. Simple redesign of the spar would not meet the required life goal because of limitations on increasing the thickness of the part due to mating surfaces. Hence, the design life requirements were achieved by using a combination of technologies such as new material powder metallurgy alloy 7093, cold working and rivetless nutplates. The life cycle analysis for the spar, based on 490 aircraft, is shown in Figure 12.

2.6 NON-DESTRUCTIVE INSPECTION (NDI)

A number of NDI methods are available and the use of a specific method depends on the type of structure being

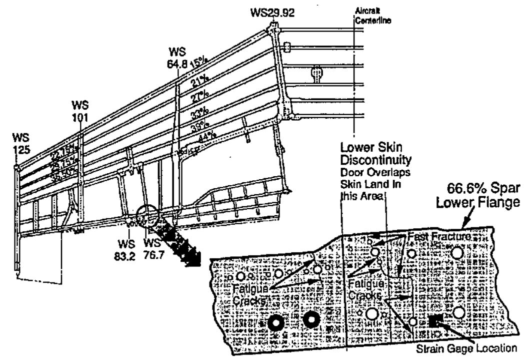


Figure 11. T-38 665 spar cracking location

inspected, available access, and the desired degree of accuracy in the inspection. Significant advancements have taken place in NDI methods recently. Some of the recent advancements in NDI techniques which show significant promise in detection of corrosion and subsurface cracks without disassembly are: Magneto-Optic/Eddy Current Imager (MOI) [9], Low Frequency Eddy Current Array (LFECA) [10] and D Sight Aircraft Inspection System (DIAS) [11].

Magneto-Optic/Eddy Current Imager (MOI)- The MOI technique makes it possible to do faster, simpler, and more reliable detection of cracks and corrosion in structures. This real-time imaging technology is based on a combination of magneto-optic sensing and eddy current induction. The key advantages of MOI are [9]: 1) Speed of operation 5 to 10 times faster than conventional eddy current, 2) Easy to interpret image formation, 3) No false calls, 4) Elimination of paint or decal removal for inspection, 5) Easy documentation of results on video or film, and 6) No operator fatigue. Typical corrosion detected by MOI is shown in Figure 13.

Low Frequency Eddy Current Array (LFECA)- The LFECA system, developed by the Northrop Grumman corporation, is a portable eddy current inspection equipment to detect subsurface cracks under installed fasteners in multi-layer aircraft structures [1, 10]. The inspections can be performed in near real time without the removal of fasteners. The LFECA system can detect cracks, determine crack length, crack depth and orientation. The Probability of Detection (POD) of cracks with the LFECA system was obtained at Federal Aviation Administration (FAA) NDI validation center at Sandia National Laboratories, Albuquerque, New Mexico, USA [10]. A comparison of POD for conventional eddy current and LFECA is shown in Figure 14, indicating superior POD of the LFECA.

DAIS- This is a fast and sensitive enhanced visual inspection system for detecting surface irregularities such as pillowing caused by corrosion. In Ref. 11, the DAIS system was used in the laboratory as well as in the field to detect corrosion in fuselage lap splices. The results of this reference showed that corrosion pillowing indicative of thickness loss as low as 2% is detectable.

COST CATEGORY	CONVENTIONAL SOLUTION	ADVANCED TECHNOLOGY SOLUTION	
		PRODUCTION QUANTITY	R&D QUANTITY
Base & Intermediate Maintenance Costs			
Labor Cost	$353,531	$353,531	$353,531
Material Cost	$0	$0	$0
TOTAL COST	$353,531	$353,531	$353,531
Depot Maintenance Costs (Repair)			
Labor Cost	$7,200,060	$3,600,030	$3,600,030
Material Cost	$0	$0	$0
TOTAL COST	$7,200,060	$3,600,030	$3,600,030
Depot Maintenance Cost (Replacement)			
Labor Cost	$30,105,600	$16,016,140	$16,016,140
Material Cost	$34,805,680	$22,399,860	$23,840,460
TOTAL COST	$64,911,280	$38,416,000	$39,856,600
Total Support Cost	$72,464,871	**$42,369,561**	**$43,810,161**
Total Support Cost Savings		**$30,095,310**	**$28,654,710**
Total Support % Cost Savings		**41.5%**	**39.5%**

Figure 12. Life cycle analysis of t-38 66% spar

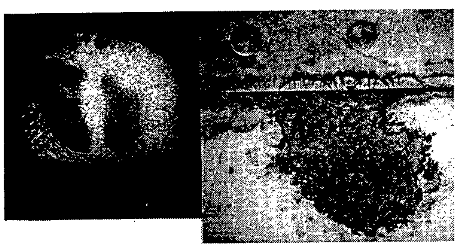


Figure 13. MOI image of corrosion

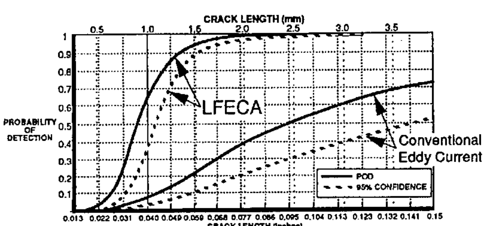


Figure 14. POD of LFECA and conventional eddy current systems

3. AGING ENGINES - PROBLEMS AND SOLUTIONS

The aging process of engines is in some respects quite different from that affecting airframes. Engines tend to age in more varied ways, and do so at considerably faster rates. This is because the operating environment is more aggressive for engine components. In addition to cyclic mechanical loads, as experienced by airframe components, engine parts are subjected simultaneously to thermal loads and hot gases. The combined effects of these external factors greatly accelerate the aging process. When damage becomes excessive, as predicted by design or established by inspection, components are replaced with new ones. Component replacement costs are high and are a significant factor in the overall life cycle cost of engines [12]. Among engine components accumulating damage in service are highly critical rotating parts, such as discs, that are critical to the safety of the aircraft.

3.1 FORMS OF SERVICE INDUCED DAMAGE AFFECTING ENGINE COMPONENTS:

A list of potential failure modes for turbine engine components is given in Table1. Rotating components such as discs, spacers and cooling plates and gas path components such as blades and vanes incur surface as well as internal microstructural damage during service.Surface damage due to erosion, corrosion, wear or impact can promote crack nucleation by creating localized stress concentration sites. These cracks can then propagate under the influence of thermo-mechanical loads to cause component failure. Internal microstructural damage accumulation in the form of plastic strain accumulation and/or metallurgical aging during service is strongly influenced by service temperature and stresses and, therefore, to a great extent by user practice. This internal damage accumulation eventually leads to crack initiation once a critical value is exceeded. Detailed accounts of these damage modes including their consequences are given below.

COMPONENTS	DEGRADATION MODES
Compressor	
Blades	ER, COR, HCF
Vanes	ER, COR
Discs	COR, LCF
Turbine	
Blades	MA, TMF, OX, HC, HCF, OT, C
Vanes	MA, TF, OX, HC, C, OT
Discs	LCF, C, MA

Table 1. Modes of degradation of turbine engine components - ER: erosion; COR: corrosion; HCF: high cycle fatigue; LCF: low cycle fatigue; MA: microstructural aging; TMF: thermomechanical fatigue; OX: oxidation; HC: hot corrosion; OT: overtemperature; C: creep [13].

3.1.1 Surface Damage

Compressor gas path components often suffer erosion damage as a result of dust and particulate matter ingestion and this can substantially alter the geometry of the parts, Figure 15. This change in airfoil geometry can deleteriously affect the performance of the engine and in extreme cases the airfoil shape change may alter the modal response of the components to the point where airfoils may resonate at their natural frequencies under normal service conditions and cause catastrophic high cycle fatigue (HCF) failures[14].

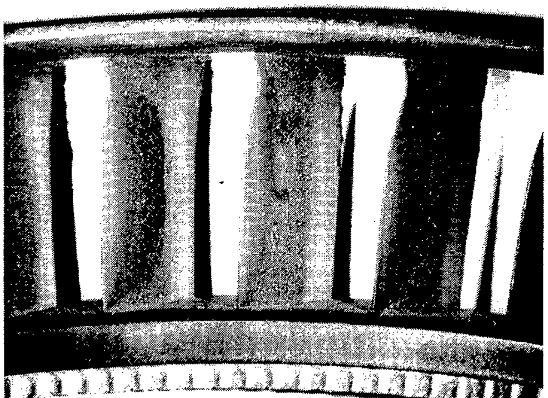


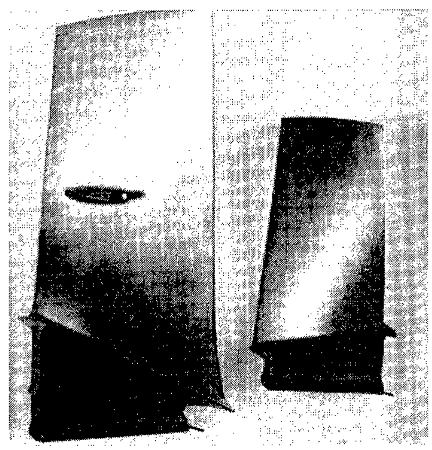
Figure 15. Erosion damage incurred by airfoils of a compressor vane segment from a CF transport aircraft engine (Time since new of component approximately 5000hrs).

A common mode of surface degradation in operating environments containing a high concentration of chloride ions is pitting corrosion. This damage mode affects a large number of stainless steel and titanium alloy components in aeroengines, and its impact on fan as well as compressor blades can be quite dramatic. This is because these pits often act as crack initiation sites for HCF or low cycle fatigue (LCF) cracks depending on the location of the pits, Figure 16.

Figure 16. Fractographic features of a compressor blade airfoil revealing the presence of an HCF crack initiating at a corrosion pit in the surface of the airfoil [15].

In some situations, however, even very extensive and deep pitting does not affect the structural integrity of the blades whereas in other situations even very minor amounts of airfoil pitting can easily initiate HCF cracks. Therefore, the effect of pitting on structural integrity is very much influenced by the blade design.

Blade-disc fixing contact surfaces are often subjected to low amplitude vibratory loads under high normal pressures and this creates a rubbing action between the blade root and disc rim slot surfaces. This rubbing action results in fretting debris formation, the entrapment of which can form a fretting scar and this scar can, in turn, act as a stress raiser and initiate a fretting fatigue crack, Figure 17.



(a) (b)

(c)

Figure 17. Areas (small arrows) of (a) fan blades and (b) compresor blades subject to fretting fatigue damage in a CF fighter engine; (c) Close up of dovetail region of the compressor blade showing deep fretting scar [16].

The susceptibility of a blade-disc coupling to fretting fatigue damage accumulation during service is governed by a number of factors including hardness difference between the blade and the disc materials, the lubrication of the surfaces and the magnitude of surface residual stresses. In extreme situations catastrophic failures can occur and in the case of Ti alloy blades, Ti fires have led to the loss of an engine on a few occasions [17].

Oxidation of coated as well as uncoated blade/vane airfoils continues to be the major reason for the hot section overhauls in most aero engines. While the application of oxidation resistant coatings provides reasonable oxidation protection in older generation engines, the new generation engines containing directionally solidified (DS) or single crystal (SC) blades often suffer tip oxidation damage because coatings very quickly rub off in these regions and the operating temperatures are considerably higher in new engine designs, Figure 18[18].

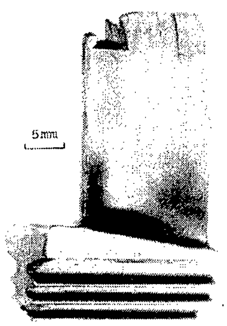


Figure 18. Tip cracking of a DS blade caused by thermal fatigue of longitudinal grain boundaries embrittled as a result of boundary oxidation [18].

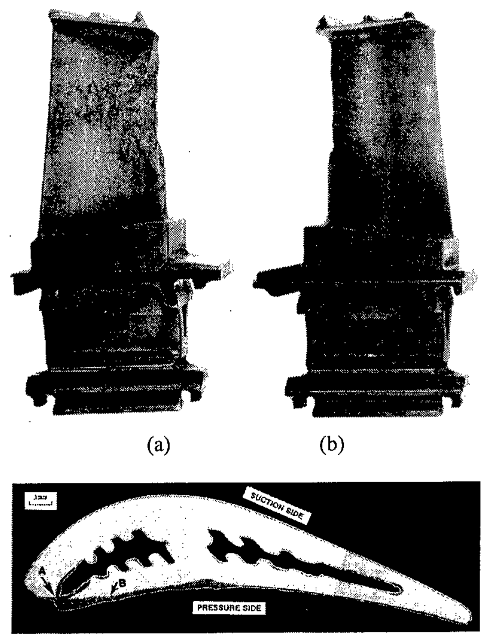
In the case of cooled blades, oxidation damage along uncoated internal cooling passages may also prove to be a life limiting factor because it reduces the load bearing area of the airfoil [19]. In aeroengines operating in marine environments, hot corrosion, particularly the high temperature (850-950C) type, is a serious problem in almost all hot gas path components. Once a hot corrosion reaction starts, it can quickly consume the component, Figure 19 [20].

Often, erosion in combination with oxidation or hot corrosion leads to substantial loss of section in coated blades and vanes in very short times thus jeopardising the structural integrity of the part. Sometimes overtemperature exposure due to high engine start-up temperature or thermocouple malfunction with age can accentuate the oxidation damage. In extreme situations coatings can blister and peel off due to melting of the coating-substrate diffusion zone.

3.1.2 Microstructural Damage

Stress and temperature assisted microdamage accumulation with age is commonly observed in superalloy hot section gas path components. This mode of damage accumulation is also common in turbine rim regions of small turbines which often operate at higher rotational speeds and temperatures than do larger engines [18].

Typical microstructural damage effects include gamma prime coarsening in Ni base superalloys or carbide coarsening in Co-base superalloys, primary carbide degeneration leading to continuous carbide film formation along the grain boundaries in components with equiaxed grain structures and topologically closed packed (TCP) phase formation such as sigma phase in older generation alloys and P/mu phase formation in DS and SC parts, Figure 20 [21,22]. While precipitate coarsening and TCP formation decrease material strength, countinuous carbide films and TCPs embrittle the components thus rendering them notch sensitive. If overtemperature excursions occur for any appreciable length of time, incipient melting along the grain boundaries may result.



(a) (b)

(c)

Figure 19. Hot corrosion damage incurred by a Mar-M246 blade in the engine of a CF maritime patrol aircraft (a) pressure side view; (b) suction side view; (c) metallographic section taken halfway accross the airfoil through the hot corroded region[20].

Time dependent stress effects at elevated temperatures may also manifest themselves in the form of surface cracks or internal creep cavities and cracks, Figure 21(a) and (b). Cyclic damage accumulation in discs and spacers, and sometimes blades, over a range of temperatures manifests itself in the form of persistent slip bands (PSBs) or wavy slip at stress concetration sites such as disc bores and bolt holes or the rim regions prior to crack initiation, Figure 21(c) and (d) [23]. In commercial aeroengines and military transport engines, combined creep-fatigue damage accumulation usually predominates.

3.1.3 Distortion and Cracking

In addition to internal microstructural damage accumulation under creep loading conditions, components such as blades and vanes are well known to distort with age. Blade airfoil untwist and vane airfoil bowing are often observed in aeroengines and these problems become worse with age if unchecked during overhaul, Figure 22 [24,25]

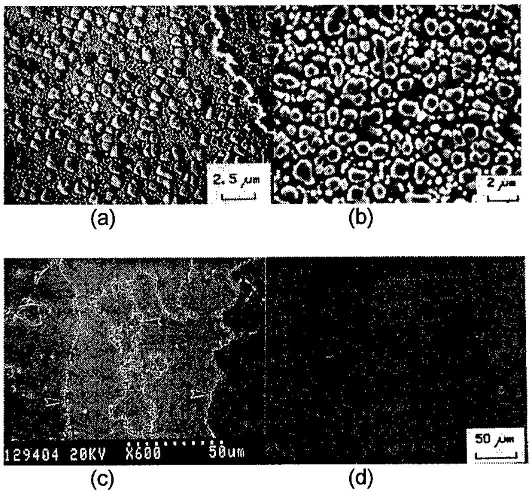


Figure 20. Internal microstructural damage in high time blades: (a) bimodal distribution of gamma prime precipitates in new blade; (b) coarsening of gamma prime precipates and elimination of secondary gamma prime in service exposed IN738 turbine blade; (c) precipitation of carbides (arrows) along grain boundaries in IN738 turbine blade; (d) precipitation of sigma phase in IN 713C blade [21,22].

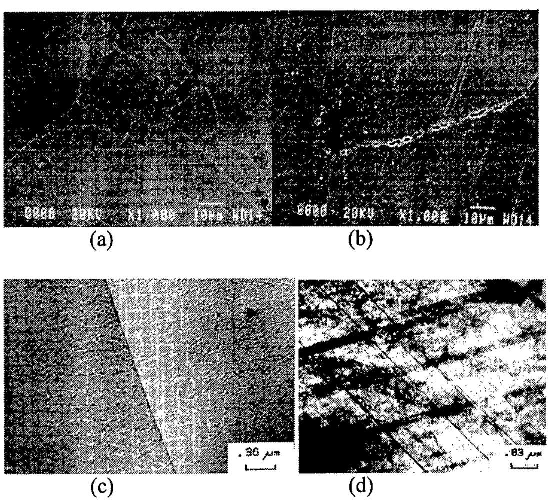


Figure 21. Effects of service exposure on microstucture (a) Virgin disc spacer ; (b) service exposed disc spacer showing evidence of creep voids along grain boundaries; (c) virgin disc; (d) service exposed disc showing evidence of dislocation activity (PSB) indicative of LCF damage accumulation [23].

Airfoil distortion in extreme cases may lead to HCF failures. Usually, microdamage accumulation in conjunction with airfoil distortion is followed by cracking due to cavity link-up or oxidation assisted creep cracking along the grain boundaries [26] which can cause catastrophic failures. PSB and wavy slip damage accumulation under LCF conditions is usually followed by crack initiation and growth in critical components such as discs, Figure 23(a) and 23(b) [27].

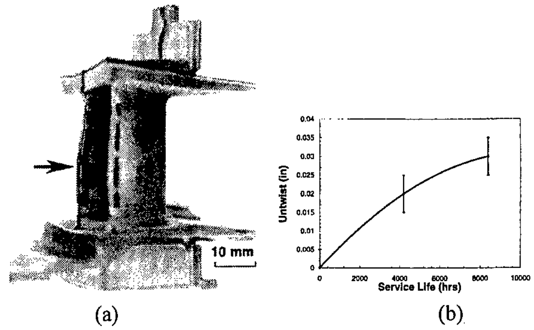


Figure 22. (a) Airfoil bowing, loss of coating and cracking of CF T56-A15 first stage nozzle guide vane; (b) Airfoil untwist accumulation as a function of service exposure for CF T56-A7B first stage turbine blade - uncooled component made of alloy 713C [24,25].

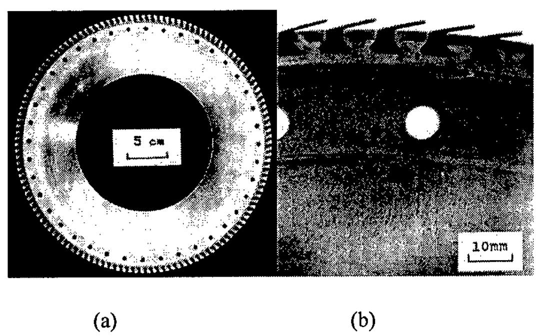


Figure 23. CF J85 CAN 40/15 compressor disc: (a) full view; (b) close up of rim region showing crack initiating from bolt hole [27].

If this cracking goes unchecked loss of engine as well as aircraft could occur. Temperature cycling also causes thermal fatigue crack initiation and growth and this problem is life limiting in many coated blades and vanes as well as combustor parts, Figure 24(a) and 24(b).

3.2 COMPONENT LIFE EXTENSION THROUGH ADVANCED TECHNOLOGIES

High acquisition costs of the new military aircraft coupled with dwindling resources for purchasing new equipment are forcing the users to take a serious look at life extension schemes for extending the usable lives of existing engines. A number of life extension techniques are actively being persued by different user services within NATO to reduce the maintenance costs and to lower the costs of equipment ownership, while at the same time ensuring continued safety and reliability of the engines.

Better parts life tracking systems and on-line damage monitoring techniques for life consumption are being used and more accurate structural analysis methods and reliable non-destructive inspection techniques are also being implemented. New technologies that are being explored also include the use of fracture mechanics based life prediction methodologies for maintaining critical rotating parts, retrofitting/upgrading the existing parts with more damage tolerant materials and coatings, using emerging surface modification treatments and implementing advanced repair techniques at depot level.

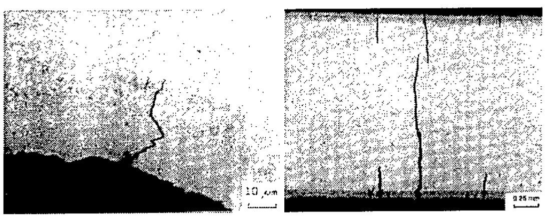


Figure 24. Coating initiated thermal fatigue cracks in a high performance turbine components (a) close-up of coating crack; (b) evidence of cracks having propagated through wall of component (Courtesy of Orenda Aerospace Corporation].

3.2.1 On-line Damage Monitoring and Parts Life Tracking: Older aircraft are being equipped with new engine life monitoring (ELM) systems capable of on-line monitoring of thermal-mechanical cyclic as well as steady state usage of life limited parts such as discs and spacers and hot section blades and vanes. Multi-channel ELMs possessing a wide range of set points are preferred for monitoring individual sections of the engine. Some of these ELMs are also equipped with advanced algorithms to account for temperature transient effects. Most user services rotate engines from one aircraft to another and some of these aircraft could be exposed to different operating environments. Similarly parts are often rotated amongst engines within a given fleet and this is particularly true for modular engine designs. To reliability assess life consumption using ELM outputs under such circumstances without causing unexpected failures, engine parts life tracking systems (EPLTS) must be in place to account for possible variations in service conditions. By the same token, life extension is possible through the implementation of ELM and EPLTS technologies if the assumed mission severity is overly conservative.

Health and usage monitoring systems (HUMS) are becoming increasingly important for optimal and cost effective life cycle management of engine parts, and they can be most effectively used in conjunction with EPLTS. In principle, any of the engine operating parameters that lead to damage in parts, such as cyclic temperature variations, hold time at temperature, and major and minor stress cycles caused by engine mission demands and aerodynamically induced vibrations, can be measured and monitored. Through the use of trend analysis, pattern recognition, and in the future, neural network techniques, the emergence of abnormal modes of behaviour or dynamic response of components may be detected and perhaps even predicted in advance. Many of the modes of internal damage accumulation, as discussed earlier, may lead to no detectable change in the physical performance of parts, such as vibration characteristics, and therefore to monitor the health of such parts the operator needs to have well calibrated transfer functions through which the internal state of a part and its residual mechanical properties, strength and life can be predicted based only on a knowledge of the conditions to which the parts have been exposed. At present our knowledge of such transfer functions is elementary, and this should be the focus of much future work.

To monitor the internal operating environment of an engine and to provide early warning of distress in parts, one needs to have available a wide variety of sensors that can be inserted into the engine at critical locations and in sufficient number to provide a full field image of critical zones. The sensors must be robust, reliable and unobtrusive, so as to not interfere with the internal aerodynamics nor combustion processes of the engine. In the future we are likely to see an increasing use of thin film thermocouples and fibre optic probes, including refractory fibre optic probes that can interrogate the internal hot sections of an engine.

At present, real-time video infra-red thermography is being used to obtain full-field images of the temperature distributions in hot gas and metal parts at critical stages of an engine. By monitoring changes over time of such thermal patterns, the early detection of faulty fuel nozzles or damaged vanes is possible [28]. At present, this is a line-of-sight technique whereby the image is obtained by looking into the exhaust plane of the engine, and therefore the method is only suitable for ground based (i.e. field or depot level) inspection. In the future, however, with the availability of small refractory fibre optic inspection leads and small low cost IR detectors, it may be possible to provide on-board, and hence continuous in-flight inspection and monitoring.

3.2.2 New Life Prediction and Life Cycle Management Methodologies

The models used to predict safe creep and/or fatigue crack initiation lives of different gas turbine components are often empirical in nature. These models may not always capture the complexity of damage evolution in parts manufactured out of complex engineering materials such as superalloys, Ti alloys and stainless steels. Large safety factors are invariably imposed on predicted crack initiation lives simply to ensure safety and reliability of the engines. However, this practice also introduces a fair amount of conservatism in the predicted lives.Therefore, attempts are continually being made to create more accurate damage evolution and life prediction models to avoid this conservatism.Over the years simple modifications of the Larson-Miller (LM) parameter involving material specific values of the LM constant [29] and modification of the Monkman-Grant type relationships [30] have led to considerable improvements in predicted creep-rupture lives. Similarly, the inclusion of strain, as opposed to stress, and frequency factors in empirical LCF models have also improved the accuracy of prediction [31]. Defining the role of environment during creep-fatigue interactions has further improved the understanding of damage evolution. In future, however, the development of mechanistic models which precisely quantify the role of microstructural variables and environment are expected to accurately depict the state of a component as a function of service life and allow one to accurately assess remaining life.

Crack initiation life is usually based on a statistical minimum,e.g. in the case of discs, only 1 in 1000 components is expected to contain a detectable crack at the end of the safe life. As a result, the remaining 999 components will be retired in a crack free condition. This is why fracture mechanics based life cycle management philosophies have emerged which propose to utilize a safe inspection interval (SII) similar to that depicted for airframes in Figure 2 once safe life expires. In principle, an inspection could be repeated several times, at a frequency dictated by the calculated SII, and the component would only be retired once a crack is found. In this manner the crack initiation life of each component would be fully utilized. In the case of engines, however, one must ensure that fracture mechanics properties do not drastically change as a result of microstructural change and loss of properties during service, Figure 25, since these changes can adversely affect the inspection interval predictions [32].

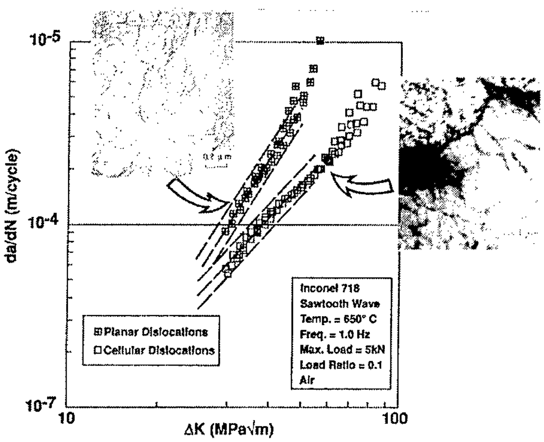


Figure 25. Comparison of fatigue crack growth rates (FCGR) in new and service-exposed alloy 718 turbine discs; high time disc shows significantly higher FCGR as compared to new and medium time discs [32].

Usually, deterministic calculations are performed for crack initiation life as well as crack growth life. It has, however, been argued that worst case assumptions for all variables in life prediction calculations are overly conservative and this is why probabilistic methodologies are being explored, Figure 26 [33,34]. A unique feature of probabilistic methdologies is that a given user can devise his own life extension strategy based on fleet size and operational conditions because risks associated with life extension can be easily quantified. It is thus expected that probabilistic methodologies along with mechanistic models will be used extensively for life predictions and extension purposes.

3.3 ADVANCED REPAIR TECHNIQUES

Application of heat treatments and hot isostatic pressing (HIPing) to eliminate service induced microstructural damage in industrial turbine blades, including blades from aero derivative engines, has now been used for over two decades to rejuvenate their creep properties. Recoating heat treatments applied during routine aero engine overhauls eliminate most forms of blade/vane microstructural damage except creep cavities and therefore rejuvenate creep properties to some degree, Figure 27 [9,25].

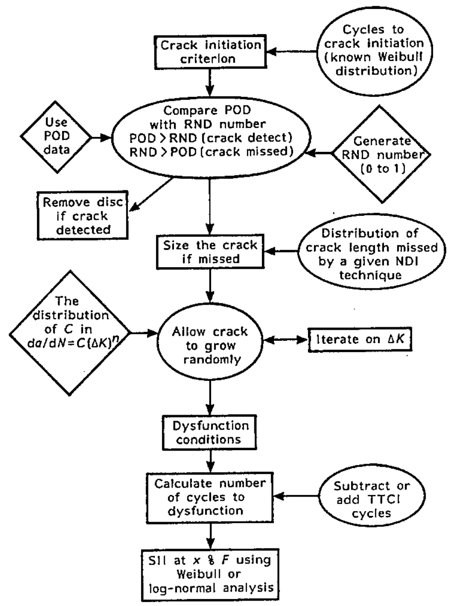


Figure 26. Flow diagram of NRC-IAR probabilistic fracture mechanics algorithm for safe inspection interval calculations [34].

It is necessary to use HIPing if creep cavities form during service. In aero engines, however, HIP rejuvenation has only been used in a few limited cases and some of these examples are listed in Table 2. In most cases it has been used in conjunction with blade tip build up.

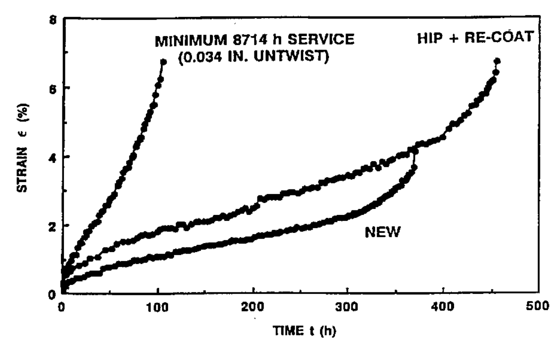


Figure 27. Demonstration of the rejuvenation of creep properties in Alloy 713C blades from T56-A7B engine; creep curves are for test coupons machined from new, service exposed and service exposed + rejuvenated blade airfoils [25]

In cast components, a repair scheme involving HIPing can also eliminate as-cast shrinkage porosity and this can improve the reliability of components by reducing scatter in material properties [31]. If the repair costs exceed 60% of the new component costs, the rejuvenation scheme is not considered cost effective. In most solid blades, the HIP rejuvenation costs are of the order of 35% to 50% of the new blade costs. Attempts have also been made to eliminate LCF damage in blades and discs through re-heat teatments but this technology has not been widely used for life extension of LCF life limited parts.

Blade alloy	Repair Technique	Repair Country	Cost w.r.t. new blade
René 80A	Tip Build + HIP	USA	50%
René 100	Tip Build + HIP	USA	50%
Nimonic 80A	Tip Build + HIP	USA	50%
Alloy 713C	HIP	Sweden	35%
Nimonic 80A	Tip Build + HIP	Canada	45%

Table 2. A list of some rejuvenated blades in service in aero engines

Welding and brazing technologies have long been used to repair cracks in gas path components such as blades, vanes and combustor liners. Guidelines for such repairs are well established and detailed repair manuals are usually provided by original equipment manufacturers (OEMs) for shop level repairs. New techniques are however constantly emerging to allow repairs to be implemented beyond the crack dimension limits set by OEMs and for components which are not covered by the standard repair manuals. For example Orenda Aerospace Corporation has recently developed a patch repair for foreign object damaged (FODed) Ti alloy fan blades using an electron beam welding (EBW) technique, Figure 28 [35]

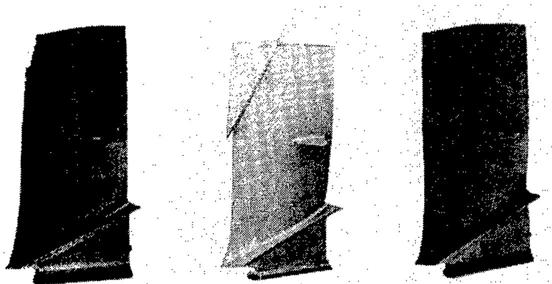
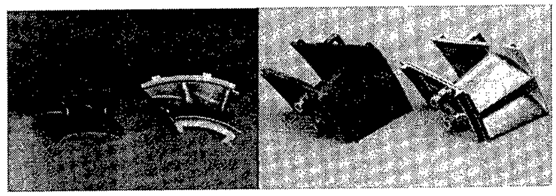


Figure 28. EBW repair of FODed F404 fan blade (Courtesy of Orenda Aerospace Corporation)

The repaired blades perform as well as new blades in qualification tests and will shortly be field tested. A similar technique is also being used by Pratt & Whitney Canada to repair the airfoils of integrally machined Ti alloy impellers. Similarly, the development of hydrogen fluoride (HF) based cleaning processes such as the Activated Fluoride Oxide Reduction (AFOR) process of Vac-Aero International [36] or the University of Dayton Research Institute (UDRI) reduction process, in combination with diffusion braze repair (DBR) technology [36] has now made it possible to routinely braze repair previously non-brazable Ni-base superalloy vanes. This is because thermodynamically stable Al oxides can be effectively removed by HF processing and the brazement can wet the surfaces to create a durable braze joint, Figure 29.



(a) (b)

Figure 29. (a) INCO 792 compressor turbine test pieces in the as received condition and after AFOR/DBR processing (Courtesy of Vac-Aero International); (b) HF cleaned and braze repaired René 80 LPT nozzle (Courtesy of Orenda Aerospace Corporation).

A number of advances in weld repair techniques such as the development of dabber welding and powder metallurgy welding techniques [37] has allowed the users to repair high strength superalloy components that were previously difficult to weld. In addition, the recent development of a fully automated tip weld repair technique by Liburdi Engineering allows thicker tip build-up and closer tolerances than was previously possible, Figure 30 [38]. The technique is capable of welding a wide variety of high strength oxidation resistant superalloy materials onto service exposed superalloy blade airfoils with minimum incidence of cracking and is particularly effective for improving oxidation and thermal fatigue resistance of directionally solidified blade tips.

Repair techniques using cold as well as hot forming operations are also used to suppress the formation of LCF and HCF cracks in cold section gas path as well as critical engine parts. For example, like in airframe components, cold expansion of bolt holes is also being considered for improving the component LCF lives of compressor discs and spacers if these holes initiate fracture [39]. Airfoil recontouring processes, such as RD305 of Sermetel, are used to control the shape of an eroded or worn airfoil to blue print tolerances, including leading edge orientation, trailing edge exit angle, twist and camber, to improve engine performance and to eliminate the possibility of an HCF failure [40]. Creep forming of bent fan or compressor airfoils as a result of FOD is also used to extend usable life.

3.4. NEW MATERIALS, COATINGS AND PROCESSES

Substituting a component material for another, adding a protective coating or treating the component surface to enhance its durability are options that can help reduce rates of damage accumulation and operating costs of engines. Implementing such changes at the depot/maintenance level is relatively straight forward for non-critical components such as compressor and turbine blades and vanes, although care needs to be exercised to ensure that the modifications introduced do not compromise the basis for parts certification. For critical rotating components such as compressor and turbine discs, depending on the nature of the change, extensive testing may be needed to qualify modifications. In all cases, the methodology should be consistent with regulatory requirements and accepted practices.

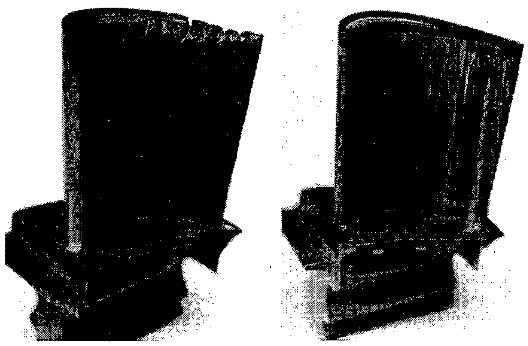


Figure 30. Weld tip repair of DS René 80 first stage turbine blade form CF F404 engine (Courtesy Liburdi Engineering, Hamilton, Ontario)

3.4.1 Retrofitting with New Materials

Both blade and disc materials can be changed. In most situations, this is done through a component improvement program (CIP) led by the engine manufacturer (OEM) but supported financially by different user services. For example, in Canadian Forces (CF) F404 engines, the first stage turbine blades were changed from conventionally cast René 125 to directionally solidified René 80 and, more recently, a change to single crystal alloy N4 has been proposed. The changes were implemented to improve creep as well as thermal fatigue resistance of the blades. With changes of this type, improvements may not always meet expectations if, for instance, cracking of the coating proves to be life limiting. In these cases, an optimized coating/substrate system must be considered. Furthermore situations may arise where changing the blade material may induce fretting damage in the blade-disc fixing regions, if the new blade material is too hard.

Replacing disc materials is not as common as changing blade alloys but occasionally retrofitting with materials having improved durability or damage tolerance has been implemented. For example, in the case of CF J85 CAN40/15 engines, one of the compressor discs was changed from AM355 martensitic stainless steel to DA 718 nickel base superalloy to eliminate premature bolt hole cracking. Figure 23.

3.4.2 Protective Coatings for Compressor Gas Path Components

The primary modes of degradation of compressor blades and vanes are erosion and corrosion by ingested contaminants. Erosion is particularly severe in the case of transport and helicopter engines operating in dusty environments. Up to 70 % of compressor blades and vanes in some transport engines are routinely rejected at overhaul, depending on compressor stage and operating environment. It has also been reported that erosion in some helicopter engines during the Gulf war was so severe that the helicopter fleets would have been grounded had the conflict lasted much longer [41]. Many coatings have been developed over the years for the protection of compressor airfoil components. Most commercial products are sacrificial type coatings designed to provide corrosion protection. However, these products usually have little resistance to erosion. Recently, there has been growing interest in hard coatings capable of providing both erosion and corrosion protection to compressor airfoils. These coatings are based on titanium nitride (TiN), a ceramic compound which has been used extensively on cutting tools to provide wear resistance and enhance durability. Titanium nitride coatings have been evaluated for use on compressor airfoils to alleviate erosion in engines prone to this form of damage.

The properties of TiN coatings depend on several factors, including hardness, cohesive and adhesive strengths, and are influenced by surface preparation and method of application [42]. Field evaluation in engines belonging to different military services has revealed shortcomings with first generation coatings. The degree of life extension achieved with these coatings has not been sufficient to warrant implementation at this stage. The major problem is a lack of erosion resistance for high angles of impact by erosive particles [41]. There have also been problems of poor adhesion with some of the products. However, results have been sufficiently promising to warrant field testing of a second generation of TiN coatings with improved overall performance. The latest coatings are designed to improve erosion as well as corrosion resistance and are based on alloying of TiN with carbon or aluminum (TiAlN, TiCN). Chromium nitride coatings are also being considered for corrosion protection. A Russian developed TiN product is claimed to have been in use since 1983 on commercial aircraft and military helicopters in Afghanistan, lowering rejection rates of blades by a factor of six [41].

3.4.3 Protective Coatings for Turbine (Hot) Gas Path Components

These components are normally coated with an aluminide intermetallic compound designed to form a protective oxide scale to provide protection against surface oxidation and/or hot corrosion. Coating life is limited owing to spalling of the protective oxide scale and gradual consumption of the coating elements. The coatings may also crack because of their low ductility and these cracks may subsequently propagate into the substrate. It is common practice to recoat components at overhaul if no other causes for rejection (e.g. distortion, nicks, overtemperature, etc...) are identified. Recoating of service exposed blades at overhaul provides an opportunity to change the coating for one that is better tailored to the operating environment. For instance a platinum modified aluminide coating can be used in situations were hot corrosion is found to be life limiting. In order to minimize the rate of coating consumption due to oxidation, a thermal barrier coating (TBC) can be added over specific areas of an airfoil such as the tip region of turbine blades or the leading edge of nozzle guide vanes to lower the component metal surface temperature. This approach is being used at Orenda Aerospace Corporation in conjunction with weld repair of blade tips to increase F404 first stage turbine blade durability. A tip repaired and selectively TBC coated DS René 80 turbine blade is shown in Figure 31.

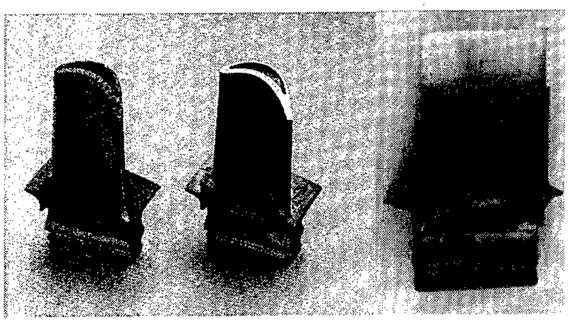


Figure 31. Tip repaired DSR 80 turbine blade with addition of protective TBC over tip portion of the airfoil (Courtesy of Orenda Aerospace Corporation).

Some components are designed to operate without a protective coating. This is the case of the F404 high pressure turbine nozzle. The oxide which forms during service on the nozzle airfoil has poor spallation resistance and low ductility. This leads to rapid surface degradation and the formation of thermal fatigue cracks at cooling holes and along the trailing edge. A braze repair has recently been developed for the component by Orenda Aerospace Corporation [43] and a coating tailored to the braze repaired

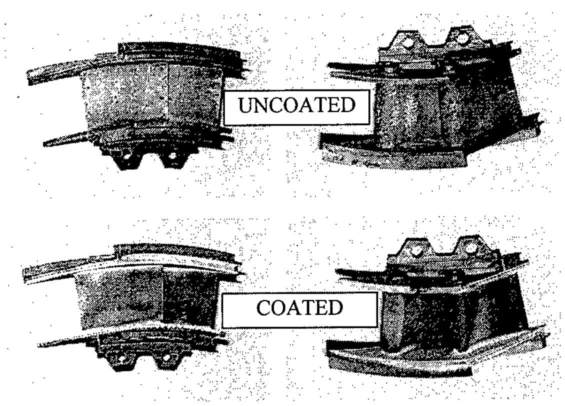


Figure 32. Conditions after accelerated testing in high velocity burner rig of F404 HPT nozzle; (a) uncoated configuration; (b) coated configuration (Courtesy of Orenda Aerospace Corporation)

material has also been developed in parallel which has been shown to greatly enhance component durability in accelerated burner rig tests, Figure 32. This coated component will shortly be tested in CF engines. Chemical vapour phase aluminizing (e.g. C-30 coating from Turbine Component Corporation) has also been applied to internal cooling passages of turbine blades to reduce the loss of load bearing section by internal oxidation in thin wall components [44].

3.4.4 Advanced Surface Modifications

New surface modification treatments such as ion implantation and chemical surface treatments have been explored for use in conjunction with conventionnal shot peening and spraying of soft coatings to alleviate fretting fatigue problems in fan or compressor blade dovetail regions [16]. Chemical treatment in combination with shot peening has been found to be quite effective in laboratory tests. Other methods such as laser shock hardening and the use of physical barriers have also been explored and preliminary results appear promising [45].

4. ON-GOING AND FUTURE RESEARCH

A number of on-going and future research activities [46] will further improve the safety of flight and lower maintenance cost of aging airframes and engines. Some of these activities are described below.

Stress Analyses

Current research is in the area of more efficient finite element techniques which will reduce computation and modeling time. Three dimensional boundary element techniques are being developed for more efficient analysis of local details.

Durability and Damage Tolerance Analyses

A significant amount of research is being conducted on corrosion, redistribution of stresses in a structure in the presence of corrosion, and interaction between fatigue and corrosion. This activity will enable one to make life predictions in the presence of corrosive environments, resulting in reliable life, residual strength, and inspection requirement predictions.

Attempts are being made to develop accurate life prediction models using deformation mechanism based materials behaviour principles. Probabilistic approaches to life prediction are also being explored for assessing risks associated with life extension. Damage tolerant microstructures are also being designed for existing materials.

Repair Technology

Current activities are geared towards developing knowledge based software to design repairs for metallic structures. This will significantly reduce the repair design time and give optimum design, resulting in reduced down time of aircraft and reliable inspection requirements. The research activities in composite patch repairs of relatively thick structures and complex structures will make the application of composite patch repair concepts more general and make it possible to repair structures which could not be repaired with conventional techniques. This will result in reduced scrap parts and lower maintenance cost.

Advanced Materials

Advanced materials such as new aluminum lithium and PM alloys and composites will significantly reduce life cycle costs of spare parts. Studies are being conducted to replace some of the existing problem metallic parts with thermoplastic composites.

Once new engine structural materials such as Ti aluminides and Ni aluminides with improved properties become available commercially, they will be considered as substitute for the degraded components. Multilayered hard coatings also appear promising and will shortly become available for combating erosion/corrosion problems in fan and compressor sections.

Structural Health Monitoring System

The purpose of automated structural health monitoring (SHM) is to evaluate structural integrity in real time. Recent advances in sensors and computers have made the development of SHM systems feasible. A SHM system will consider both battle and in-service damage in real time. After the damage has been detected, the structural degradation and performance will be evaluated by using an on-board expert system which has built in capabilities to evaluate the effect of damage on structural performance.

Sensors such as thin film thermocouples are expected to provide better estimates of operating temperatures and transient loads and this will also facilitate engine life monitoring.

Non-Destructive Inspection

Recent research activities in eddy current technology have been towards the computerization, automation, improving capabilities to detect small flaws and flaws in multi-layer structures. Significant activities are taking place in the development of robots to perform NDI.

Automated ECI and ultrasonic techniques with signal processing and pattern recognition capabilities are being considered for depot level inspections. Novel NDI techniques such as neutron diffraction, positron annihilation sprectroscopy and small angle neutron scattering are also being explored for microstructural damage detection at fracture critical locations.

ACKNOWLEDGEMENTS

The authors thank Mr. Dave Morphy of NRC-IAR-SMPL for his help in formatting the manuscript to AGARD standards. The Canadian authors also wish to thank Canadian companies, (Orenda Aerospace Corp, Liburdi Engineering, Vac-Aero Int. and Standard Aero Ltd.) for supplying some of the illustrations. Financial support provided by the Chief Research and Development of the Department of National Defence of Canada (Air Vehicle Research Detachment) for work on life extension of engines is also gratefully acknowledged.

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LA REDUCTION DES COUTS DE MAINTENANCE DES CELLULES D'AVIONS DE COMBAT

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0. RESUME

Le maintien d'une flotte d'avions de combat en condition d'emploi opérationnel pour un ensemble de missions avec un taux de disponibilité fixé nécessite de toute évidence que soient effectuées tout au long de la durée de vie des aéronefs des opérations soit d'entretien et de vérification, soit de remise en état par réparation ou rechange, l'ensemble des actions étant essentiel pour la sécurité des vols.

Différentes situations de maintenance se présentent en fonction de la criticité et de la fiabilité des organes visés, de l'ampleur des opérations et de leur périodicité, des ressources et compétences requises. La maintenance sera une maintenance du type programmée, donc à planifier, et/ou une maintenance non programmée, et concernera la cellule, le moteur, les systèmes et équipements.

Le coût global de maintenance inclut donc à la fois les dépenses consenties à l'acquisition des matériels pour le système de soutien, et les dépenses occasionnées pendant la phase d'utilisation. Il apparaît que les deux plus importants contributeurs de ce coût de maintenance sont le volume de stock requis d'une part, et le volume d'heures de main d'oeuvre d'autre part effectuées aux différents échelons d'entretien et de réparation.

Pour ce qui concerne la cellule, l'étude de la répartition du coût de maintenance entre la cellule, le moteur et les équipements révèle un coût de maintenance relatif "cellule" faible, pour un avion de combat tel que le MIRAGE 2000, qui a par ailleurs des coûts globaux de maintenance compétitifs. Des données sur les coûts de maintenance sont présentés et attestent de cette qualité.

Ce niveau sur la cellule ne peut être atteint que par des méthodes de conception et de maintenance appropriées :

- la prise en compte de la maintenance dès la conception de l'avion, de ses systèmes et de la cellule : c'est le concept du Soutien Logistique Intégré (SLI).
- les règles de conception de la structure essentielles sont :
  - un bon choix pour le dimensionnement en fatigue
  - un bon système de protection anti corrosion et d'étanchéité
  - des conceptions tolérantes aux dommages, notamment aux petits dommages accidentels en service.
- Les méthodes d'établissement du programme de maintenance : depuis 1966 est appliquée aux avions de combat français la méthode MAPIE (Méthode Analytique pour l'élaboration du Programme Initial d'Entretien).
- Le suivi des avions en service : le suivi des charges et le retour d'expérience des contrôles non destructifs permettent d'ajuster le programme de maintenance et de piloter le potentiel structural de la flotte.

Par contre, des exigences renforcées sur la réduction des signatures peuvent avoir une influence défavorable sur les coûts de maintenance. On devra aussi investiguer les gains potentiels des matériaux intelligents et des méthodes de contrôles non destructifs évoluées.

1. INTRODUCTION

Conserver des avions de combat suffisamment disponibles, et aptes à remplir la totalité de leurs missions opérationnelles en toute sécurité, nécessite d'effectuer des opérations de maintenance qui concernent la structure et les équipements, le(s) moteur(s), les systèmes.

Le thème de cette présentation porte sur la réduction du coût de maintenance de la cellule.

L'analyse du coût de maintenance pour la cellule seule doit donc exclure du champ au moins le poste moteur et le poste SNA (Système de Navigation et d'Attaque); toutefois, l'étude est effectuée :

- en examinant d'une part les caractéristiques générales, et l'organisation, de la maintenance avion, et d'autre part, les facteurs prépondérants de coût,
- en faisant ressortir les spécificités propres à la cellule.

Paper presented at the AGARD Symposium on "Future Aerospace Technology in the Service of the Alliance", held at the Ecole Polytechnique, Palaiseau, France, 14-17 April 1997, and published in CP-600 Vol. 1.

2. CARACTERISTIQUES GENERALES DE LA MAINTENANCE

2.1. Description de la maintenance

Les opérations à effectuer tout au long de la durée de vie d'un aéronef sont soit des opérations d'entretien et de vérification (maintenance préventive), soit de réparation ou d'échange après constatations de pannes ou dommages (maintenance curative).

La maintenance préventive pour la cellule est en principe plutôt une maintenance du type programmée (récurrent prévisible) qui s'applique dès la mise en service des aéronefs, alors que la maintenance non programmée est du type récurrent aléatoire. Lorsqu'une inspection programmée révélera un fait technique non attendu, on procédera à une expertise sur un nombre suffisant d'avions pour en déduire les actions (additionnelles) à entreprendre.

Les échéances planifiées sont définies soit:

- en nombre d'heures de vol réalisées, paramètre représentatif des charges rencontrées par l'avion,
- en durée calendaire, paramètre représentatif du vieillissement.

En temps de paix, dès qu'une des deux conditions est atteinte, l'opération prévue doit être effectuée Les périodicités et la nature des interventions sont le résultat :

- pour les parties mécaniques, des études de résistance à la fatigue, de tolérance aux dommages et à la corrosion,
- pour les parties électriques et électrotechniques, des données de fiabilité et des analyses de risques.

Il est ainsi d'usage de distinguer trois niveaux d'intervention :

-1er niveau : NTI1-entretien élémentaire (0 Level ou Operational Level)

Maintenance en ligne, c'est à dire sur avion ou à la rigueur au pied de l'avion ; concerne surtout, les URL (unités remplaçables en lignes). Ce sont des opérations simples ne nécessitant pas de moyens de maintenance importants.

-2ème niveau : NTI2-entretien mineur (I Level ou Intermediate Level)

Maintenance en atelier, c'est à dire sur équipements déposés ou pour des interventions significatives sur avion ; concerne les URA (unités remplaçables en atelier). Ce sont des opérations qui justifient des moyens conséquents en outillages, rechanges, qualification de personnels, documentation,...

-3ème niveau : NTI3-entretien majeur (D Level ou Depôt Level)

Regroupe les interventions exécutées chez l'industriel ou dans des établissements spécialisés disposant de moyens industriels.

Un cycle d'entretien est donné ci-dessous à titre d'illustration (Figure 1).

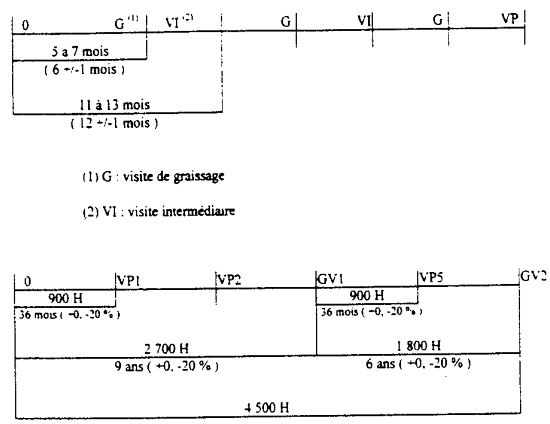


Figure 1 - Cycle de maintenance typique

2.2. Organisation de la maintenance

L'application de la maintenance concerne la phase d'utilisation de l'avion, désigné le système principal. Pour être efficace, cette maintenance doit être organisée non seulement pour ce qui concerne la méthodologie, élaboration du plan de maintenance, mais aussi pour ce qui concerne la logistique associée, ce dernier point se rapportant au système de soutien : stock d'approvisionnement initial (réparable, consommable) et réapprovisionnements, documentation utilisateur initiale et mises à jour, bancs de tests, outillages, matériels de servitudes, système de gestion de la maintenance, instruction et formation des personnels, simulateurs, infrastructure...

Dans le processus d'acquisition et d'utilisation d'un avion de combat, il convient donc que l'élaboration de la maintenance débute dès la phase de conception et de développement, la première mise en place des moyens du système de soutien intervenant progressivement lors de la phase de la mise en service du premier avion.

Des visites d'aptitude à la mise en œuvre et à la maintenance (VAMON) qui concerne surtout le

NTI1 sont organisées pour l'avion complet (prototype) lors de la phase de lancement du programme. Il convient également de lancer des études MAPIE (méthodes analytiques pour l'établissement d'un programme initial d'entretien) qui présentent des analogies avec les méthodes MSG en vigueur dans l'aviation commerciale, qui permettent de définir les interventions NTI2 et NTI3 sur l'avion.

A partir de ces études, il est défini les moyens à mettre en place dans les forces (stock, matériels de servitude, effectifs, ..) et les travaux à confier à l'industrie.

Dans la constitution du stock, il est à distinguer :

- les stocks techniques :
  correspondent à des besoins temps de paix et compensent les envois des matériels dans les circuits de réparation NTI2 et NTI3.

- les stocks opérationnels :
  pour permettre soit à la base opérationnelle de fonctionner coupée de l'extérieur pendant une durée déterminée, soit aux unités de se déployer sur les terrains extérieurs et de commencer à fonctionner seules pendant un certain temps, temps qui permet d'établir le flux logistique avec la base mère.

- les stocks pour le NTI3.

D'une manière générale, on désignera les éléments du stock par VR pour les volants, rechanges, et D les matériels de servitude.

2.3. Les coûts de maintenance

Les coûts de maintenance interviennent dans la notion de coût de possession ou coût global du système, pour lequel il convient de distinguer toutes les phases du cycle de vie (système principal et système de soutien) ; le coût global est alors défini par :

C = C1(acquisition) + C2(utilisation),

- les coûts d'acquisition concernent les coûts de faisabilité, de développement, d'industrialisation et de production d'un programme.

- les coûts d'utilisation concernent les coûts d'exploitation, de soutien et de retrait de service.

Il est constaté que le poste « maintenance » constitue un poste non négligeable.

Les coûts de maintenance sont le plus généralement associés aux dépenses effectuées en heure de main d'œuvre d'intervention et aux coûts des VRD pendant la **phase d'utilisation**. En fait, de façon plus précise et exhaustive, les coûts de maintenance sont définis comme étant les coûts directement imputables aux actions de maintenance. Or, il a été mentionné précédemment que la conception de la maintenance et la mise en place du système de soutien concernaient un programme d'avion dès son lancement: des coûts imputables à la maintenance sont donc générés lors du processus d'acquisition; ils sont imputés au programme, alors que les dépenses en utilisation sont payées par l'utilisateur, au titre du Maintien en Condition Opérationnel (MCO).

3. LA REDUCTION DES COUTS DE MAINTENANCE

Il est constaté que les contributeurs essentiels au coût de maintenance sont les postes:

*Stock,
*Main d'oeuvre,
*Documentation,
*Matériels de servitude.

On se focalisera dans la suite sur les deux premiers, bien que les deux autres ne soient pas négligeables.

3.1 Coût du stock (principalement les Volants et Rechanges)

- Il est constaté que le coût de l'approvisionnement initial (VRD) représente un coût non négligeable, rapporté à la valeur de la flotte. Ce premier point constitue probablement une piste de réduction de coût ; il convient en effet d'examiner la réelle nécessité de mise en place d'un tel volume de stock.

- Au cours de la phase d'utilisation, il est constaté que l'évolution des dépenses pour les réapprovisionnements en rechanges structures et certains équipements associés (hors coût de leur réparation), en fonction de la durée de vie de l'avion, a schématiquement l'allure suivante:

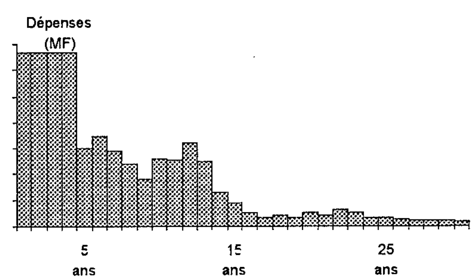


Figure 2 - Courbe donnée pour un taux de disponibilité identique au cours de la vie de l'avion.

Les dépenses sont les plus importantes au début des premières années d'utilisation: il importe donc de disposer du plus grand nombre d'avions, et de maîtriser le nombre de standard. Cette idée est illustrée d'une autre façon par les résultats d'une étude paramétrique montrant l'évolution du budget nécessaire en approvisionnement initial de VR pour 4 valeurs de taille de flotte d'un avion de combat, les hypothèses d'organisation de la maintenance étant inchangées:

Nombre d'avions	N/9	N/3	N	2N
Budget néces-saire	0,21P	0,47P	P	1,75P
Coût par avion	1,89P/N	1,41P/N	P/N	0,875P/
Ecart	+ 89 %	+ 41 %	Réfé-rence	-.12,5 %

- Au cours de la phase d'utilisation, le système de soutien, en particulier le volume du stock, doit être périodiquement corrigé et remis à niveau, en fonction des données réelles constatées, Il s'avère que le calcul du volume du stock ,et donc le coût résultant, est directement lié:

- au délai global du processus de commande des rechanges: délai entre l'expression d'un besoin par l'utilisateur et la réception du matériel en magasin. Il a été estimé que la réduction de moitié du délai du processus permettait un gain de **10 % sur le coût des réapprovision-nements** (ce coût constituant une part du coût des VRD).

Les délais jouent, apparemment, un rôle non négligeable sur le coût du stock, et en particulier, la durée d'immobilisation pour remise à niveau. Les deux tableaux ci-dessous donnent la sensibilité du stock initial VR aux délais de réparation du NTI2 (1er tableau) et du NTI3 (2éme tableau). Ceci est surtout vérifié pour les équipements.

Délai NTI2 Jours calendaires	1,5 à 7,5 jours	3 à 15 jours	4,5 à 22,5 jours	6 à 30 jours
Ecart budget référence	- 7 %	Réfé-rence	+ 6 %	+ 13 %

Délai NTI Mois calendaires	3 mois	6 mois	9 mois	12 mois
Ecart budget référence	- 7 %	Réfé-rence	+ 7%	+ 14 %

Remarque: ces résultats (influence de la taille de la flotte et des délais) sont issus d'une étude paramétrique ayant eu pour but d'estimer les budgets prévisionnels à mettre en place lors de la conduite d'un programme d'avion de combat. Les calculs de stock ont été effectués avec les règles en vigueur de l'utilisateur. Ces résultats donnent des indications et des ordres de grandeur, vis à vis du concept de maintenance, de l'organisation de la logistique choisie, ...

Pour ce qui concerne la structure, les résultats des études paramétriques sont peu transposables, car la consommation des éléments de structure est peu prédictive. Il convient de stocker pour un avion de combat des voilures, dérives, empennages, verrières. Les calculs sont basés sur des statistiques en étudiant la consommation de ces mêmes éléments pour des avions précédents au cours de leur utilisation. On peut d'ailleurs s'interroger sur le type d'élément le plus adapté à stocker dans une optique réduction du coût: voilure complète?, longerons seulement?, ébauches?...La démarche en fait consiste à une gestion du risque logistique ; tant que l'avion est en production, les besoins peuvent être satisfaits par prélèvement sur chaîne ; il importe de tenir compte de l'état de la chaîne : début, phase critique, fin ; le problème de la constitution de stock se pose réellement environ 5 ans avant la fin de la production.

- Il apparaît en fait que les postes budgétaires (en relatif) les plus lourds sont constitués par le moteur d'une part, surtout s'il s'agit d'un avion bi-moteur, et par le SNA d'autre part, comme l'illustre le tableau ci-dessous, issu de l'étude paramétrique précitée, qui montre la répartition du coût pour la mise en place des VRD initiaux:

Structure	Moteurs (Nombre = 2)	Equipe-ments généraux	SNA	Autres
7 %	47 %	17 %	22 %	7 %

Le système avion comprend le train, les commandes de vol, les câblages, le système hydraulique.

3.2. Coût de la main d'oeuvre

Ce coût est évidemment lié au nombre d'actions de maintenance à effectuer, à leur durée, et donc au concept de maintenance adopté, au caractère de maintenabilité du système, et au nombre de dégradations survenant .

- Le taux de panne ou de défaillance, d'anomalies et dommages constatés est relié à la fiabilité et donc dépendant de la conception; la durée d'intervention est liée également à la conception (facilité de maintenance, existence de solutions de réparations rapides, résistantes et économiques, ..) ainsi qu'à la conception de la logistique.

A ce titre, il apparaît donc fondamental de caler et d'optimiser le processus entre les différents intervenants; en effet, dans le cas où un dommage est effectivement découvert, une expertise s'impose:

* soit l'échelon intervenant sait réaliser cette expertise, il peut éventuellement faire la réparation, soit il ne peut pas et doit faire appel pour la réparation à un intervenant de niveau supérieur ;
* soit il ne peut pas faire l'expertise et fait appel à un intervenant de niveau supérieur, le dommage est réparable et réparé, ou déclaré non réparable.

Les **délais de réaction de l'ensemble du processus lors de la phase d'utilisation** constituent donc probablement un gisement de gain de coûts de maintenance indéniable.

- Pour ce qui concerne le choix de la méthode de maintenance, il est possible d'envisager un concept de maintenance selon état, au lieu d'un concept de maintenance préventive programmée. Si les pièces primaires de la structure font essentiellement l'objet d'une maintenance programmée, la maintenance selon état est en général préférable pour les équipements surtout si elle est accompagnée d'un système développé de Maintenance Intégrée permettant une détection et une identification des pannes par le système avion lui même.

De façon évidente, la maintenance initiale programmée doit évoluer vers une maintenance optimisée, par adaptation en permanence du programme de maintenance à l'utilisation réelle de l'avion, et du retour d'expérience.

* Il doit être tenu compte du vieillissement réel de la flotte, et de la consommation effective en nombre d'heures; dans le cas où il est effectivement constaté que les butées calendaires de visite sont atteintes avant la butée en heures de vol, il sera pertinent d'aménager le cycle initial de maintenance, afin de ne pas perdre du **potentiel opérationnel** avion, en effectuant une nouvelle ventilation des opérations de maintenance.

* La diminution du volume de maintenance peut également s'obtenir par une application adaptative des opérations à effectuer.

Au NTI3 par exemple, il est possible d'envisager deux alternatives pour réduire le nombre d'opérations prévues par le plan d'entretien initial :

- pratiquer par échantillonnage de la flotte une expertise sur un groupe d'avions témoin arrivés à un certain stade de vieillissement ; en déduire le niveau d'entretien optimum à appliquer sur le reste de la flotte.

- pratiquer un échantillonnage par blocs: l'avion est divisé en un certain nombre de tranches; pour une GV concernée, l'entretien majeur est effectué uniquement sur un bloc, différent pour chaque avion visité.

Un gain net de 5 % par rapport à une application nominale du plan d'entretien peut être estimé.

- On peut également avoir moins de raisons à intervenir sur l'avion, en particulier sur la cellule, en raison de la conception de structures plus robustes et tolérantes aux dommages en prenant en compte, dès le début de la conception, l'environnement réel d'utilisation sur une base aérienne ou sur un porte-avions. Ce point sera détaillé au paragraphe 5.

4. SITUATION ACTUELLE

Il a été montré précédemment que pour la phase d'acquisition, le coût de maintenance était pour l'essentiel (indépendamment des coûts d'études en phase de conception) relié au coût de mise en place du stock initial, et que la cellule en constituait un des postes les moins prépondérants.

L'examen de la situation actuelle pour ce qui concerne le coût de maintenance, et plus particulièrement celui de la cellule, d'un avion de combat en phase d'utilisation est abordée par les bilans suivant .

- L'exploitation de données de dépenses disponibles au sein de la DGA, permet d'indiquer **l'ordre de grandeur** de la répartition relative entre les différents postes, des dépenses en rechanges (non inclus le coût de leur réparation) représentées par la somme (Cvr+Cmo), pour une période considérée, pour deux avions mono-moteur Mirage F1 et 2000:

Cmo + Cvr	Cellule	Equipements (dont SNA)	Moteur
Mirage F1	22 %	28 %	50 %
Mirage 2000	18 %	42 %	40 %

Cvr = coût de VR pour les trois niveaux.
Cmo = coût des heures MO au NTI3.

- Certaines données rassemblées par l'Armée de l'air permettent d'apprécier, pour un avion de combat récent comme le Mirage 2000 DA et N:

Taux de disponibilité.

- Disponibilité moyenne démontrée en unité supérieure à 80 % (nombre d'avions disponibles en ligne/nombre d'avions en unité).

  Dans certains cas de détachements lointains (par exemple exercices du type RED FLAG), des disponibilités de plus de 95 % ont été constatées.

- Fiabilité avion (temps moyen entre pannes)

Mirage 2000 DA	1992	1993
Nombre de sorties effectuées pour une panne	5	5
Nombre d'heures de vol effectuées pour une panne	07H20	07H00

- Coûts de maintenance en main d'oeuvre :

  Les chiffres moyens sont environ 4,5 heures par heure de vol au NTI1 (0 Level) et 6,5 heures par heure de vol au NTI2 (I Level).

- Délais d'immobilisation

Le délai moyen mesuré en jours ouvrables par visite périodique NTI2 est :

Mirage 2000 DA	1992	1993	1994
Nombre de visites périodiques	33	21	?
Délai moyen d'immobili-sation	24,5	23,5	24

Ces données disponibles permettent d'appréhender la réalité de la situation pour une famille d'avions de combat les plus récents en service dans les forces et issus d'une longue expérience et tradition en matière de construction nationale, les Mirages 2000. Il apparaît ainsi que les coûts globaux de maintenance sont très compétitifs,, et donc cela prouve que la cellule contribue implicitement à la tenue de ces qualités.

Ce niveau sur la cellule ne peut justement être atteint que par des méthodes de conception et de maintenance appropriées, ce que va détailler la suite de la présentation, pour le cas précis du Mirage 2000 (mais cela s'applique aussi au Rafale).

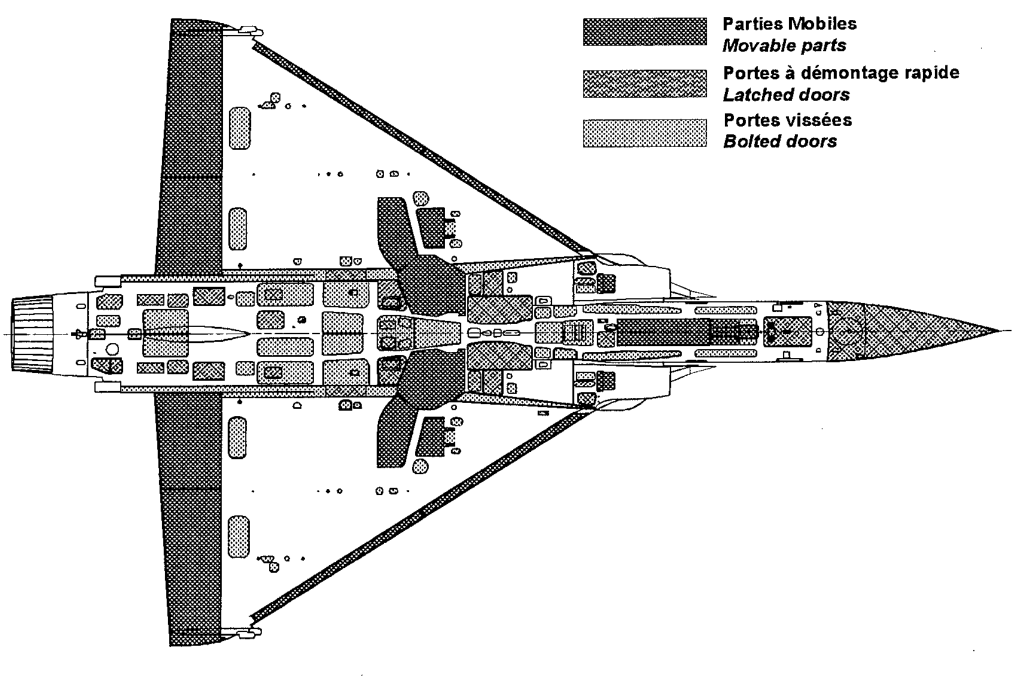
5. REDUCTION DES COUTS DE MAINTENANCE DE LA CELLULE

5.1. Le rôle de la cellule dans les coûts de maintenance de l'avion et de ses systèmes

Comme l'a montré le chapitre précédent, la maintenance de la structure représente en elle même une faible partie du coût total de maintenance et de réparation de l'Aéronef. Il ne faudrait cependant pas oublier que la structure joue un rôle important en ce qu'elle conditionne l'accessibilité et la démontabilité des systèmes et équipements qu'elle contient. Cet aspect doit être pris en compte dès le stade de la conception dans le cadre du concept plus général de Soutien Logistique Intégré (SLI).

Ces contraintes d'accessibilité, modulées par la fréquence prévue d'accès aux équipements qui conduisent à prévoir des portes à ouverture plus ou moins rapide, présentent l'avantage de faciliter l'accès à la structure elle même mais induisent une structure plus compliquée et plus chère, voir exemple les portes d'accès à l'intrados d'un Mirage 2000 (voir planche 3). Mais c'est le prix qu'il faut payer pour avoir un avion de maintenance facile. De même, on a visé à ce que les équipements soient disposés de façon à être accessibles sans avoir à démonter d'autres équipements.

Figure 3 - Portes d'accès Mirage 2000



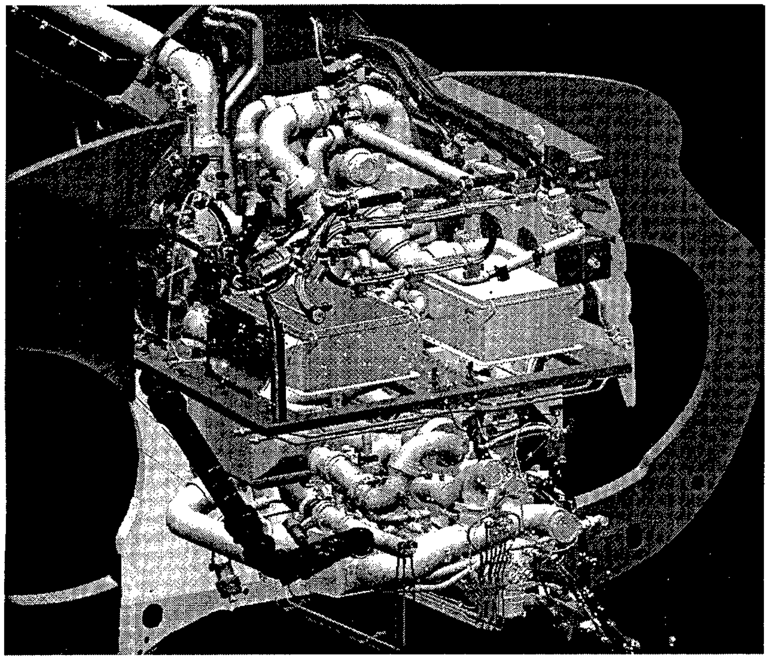


Figure 4 - Exemple d'aménagement maquette numérique

Cette accessibilité s'étudie maintenant par les Maquettes numériques d'aménagement (voir figure 4) (une maquette numérique Catia d'une soute du RAFALE) et est vérifiée avec les utilisateurs lors de visites VAMOM (Vérification de l'Aptitude à la Mise en Oeuvre et à la Maintenance).

5.2. Les méthodes de conception de la cellule pour un bas coût de maintenance

Comme l'indique l'expérience de l'Armée de l'Air Française, la maintenance de la structure représente une faible partie des coûts de maintenance.

Ceci n'est vrai que dans la mesure où l'on a su éviter un problème majeur en fatigue ou en corrosion qui entraînerait des opérations coûteuses de réparation ou de remplacement de pièces.

En dehors de l'accessibilité et de l'inspectabilité, les trois points principaux à considérer lors de la conception des structures sont : le dimensionnement en fatigue, la protection anti corrosion et la tolérance aux dommages accidentels.

- Le dimensionnement en fatigue : il est essentiel de concevoir les cellules pour une bonne tenue en fatigue. Une des difficultés de l'exercice est la prédiction des charges que l'avion rencontrera en service. L'expérience des trente dernières années a montré une triple inflation :

  - inflation des facteurs de charge en service : d'abord après la guerre du Viet Nam, l'évolution d'une utilisation du type intercepteur à une utilisation du type combat aérien rapproché. Ceci a été accentué par la mise en service d'avions à commandes de vol électriques très manoeuvrants comme par exemple le Mirage 2000. La planche montre l'évolution des spectres de facteurs de charge en service de trois générations d'avions de combat MIR III, MIR F1 et Mirage 2000.

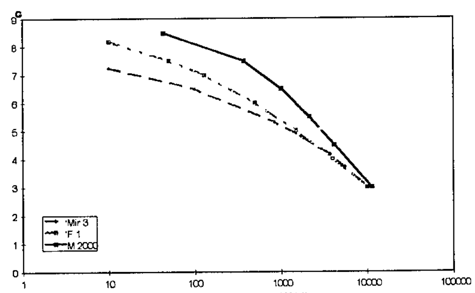


Figure 5 - Spectres de facteurs de charge en service

  - augmentation des durées de vie opérationnelles, les avions étant utilisés de plus en plus longtemps.

  - augmentation des masses à vide entre versions successives du même avion.

- Le système de protection anti corrosion et d'étanchéité

  Un défaut de protection contre la corrosion peut surtout s'il n'est pas détecté et soigné au plus tôt lors des opérations de maintenance, être la source de dépenses importantes de réparations sur la flotte.

Les quatre composantes de la protection anti corrosion lors de la conception sont :

- le choix des matériaux
- le choix des protections et interpositions
- le drainage
- le plan d'inspection et de maintenance.

Une des difficultés est la faible représentativité des essais accélérés de corrosion. D'où la très grande importance du retour d'expérience en service des générations d'avions précédents, et l'incitation à éviter de changer un plan de protection qui a marché.

- La tolérance aux dommages accidentels

La cellule est soumise en service, au sol ou en vol, à un certain nombre d'agressions accidentelles (chocs divers, érosion).

La tolérance aux dommages doit d'abord assurer le maintien de la sécurité en utilisation. En supposant la sécurité assurée, le coût de maintenance dépend de deux autres facteurs :

- la robustesse, c'est à dire la capacité de subir un certain niveau d'agression sans nécessité de réparation.
- la réparabilité quand une réparation devient nécessaire.

Le coût de maintenance pour un certain spectre d'agression est en fait une combinaison des deux facteurs, une structure peu robuste devant être facilement réparable, et une structure difficilement réparable devant être robuste.

5.3. Les méthodes d'établissement du programme de maintenance

Depuis 1976 est appliquée aux avions de combat Dassault la méthode dite "MAPIE" (Méthode Analytique Pour l'élaboration du Programme Initial d'Entretien). Cette méthode concerne la structure ainsi que les autres systèmes. On s'est inspiré de ce qui se faisait sur les avions civils (MSG ou MRB) mais en tenant compte des spécificités de l'avion de combat qui n'a pas besoin d'un niveau de sécurité structural aussi élevé.

En particulier, pour une structure correctement conçue, le "Safe life" est suffisant pour justifier la tenue en fatigue pendant la première partie de la vie de l'avion, en le complétant d'inspections simples ou par sondage. L'approche tolérance aux dommages ne rentre réellement en jeu que pour des extensions de durée de vie au delà du "safe life".

La méthode MAPIE couvre les trois modes de dégradation en service : la fatigue, la corrosion et les dommages accidentels selon le schéma de la planche 6. La planche 7 montre un exemple de schéma logique appliqué au cas de dommage accidentel d'impact sur une structure composite carbone résine.

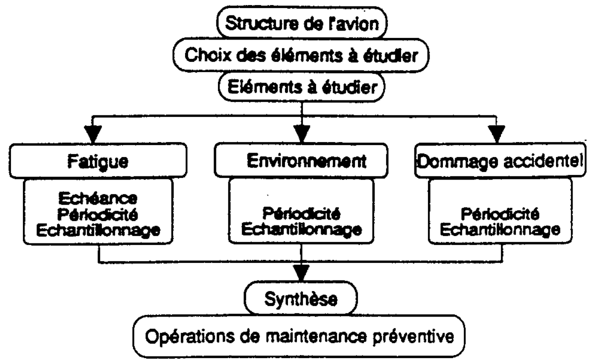


Figure 6 - Schéma logique "MAPIE"

Marge après impact	Sensibilité aux impacts 1	2	3
1	1	2	3
2	2	2	3
3	3	3	3

⇩

Criticité	1	2	3
1	1	2	3
2	2	2	3
3	3	3	4

⇩

Exposition	1	2	3	4
1	1	2	3	4
2	2	3	3	4
3	3	4	4	4
4	4	4	4	4

⇨

	CND
1	P = 4 ans
2	P = 8 ans
3	P = 12 ans
4	Aucune inspection

Ces inspections sont à appliquer sur 10% de la flotte.

Figure 7 - Cotation pour les dommages d'impact

Une telle méthode peut être appliqué rétroactivement à un avion déjà conçu, mais il est très intéressant de l'appliquer dès le stade de la conception, en ingénierie concourante, en permettant éventuellement de modifier la cellule pour mieux prendre en compte la maintenance.

5.4. Le suivi des avions en service

Le suivi des charges en service (notamment le suivi des indices de fatigue IF) et le retour d'expérience des contrôles non destructifs permettent d'ajuster les inspections établies initialement dans le cadre de la "MAPIE" et de piloter le potentiel structural de la flotte.

5.5. Les évolutions futures

Du point de vue du coût de maintenance, on peut en attendre des améliorations comme des aggravations.

- Des améliorations :

  - par des moyens de contrôles toujours plus performants notamment des moyens globaux permettant de réduire le coût des inspections.

  - par l'extension des composites qui, à la condition de réduire drastiquement le nombre de pièces métalliques, peuvent permettre d'espérer la réduction des problèmes de fatigue et de corrosion.

- Des aggravations :

  - par l'introduction de cellules à signature radar réduite, qui nécessite un compromis discrétion/maintenance.

  - par les possibles évolutions des réglementations de santé et d'environnement qui risquent d'interdire des méthodes de protection qui n'auraient peut être plus d'équivalent (exemple l'utilisation d'inhibiteurs de corrosion chromatés).

Un autre sujet pour lequel il n'y a pas aujourd'hui de réponse claire : l'utilité des matériaux intelligents pour la détection des dommages de fatigue, de corrosion ou d'impact. L'efficacité, le coût, le durabilité du système reste une inconnue, à comparer avec le coût et l'efficacité que l'on pourra attendre des contrôles non destructifs globaux qui deviendront disponibles pendant la durée de vie des avions considérés.

6. CONCLUSION

Finalement, l'ensemble des arguments développés mettent en lumière l'importance des règles de conception, d'organisation de la logistique et de management. Les gisements du coût de maintenance des cellules d'avion de combat sont donc situés lors de la phase d'acquisition du système principal et lors de la phase d'utilisation. L'étape de conception du système principal joue un rôle déterminant sur la fiabilité et la durabilité ultérieure. La maintenabilité fixera la durée des interventions. La conception du système de soutien (allocation des ressources au bon endroit) constituera un facteur clef de réussite: en particulier, le soutien logistique intégré SLI permettra d'optimiser dès le départ la maintenance à effectuer en utilisation.

Il apparaît, en fait, que le coût de maintenance soit la résultante de facteurs (objectifs de disponibilité, mode d'utilisation, politique de maintenance, pertinence de la conception produit) interagissant entre eux et qu'une analyse de réduction du coût de maintenance, des cellules pour avions de combat en particulier, doive être envisagée dans une problématique plus large d'optimisation de coût global.

SMART AIRCRAFT STRUCTURES

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SUMMARY

The broad but strongly interdisciplinary field of smart structures and materials seeks to apply multi-functional capabilities to existing and new structures. By definition, smart structures and materials are those which can sense external stimuli and respond with active control to that stimuli in real or near-real time. The most common analogy is to a human (Figure 1): the nervous system senses the stimuli; then the brain processes the information causing a muscle (actuator) to respond. For purposes of this paper, smart structures and materials consist of active devices--primarily sensors and actuators--either embedded in or attached to a structure.

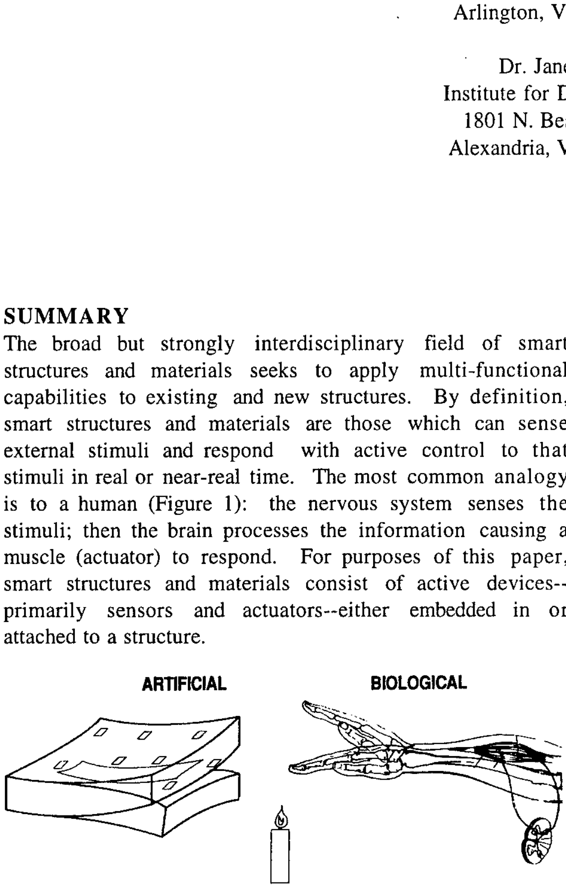

Figure 1. Smart structures analogy to a human.

These smart structures technologies are expected to provide new and innovative capabilities in future military aircraft including fighter and transport aircraft, unmanned aerial vehicles (UAVs), and helicopters and tilt rotorcraft. Specific applications are described in terms of system functional capability enhancements (e.g., vibration damping and suppression) and overall system performance benefits (e.g., reduced life cycle costs).

Current activities in the field range from the design, fabrication, and test of fully integrated structural systems like those identified above to enabling research in individual discipline areas--i.e., materials, sensing and actuation techniques, control algorithms and architectures, etc. Current demonstration efforts are highlighted as are technical needs in the broad areas of materials, design, devices, manufacturing and integration, and control. An estimated timeline for technology maturation, which would pace the insertion of the technology into production systems, is also provided.

1. INTRODUCTION

The idea of synthesizing smart materials and structures dates at least as far back as 1968 [1] when Henry Clauser published this idea in a broad, conceptual form. By 1975, Clauser had fully developed the concept of engineered materials as dynamic systems that could replace mechanical and electrical components and that the materials could respond to service conditions [2]. By 1978 the idea had received international attention. R.L. Forward, among the first researchers to investigate the possibility of using piezoceramic devices as passive dampers in mechanical systems, patented several innovative concepts in the late 1970's [e.g., 3-5]. In 1983 Forward, Swigert, and Obal [6] completed one of the first successful vibration control demonstrations using surface-mounted piezoceramic sensors and actuators. A substantial amount of jitter reduction was achieved on a cavity resonator mirror by combining a passive tuned mass damper with an active rate feedback vibration control network that included piezoceramic devices. Much of the work following these early efforts into the early 1990's focused on spacecraft applications [e.g., 7-10].

Beginning in 1993, the Defense Advanced Research Projects Agency (DARPA) recognized that smart materials and structures technology provided a specific opportunity for many technological breakthroughs. An eight year program was initiated to develop new, affordable smart materials and structures and to demonstrate the performance gains achievable in system applications. The program focus to achieve aerodynamic and hydrodynamic control and to reduce noise and vibration in structures.

At present, there are two approaches to the development of smart materials and structures. The first attempts to synthesize new materials at the atomic and molecular level to produce new materials with smart functionality. The success of this approach will depend on new scientific discoveries, and because of this, technologies deriving from this approach are very immature.

The second approach attempts to develop new materials by synthesizing composite materials and structures from known constituents. The active elements are either embedded in or attached to conventional structural materials. Typical smart structure sensors include fiber optics and piezoelectric ceramics and polymers. Embedded sensors can be used in discrete or distributed locations to provide built-in structural

Paper presented at the AGARD Symposium on "Future Aerospace Technology in the Service of the Alliance", held at the Ecole Polytechnique, Palaiseau, France, 14-17 April 1997, and published in CP-600 Vol. 1.

quality assessment capabilities, both during composite processing and system operation. In terms of system performance, it is important that the right feature be measured--e.g., strain associated with curvature or deflection--and its signal interpreted with respect to the desired performance outcome--e.g., a change in lift. Typical smart structure actuators are shape memory alloys (SMAs), piezoelectric and electrostrictive ceramics, magnetostrictive materials, and electro- and magneto-rheological fluids and elastomers. When embedded with a sensor/signal processing network and an appropriate control system, actuators allow structural performance to be changed--e.g., to repair damage--or adapted to meet various operational performance criteria--e.g., to change wing lift. Actuator devices can be dynamic, such as for vibration suppression, or static, such as for shape control. The challenge then becomes one of designing and constructing the material and structures to realize the anticipated performance gains.

A number of programs have been initiated by the Air Force (AF), the Army, Defense Advanced Research Projects Agency (DARPA), the National Aeronautics and Space Agency (NASA), and the Navy to demonstrate the application of smart structures in a variety of systems--most specifically, aircraft, helicopters, and submarines. These efforts are essentially focused on aerodynamic and hydrodynamic flow control, vibration and noise suppression, optimization of lifting surfaces, modification of structural dynamics and aeroelastics, and provisions for flight path controls [11].

The idea of using adaptive structures to improve the performance of military aircraft is not new. A joint NASA/Wright Laboratory demonstration program--the Mission Adaptive Wing, flight-tested during the 1980's on an F-111A test aircraft--investigated active control of chordwise camber, spanwise camber and wing sweep while maintaining a smooth, continuous airfoil. Variable leading and trailing edge shapes were of particular interest. Shapes with large camber, large leading edge radii, and large thickness are desired for low speed flight because they provide high maximum lift coefficients. In high speed flight, on the other hand, drag becomes the dominate parameter; therefore, low camber, small leading edge radii, and small thickness are required. Observed benefits for the F-111A wing with variable leading and trailing edges were improved performance and terrain following, control of maneuver loads, and reduced radar cross section. While aerodynamic benefits were achieved, the devices and linkages needed to obtain the shape changes were so complicated as to be impractical for implementation.

2. VISION

Future military aircraft will benefit substantially from smart materials and structures technology. These structures may include aircraft wings, rotorcraft blades, air inlets, and engine nozzles, among others. Some of the expected benefits are, for example, enhancing aircraft and rotorcraft handling by manipulating lift or reducing drag, by changing control surface shape, or by affecting flow conditions over the lifting surface; producing twist in aircraft wings or helicopter rotor blades; reducing structural vibrations such as panel flutter, tail buffet, and blade-vortex interaction, including those caused by other mounted components like motors or gear boxes; reducing interior cabin noise; and monitoring system health to include damage detection, mitigation, and repair. Integrated electronic systems for improved aerodynamics and low observable characteristics as well as reduced manufacturing and assembly costs provide additional potential pay-offs.

The concept of shape adaptive structures and aerodynamic flow control figures predominantly in current thinking. Smart structures approaches consider either adding actuators to make a structure bend or adding actuators to the material to make a structure that bends. Design concepts of interest include wing warping, camber shaping/control surface deformation, and variable stiffness structures (Figure 2). Specific objectives in the shape adaptive structures area include developing innovative design processes, enhancing maneuver performance and eliminating discrete control surfaces. Among the expected performance benefits are reduced signature and drag, and increased take-off gross weight and increased range capabilities.

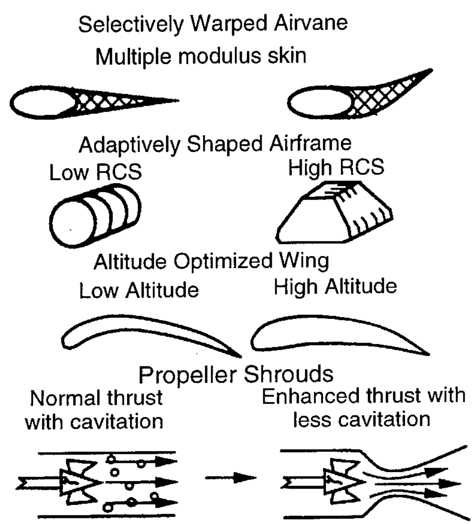

Figure 2. Design concepts for shape adaptive structures.

The inlet system of jet powered aircraft pre-conditions the air entering the engine. Jet engines require air to enter the engine at less than approximately Mach 0.5. Because of the wide range of Mach speeds, altitude, angle-of-attack, angle-of-slip, and engine airflow conditions, a fixed geometry inlet cannot provide ideal performance under all conditions. At low speeds it is desirable to have large inlets with very blunt lips. This allows the high airflows associated with take-off conditions to be drawn into the inlet without flow separation. At subsonic cruise, sharp inlet lips are desirable because they produce less drag. Sharp inlets also reduce radar cross section. At supersonic conditions, the losses resulting from rapidly decelerating the flow from supersonic to subsonic results in substantial losses in pressure and thrust. To overcome these limitations, variable geometry inlets have been used. The variable geometry inlets used on the F-15, for example, improve performance over a range of conditions, but their mechanical complexity adds weight and cost to the aircraft. Compliant mechanisms using smart materials and structures technology for variable leading and trailing edges are thought to be a simpler alternative to implement. These are flexible structures which change shape by deformation rather than by conventional rigid body motions.

When applied to structural dynamics problems, the use of smart materials and structures technology is expected to significantly reduce dynamic instabilities and vibrations (and hence, fatigue damage caused by vibrations). Acoustic signature affects military operations by increasing detectability; it also affects commercial operations--high noise levels in fly-overs or landing result in limited community acceptance. Vibrations impact passenger/crew comfort, weapons accuracy, and the fatigue life of most structural and electronic components; as a result, system reliability is reduced and maintenance activity increases. Several problems have been identified: tail buffet, wing/store flutter, isolation of electronic components from forced vibrations, helicopter blade-vortex interaction, and blade tracking.

- Twin tail buffet arises at particular angles of attack and tail locations when unsteady vortices generated near the wing leading edge impinge on the tails and induce severe structural vibrations. This can lead to premature fatigue failure. The buffet problem is particularly severe for the F/A-18 and F-15, evidenced by high costs associated with special inspections, repair or replacement of damaged tails, and redesign.
- Flutter results from an interaction of structural dynamics with the aerodynamic characteristics which causes divergent and destructive oscillating motions; it is a safety of flight concern. Solutions generally involve increasing structural stiffness, mass balancing, or modifying geometry, all of which typically increase weight and cost while decreasing performance.
- Blade-vortex interaction (BVI) noise is caused by the wake from the previous helicopter blade meeting the leading edge of the next blade. The aerodynamics of rotating blades are quite complex: the aerodynamic environment varies with blade position around the azimuth and leads to sub-optimal performance throughout much of the flight envelope, dynamic stall, etc. Note that helicopter acoustic noise, vibration, and aerodynamics cover frequencies up to about 40 Hz.
- Blade tracking adjustments, required to account for slight physical differences between the helicopter blades, is done infrequently due to the high cost and significant set-up time and subsequent maintenance. Vibrations increase when blades are out of track. Note that blade tracking adjustments are made at very low frequencies, less than 1 Hz.

All of these problems are of great concern and interest to the military. Smart structures approaches can be used to solve these problems. For example, BVI noise can be reduced by increasing the blade/wake separation, by reducing lift at the BVI point, or by weakening wake vortices. Specific techniques could include actively changing blade flapping, vortex trajectory, or lift/wake roll-up; reducing local blade lift; or deploying by vortex diffusion devices.

Aircraft structural maintenance has evolved considerably since the late 1950's when fatigue problems in aircraft were first observed. Recent advances in sensors, data acquisition capabilities, electronics miniaturization, and sensor system integration offer unprecedented opportunities for a structural health monitoring system (SHMS) and, eventually, to "maintenance on demand" [e.g., 12]. Such integrated systems could provide accurate, detailed stress histories for the aircraft and locations of damage (including the amount of damage). Large area damage such as would result from gunfire is much easier to assess; finding small, damaged areas that may later lead to failure is a much more difficult and challenging problem. Recent concepts look to combine sensors capable of detecting loads and environments with local preprocessors; the central processor interrogates each of the local preprocessors to obtain sensor data which are then analyzed and stored as required. This type of system offers flexibility in that it can be easily enlarged to handle growth; having a network of sensors also offers fault tolerance and redundancy.

Other approaches use multi-functional structures--i.e. structures that are designed to include multiple functional components such as radio frequency (RF) antennas, signal processors, and various types of sensors into a conformal structure--a smart skin. Military air vehicles typically contain large numbers of antennas which protrude from the surface. For example, the F-18 has 66 antenna apertures, covering frequency bands from 200 MHz to 18 GHz for radar and communications functions, located at 37 sites. These externally-mounted antennas require local reinforcement of the structure, which adds weight and cost, to accommodate electromagnetic windows. Non-conformal antennas degrade vehicle aerodynamic performance, require substantial maintenance, and increase the vehicle signature. The services are looking to reduce the number of antenna sites to some minimum number by combining functional capabilities of the different devices at fewer sites while still maintaining equivalent or better coverage. Some believe that up to 50% of the vehicle's surface could be used to exploit this capability [13]. Controllable, reconfigurable antennas or conformal antennas are probably required to achieve the desired mission flexibility. Potential benefits include reduced weight and volume; low observability (especially for conformal antennas); reduced energy consumption; improved system performance including flexible capabilities to enable new missions; and lower costs due to reduced duplication and potentially easier repair and maintenance.

3. CURRENT DEMONSTRATIONS

3.1 Shape Adaptive Structures

DARPA sponsors two programs particularly concerned with shape adaptive structures for aircraft.

- The Smart Wing program with Northrop Grumman, monitored by Wright Laboratory, is developing techniques for wing twist and camber control using smart structures approaches [e.g., 14]. Other team members include Lockheed Martin-Denver, Mission Research Corporation, and Fiber and Sensor Technologies; NASA-Langley is closely involved in the wind tunnel testing effort. Shape memory alloy (SMA) actuators are being used in the form of torque tubes to twist a 1/6 scale F/A-18 wing and in the form of wire tendons to create a continuously contoured trailing edge (with both up and down motion), both for improved lift. Distributed piezoelectric strain actuators will be used in Phase 2 for flutter suppression and gust load alleviation. Estimated performance improvements include an 8% increase in allowable take-off gross weight, 30% increase in weapons payload, and 20 to 40% reduced drag. The first Phase 1 model (Figure 3) was tested in FY96 in the NASA-Langley Transonic Dynamics Wind Tunnel (TDT); the next entry is scheduled for late 1997. Fiber optic

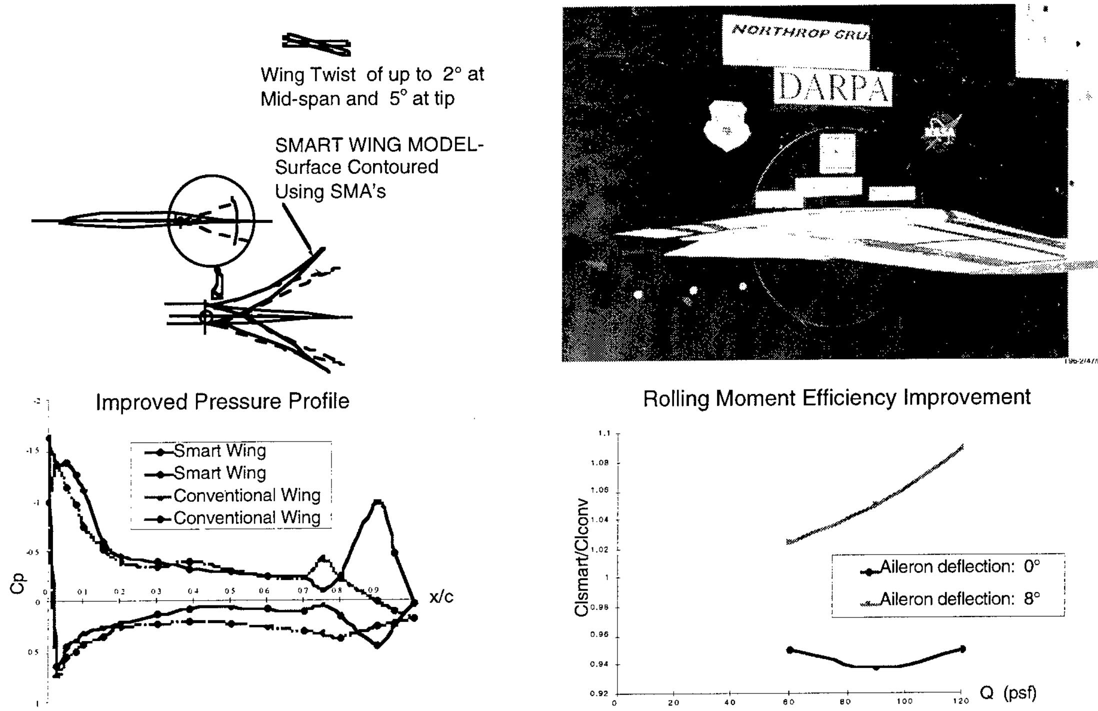

Figure 3. Smart Wing Phase 1 model with pressure distribution and rolling moment efficiency data.

pressure and strain sensors were included in the first wind tunnel test; the strain sensors were used as part of the feedback control; the specially developed pressure sensors were shown to be highly accurate. While the desired angle of twist (5° at the leading edge wing tip) was not achieved in the first wind tunnel test, 1.25° of twist was achieved; this resulted in an 8% improvement in lift. The hingeless control surface--SMA wires in the trailing edge flap--provided an increase in rolling moment of between 8% and 20%, a function of the particular test conditions, relative to that for a conventional design.

- Another Smart Wing task is examining approaches to allow subtle changes in wing cross-section to reduce transonic drag. What happens is that at the speeds most transport aircraft fly, just under Mach 1--air flowing over the wing can be supersonic in some locations and sub-sonic on others. When the airflow changes abruptly between those regions a shock wave forms over the wing. The objective is to provide a capability for shockless transonic cruise, allowing up to 75% reduced drag as well as reduced fuel consumption. The concept involves a truss-like system of magnetostrictive actuators, designed to fit a full-scale Gulfstream III wing [15]. This system will be ground-tested.
- The second major program, a new start called the Smart Aircraft and Marine Propulsion System Demonstration (SAMPSON), involves McDonnell Douglas with the following team members: Lockheed Martin-Denver, Georgia Institute of Technology, NASA-Langley, Naval Research Laboratory, Electric Boat Corp., BBN, and Pennsylvania State University-Applied Research Laboratory (PSU-ARL). This program is focused on both aircraft and submarine applications with a specific interest in shape and flow control approaches.

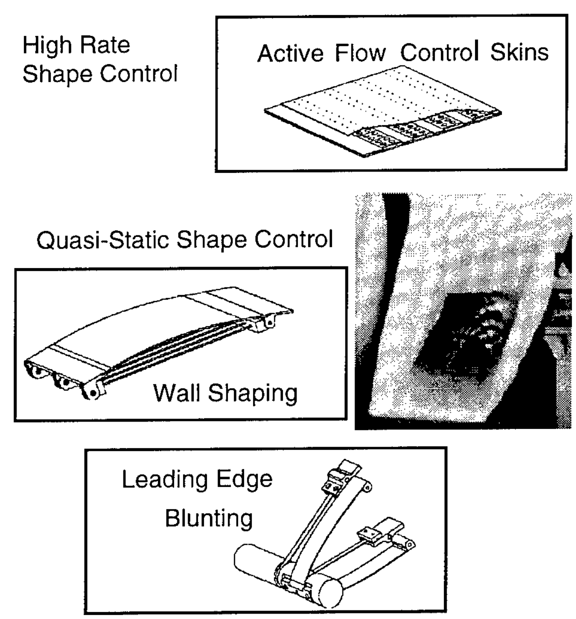

Figure 4. Active inlet with smart structures technology concepts.

Objectives for the aircraft portion include design, fabrication, and demonstration of a full-scale adaptive inlet for a tactical aircraft (Figure 4). Important core technology building blocks consider high rate shape control via airfoil shaping and active flow control skins (synthetic jets, see section 4.1.2) and quasi-static shape control by wall-shaping and leading edge blunting (both essentially compliant surfaces using SMAs). Potential benefits include improved range (20% for tactical aircraft) and maneuverability, flutter and buffet control,

Figure 5. ACROBAT model showing piezoelectric patches on fighter twin tail.

and reduced signature. Bench tests of some of the actuator devices are planned for 1997. These devices will be integrated into sub-components and tested in 1998. A wind tunnel test of the full-scale section is planned for 1999; the test is expected to demonstrate separation control with quasi-static shape changes and high rate flow control of inlet walls. Note that MDA has a related program with NASA-Langley and Georgia Tech for an Integrated MEMS Flight Maneuvering System. The objectives of this effort are to develop and test an integrated synthetic jet flight control module using micromachined fluidic drivers and multi-functional composite structures design and manufacturing. Each of these programs leverages the other.

Air Force efforts are focused on enhancing vehicle performance through elimination of discrete control surfaces and eliminating structural dynamic problems on current and future aircraft. Some of the AF demonstration activities have been done in conjunction with NASA.

- The Twist Adaptive Wing Structure is a Northrop Grumman effort not unlike the twisting helicopter blades described later in this section in function but it uses conventional actuators in an unconventional way. It is to be demonstrated during FY97 in ground and flight tests on an unmanned reconnaissance vehicle.
- The Active Aeroelastic Wing (AAW) (also called Active Flexible Wing) is a more complex project involving vehicle structure, controls, and aerodynamics to maximize performance [e.g., 16]. This multi-disciplinary effort takes advantage of inherent aeroelastic flexibility in the wing with the leading and trailing edge control surfaces being used as aerodynamic tabs. The airstream twists the wing with minimal deflections of the control surfaces. And surfaces can be optimized as a set for most efficient control under all flight conditions. This technique is expected to be flight tested. Combining variable stiffness mechanisms with this concept is expected to reduce the size and power of the control surfaces and actuation systems presently being used in the AAW as well as the weight--by as much as 30%, depending on the aircraft configuration and mission profile. Variable stiffness devices could also result in improved stealth characteristics and cruise efficiency and reduced drag, attractive in both manned and unmanned vehicles.

3.2 Vibration Suppression

Both the AF and NASA have supported extensive work in the area of vibration suppression. Specific vibration problems have been addressed to date with scaled models in various ground tests and wind tunnel tests. Flight tests are expected.

- In a NASA-Langley-sponsored program, with participation from Wright Laboratory and Daimler Benz Aerospace--Actively Controlled Response Of Buffet Affected Tails (ACROBAT)--a 1/6 scale F/A-18 drop model was tested in Langley's TDT in 1995-96 (Figure 5). Piezoelectric actuators were placed at the root for root bending and at other span locations for torsion [17]. Test results showed that, with single input/single output control, the piezoelectric actuators alleviated buffeting over the entire angle-of-attack range. This is believed to be the first model-scale demonstration of active buffet alleviation. Additional TDT tests are planned for 1998 and 1999. Full-scale ground tests are planned with an F/A-18 in Australia under the auspices of the Technology Technical Coordinating Committee (TTCP) program.
- The Active Vertical Tail (AVT) project to reduce buffet response was a joint venture between McDonnell Douglas Aerospace (MDA) and Parks College of St. Louis University [18]. The AVT is a 5%-scale, aeroelastically-tailored structure having similar vibration response to that of a full-scale aircraft. The piezoelectric actuators were attached to the spar to control the first two bending and torsion modes. This structure was tested in a low speed wind tunnel on a generic, twin-tail, double-delta wing, fighter model. Results were promising: the peak strain responses of the controlled AVT under various flight regimes were up to 65% lower than those of the uncontrolled AVT.
- The AF has sponsored several other projects addressing buffet load alleviation. Two of these--with ACX [19] and Rohini International--are examining layered and stacked

piezoelectric actuators, respectively, to solve this problem. A ground demonstration of the ACX system is expected in mid-1997 in Australia. The Rohini system will be demonstrated in ground and wind tunnel tests in late 1997. A scaled F-15 model was tested in the Subsonic Aerodynamic Research Laboratory facility under an in-house program at Wright Laboratory. A two-year, inter-agency program scheduled to begin in FY98 will down-select the most effective buffet load alleviation systems. A flight demonstration program is scheduled for FY00.

- A joint project between NASA-Langley and the Massachusetts Institute of Technology (MIT)--Piezoelectric Aeroelastic Response Tailoring Investigation (PARTI)--focused on addressing the wing flutter problem [20, 21]. The model, first tested in the TDT in 1994, is a 5-foot long, transport-type wing designed to flutter at low speeds [20] (Figure 6). Wind tunnel results from the first closed-loop test showed a 12% increase in flutter dynamic pressure and a 75% reduction in PSD of the peak response at sub-critical speeds by using the piezoelectric actuators with the best control law [21].

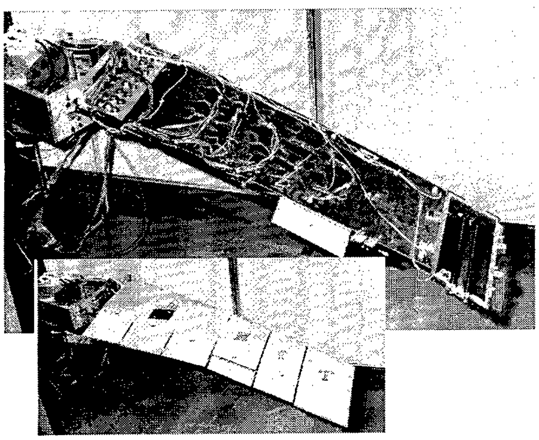

Figure 6. The PARTI wing model.

- An active fuselage panel containing a piezoelectric vibration suppression system will be flown on the B-1. This is the first known flight test of such a system on primary aircraft structure. The objective is to suppress forced response from separated flow. But it will also demonstrate that piezoelectric actuators can withstand the operational environment and loads of a real aircraft.
- Under a DARPA-sponsored program Lucent Technologies has applied active structural control to reducing structural vibrations in gas turbine engines [22]. They worked with Pratt & Whitney to develop solutions for particular vibration-induced problems in engine fan blades and vanes, engine cases, and external engine components. Expected benefits included improved engine durability, improved engine performance, reduced operating and support costs, and shorter engine development cycles.
- Boeing Defense and Space Group formed a DARPA-supported consortium--Smart Structure for Rotorcraft Control (SSRC)-- involving the Helicopter Division, MIT, PSU, and Analytic Engineering. This team is addressing active twist control of helicopter rotor blades as well as control of trailing edge flaps and trim tabs. Expected performance improvements include 80 to 90% reduction in vibrations, 5 to 10 dB reduction in BVI noise, blade twist of ≤±2°, and trailing edge flap motion of ≤±3°, all to be achieved without compromising the required safety levels. The designs and performance benefits are based on an existing CH-47 Chinook blade. Actuation schemes under consideration include SMA torsional actuators for trim tab motion, a discrete piezoelectric actuator for flap motion, and a distributed, interdigitated electrode-piezoelectric fiber "composite" (IDE-PFC) actuators for blade twist. The SMA actuator will be bench-tested and the two piezoelectric concepts will be integrated into a 1/6-scale blade and spin-tested. Experiments to evaluate integrity of the embedded piezoceramics as well as characterize their performance under loading conditions (especially fatigue) are planned. In addition, some efforts are underway to examine new ceramic actuator materials such as the phase-switching materials. A 1/16 Froude--scale CH-47 blade was fabricated using the IDE-PFC and bench tested to evaluate twist actuation performance: a maximum twist of 1.4° was measured (at 2000 V) under static conditions [23]. Preliminary analytical/simulation results for a rotating 1/16-scale rotor suggest that these concepts will be effective: when twisting the blade in forward flight a 70% reduction in 3/rev vibratory vertical shear was predicted with a 2.5% penalty in power; with no penalty in power the predicted vibration reduction was 40%. Promising benefits are predicted for hover flight conditions, too. Issues associated with such integrated devices include, particularly, actuator ability to handle the large centrifugal loads, as well as drag associated with external actuator elements and harsh operational environments.
- The McDonnell Douglas Helicopter demonstration, Smart Materials Actuated Rotor Technology (SMART) program (also supported by DARPA), considers active control of a rotor blade trailing edge flap and trailing edge trim tab [c24] (Figure 7). Expected performance improvements for the flap include a 10 dB reduction in BVI noise while landing; an 80% reduction in airframe vibrations; a 10% gain in rotor performance (lift/drag); and improved maneuverability from stall alleviation. For the trim tab the goal is to eliminate manual tracking requirements, relax blade manufacturing tolerance, and reduce vibrations. The designs and performance benefits are based on an existing MD900 Explorer system. Current actuator concepts for the flap include a multi-layer, co-fired electrostrictive stack with a pre-load mechanism and a stroke amplification flexure. Two torsional SMA tubes with a locking mechanism (to hold the tab in place so that power is not continually required) are being considered for the tab actuator device. Integration issues include actuator ability to handle centrifugal force loading, mass balance in the chordwise direction, actuator reliability and durability, actuator size with respect to blade geometry constraints and aerodynamic profile considerations, and blade structural integrity with the integrated devices. Risk reduction tests include characterization of actuator materials, actuator bench and spin tests, integrated system tests, and a full-scale rotor whirl test. Tests in the NASA-Ames 40x80 wind tunnel and flight tests are planned for Phase 2.

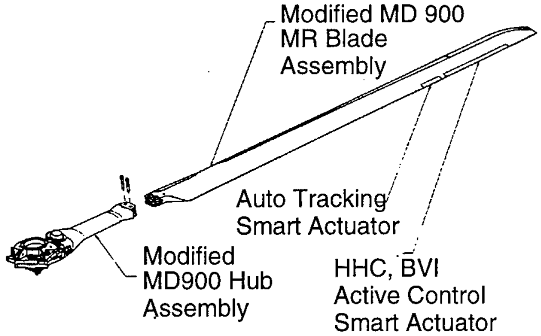

Figure 7. Smart helicopter rotor demonstration.

- In a new DARPA-sponsored program, Lucent Technologies and Sikorsky Aircraft are working two helicopter problems: (1) to reduce rotor blade noise via active rotor control and (2) to cut vibration and noise levels in helicopter cabins via active control of noise and vibrations carried through transmission mounts [22]. They are concerned about both low (e.g., from the rotor blades) and high (1 kHz from the transmission system) frequencies. Approaches being considered in the trade-off studies include blade root control, blade twist, blade flaps, and other active airfoil concepts. Technical issues identified to date are similar to those identified in the Boeing and McDonnell Douglas programs. Since the program was just initiated there are no results to report yet. Plans include design and fabrication of a model active rotor control system. The model will be tested at Sikorsky rotor test facilities as well as in an acoustic wind tunnel.

Concurrent with these DARPA programs are a number of other Army-sponsored efforts. These programs are focused on similar activities but at a more fundamental level: active circulation and trailing edge flap or tab control, active suspension for adaptive vibration isolation, active blade twist control, active fuselage walls for vibration damping and noise reduction, and active vibration control in a 20-mm gun. In a project at the University of Maryland, for example, researchers studied piezoceramic actuators embedded at 45° angles in a rotor blade to obtain 2° blade tip twist to reduce blade vibrations [25]. A two-bladed, Froude-scale rotor (1/8 dynamically scaled, 6 feet in diameter) was used in the analysis and for hover testing. Their data show that linear twist distributions of up to 0.6°, possible with current piezoelectric actuator technology, result in up to 10% increases in nominal rotor lift. While they did not achieve the target value of twist, it's expected that partial reduction of hub vibration is possible with current smart rotors. Among other projects at the University are examination of bimorph actuation concepts for trailing edge flaps, active/passive constrained layer damping treatments using shunted electrical circuits, and fiber optic sensors for strain and temperature measurement.

3.3 Structural Health Monitoring

Structural health monitoring represents a more near term opportunity for implementation of smart structures technologies.

- Northrop Grumman has developed and demonstrated a prototype Structural Health Monitoring System (SHMS) on a simulated wing spar and a multi-bay structure simulating a wing carry-through bulkhead [12]. Results indicate the acoustic emission sensors can detect cracks as far away as 18 inches in simple geometries (e.g., wing spar web); they are much harder to detect in complicated geometries (e.g., stiffeners between the bays in the bulkhead). Fiber optic sensors were more sensitive, detecting a small torsion in the wing spar which was not detectable with a conventional strain gage. These approaches will be evaluated on a full-scale fatigue test of an F/A-18 F.S. 488 bulkhead. Expected benefits of this technology include improved safety, reduced and simpler maintenance, and reduced life-cycle costs. Cost savings could be quite substantial: >$35 million is predicted for the F-18 (assuming 33 flight hours/aircraft, 1000 in fleet) [26]; >$9 million is predicted for the T-38 (assuming 420 flight hours/aircraft, 720 in fleet) [27].

3.4 Integrated Electronics

All of the services are interested in technologies which result in low observability. Specific approaches which allow a smooth surface shape to be maintained are, therefore, desirable. In all of the smart structures applications identified previously, the miniaturization of processing and control electronics will be one step toward achieving this goal. Some developments in this area described in section 4.1.3.

- The Air Force is supporting a demonstration program at Northrop Grumman--Conformal Load-Bearing Antenna Structures (CLAS)--to address some of these problems. Northrop Grumman, with TRW and PSU, will design and fabricate a full-scale, load-bearing antenna embedded in typical fighter fuselage skin structure (actually a hypothetical F-18 for a next generation mission) [e.g., 28]. Planned for 1997 are tests of the CLAS component, a communication/navigation/identification (CNI) antenna in the 0.15 to 2.2 GHz frequency regime. Their analyses indicate that many requirements can be met with a single broad band element, but selected narrow band elements-- annular slot, crossed slot, conformal patch, and/or spiral elements--are necessary to achieve the right gain levels as well as for special functions (e.g., GPS). Expected performance benefits include an entirely new electronic warfare (EW) capability for tactical fighter aircraft at very high frequencies--threat identification, threat angle of arrival, and situational assessment; potential to use higher EW frequency bands using same materials and processing techniques; significant low observable performance at relatively low cost; reduced drag/improved range; and enhanced low frequency performance at voice frequencies for panel area. Secondary benefits include reduced weight and ease of manufacturing due to eliminated fasteners and doublers and reduced structural cut-outs. For example, the AF predicts a cost savings of about $250k per airframe with a weight savings of about 70 pounds for the F-22. Future smart skin efforts will look at improved avionics and, eventually, completely integrated antennas and avionics (load-bearing) combined with adaptive structures, vibration suppression, and health monitoring capabilities.
- Northrop Grumman has investigated conformal antenna installation in the vertical tail of a military aircraft [29]. Their analyses indicate that communication link ranges--VHF-FM (30 to 88 MHz), VHF-AM (108 to 156 MHz), and UHF (225 to 400 MHz)--can be significantly

improved by such installation. They are particularly interested in the 30 to 88 MHz band (low VHF). Gain improvements of up to 100X are predicted for various combinations of element excitation. Structural integration considerations are significant due to the number of items already located there: lights, fuel dump, fuel vent tank, rudder actuator mechanisms, access doors, and narrow band radar warning antennas. Tail buffet and flutter must also be considered. Material concerns--moisture absorption and acoustic fatigue--for the candidate structural foam core were addressed by environmental and fatigue testing. Material and/or device susceptibility to lightning damage remains an issue. The resin transfer molding process (RTM) was selected, primarily for reasons of cost, to fabricate the vertical tail end cap. Note that both of these Northrop Grumman projects are constrained, to some degree, by the requirement to use existing avionics/electronics. With advanced avionics even greater benefits may be realized.

- As another example, the Joint Attack Strike Technology program is funding design studies and limited demonstration work at Westinghouse (now Northrop Grumman) and Hughes for multi-function radio frequency systems [30], the goal being lighter weight and lower life-cycle cost relative to current systems. These systems will include the multi-function nose array antennas, support electronics, appropriate application software, and sensor/resource management control. These nose arrays are expected to be used for air-to-ground and air-to-air radar functions as well as for traditional radar electronic warfare and communications/navigation/identification.

4. TECHNOLOGY STATUS AND ISSUES

In assessing the status of smart materials and structures technology, it is useful to estimate the time it will take to mature the technology for potential use. A schematic timeline is illustrated in Figure 8. While some elements of smart materials and structures technology are being demonstrated in current programs, there are still many technical issues to be addressed. Technical issues fall into the broad areas of devices, design, materials, manufacturing and integration, and control. Many of the specific concerns are being addressed by universities, government and national laboratories, and industry in on-going, government-supported research programs.

4.1 Devices

Performance of the individual elements in a smart structure--e.g., sensors, actuators, signal processing electronics, power conditioning and control electronics--will be critical to the successful demonstration of completely integrated systems.

4.1.1 Sensors

The most important performance parameters for these fiber optic and piezoelectric sensors include [32]:

- reliability/durability;
- consistent, predictable response;
- low cost (important if many devices are required);
- mechanical tolerances (device fit and finish for improved manufacturability);
- ability to handle an acceptable range of temperatures (composite processing temperatures for embedded devices as well as operational temperatures);
- aging (stable performance over long periods of time);
- sensitivity (figure of merit, varies with sensor type);
- electrical bias (for electrostrictive ceramics, complicates use).

Various types of fiber optics sensors (e.g., extrinsic Fabry-Perot interferometers, short- and long-period Bragg grating sensors) are frequently used due to their low weight, small size, high sensitivity to strain, multiplexing capability, and no electro-magnetic interaction (EMI) problem [e.g., 33] (Figure 9). While these sensors have a relatively large strain-to-failure compared to other devices, they are fragile and require special handling procedures in manufacturing,

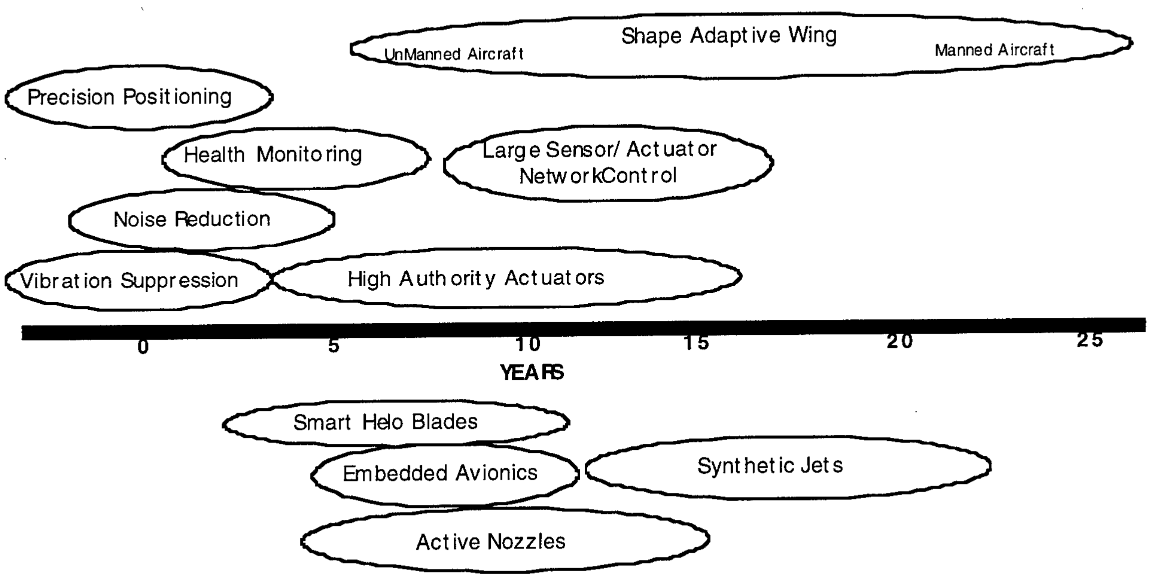

Figure 8. Estimated timeline for insertion of smart structures technologies into real systems.

particularly when they are being embedded. Fiber optics do require an external power supply in order to generate the signal. Signal interpretation is also an issue since the output is not electrical but they have a demonstrated ability to measure strain [e.g., 33, 34] and vibration [e.g., 35]. The issue of separating thermal effects from strain due to loads, a particular signal interpretation issue, has been addressed using a number of approaches. A particularly promising approach is a special variation of long-period Bragg grating sensors [33]. Piezoelectric ceramics and polymers are also highly sensitive to strain and have easily measured electrical outputs with the added advantage of no external power source required but suffer from EMI constraints (if embedded in composites electrical shielding is necessary) and temperature limitations. The ceramics are also limited by a relatively low strain-to-failure.

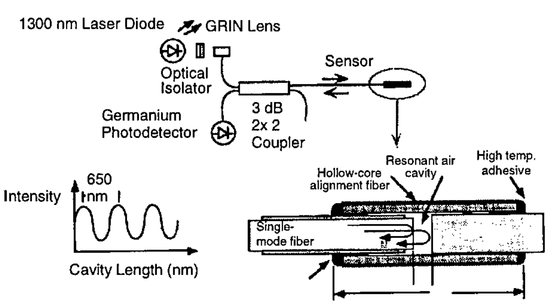

Figure 9. Extrinsic Fabry-Perot Interferometer (EFPI) fiber optic strain sensor.

4.1.2 Actuators

Desirable features for actuators include [e.g., 7, 8, 32]:

- consistent device-to-device and cycle-to-cycle response;
- extreme mechanical tolerances (especially surface parallelness and flatness in electro-active ceramics);
- low (or at least predictable) hysteresis;
- low creep (important when actuators must hold a position for a "long" time);
- large force/load-carrying capability (generally a trade-off with displacement capability) and large dynamic range;
- high frequency response (application-dependent need);
- linearity (displacement with respect to applied field);
- capacitance (for electro-active ceramics, important in high frequency applications for which drive current is a concern).

SMA actuators, which work via a temperature-induced microstructural phase change in the material, exhibit relatively large actuation force (recovery force) and high strain (recovery strain) output and damping capabilities but may also a large hysteresis. Note that the temperature at which the phase transition occurs and the amount of observed hysteresis can be adjusted by changing the material composition [36]. Typical forms include wires and rolled foils or sheets. Some researchers are examining sputtering techniques to deposit thin films for micro-scale devices [37]. The actuation mechanisms themselves can be fairly simple in design, an advantage over other types of actuators. However, due to their slow response time--attributed partly to the slow cooling capacity of the material--they are best suited for low frequency applications, on the order of a few hertz. Operational parameters such as temperature, time at temperature, stress levels, required transformation strains, and number of transformation cycles, will affect the long-term durability of these devices. The SMAs are quite suitable for slow motion of control surfaces such as flaps in helicopters [24] or trailing edges in aircraft [38].

The piezoelectric and electrostrictive ceramics both have limited strain-to-failure capability but a wide frequency response range and fast response time as well as a fairly large force output. The electrostrictive materials have additional disadvantages in that they are sensitive to temperature and exhibit non-linear performance which, in some cases, requires application of a bias voltage. The ceramic actuators are found in a variety of forms--thin plates [e.g., 39], multi-layer stacks [e.g., 40], injection-molded shapes [e.g., 41], and fibers [e.g., 42]. Thin plate-type actuators are a more or less standard product and have been utilized in many vibration suppression applications [e.g., 19-21]. NASA-Langley researchers have developed two unique configurations of piezoelectric actuators: RAINBOW (Reduce and INternally Biased Oxide Wafers) [43] and THUNDER (THin layer UNimorph DrivER) [44]. The RAINBOW actuators are fabricated by selectively reducing one surface of a piezoceramic at elevated temperature; these devices exhibit displacements which are several orders of magnitude greater than those of conventional piezoceramics but at the expense of actuator authority. The THUNDER actuators operate from the dc into the megahertz region and have high displacement, also at reduced authority. THUNDER actually refers to a process for packaging the ceramics: it is laminated to the ceramic under heat and pressure to place the ceramic in a pre-stressed state, giving it a domed shape. Such packaging offers increased environmental resistance and improved durability while maintaining the basic electrical properties of the piezoceramic. Interestingly enough, although the piezoelectric polymers are not typically used for actuators due to their very low authority, a group at Virginia Polytechnic Institute and State University (VPI) is considering a unique configuration of a poly-vinylidene-fluoride (PVDF) film over a shaped acoustic foam for control of interior cabin noise [45].

The rare-earth magnetostrictive alloys have high force and strain capabilities but are extremely heavy; magnetic field shielding is an issue. These actuators are often found as rods or multi-segmented stacks [46]. A group at Northrop Grumman has examined use of a magnetostrictive linear motor for controlling air foil shape of transport aircraft to optimize performance--e.g., improved lift/reduced drag, increased range, reduced fuel consumption--over a range of flight conditions [15].

Electro- and magneto-rheological fluids and elastomers consist of field-responsive particles suspended in a carrier fluid (with a stabilizer to help maintain particle suspension in the fluid) or embedded in an elastomer [e.g., 47]. These materials change their mechanical properties as function of applied field; these changes, evidenced by rheological variations (viscosity, elasticity, plasticity), are essentially reversible. Electrical or magnetic and thermal and acoustic properties are affected. The fluid-based materials are frequently considered for clutch, brake, and valve-type devices, dampers, shock absorbers, and the like. Issues for electro-rheological fluids include temperature stability, high power requirements, and fluid stability; these are not as significant a concern in magneto-rheological fluids.

Because the performance capabilities of currently "available" actuators are still orders of magnitude inadequate to address many application needs for large structures like aircraft wings, some researchers are investigating hybrid devices combining hydraulics and electro-active ceramics or magnetostrictives [e.g., 48]. Others are investigating the use of small micro-electro-mechanical system-scale (MEMS) devices to alter air flow over a surface. For example, the location of local flow separation over a wing could be changed by the placement of microactuators at the leading edge [e.g., 49]. The problem with this concept is that MEMS devices are fragile and this may preclude their use in many situations. As another example, aerodynamic shapes could be modified or turbulence, pressure gradients, and flow noise could be controlled by the placement of synthetic jets or "puffers" across the skin of the wing or in an engine air inlet [e.g., 50]. In addition, to help meet the expected future requirements for environmentally robust, durable, low power, high authority, high strain, fast response actuators, DARPA has recently initiated a number of new programs to develop higher authority actuator materials including, among others, shape memory alloys, single crystal electro-active ceramics, piezoelectric fibers, and injection-molded piezoelectric ceramics.

4.1.3 Electronics

Of primary concern in the area of electronics are the large size, weight, and high power requirements, particularly for ancillary support equipment--e.g., processors, amplifiers, cabling. Miniaturization of electronics devices will be a key advantage in addressing this problem. The Air Force and Ballistic Missile Defense Organization supported work at TRW on a modular control patch (MCP) [51]. The MCP, a 1-inch x 2-inch multi-chip module patch, provides retrofittable, miniaturized diagnostic and control electronics for vibration sensors and actuators. This patch integrates all the necessary features into a single, small, light weight, low power but reasonably capable package that can be embedded or attached to a structure. Note that an individual patch may be used in a local manner at a discrete location or in concert with a network of other patches in a global manner. A device like this was actually used to control embedded piezoceramic actuators in the yoke of a solar array structure to demonstrate vibration suppression capabilities [52]. The researchers noted a thermal dissipation issue with the electronics, particularly since composites may act as an insulator.

DARPA is supporting the development of high frequency switching amplifiers for use with electrostrictive actuator arrays [53]. The ultimate goal of this VPI/Virginia Power Technologies effort is to miniaturize these devices so they can be embedded into the structure with the actuators. This high efficiency amplifier is specifically designed for the capacitive loads that the small, "chiplet" actuators present to it (Figure 10). These are high efficiency devices: the measured efficiency is about 90% at 0.5 kHz with a decrease down to about 20% at 40 kHz.

Another important feature could be the development of small, lightweight power supplies that can be placed with the appropriate electronics for local control. For example, researchers at the AF's Rome Laboratory and at Johns Hopkins University have developed an all-plastic battery using polymers for electrode materials [54]. These batteries, useful in a wide variety of applications, can be recharged hundreds of times and can operate under extreme conditions without serious performance degradation. The finished cells can be as thin as a business card and are malleable so they can be cut to fit. Specific energy densities of 30 to 75 W-hrs/kg are thought possible with these batteries.

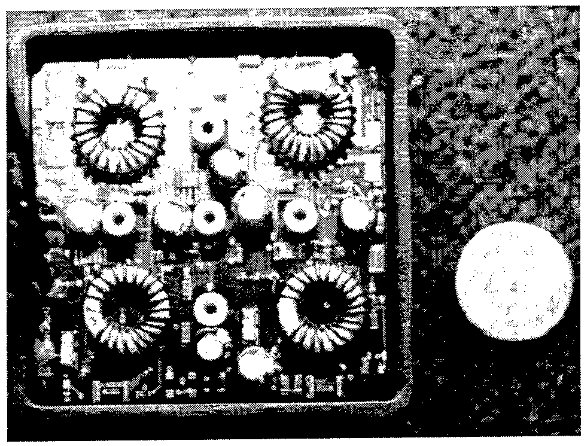

Figure 10. Miniaturized amplifier device.

Another jointly sponsored (AF, BMDO, and DARPA) program, the Spacecraft Integrated Electronic Structure (SIES), is addressing the weight issue by embedding power distribution and data transmission lines into structural skins [51]. General program objectives include reducing weight and volume by eliminating brackets and connectors and incorporating bulky cables into the composite skin. Electronics enclosure and harness weight reductions of 70% are predicted--note that these items typically represent about 68% of the total weight of a small spacecraft. Lockheed Martin-Denver has addressed issues associated with panel-to-panel connections and multi-chip module attachment to (and removal from) the skin.

Several researchers at PSU are examining innovative antennas for use in smart skins. Jose *et al.* [55] are investigating the use of barium strontium titanate (BST) for use as a tunable substrate in microwave phase shifters. The dielectric constant of these materials can be changed more than 50% by varying the composition and changing the applied bias voltage. In addition, the porosity of BST can be controlled during processing to some degree to produce dielectric constants ranging from 15 to 1500, with some trade-off in tunability. The substrates are prepared via tape casting or sol-gel processing of powders or microwave calcination, a combination of which seems to lead to the best performance. Varadan and Varadan [56] are developing spiral antennas with chiral absorbers. their efforts are focused mainly on reducing the size of these antennas using tunable dielectric materials. Their concept involves deposition of the radiator (e.g., using standard photolithography or thick film techniques) directly onto the radome. The primary advantage of the high dielectric materials combined with chiral absorbers in this application is the ability to make thinner antennas (factors of 4 to 10). They are combining these antenna concepts with advanced polymer materials and

MEMS, to develop a remote, local and global sensing and control system for a helicopter [57]. The idea behind the physical concept is detection of laminar flow-to-turbulent flow transition followed by transmission of acoustic energy into the boundary layer, the end objective really being to reduce drag. The physical concept includes piezoelectric polymer sensors with interdigital electrodes mounted onto an RF antenna. The sensors measure pressure and shear of the fluid flow over the structure. The resulting waveform measurements may be monitored at a remote location via the antennas in the sensors along with an outside antenna. The MEMS actuator devices are controlled by the integrated antennas via some feedback and feedforward control architecture. A later study applies similar concepts to cabin noise suppression, sensing of ice formation and de-icing, remote measurement of tip deflection of helicopter blades, a telemetry device for communication between sensors and actuators, and health monitoring [58].

4.2 Design and Analysis

Much progress in the area of smart structures has developed from interest in specific applications and devices with generally limited analysis. Models and analytical techniques that can reliably reproduce and predict system responses are necessary in order to achieve effective and useful designs. As an example, the primary focus of the AF-supported fluid-structures interaction studies is the development of methods to provide a better understanding of interactions between fluids (air) and structures. This is more fundamental research to gain knowledge and develop analytical/computational tools, for example, for solutions of problems of transonic and high angle-of-attack flutter using variable stiffness mechanisms and distributed actuation. Individual tasks will address adaptive structures, distributed actuation, and computational aeroelasticity. Basic wind tunnel aeroelastic models with variable stiffness devices and deformable control surfaces will be built and tested to verify analyses in the area of adaptive structures. Laboratory sub-scale models with piezoceramic strain actuators distributed through wing and/or tail structures will be built and tested as part of the distributed actuation tasks. Analytical tools will consider actuator size, placement, and force amplitude optimization issues.

One would like to begin with constitutive laws describing the active material/device behavior in terms of its inherent material properties. For example, Hom and Shankar [e.g., 59] have developed a constitutive model to describe electrostrictive ceramics. This fully coupled, 3-D model relates key variables--stress, strain, electric field, polarization, and temperature--based on particular material constants. As an additional example, five types of constitutive models--ferroelectric, internal variable, plasticity, hysteresis, and non-isothermal--have been developed to describe shape memory alloy behavior [e.g., 60]. These non-linear models rely on different characteristics and properties of the SMAs to describe stress-strain relationships, the superelastic effect and its attendant energy dissipation, one-way and two-way shape memory effects, etc. Physical constitutive models like these would be combined with constitutive equations for the host structure and then field equations to create equations of motion. The models must include all cross-coupling phenomena. Such an approach allows for a detailed understanding of the system.

To be ultimately useable by a design engineer, however, faster, more efficient computational methods that retain important features of the detailed physical models are necessary. The DARPA/industry- supported Synthesis and Processing of Intelligent, Cost-Effective Structures (SPICES) program, for example, addressed this efficiency issue via the use of superelements to describe piezoelectric device behavior within the context of a large finite element code--specifically ABAQUS--already being used by designers in industry [39]. Results showed good agreement between experimental and predicted broadband and modal responses for simple structures; techniques to improve this finite element modeling capability have been identified for more complex structures, too. As another example, Regelbrugge [61] modified Hom and Shankar's model to more easily evaluate the performance of a vibration cancellation device. He obtained excellent agreement between test data and the model for strain polarization as a function of induced strain and of electric field. The Air Force is supporting work at CSA Engineering to develop finite-element modeling techniques for smart structures, mostly considering vibration suppression applications such as buffet load alleviation, flutter suppression, and component isolation. Presumably, having such models available will allow designers to more easily characterize the collective system behavior and to evaluate system performance enhancements (e.g., increased lift, decreased fuel consumption, etc.).

Along with the general design approach and models noted above, come a range of more specific concerns. These include an inability to predict life of the device in a free or integrated condition, especially its durability and reliability in terms of fatigue, fracture and other mechanical performance criteria; a lack of understanding of cross-coupling (electrical, magnetic, thermal, mechanical, fluidic, etc.) among the various devices and the structure; and no fast, reliable method for determining the correct number and placement of individual sensors and actuators within/on the structure. Efforts to address life prediction, in particular, may require further development of micromechanics and non-linear mechanics models; such efforts will require extensive experimental tests to simulate the end-use operational conditions as well as to verify models.

4.3 Control Approaches and Algorithms

Control is one of the most challenging aspects in the smart materials and structures arena, in large part because of the complexities and uncertainties inherent to materials and structural dynamics of complex systems. One measure of controller performance is robustness. Robustness implies that the closed-loop stability and performance of the control system are insensitive to uncertainties stemming from modeling errors, nonlinearities, unmodeled dynamics, measurement errors, and other unknown disturbances: the more able a control system is to handle these uncertainties, the more robust it is considered to be. Inadequacy of the modeling capabilities certainly increases the degree of difficulty in achieving structural control. The complex behavior of the actuator materials, for example, presents a particularly difficult theoretical problem that may require development of new non-linear control theories and algorithms.

The selection of the control approach or of local vs. global control options is not straightforward. An even more significant problem lies in the control of large numbers of sensors and actuators, desirable for reasons of wide-band, spatially-distributed structural control, redundancy, and robustness. Rapid, real-time computational capability at high bandwidth is required in order for structural control objectives--mapping sensor outputs into actuator inputs in real-time--to be satisfied. The computational complexity is substantial and communication bottlenecks are expected. Current hardware limitations prevent full interconnection of all the devices, too. Control of these large device networks and the associated information management needs may, therefore, require development of new control approaches such as hierarchical control schemes, neural network schemes, or fuzzy logic controllers. While all are in development, none have been experimentally validated to any substantial degree in complex systems. SRI International is developing a hierarchical control methodology to address the kilo-input/kilo-output problem [62]. The technical approach is based on the wavelet transform commonly used in signal processing and numerical analysis [63]. It's akin to a Fourier transform except that it's decomposed into time and scale rather than frequency. Figure 11, a vibrating surface, schematically illustrates this scaling approach: the pyramids above the surface are projections of a virtual surface at coarser and coarser scales (in this way the every device is connected to every other device, although not directly); in essence, data points are being thrown away as one progresses away from the surface. Control can actually be implemented at any of these virtual surfaces, one way to get around the issue of local vs. global control. This computationally efficient processing scheme also provides a method for device selection and placement. A particular advantage of this approach is that it does not require optimization of placement of a small number of devices, a challenge when broadband control is desired.

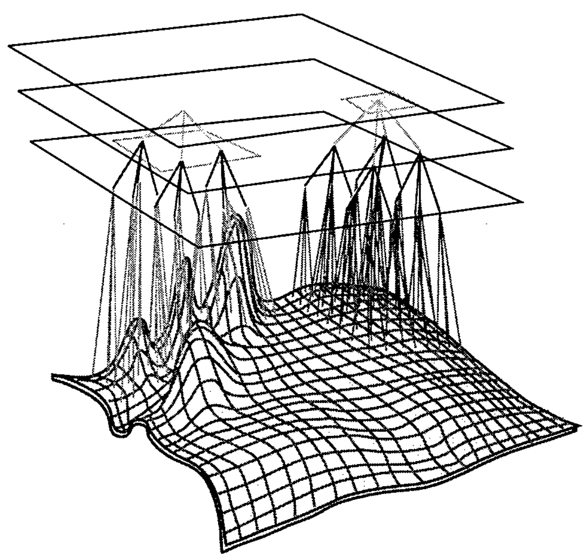

Figure 11. Schematic illustration of MIMO control concept.

A neural network (NN) is really a data processing structure in which processing elements are fully interconnected [e.g., 64]: each processing element can receive data from many sources but it can only be sent out in one direction; the output can branch with other connections but each one would carry the same signal. Typically each input is weighted and all the weighted inputs are summed. The weighting factors are adjusted by the NN during "training" to minimize the errors between the desired output and the NN output. It is important to note that these systems are not programmed but actually learn the way humans do, by example; the quality of the examples determines how well or efficiently the network will perform. The primary advantage of a NN is the orders of magnitude faster computational speed. There are several types of NN architecture but multi-layer back-error propagation is the most common: "multi-layer" refers to a feedforward arrangement while "back-propagation" refers to the method by which the NN is trained. These types of NNs are suitable for non-linear control problems such as for system identification (the first step in design and implementation of active controllers) [e.g., 65], damage detection [e.g., 66], and vibration control [e.g., 67].

A fuzzy logic controller is regarded as a set of heuristic (experience- or knowledge-based) decision rules which can be implemented on a computer [68]. Such control approaches are of interest to the smart structures community, primarily because the control system can be designed without complete analytical knowledge of the structural system. It is believed that these control systems will be quite stable, reliable, and robust; they also allow for adaptive control to suit changing needs. The fuzzy control process works as follows: controller input is "fuzzified" and processed by the fuzzy interface engine; fuzzy output is obtained by a "defuzzification" process and is converted to a control input to the system. The major issue in designing these systems is determining/selecting the appropriate rules. Geng *et al.* [69] have combined the fuzzy logic approach with a neural network scheme--Fuzzy Cerebellar Model Arithmetic Computer (FCMAC)--to allow for an adaptive, self-learning control system. Combining the two offers the advantages of both, apparently without too much loss in performance: e.g., ability to learn and handle non-linear behavior, rapid multiple input/output responses, and no need for complete, detailed analytical models. FCMAC controller hardware, MDSP-100, was successfully designed, built, and tested for controlling a magnetostrictive actuator to demonstrate active vibration isolation of a hexapod (Stewart platform).

One interesting technique--Vibration Control by Confinement™ or VCC™--has been developed by QRDC, Inc. [70]. This approach takes advantage of the phenomenon of modal energy localization: geometric or material property variations in a structure can result in vibrations concentrated in particular locations of the structure. This is observed most often in rotating and periodic structures but it can occur in all structures under the right conditions. By re-directing energy to non-critical parts of the structure, vibration in critical areas can be reduced. This energy re-direction can be achieved passively, through design, or actively via the use of a sensor/actuator/controller network. This approach results in simpler control systems--instead of having to control the whole structure one only needs to control selected regions. This approach has been successfully demonstrated on relatively simple structures.

Much of the university research in the area of smart structure control is focused on control of a few modes--using more conventional linear control approaches--in simple structures like beams and plates with just a few sensors and actuators.

Some of the more complex demonstration structures are being used to evaluate the effectiveness of a variety of control laws. For example, 28 different control laws were evaluated in the series of tests on the PARTI wing [21]: a linear quadratic Gaussian form using single input/single output with a strain gage for feedback along with all 15 piezoceramic actuator groups operating was the best. Even so, efforts to adequately assess the state of controls technology for more complex systems using smart materials and structures are inadequate.

4.4 Materials, Manufacturing, and Integration

Selection of the host material strongly influences the types of manufacturing and fabrication processes used to create smart structures. It's a relatively easy choice if the devices are to be attached to a metal structure, typically achieved via adhesive bonding. When devices are to be embedded in the structure--this implies a polymer composite host material--selection of the process can be more difficult. Early efforts to embed piezoelectric sensors and actuators, fiber optics sensors, and SMA actuator wires required hand lay-up and other special handling procedures [7, 8], a time-consuming and expensive process. Many current research programs are still using hand lay-up processes. Thus, there has been and continues to be considerable user interest in developing cost-effective, automated methods to fabricate these structures.

One of the primary objectives of the recent SPICES program was the development and demonstration of cost-effective methods for fabrication of smart structures [39]. This consortium evaluated two potentially low-cost techniques for embedding ACX Quickpack™ piezoelectric plate actuators, frame-type piezoelectric stack actuators, fiber optics, and SMA wires: resin transfer molding/RTM for a flat plate component and advanced fiber placement for a trapezoidal rail component. Concerns about device compatibility with the host material, interfaces and interconnects between the devices and the structure, methods to fix devices in place during processing, and edge egress of wires/cables from the structure were all addressed. For example, to prevent shorting out of the SMA in the rail component, an SMA towpreg consisting of wires embedded in a thermoplastic sheath was developed. For the RTM plate a rigid substrate--SMA wires embedded in a thin E-glass fiber-reinforced substrate--was developed; in this way the fibers could easily be pre-strained. Special shielding methods were developed to protect the piezoelectric actuators from the laser during fiber placement. For the RTM component, registration holes were required to hold the Quickpack™ actuators in place. A unique method--a clean-trim utility conduit--eliminated the edge egress problem so there were no wires hanging from the part. Lessons learned from this program are being applied in follow-on efforts.

While the SPICES program was very successful in identifying and solving problems unique to their selected processes, there are some others that have not been addressed to any significant degree. Some of the modeling and design issues with respect to materials have already been identified. Other concerns include a lack of methods to calibrate embedded sensors and actuators, very few reliable approaches to evaluate manufacturability--and cost--of smart structures, and limited understanding of environmental and operational durability of structures with embedded devices. One area that has not been adequately addressed is the embedding of electronic devices for computing and signal processing into structures.

5. CONCLUDING REMARKS

Smart materials and structures are those which can sense external stimuli and respond with active control to that stimuli in real or near-real time. These technologies are expected to provide new and innovative capabilities in future military aircraft including fighter and transport aircraft, unmanned aerial vehicles (UAVs), and helicopters and tilt rotorcraft. Current activities in the field range from enabling research in individual discipline areas--i.e., materials, sensing and actuation techniques, control algorithms and architectures, etc.--to the design, fabrication, and test of fully integrated structural systems. An estimated timeline for technology maturation, which would pace the insertion of the technology into production systems, is presented.

6. ACKNOWLEDGMENTS

We would like to acknowledge the assistance of the following individuals and organizations in the preparation of this paper: Mark Hopkins and James Tuss at the Air Force/Wright Laboratories; Spencer Wu at the Air Force Office of Scientific Research; Gary Anderson at the Army Research Office; Leo Dadone at Boeing Defense & Space Group, Helicopter Division; Ed White at McDonnell Douglas Aerospace; Friedrich Straub at McDonnell Douglas Helicopter; Garnett Horner, Anna McGowan, Bob Moses, and Darrel Tenney at NASA-Langley; Bob Badaliance at Naval Research Laboratory; Jay Kudva at Northrop Grumman; Kam Ng and Wally Smith at Office of Naval Research; Ken Chou at SRI International; Doug Lindner at VPI and Troy Schelling at Virginia Power Technologies.

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SURVIVING A HELICOPTER DITCHING: AN ENGINEERING CHALLENGE

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Introduction

The audience today is primarily engineers, and the first objective is to convince them that flying a helicopter over water is more dangerous than flying a fixed wing aircraft over water. The evidence for this was first reported in 1984 by the UK Civil Aviation Authority (CAA) in the HARP Report (16). It concluded that the accident rate for helicopters operating over the North Sea was 2.0 per 100,000 flying hours compared to 0.4 for fixed wing aircraft. A subsequent review of accident data by the CAA (17) in 1995 reported that "In the 18 years from 1976 to 1993, the offshore industry has generated 2.2 million helicopter operating hours in the transportation of 38 million passenger for the loss of 85 lives in eight fatal accidents. This represented a fatality rate of 3.86 per 100,000 flying hours."

Survival rates for military helicopter accidents into water were presented at the AGARD Symposium in 1992 (1). These ranged from sixty-five to eighty-four percent (US Navy and Marines 83%, Canadian Forces 76%, British Military Forces 84%, and French Navy 65%). In 1996, the US Navy reported a 19 years record of helicopter ditchings. From 1977 - 1995, there was an overall 75% survivability associated with survivable Class A over-water mishaps (23). The survivability rates associated with night accidents for the AH-1, CH-46 and CH-53 were lower, and for the CH-46, less than 50% of the victims survived. On the civilian side, Ferguson reported (11) an overall survival rate of 62% for helicopters operating in the North Sea from 1969 to 1987. The current ditching data (Table 1) for the North Sea from 1969 to 1996, including the Super Puma LN-OBP that ditched off Stavenger in January 1996, shows a survival rate of 65% (number of helicopters 38, number of crew and passengers 431, number of fatalities 150).

Many of these accidents are survivable yet mortality is high. The Human Factors of survival from a helicopter ditching have been described in an AGARDograph (11); many of the problems are caused by poor human engineering. Since the AGARDograph was written eight years ago, there has been little attention paid to improving the human engineering of the cabin and the fuselage. It is still not realized by engineering designers that escape from an inverted rapidly sinking helicopter in cold water is far more complicated than making an emergency ground egress from the cockpit or cabin on dry land. It is, therefore, the intention of this paper to step through a typical ditching and describe at each stage where engineering problems lie and recommend solutions. The objective is to persuade helicopter designers and manufacturers to make improvements, and for operators to demand improvements.

Preflight

For civilian and many military operations, helicopter flights over water tend to be of short duration. They are typically between shore and ship and rig. They are often unscheduled and there is an urgency to lift off as soon as possible, particularly if the weather is closing in. For personnel returning from duty on a ship or rig, there is a sense of "get home-itis". As a result, little attention is paid to finer details concerning personal equipment such as (1) correct donning of immersion suits, (2) physically or visually locating lifejackets and emergency doors/ hatches/windows, (3) correctly stowing personal equipment, (4) checking the strapping in procedures and (5) mentally checking the primary and secondary emergency escape paths. Just a simple action such as insuring that the loose or tail end of the seat belt is tucked inside the fastened belt to stop it floating across the release latch can be life saving. In the underwater escape trainer, it has been noted that with water turbulence, the end of the belt naturally floats free and often obscures the release box. As observed many times, a disoriented subject panics when unable to find the edge of the catch to insert the fingers and release the harness. The harness is a typical example where a standard type used for all fixed wing aircraft has been adopted for the helicopter. Unfortunately no consideration has been given for the fact that the survivor will likely be in an inverted underwater situation. With additional thought, the simple addition of a Velcro strip will solve the problem.

Because the stay on a rig or ship is short and often on business, passengers tend to have more carry on hand baggage (i.e., a briefcase, overnight bag and lap top computer than suitcases that stow in the hold). But there is not as much room in the cabin to stow it. It tends to be crowded around the feet and under the seat ahead. In the event of an accident, not only does the baggage become a missile flying around the cabin, but when the helicopter comes to rest, it can severely physically hinder access to the escape path.

There is always a reluctance to read instructions in the seat back pocket and pay attention to pre-flight briefings. This is part of the self-denial attitude that is inherent in all of us - "an accident simply isn't going to happen to

Paper presented at the AGARD Symposium on "Future Aerospace Technology in the Service of the Alliance", held at the Ecole Polytechnique, Palaiseau, France, 14-17 April 1997, and published in CP-600 Vol. 1.

Table 1 List of Civilian Helicopters Ditched into the North Sea or off the Coast of the British Isles 1969-1996 (modified from J.D. Ferguson)

HELICOPTER		DATE	ONBOARD	FATAL	ACCIDENT SITE	CAUSE
United Kingdom						
Bristow						
S-55T	G-AOHE	12/06/69	3		E of Gt Yarmouth	Engine Failure
S-61N	G-AZNE	04/04/73	1		NE of Aberdeen	Excessive deck movement
B206A	G-AXKE	01/08/75	1		Forties Field	Fuel shortage?
Wessex	G-ATSC	08/03/76	14		E of Bacton	Intake covers not removed?
S-61N	G-BBHN	01/10/77	3		NE of Aberdeen	Main rotor blade pocket failure
B212	G-BIJF	12/08/81	14	1	S of Dunlin Field	Pilot disorientation
Wessex	G-ASWI	13/08/81	13	13	Off Norfolk Coast	Mechanical failure?
B212	G-BDIL	14/09/82	6	6	N Murchison Field	Night SAR-bad weather
B212	G-BARJ	24/12/83	2		Brent Field	Winch cable snagged during training
B212	G-BJJR	20/11/84	2	2	NE of Humber	Flew into sea-mechanical failure
S-61N	G-BDII	17/10/88	4		2OM S of C. Wrath	Ditch on night SAR
Tiger	G-TIGH	14/03/92	17	11	Cormorant Alpha	Ditched after bad weather take-off
S Puma	G-TIGK	19/01/95	18		East Brae P'form	Lightening Strike
British Caledonian						
B214ST	G-BKFN	15/05/86	20		NE of Fraserburgh	Main rotor collective problem
British Airways International						
S-61N	G-ASNM	15/11/70	3		E of Aberdeen	Main gearbox oil leak
S-61N	B-BEID	31/07/80	15		ESE of Aberdeen	Oil cooler drive belt failure
S-61N	G-ASNL	11/03/83	17	20	NE of Aberdeen	Main gearbox failure
S-61N	G-BEON	16/07/83	26		Penzance/Scillies	Flew into sea in fog
Chinook	G-BISO	02/05/84	47	45	Cormorant Field	Double hydraulic failure
Chinook	G-BWFC	06/11/86	47		E of Sumburgh Airport	Crashed into sea - gearbox failure
S-61N	G-BEID	13/07/88	21		E of Bressay	Ditched, sank - engine failure
S-61N	G-BDES	10/11/88	13	6	Nr Claymore Field	Vibration/oil leak
S-61N	G-BEWL	25/07/90	13		Brent SPAR	Tail Rotor Strike on crane
Management Aviation						
B0105	D-HDGB	12/07/76	4		Off E Anglia	Engine failure - ditched
Bond						
B0105	G-AZOM	24/07/84	3		Off Hunstanton	Tail rotor failure
B0105	G-BGKJ	25/04/89	2		Yellsound	Engine failure/slush ingestion
Denmark						
Maersk						
B212	OY-HMCS	02/01/84	3	3	22nm E of Dan B	Tail rotor failure
Netherlands						
KLM						
S-61N	PH-NZC	10/05/74	6	6	110nm N of Texel	Main rotor blade failure
Schreiner						
SA365N	PH-SSN	19/04/88	5		40nm off Rotterdam	Disorientation
Norway						
Helikopter Service						
S-61N	LN-OQA	09/07/73	17	4	SW of Stavanger	Tail rotor gearbox failure
S-61N	LN-OSZ	23/11/77	12	12	SW of Stavanger	No cause established
S-61N	LN-OQS	26/06/78	18	18	W of Bergen	Main rotor spindle failure
B212	LN-ORL	31/07/79	3		Off Stavanger	A/rotation accident
S Puma	LN-OMC	15/07/88	18		70nm Stavanger	Main rotor blade leading edge failure
B212	LN-05C	10/08/91		3	Ekofisk Field	Main rotor hit flare stack
S Puma	LN-OBP	18/01/96	18		30nm Stavanger	?
EIRE						
Irish						
B105C	E1-BD1	03/06/81	1		Arran Isl Donegal	Fuel Starvation? Cargo slinging
Private						
Ball Jet Ranger	G-MHCC	20/03/92	1		Morecambe Bay	Engine problem

us". In association with this, because there is often an urgency to get airborne, the crew tend to hurry the pre-flight briefing and in some cases, simply omit it. The 1992 Tiger (G-TIGH) accident from the Cormorant Alpha Rig is a typical example of a short flight (32). The shuttle flight was only planned for a few minutes between an oil production platform and a nearby accommodation "Flotel". Forty-seven seconds after take off, the helicopter ditched and 11 out of 17 crew and passengers lost their lives. Post accident, it was found that several people who perished had not closed their immersion suits securely and one person was found drowned with the cord from the headset wrapped around his neck. The quick release jack plug had failed to separate because it had been trapped in the headrest.

Thus, a pre-flight briefing is essential to re-emphasize all the hazards of a ditching. However, it is not a substitute for underwater escape training, which should be mandatory for all who fly in a helicopter over water for a living. Therefore, engineers should design seats, harnesses, and safety equipment that need the least explanation of use if any explanation at all, and that are simple to operate; and they should provide ample stowage in the cabin for hand luggage.

Once in Flight

The accident occurs with very short warning and during a critical phase of flight

There is commonly less than one minute of warning before a helicopter ditching occurs. In nine out of ten Canadian Sea King ditchings between 1952 and 1987 (10), there was less than 15 seconds warning; and in the tenth, only 2-3 minutes. The CAA review in 1995 (17) reported that of 15 survivable accidents, warning time was greater than 5 minutes in five cases, 1-5 minutes in three cases, and less than 1 minute in seven cases. If the pilot becomes disoriented, the helicopter flies into the sea without any warning, and the crew and passengers instantly find themselves in a life-threatening situation. This must be recognized and appreciated by engineers when designing crashworthy seats, harnesses, dashboards, escape paths, doors/hatches and windows.

The accident usually occurs during one of the critical phases of flight, i.e., take off, transit, hover, missed approach and landing. Due to the shortness of flight, or to the excitement of getting back on board the ship/rig or of returning home, passengers generally pay little attention to the phase of flight. Survival training establishments should emphasize to students that it is most important to be aware of the critical phases of flight. During these phases, students should be taught to mentally rehearse the crash position and the escape path, physically check the immersion suit, the lifejacket and harness, verify the escape path is clear of hand luggage and practice a crash position. It is obviously too late when upside down in frigid water at the point of drowning.

The accident - impact with the water

Helicopters, in spite of flotation bags, do not float well. Current data of the percentage of helicopters that have sunk immediately is 72% in the French Navy (20); 50% in the British Military forces (25); 39% in civilian helicopters operating in the North Sea (11) and 26% in the Canadian Forces (1). They commonly roll inverted and sink rapidly. The RAF (34) reported all four ditchings between 1971 and 1983 had resulted in an inverted helicopter; and between 1972 and 1984, the Royal Navy (35) reported that in 53 ditchings, 25 helicopters had inverted. At this stage, if the accident has been "a fly in", or has occurred with little warning, the cabin becomes severely distorted. If it is not crashworthy, and many are not, there will be contact injuries to the crew and passengers which transiently incapacitates the potential survivor from making an escape in the vital 20 seconds post impact. In addition, the phenomenon of in-rushing water is terrifying. One pilot described it like being hit in the chest with a fire hose. It causes panic, hyperventilation, disorientation, reduced breath holding, arrhythmia and drowning. It is critical to adopt a good crash position to reduce the body profile to the in-rushing water, to stabilize the body in the seat to prevent flailing, to reduce the body profile as a human target to flying debris and to assist in reorientation post accident. It is, however, more critical that engineers first design a crashworthy cabin with a good restraint system.

The helicopter has now come to rest sunk and inverted

Post accident, the cabin anatomy may be considerably distorted and bear little resemblance to the pre-accident condition. The survivor is now strapped in underwater holding his/her breath and the survival clock is ticking. Drowning, particularly if the accident has occurred in cold water, is the immediate threat. Hayward (21) demonstrated that breath-holding ability is reduced from 25 - 50% in water under 15°C, and at 0°C breath-holding is approximately 17 seconds. Tipton and Vincent (30), during a test of partial coverage wet suits in 5°C water, showed that maximum breathholding time may be as short as 10 seconds. In an underwater escape trainer with warning and under the best conditions, it takes most students at least 15 seconds to escape.

The concept of providing a source of air to enable escape from underwater is not new. An A-13 mask and A-14 oxygen regulator with US Navy walk-around assembly was tested and approved for fitting in US Navy aircraft in 1945 (2). In the recent past, compressed air supplies in the form of a small cylinder fitted on the body or in the back pack have been introduced by the US Navy, the US Coast Guard, the Canadian Air Force, the Royal Navy, and the Italian Navy. Before adopting compressed air, the US Coast Guard introduced an LPU-28-P lifejacket made by Soniform that had a bladder which could be inflated with pure oxygen. This lifejacket is still available for civilian crews. Whenever a compressed air supply is considered, there is always the slim risk during the escape training of an air embolism. Such a case was reported by Benton et al (8) from a one meter ascent in 1996. In the North Sea, Shell UK, in conjunction with Shark Sports Ltd, have introduced a survival suit which is provided with an air pocket for rebreathing exhaled air. This solves the problem of side effects from breathing compressed air.

Sowood and Higenbottam (28) demonstrated that it was possible to stay underwater (32 - 34°C temperature) for over two minutes using a compressed air HEED II system. This compares to 50 seconds for a rebreathing system. Sowood (27) found that in 11°C water, subjects could remain submerged for over 40 seconds with the HEED II, twice as long as with a rebreathing system. However, there has been little data published in the literature on the subject. In the next generation of helicopters, a review should be undertaken comparing the advantages and disadvantages of a compressed air supply versus a rebreathing system, and whether it should be engineered into the seat as is the oxygen system of a passenger airliner.

After all motion has stopped, the survivor must then unstrap and navigate in the pitch black through bubbles and debris to an escape exit. Underwater lighting is not the solution to the problem, it is only an adjuvant. Allan et al (4) demonstrated that the majority of people can only see 1.5 meters underwater and 3.1 meters in the best well lit conditions. People do not like opening their eyes underwater and many trainees do the underwater escape trainer exercise entirely by touch rather than vision. For those who do not have to wear a protective helmet and other helmet mounted devices, a pair of good diving goggles fitted in the pocket of the immersion suit is as good a help for escape as any current underwater lighting system. The solution is to have an escape exit within easy reach of each crew/passenger without them having to travel any distance. Swimming to an escape hatch is fraught with danger. It uses up precious breath-holding time to reach the hatch, and it is possible the survivor may swim in the wrong direction or simply get lost in the cabin. This is due to the disorientation produced by sudden immersion in water, loss of gravitational references, inversion, water up the nose, darkness and being over buoyant wearing an immersion suit. Even the most stoic person may perish. So the primary escape path must be very short, within arms reach and preferably within hands reach of each seat.

The secondary escape path must also be within arms reach, so negating the requirement to swim to an exit. Then, escape hatch lighting becomes a secondary rather than a primary help. Allan demonstrated a simple strobe light bar fitted on the deckhead and deck to aid in escape (3). To date, no helicopter manufacturer has introduced this excellent, simple, cheap idea into their helicopter.

Releasing the door/window/hatch

Consider the survivor so far. He or she has survived the impact, undone the harness and has navigated him/herself to the emergency escape hatch, whether it be a primary access door, a cargo/hoisting door or an emergency escape hatch. Unfortunately, there is complete ergonomic confusion how the escape door/hatch or window should be designed and operated. In 1991, a preliminary study by Bohemier et al (9), reviewed the factors that affected egress from a downed flooded helicopter. Of particular note was the difficulty in locating and jettisoning the escape exits. Later, in 1994, Brooks et al (15) demonstrated that in the four Canadian helicopters (Sea King, UH-1 Huey, Bell Kiowa and Boeing Labrador), the jettison mechanisms were not standardized either in type or position relative to the operator. Thus, there were many occurrences of rotation errors accentuated by being inverted and neutrally buoyant. The mechanism was hard to locate and did not in many cases match the task, i.e., depart the fuselage with the door or window; this was because the lever was mounted in the door frame and not on the door/window/hatch. Thus, underwater the survivor had no feed back that operating the lever had any effect on jettisoning the door; and except in the case of the Labrador, all the levers rotated in only one direction, rather than in either direction from a single detent. Finally, there was no agreement whether the door/hatch/window should push out or pull in. Confirming these findings, in 1996, Barker and Bellenkes (7) reviewed 210 survivable US Navy and Marine Corps ditchings from 1980 to 1994. They reported 489 egress problems in 128 of the mishaps. Difficulty finding and releasing hatches was the most frequent reported problem in the cockpit, particularly in the H-3 and H-60 helicopters.

Brooks and Bohemier (14) conducted a further study of 35 helicopters that earn their living over water and revealed the problem is universal. There were 23 different mechanisms on these helicopters which could be pushed, pulled, lifted up, or rotated. The position of activation relative to the body ranged from shoulder level to foot level; moreover, there was complete inconsistency in which direction the door/hatch/ window should jettison, indeed in one case it had to be first pulled in and then pushed out! Finally, there was inconsistency between types of mechanisms within each type of helicopter. For example, the Sea King has three different mechanisms and the EH101 has four; and on helicopters such as the CH-53, the pull out tab on the window seal can be found in four different positions. The maintainer can fit the window with the tab in any corner. The regulations in Europe and North America covering jettison mechanisms and escape hatches (19, 31, 33) are not specific enough, eg, the statement that the requirement for exit actuation should be obvious and natural to the operator is too vague. Finally, as Redman et al (25) demonstrated, the exit should be lighted for ease of location. Nothing is obvious and natural to an inverted submerged human holding on to his/her last breath of air. There should be one system common to the helicopter fleet, it should operate no more than 25 cms away from the resting bent arm, the mechanism should provide positive feed back to the survivor that the door/hatch/ window has jettisoned and all should jettison out. If a lever is considered it should rotate in either direction from a central detent to avoid rotation errors, and be easily grasped with a wet gloved hand.

Lifejackets, liferafts and immersion suits

The immersion suit is a vital piece of survival equipment. In the first one to three minutes, it protects the survivor from all the immediate physiological problems of sudden cold water immersion and rapid cooling of the skin such as hyperventilation, cardiac arrhythmia and drowning. It then protects against cooling of the muscle mass and consequent swimming failure that unprotected, occurs within about 15 minutes. Finally, it protects against longer term hypothermia (29). Nevertheless, it remains an unpopular piece of equipment because it is hot, bulky and, in many cases, not designed in conjunction with the lifejacket. It has reached the end of its design potential. The need is still to wear a protective suit, therefore new concepts are required (13). Seats and escape hatches have been designed for emergency ground egress and are often not large enough to accommodate the bulkiness of the current suits, lifejacket and any additional personal equipment (5). The UK Civil Aviation Authority airworthiness requirement for the smallest Type IV hatch is a minimum size of 483mm (19 inches) wide by 660mm (26 inches) high - not a lot of space to allow a large man in a survival suit and lifejacket to make an emergency escape. The smallest exits have great potential for snagging too. In addition, little attention has been paid to the final position of the jettison mechanism if it remains on the fuselage. For instance, in the Sea King, the pilot's lever rotates from nine o'clock to twelve o'clock. In this final position, it impinges on the open orifice for escape and has great potential to snag the lifejacket and immersion suit of the pilot as he/she makes an escape.

The situation with lifejackets is also not satisfactory. Lifejackets and immersion suits are often not, made by a single manufacturer, consequently integration between the two is poor. Humans using the current highly buoyant immersion suit can only be self-righted in a lifejacket of 275 Newtons. On the water surface, the bladder containing 50 litres of CO_2 or air is more of a hindrance than a help. The bladder interferes with vision and communication in the water, and only the strongest individuals are able to enter a liferaft unless it is partially deflated. Regulating bodies should require lifejackets and immersion suits to be designed as an integrated unit or pair.

There are two problems with the liferaft. First, in the majority of helicopters, it is mounted inside the fuselage and somewhere aft. Because there is very little warning of an accident, the survivor has precious little time to make his/her <u>own</u> emergency egress. There is no time to swim aft and use up precious breathholding time to locate and release the liferaft(s). It is also psychologically unnatural for a human to travel backward; in an emergency, one always goes forward. So, in the majority of accidents, liferafts do not find their way to the surface and the survivor is left floating in the sea exposed to all the dangers of cold water immersion. In the recent US Navy study of 67 survivable over water ditchings in the last 19 years, Kinker et al (23) demonstrated that the liferaft was successfully deployed in only 26% of the cases. A civilian example is the Schreiner Dauphin helicopter (PH-SSN) which ditched off Rotterdam in 1988. The pilot had become disoriented on approach to the ship and the helicopter hit the sea, capsized and floated inverted. Four of the occupants sat on the underbelly of the inverted fuselage of the floating helicopter for <u>30 minutes</u> while the pilots worked to release the liferaft stowed in the fuselage! This is a common problem across the entire military and civilian fleet (11).

Liferafts in the Bell 214ST are mounted external to the fuselage. They can be jettisoned manually by one of the pilots (if they have enough warning), or automatically by a pressure water activated switch if the helicopter sinks rapidly. The Sikorsky S76 and Puma can also be fitted with external liferafts, and as early as 1976, King (22) confirmed it was possible to fit external liferafts on the US Navy H-46. Yet operators have stubbornly continued to consider it acceptable to mount the liferaft(s) within the fuselage even though the track record of successful launching is poor.

There are two other problems with the liferaft; first is full inflation at the surface with the correct side facing the sky, and second, the difficulty with subsequent physical evacuation from the floating helicopter. In 1995, the CORD Group (12, 18) conducted a study for the Canadian National Energy Board on the problem of surface evacuation, they examined all fixed and rotary wing accidents from 1962 to 1995 where liferaft performance was reported. This included Anton's findings (6) in the North Sea between 1970 and 1983. They concluded that the liferaft had not performed well, noting the following problems: (1) raft loss because the helicopter rolled on top of it, (2) raft puncture or abrasion against the fuselage or by tail rotor strike, (3) raft being blown on to its side against the side of the fuselage, impossible to right, (4) survivors having difficulty in boarding, (5) line or painter securing raft to the helicopter cut by a sharp edge, and (6) raft difficult or impossible to launch with the helicopter balancing precariously on the water or in the process of capsizing and/or sinking.

Using the Nutec Super Puma simulator in the Bergen Fjord, the CORD Group (18) compared the dry shod or dry method of surface evacuation with the swim away or wet method. Forty-six subjects conducted evacuation from both the leeward and windward side of the helicopter in the Bergen Fjord in calm (sea state 1) conditions. It was concluded that if possible evacuations should be conducted dry and irrespective of techniques from the windward side. The wet evacuation should still be taught, but used only if the helicopter is immediately in danger of capsizing. The second conclusion was that for training pilots in a swimming pool is not satisfactory. In order for them to realize the gravity of the situation and be able to make the correct decision of which technique to use, they should be trained in open ocean conditions. The third conclusion, and this is important for engineers, is that in order to be able to evacuate on the windward side, helicopters must have a door on both sides.

Post immersion collapse

The survivor on the surface of the water in a fully inflated lifejacket is still not out of danger. If the liferaft has not been deployed and the immersion suit is leaking, then the immediate or short term effects of cold water may drown the person through hyperventilation, arrhythmia, cardiac arrest or swimming failure. For the survivor in the water for over 30 minutes, hypothermia is a potential cause of death. When rescue arrives, even if the survivor is alive in the water, there is a serious danger of cardiac arrest from rough handling and post rescue collapse. Post rescue collapse is caused by a precipitous drop in blood pressure through loss of hydrostatic squeeze which can occur if hoisted out of the water vertically rather than horizontally. During the 1979 Fastnet race (water temperature 15 - 16°C), three (20%) of 15 competitor fatalities occurred during rescue following a storm - one while being hoisted into a helicopter, the other two while climbing up a scrambling net that had been thrown over the side of a ship. In 1994, Ocker et al (24) demonstrated the seriousness of this problem by hoisting 20 young, healthy males out of the water after they had been cooled to 35°C. This was an enormous strain on the heart and the blood pressure could not be maintained in a vertical lift, but could be in a horizontal lift. Unfortunately, it is difficult to manoeuvre stretchers and litters through the cargo door of the majority of helicopters. So, rescue is conducted using either a single or double vertical lift harness. The US Coast Guard have made the most progress, using the Empra basket; here the survivor can be hoisted in a sitting position and can be easily negotiated through the hoisting hatch. A similar style Billy Pugh net is used by the Canadian Air Force. The RN now use a double strop which lifts the survivor up with the knees kept positioned at mid-chest level, reducing the pooling of blood in the lower abdomen and limbs, but the majority of SAR operations worldwide still use the single or double lifting harness.

Conclusions

Statistical data for helicopter ditchings worldwide demonstrate that survival rate from survivable helicopter accidents over water, whether military or civilian, is 65 - 86%, and about 10% worse for night accidents. The entire helicopter ditching event experienced by a crewman from preflight briefing to rescue is described. The principal reason for this 14 - 35% mortality rate is the poor design of helicopters - engineers do not realize or consider that a helicopter suddenly immersed and inverted in cold water is entirely different and far more difficult to escape from than on land. Yet it is an immediate life threatening situation, that needs special human engineering design to provide the crewmember with optimum chance of survival. Attention has been drawn to items for which improved human engineering would reduce the unnecessary loss of life. Specific areas that should be improved are crashworthiness of the fuselage; seat and restraint systems; escape distance and ease; standardization of mechanism and operation of escape doors, windows and hatches; liferaft stowage external to the fuselage and access from both port and starboard sides of the helicopter; and emergency breathing systems to extend endurance underwater. The solution to each issue is simple and involves low technology. Hopefully, both engineers and operators of helicopters will take heed. They should implement the solution in new helicopter design and where possible retrofit into old helicopters which still have a long projected service life.

Acknowledgements

Thanks are extended to Mr Bob Michas for his technical engineering advice and editing skills and to Mrs Nancy Wisteard for typing and formatting.

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Cockpit Usability - A Design Checklist

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1. SUMMARY

'Usability' represents the degree of help or hindrance provided to the pilot or crew member as they attempt to complete the operational missions with which they may be tasked; it also acknowledges the financial/technological realities against which designs are developed. The factors which impact cockpit and system usability, some of the steps necessary to achieve it, and suggested items for inclusion in a usability design checklist are discussed.

2. INTRODUCTION

A military cockpit must be 'fit for purpose' in that it should assist, or at least not hinder, the crew member from completion of his tasks; acknowledging the real technological and budgetary constraints of the future, it must also be affordable for industry and the customer. (The terms 'he', 'his' and 'pilot' are used herein to indicate both male and female aircrew.) In recognition of the potential impact of cockpit man-machine-interface (MMI) issues on the safety of flight,[1] human factor criteria are now being included in the airworthiness requirements of civilian regulatory authorities. However, the criteria for and measurement of MMI for certification raises its own problems.[2] Recent work on MMI applications in military cockpit design has concentrated on techniques for analysis and measurement of pilot workload; while some useful insight has been gained, it has not yet provided any direct improvement in the design tools used for cockpit development.

Historically, military aircraft specifications have relied on system performance measurements. However, as in the civil world, the influence of the MMI design on the pilot's ability to exploit that performance is now increasingly an issue and the degree of help or hindrance provided by the design to the pilot or crew member (as they attempt to complete the operational missions with which they may be tasked) becomes a critical factor; this is represented by the global term usability. There can be no single definition of usability since it relates to the various influences and interactions of each of the cockpit components: ease of ingress/egress, controls, displays, seating and restraint, body mobility, temperature, field of view, field of regard, etc. Usability is thus a design paradigm. We can be sure that good usability is a good thing and that poor usability will adversely affect the crew member's ability to carry out his operational tasks.

3. THE STARTING POINT

The combat cockpit is rarely comfortable. Comfort is not seen as mission enhancing. Ejection seats are incompatible with cushions and most protective equipment, designed to withstand ejection and high 'g' forces, increases the discomfort. Seated under a large expanse of perspex - a perfect green-house - the pilot's body will be physically stressed as helmet, head, arms, heart and other internal organs increase in weight many times under the application of 'g'. Depending on circumstances, the usual sensations often include some mixture of: heat, sweat, chill, vibration, hunger, thirst, bursting bladder, fatigue, numbness, aches or pain (bottom, back, neck), noise and - when threats are trying to kill you - fear.

Events change rapidly during combat and success depends on making timely, correct decisions. The pilot constantly strives to prepare for the next (unknown) event. For example, in modern air combat the opportunity to fire at an enemy aircraft often lasts less than 2 seconds and the shot can only be taken if the correct weapon selections are already made. Time pressure applies to every thing the pilot does and he can only allocate limited time to the multiple tasks of viewing displays, operating controls, looking outside and making decisions.[3]

Since the Wright brothers first flight, the meteoric growth in number and scope of aviation technologies has been matched, particularly in the military cockpit, by continuous increases in workload with each additional electronic box and dial. Recently, new display and databus technologies have allowed some consolidation and offered the possibility to depart from 'traditional' cockpit design. This

Paper presented at the AGARD Symposium on "Future Aerospace Technology in the Service of the Alliance", held at the Ecole Polytechnique, Palaiseau, France, 14-17 April 1997, and published in CP-600 Vol. 1.

introduces a new dilemma; should we start from a 'clean sheet' to maximise the new potentials, or should we rather build on old designs, taking the bad as well as good aspects? For a designer, the 'clean sheet' approach offers unlimited scope - for failing to learn from the past. Perhaps a better usability starting point is that the cockpit, display, equipment, whatever, should be *no worse* than any previous design.[2]

> *"A design which passes the 'Usability' test will be no worse than any previous design."*

Thus, the first question to be addressed in any cockpit, aircrew equipment or pilot-interactive system design process must be, "What is the *current best example*?" Establishing this baseline requires research; historic, since the lessons of the past are no less valuable in aviation than in other aspects of life, and innovative to exploit latest technological advances or possibilities. This requirement also begins to establish the composition needed for a 'Usability' design team.

4. FUNCTIONALITY & REALITY

Almost all design for the real world is a compromise and this is especially true for the military cockpit environment. While it may be easy to list the ideal operational or functional requirements for a military cockpit, there are inevitably technological and/or financial constraints that limit the achievement of those ideals. The helmet provides an example of the interaction of these constraints since, even before the pilot attempts to interact with the cockpit, he must be adequately clothed and equipped just to stay alive.

Early aviators needed hats or helmets simply to protect their eyes and keep their heads warm but, with the introduction of radio and high altitude capabilities, these also needed to contain, and correctly locate, headphones, microphone and oxygen supply. Subsequently, the combination of increasing speeds and ejection seats called for head impact protection, NBC weapons called for gaseous and liquid protection and now the need to feed the pilot information in as intuitive a way as possible has added further electronics to drive visual displays on the helmet visor.

Thus the hat originally chosen for comfort has developed into a hard shell that supports electrical, gaseous and optical technologies and in some projects its name has expanded to 'Head Equipment Assembly' (HEA). Even before the advent of HEA, the helmet mass and size necessary for impact protection hindered head mobility and look-out, especially at higher 'g', and so reduced the chance of surviving in combat. Aircrew would often joke that helmet mass provided the protection necessary to survive the ejection that it caused through restricting their ability to look out in combat and, where possible, many retained earlier cloth versions for use in the event of war.

> CHECKLIST 1 - A design that does not *sell itself* to the (informed) user fails the 'usability' test.

5. BALANCING REQUIREMENTS

Modern HEA design is inevitably driven in the two disparate directions of technical functionality and pilot usability; in addition to carrying life support, it is expected to protect the pilot's head during crash, ejection, parachute deployment and landing and also to display an intelligible image. However, it must be possible to wear the HEA for extended periods while on Combat Air Patrol (CAP) or in transit and it must remain usable during close-combat manoeuvres at high sustained 'g' levels.

Given identical life support and display capability, heavy HEA will always be less usable than light HEA and if the weight is excessive the pilot may be unable to exploit the helmet display or aircraft at all under 'g'. Design specifications may identify measurable, ideal, system performance from all aspects of HEA functionality (life support, protection and optical display performance) but may well fail to recognise the impact of these requirements on usability. To keep HEA mass within usable limits using current and projected technology, a compromise between protection, display performance and life support is essential. The need is to evolve a usable system, not one that simply complies with the largest portion of the specification (unless that identifies 'Usability' as the principle indicator of compliance).

There is now a broad base of aircrew experienced with night vision systems, including night vision goggles (NVG) and Forward Looking Infra-Red (FLIR). If asked how much field of view (FOV) they would *like* for such systems, most aircrew will say, "as much as possible". Generally, an image size of 40° is considered adequate for safe low level flight by NVG alone. However, most pilots familiar with such systems find their flying performance degraded to some extent - even if only by an enhanced state of concern - when operating with only 30° FOV. Any increase in FOV carries a significant weight penalty but no-one has defined the minimum, usable, display FOV thereby incurring the smallest weight penalty. As with many design decisions, this compromise involves multiple technical disciplines including aircrew and, to achieve a usable balance, there can be no sacred cows; for example, impact protection that improves ejection survival must not automatically take precedence over increased display field of view (FOV), which makes controlled flight into the ground at night less likely.

> CHECKLIST 2 - 'Usability' may require *all* aspects of a specification to be reviewed and harmonised and may preclude meeting any.

The ideal clothing for survival while immersed in a cold sea is something like a deep sea 'dry' diving suit; we would never contemplate making a pilot wear one in the cockpit. Yet, while much effort has been expended in devising systems to allow the pilot to operate in the high sustained 'g' environment which modern aircraft can achieve, the design has often focused on 'protection' at the expense of comfort or usability. Inevitably the specifications for such equipment are written in detailed engineering terms - zero water ingress though wrist or neck seals, 'x'mm HG breathing/anti-g suit pressure at 'y'g - with a passing reference to usability in "and it should be comfortable to wear." Specification compliance has always outstripped pilot comfort or even practicality in the design of most equipment we force our pilots to wear. Thus we have pilots who are perfectly protected from NBC agents but are prevented, by multiple layers of special garments and NBC equipment, from looking back as far as their own wing tip. Equally, we can produce highly efficient 'g' protection systems that work perfectly in the centrifuge but with-which it is impractical to climb the steps and enter a cockpit!

> CHECKLIST 3 - Specification compliance does not guarantee either 'fit for purpose' or 'usability'

6. HABITABILITY & COMFORT

Cockpit design based on specified anthropometric range data is unable to place a value on the un-measurable of crew comfort. The relatively high rates of postural and hearing problems amongst military aircrew suggest few (if any) military cockpit designs start from the premise that the pilot will be in it for long periods. As a result, we apparently ignore the adverse impact of physical discomfort on performance. Thus we spend lots of time deriving population spectra for potential pilot anthropometric ranges and use these data to configure cockpit controls and seats, but little effort is expended in ensuring the same cockpit is comfortable for the pilot who must sit in it for up to 12 hours. Judging by the limited progress in arrangements for body restraint and pilot in-flight relief over the last 30 years, effort has been concentrated on the measurable aspects of each specification and not on the equally important subjective aspects.

Usable cockpits must, in partnership with the aircrew equipment, be sufficiently comfortable to allow the pilot to operate at maximum performance levels throughout the duration of any intended mission; to achieve this, and constrain costs, all cockpit and AEA aspects which impact on comfort (such as cockpit cooling air provision and AEA thermal protection, ejection seat headbox, parachute risers and helmet impact attenuation) must be designed and developed in parallel. Quantitative specification compliance, especially at the expense of meeting qualitative requirements, does not necessarily equate to 'fit for purpose' and is no guarantee of usability.

> CHECKLIST 4a - All aspects of the design which impact on cockpit comfort must be designed and developed in parallel.

> CHECKLIST 4b - Quantitative specification compliance at the expense of meeting qualitative requirements, does not achieve 'usability'

7. WORKLOAD & AUTOMATION

Insulated from the world by aircraft structure and the limits of his vision, a pilot relies on the cockpit displays to fill the gaps in his knowledge. His workload can therefore be described in terms of information processing, coupled with decision making. Anything in the cockpit that increases the load on his information processing capabilities increases his workload and reduces his capacity for decision making while simultaneously increasing the number of decisions required. If workload becomes too great, he may miss, forget or ignore information, each of which potentially decreases his air picture, operational effectiveness and chance of survival. Although no one has yet developed a system to filter, allocate priorities and action inputs as effectively as a human, this does not exclude the cockpit designer from responsibility for making the task as manageable as possible.

Future MMI design should be focused on providing 'intelligent' help for the pilot through automation but this must also be done in a balanced way, resolving factors of cost and pilot expectation. Pilots require different types of automatic decision making assistance at different times in the mission. Sometimes the pilot will wish automation to simply calculate data, sometimes he will expect it to execute any decision immediately, at others he will require a veto option and at others he will expect to be advised of the decision and asked whether he wishes to execute it.

A cockpit that exploits all the information generated by modern avionics but maintains pilot workload at a manageable level must use automation to optimise the way the pilot controls and receives information. In simple terms, the cockpit must provide - at all times - not only the information the pilot needs *now* (in an intuitive format), but it must also filter out all information that he does not need *now* and provide simple (intuitive) controls to allow the pilot to implement his decisions.[3] Since the required information varies with time, it is necessary to breakdown the aircraft's missions into tiny segments and to identify the display and control requirements for each segment. The judgement of what is and is not required at any instant cannot always be made quantitatively. Technologically aware aircrew with extensive experience and understanding of the operational environment are therefore an essential part of the MMI design team.

> CHECKLIST 5 - Ensure that aircrew are fully utilised in defining and designing both the MMI and information-handling protocols.

Another way to reduce pilot workload and so increase the time slice available for tactical decision making is to remove the pilot's 'housekeeping' tasks such as system monitoring. The non-tactical displays can bombard the pilot with information on engine temperature, speed and reheat nozzle area, undercarriage, airbrake and flap positions, numerous gas and fluid temperatures and pressures, air speed, Mach Number, heading, height, attitude, oxygen and fuel contents; although only indicating equipment status, they can be important because each can impact dramatically on the pilot's tactical decision making. There is little point in engaging an enemy fighter and shooting it down, only to be left with insufficient fuel for a safe landing and most pilots will insist that they must know *how much* available fuel they have. In actual fact they really want to know whether they have *enough* - including contingency allowances - to safely complete their mission. Since the advent of electrical fuel gauges, the aircraft has 'known' how much fuel was available but, without information on the pilot's intentions and mission constraints, could not tell if the contents was enough; it was therefore unable to help the pilot.

A data-bus design makes extensive information transfer available. With a knowledge of fuel contents, weather conditions, pilot aims (recovery to a certain airfield via a certain route) and operational constraints (maintenance of a fuel reserve against an unexpected dogfight en-route) the aircraft can compare fuel needed with fuel available and warn the pilot if things get tight. If the calculation result is correct, the pilot can leave fuel management to the aircraft, allowing automation to reduce his workload. However, in addition to the fuel available, the calculation requires inputs from engines (fuel flow), navigation (position, planned route and wind conditions) and stores (drag index), none of which may have been originally designed, in terms of data accuracy, to meet this particular requirement. A design that achieves usability will maintain cockpit workload at acceptable levels while constraining cost by anticipating the possible applications of data from *all* the aircraft systems from the outset.

> CHECKLIST 6a- Establish realistic accuracy parameters for all systems from the outset by identifying all potential applications.

Examination of pilot tasks at various phases of a mission can reveal other areas where information 'cross-telling', similar to the example above, can be exploited; e.g. linking navigation (position information), displays & controls (selection) and radios (comms frequencies) can allow automatic selection of radio frequencies appropriate to either an airfield or tactical operating area. However, without identification (at the initial design stage) of a requirement for navigation information at the radios, this functionality becomes either impossible or prohibitively expensive to implement as an MMI add-on late in the development programme.

> CHECKLIST 6b - Establish availability requirements for systems information from the outset by identifying all potential applications.

8. AUTOMATION & FLEXIBILITY

Automation does introduce its own problems. At a tactical level, automatic filtering and fusing of sensor information requires the application of algorithms that can make the pilot's response to any given situation predictable and so create vulnerability. Conversely, it is important to keep the cockpit predictable. Simulation has shown that automation can hinder the pilot if it makes the cockpit, or even individual displays, behave in an unexpected or inappropriate manner. A display which changes format just when you are trying to interpret it does not reduce workload! Additionally, the requirement for automation in a vehicle that, almost by definition, will be used in an infinite number of unpredictable and rapidly changing scenarios seems impossible to meet.

In reality, there need be no conflict between automation and flexibility, providing that it is possible to both tailor the automation sufficiently pre-flight and to over-ride the automation manually in flight. Potentially, every automated function may need two modification modes, one through data loaded pre-flight and one through cockpit controls. By recognising this need early in the design, both late and expensive redesign work and unnecessarily rigid automation can be avoided.

> CHECKLIST 7 - Anticipate the need for pre- and in-flight over-rides when implementing cockpit automation.

9. 'INTUITIVENESS'

The requirement for intuitive displays exemplifies the wish to keep workload to a minimum; since most of the pilot's knowledge of his aircraft and the world around him comes from his displays, he needs to access that information with minimal mental correlation or interpretation. While the requirement for intuitive displays is easy to state, it is hard to write a specification for intuitiveness and even harder to test for compliance. However, it is possible to achieve intuitiveness.

The EF2000 Track Group Symbol (TGS) - part of the EF2000 display suite that has already been shown publicly on the Eurofighter Avionics Demonstrator at numerous air shows - originally arose from a need to reduce clutter on the Attack and Pilot Awareness formats, where the relationship between display scale and symbol size meant that tracks flying in even loose, tactical formations became overlaid. This problem appeared insoluble until the tactical perspective in dealing with such information was considered. While the targets are at long range, the pilot thinks of them as groups or formations; he may have an interest in the formation shape, since this may indicate intended roles, but early own aircraft manoeuvring will be related to the group rather than to individual elements thereof. As range reduces and an attack plan is developed, the pilot's focus shifts towards individual targets; in parallel, the associated reduction in display scale also causes scattered elements of the TGS to dissemble into individual tracks.

> CHECKLIST 8 - Whenever possible, match system functionality to operational logic.

Clearly, the only people with the ability to pull all of these aspects together, including each of the previously mentioned checklist points, are the end users - aircrew. Since all of these activities start at the outset of the programme, it is essential that aircrew are core design-team members from day one.

> CHECKLIST 9 - Aircrew, both experienced in the operational role and aware of the possibilities and limitations of supporting technologies, must be core to your team.

10. TEST & DEVELOPMENT

Usability, at least that part which impacts directly on the aircrew, can only be proved by rigorous testing which must itself must be recognised as an integral part of the design and development process. Operationally, the pilot often has only short and separated time slices to view his cockpit displays, which themselves vary quickly and rapidly with changes in the tactical situation. Displays that appear to show all the necessary information when a static format is viewed for an extended period, may not give the same impression when used in combat.

To optimise their formats, complex displays must be developed and assessed under dynamic conditions such as part or full mission simulation. Equally, moding which appeared sensible in discussion or on paper may prove completely inappropriate in practice. The only robust development route is to expose an initial design to extensive dynamic assessment by a number of aircrew with experience and knowledge of the likely environment in which the aircraft will be used. The simulation used must be as detailed, dynamic and complex as resource allows and is an ideal candidate for the use of rapid-prototype tools.

> CHECKLIST 10 - The design must be tested and developed through extensive dynamic assessment by a number of aircrew with experience and knowledge of the likely environment in which the aircraft will be used.

However, aircrew form only one part of the development team; they must be supported by specialist engineers who understand what is feasible in terms of equipment and system functionality. Usability is about balancing the design to meet the operational requirement within the available industrial design and production resource and customer's budget. Premature specification of equipment, before the bulk of the design development is complete, is likely to make adherence to Checklist Pilots 6a and 6b impossible; this will create either high costs in later equipment modification or degrade the operational capability. Given the complexity of modern combat aircraft, the need to correctly identify accuracy and availability parameters and the necessary interfaces for all aircraft systems before generating equipment specifications extends beyond MMI and operational aspects. For example, modern flight controls are critically dependant on information about aircraft total mass and mass distribution, which can only be provided by fuel and weapons systems.

In the same way that the MMI design starts from "no worse than any previous" and grows within available resource to meet the forecast operational requirements, all areas of systems design must not only start from the same point but they must have a clear understanding of what all the other design areas need from them. Again, establishment of the starting point requires aircrew involvement. Efficient resolution of individual system design development problems requires cross-specialist engineering teams to achieve a cost-effective solution through balancing individual system requirements to achieve usability at an affordable cost.

> CHECKLIST 11a - Establish the design before generating equipment specifications

> CHECKLIST 11b - Cross-specialist engineering teams are required to achieve usability.

11. CONCLUSION - THE CHECKLIST

"A design which passes the 'Usability' test will be no worse than any previous design."

1 - A design that does not *sell itself* to the (informed) user fails the 'usability' test.

2 - Usability may require all aspects of a specification to be harmonised and reviewed and may meet none.

3 - Specification compliance does not guarantee either 'fit for purpose' or usability.

4a - All aspects of the design which impact on cockpit comfort must be designed and developed in parallel.

4b - Quantitative specification compliance, especially at the expense of meeting qualitative requirements, does not necessarily equate to 'fit for purpose' and is no guarantee of usability.

5 - Ensure that aircrew are utilised in development of the MMI and information-handling design.

6a - Establish realistic accuracy parameters for all systems from the outset by identifying all potential applications.

6b - Establish availability requirements for systems' information from the outset by identifying all potential applications.

7 - Anticipate the need for pre- and in-flight over-rides when planning cockpit automation.

8 - Whenever possible, match system functionality to operational logic.

9 - Aircrew, both experienced in the operational role and aware of the possibilities and limitations of supporting technologies, must be core to your team.

10 - The design must be tested and developed through extensive simulation by a number of aircrew with experience and knowledge of the likely environment in which the aircraft will be used.

11a - Establish the design before generating equipment specifications.

11b - Cross-specialist engineering teams are required to achieve 'usability.'

DISCLAIMER

All views expressed here are those of the author alone. They should not be taken to represent the current views or policies of either British Aerospace Military Aircraft or Eurofighter.

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PSYCHOPHYSIOLOGICAL READINESS AND SUSTAINABILITY

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Good morning, AGARD colleagues, fellow scientists, ladies and gentleman. Thank you for allowing me to address this meeting on future aerospace technology in the service of the Alliance. Of my 28 years in Aerospace Medicine, I have been involved in AGARD for 17 years as a presenter of abstracts, lecturer, session chairman, subject matter expert, short course director, and vice-chairman of two working groups of the AGARD Aerospace Medical Panel. As I look back, a great deal of my military career, as well as my civilian career, has been spent producing data in the aeromedical sciences for AGARD. For such opportunities, I have been truly grateful. Today, I hope that you will allow me to present some viewpoints of aerospace medical research in NATO. I have always been a great believer in the classical abstract, which is data rich. Today, I have no confidence limits or statistical tests to support my conclusions, so I remain today in an advisory role.

What does psychophysiological readiness and sustainability have to do with affordable combat aircraft? During the lifetime of many of our airplanes, which may be 30 years, or longer in many instances, the human subsystem (the operators, maintenance, training and support personnel) represent a continuing personnel expense which eventually dwarfs the pure cost of the airplane. It is no secret that every military organization in the world is driven by personnel cost. The continual struggle for military commanders to balance hardware and personnel costs has produced intense competition for funds remaining after the airframes are bought, and the personnel costs are met.

Most of our human centered research in NATO laboratories is controlled by commands or ministries of materiel or armaments. This juxtaposition of human centered research in the large weapons related commands makes good scientific sense, from a systems standpoint. However, riding on the tiger's back is a dangerous position. Most of us are aware that several of our large aerospace medical activities in NATO, embedded in large R&D or armament organizations, are declining. This may simply be a matter of large scale priorities, and not one of advocacy or performance. Nevertheless, human centered research in NATO will almost surely continue to be a funding struggle.

How then, do we in NATO, particularly in the NATO aeromedical community, contribute to the affordability and sustainability of the human subsystem in order to guarantee mission completion? In a new NATO, what should be the role of an AGARD-like organization in aerospace medicine research? Let us examine just four areas of Aerospace Medicine, which demonstrate the issues and potential solutions wherein the NATO R&D structure will be critical.

- I. The epidemiological approach to selection and retention medical standards.
- II. Occupational medicine concerns.
- III. Cardiovascular physical standards for high performance pilots.
- IV. Evaluation of pharmacological agents for aeromedical use.

Paper presented at the AGARD Symposium on "Future Aerospace Technology in the Service of the Alliance", held at the Ecole Polytechnique, Palaiseau, France, 14-17 April 1997, and published in CP-600 Vol. 1.

I. The epidemiological approach to selection and retention medical standards.

Medical selection and retention standards within NATO represent a wide variety of opinions, viewpoints, data, and beliefs. Every flying organization begins with a set of physical standards, which gradually evolve over time. The standards do not necessarily represent scientific truth, nor do they always contain deep wisdom--what they do represent is a framework from which to learn the answers.

Figure 1 represents a schema for long-term aircrew epidemiological studies. An aircrew member referred for disorder "x" undergoes a series of standardized evaluations, with a subsequent assessment of aviation risk, resulting in either a disqualification or some type of waiver. Generic groups of aircrew are then followed longitudinally, frequently undergoing periodic special waiver examinations. The goals are to record endpoints (outcome) and to determine which of the recurrent testing cofactors best predicts the outcome. Endpoints without cofactors are worthless, and cofactors without endpoints are equally worthless. When sample size becomes adequate, the endpoint and cofactor analysis allows new waiver policy to be adopted. Then, the iterative process begins anew. When this process of cofactor and endpoint research is devoted to airmen who have already been trained to fly, it is retention research. When it is devoted to following newly selected trainees, it is selection research.

This is not a theoretical concept. The epidemiological approach to physical standards has been used, for example, by the USAF for almost 30 years. Let us look at one example of a long-term epidemiological project in the USAF--the USAF supraventricular tachycardia study (SVT) group.

Colonel Londe Richardson and Dr. Paul Celio completed the USAFSAM SVT protocol in 1993--a 20-year natural history study of 430 cases of SVT, composed of 957 SVT evaluations at USAFSAM. The mean followup was 11.4 years, with followup 99% complete (Table 1).

Table 1
The USAF Supraventricular Tachycardia Study Group*

- 430 cases, aviator SVT
- 1973-1993
- Mean followup 11.4 yrs.
- 957 USAFSAM evaluations
- 99% complete followup

*Richardson, L.A., Celio, P.V. (in press)

What has been clear for many years is that aircrew members who demonstrated hemodynamic compromise with SVT (sudden death, syncope, presyncope, ischemia, or visual symptoms) were unacceptable aeromedical risks. What has not been clear prior to this landmark study is the correct aeromedical disposition of aircrew members with recurrent, sustained, or recurrent sustained SVT.

Table 2
USAF SVT Study Group*

Endpoints	
Sudden death	0
Syncope	5
Presyncope	20
Angina/Dyspnea	11
Visual changes	6
	42 (10%)

38 presented with hemodynamic symptoms.
4 subsequently had hemodynamic symptoms

* Richardson and Celio (in press)

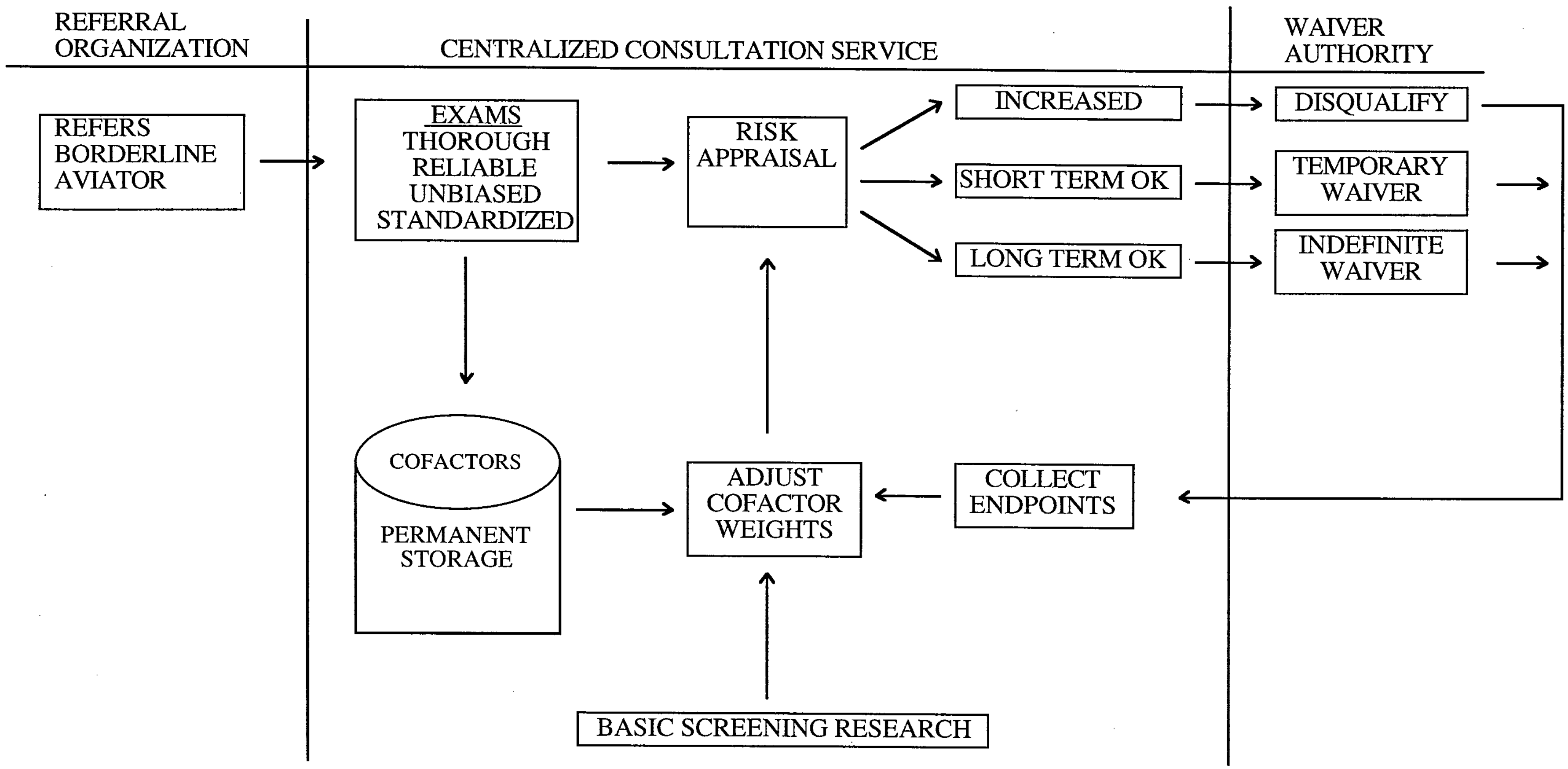


Figure 1 SCHEMA FOR LONG TERM AIRCREW PHYSICAL STANDARDS RESEARCH

Table 2 outlines the aeromedical risk. Of the 42 crewmen with hemodynamically unstable SVT presentations, 38 declared themselves initially and 4 more occurred during followup. Table 3 notes that three of the four subsequent hemodynamically unstable cases presented initially with recurrent sustained SVT, and the fourth case had single sustained SVT.

Table 3
Initial Presentation of the 4 Aircrew with Subsequent Hemodynamic Compromise*

Recurrent sustained SVT	- 3
Single sustained SVT	- 1

*Richardson and Celio (in press)

Table 4 lists the initial presenting cofactors predictive of sustained SVT events. Of the 214 aviators who presented with single nonsustained SVT, only one had a subsequent sustained event of SVT. Of the 108 who presented with recurrent, but nonsustained SVT, only two had a subsequent sustained event. In summary, of the 322 aviators with a nonsustained presentation, only three (0.9%) had subsequent sustained events, and none had hemodynamic instability. Of the 28 with an initial sustained episode, three (11%) developed sustained events, but only one was hemodynamically unstable. Of the 23 with an initial recurrent sustained presentation, five (22%) developed sustained events, with three hemodynamically unstable events. The cofactors which best predicted the endpoints of interest were length and recurrent nature of the initial SVT episode. This is a very condensed summary of an aeromedical problem solved by a long-term epidemiological approach. What are the implications of such studies, and what are the medical manpower requirements to produce such epidemiological studies? Several years ago at USAFSAM, we performed an analysis of the Aeromedical Consultation Service resources utilized in a typical long-term epidemiological study.

Table 4

USAF SVT Study Group*

Cofactor predictors for subsequent sustained events based upon initial asymptomatic SVT presentation

INITIAL EVENT	SUBSEQUENT SUSTAINED EVENT	HEMODYNAMICALLY UNSTABLE
Single nonsustained SVT	1/214 } N=322	0
Recurrent nonsustained SVT	2/108 }(0.9%)	0
Single sustained SVT	3/28 (11%)	1/28
Recurrent sustained SVT	5/23 (22%)	3/23

*Richardson and Celio (in press)

Table 5
Manpower Costs of a Single Epidemiological Study to Recommend a Physical Standards Change*

Analysis based upon USAFSAM Aeromedical Consultation Service 1991-93, 170 personnel

Assumptions:

- Consultation personnel spend 70% of time in activities relating directly to aeromedical consultation
- 750 full evaluations per year
- 10 years mean follow-up
- Mean of 3 evals per subject

* Communication to USAF Scientific Advisory Board, 13 Nov 91, J.R. Hickman, Col USAF (MC)

Table 5 outlines the resources available for aeromedical consultation in the Clinical Sciences Division at USAFSAM in the timeframe 1991-93, revealing a manpower quota of 170 personnel, with 70% of all activities devoted to aerospace medical consultation. The Consultation Service was capable of producing 750 full aeromedical evaluations per year. The usual 20-year study included a mean of three evaluations per subject, with a mean follow-up of 10 years. At a mean of three evaluations per subject, Table 6 indicates that a study group of 200 subjects would require 600 total evaluations during the course of the study.

Table 6
Manpower Costs of a Single Epidemiological Study to Recommend a Physical Standards Change

- Study group of 200 subjects
- 600 Total evaluations

$$\frac{600 \text{ evaluations}}{750 \text{ evaluations/yr.}} = 0.8 \text{ Consultation Service years}$$

(0.8) Cons. Svs. yrs) (.70 dedicated cons. time)
= .56 adjusted Consultation Svc. yrs.

- At a mean strength of 170 personnel (170 persons) (0.56 yr.) = 95 man yrs.

In terms of man years expended, 600 total evaluations would require the equivalent of 80% of the resources for one year, or 0.8 Consultation Service years. With a 70% time dedication to clinical consultation, the adjusted consultation total service years would be 0.56 years. At a mean strength of 170 personnel, such a theoretical project would require 95 man years of aeromedical manpower. Table 7 demonstrates the return on investment if a waivered aviator actually flew for only five years on a special waiver as the result of the study.

Table 7
Manpower Costs of a Single Epidemiological Study to Recommend a Physical Standards Change

- If each salvaged aircrew member flies only 5 years on a waiver:
  1000 flying years saved
- Return on investment is 10:1 in aviator man years per medical Consultation Service man years expended.
- In the SVT study group, the return on investment was 13.3:1.

In a new waiver group of 200 pilots, 1000 flying years would be saved. The return on investment is 10:1 in aviator man years per medical consultation man years expended. For a previously grounding disorder, would you invest one medical research man year to gain 13.3 flying years? 13.3:1 was the return on investment in the Supraventricular Tachycardia Study Group. If one considers the training and recurrency costs, not to mention the incalculable value of aircrew experience, the medical research investment seems very wise. When this study began, supraventricular tachycardia was permanently grounding. I will leave it to your own estimation as to the cost avoidance for 400 aircrew members, in a single disorder which has progressed from 100% grounding to 90% waiverable. If we are truly interested in affordable aircraft, physical standards research offers an unarguably favorable investment which limits attrition of a very expensive element of the system--the human. Very similar long-term studies have been accomplished in cardiovascular, visual, and neuropsychiatric disorders. However, the aircrew epidemiology mission is never finished, but is a continuum. Decision rules for physical standards are continually affected by new diagnostic techniques, new therapies, new drugs, and multiple new disease subgroups of previously discrete diagnostic categories. Today's physical standards are for contemporary aircraft and life support systems.

Table 8
Impact of New Technology on Aircrew Standards Research

- Two dimensional, color Doppler echocardiography
- Transesophageal echocardiography
- Intracoronary ultrasound
- Intracoronary angioscopy
- Ultrafast CT (electron beam) for coronary calcification
- Multiple gated acquisition scans (technetium)
- Positron emission tomography
- Single photon emission thallium scintigraphy
- Sestamibi myocardial scintigraphy
- Dipyridamole, adenosine, dobutamine stress studies
- Full disclosure Holter monitoring
- Radiofrequency ablation
- Percutaneous transluminal coronary angioplasty
- Percutaneous transluminal atherectomy
- Percutaneous transluminal laser angioplasty
- Magnetic resonance imaging of the myocardium
- HDL and apolipoprotein subfractions
- Calcium channel antagonists
- Angiotensin enzyme converting inhibitors
- HMG CoA reductase inhibitors
- Minithoracotomy bypass surgery

Table 8 lists cardiovascular medical procedures and treatments which have all arisen since the supraventricular tachycardia study group was started in 1973. No natural history study is ever really finished because of the evolution of aircraft systems and medical technology. Every long-term study must be continually revised as new medical and aviation technology becomes available. Who, then, will be making the decisions regarding aircrew waivers? Will they be made by the flight surgeon or the hospital clinician for whom flying is largely an abstraction? Will NATO recognize that aircrew studies, with burgeoning technology and new drugs, are absolutely critical to maintaining the best human systems, and the most affordable aircraft. Based upon my 28 years of experience as a flight surgeon, and my personal view of the current state of some of our aeromedical centers, I am deeply concerned that NATO has not fully grasped the critical state of affairs. The clinical community and the aircraft designers are outstripping the ability of individual aeromedical centers to keep pace with this evolution. Is it not time for NATO to do more than sponsor excellent symposia and outstanding educational programs? In the area of aircrew epidemiology, we are simply not taking advantage of the huge NATO denominator, which would allow us to reach statistical conclusions in years instead of decades. If one is inclined to accept the thesis that NATO should be leading in the conduct of conjoint aeromedical projects, what is the evidence that NATO could actually do it? The best evidence of whether NATO can actually do collaborative science is to present an outstanding example of where NATO has already done it. To demonstrate to you that NATO has the scientific prowess, the sample size, and the organizational skills to conduct multinational collaborative research, let me move to the next topic--occupational medicine.

II. Occupational Medicine Concerns in NATO

Not every aerospace medical concern revolves around the issue of cost effectiveness, cost avoidance, performance enhancement, or aircrew longevity. It is a basic tenet of occupational medicine that we do not place workers (or aircrew) in an environment for which they are medically unsuited. There is a strong occupational medicine aspect of aerospace medicine which requires us to honor this basic tenet. As resources decline, and as operational medicine appears more often as a candidate for funding and manpower reduction, we should become very concerned that aircrew epidemiology and physical standards research may be viewed as optional or elective pursuits. Assuring that workers are not placed in activities for which they are medically unsuited is not a discretionary activity--it is an ethical imperative. Fortunately, the interests of occupational medicine and aerospace medicine are fortuitously congruent--the greater the epidemiological data base, the more capable and economical the systems have become. Let us now turn to an example of a critical occupational medicine issue, solved by NATO. In the 1970s and 1980s, concerns were raised in multiple nations about possible long-term deleterious effects of repeated high sustained $+g_z$ exposure on the heart. AGARD's Aerospace Medical Panel commissioned Working Group 13 and 18 to address this critical operational issue. Working Group 13 wrote an extensive protocol which was subsequently executed by Working Group 18. This was NATO's first multinational collaborative medical study. Over 1600 echocardiograms were enrolled into an agreed upon data base, using diskettes forwarded to a central facility. Data analyses compared 289 pilots of high sustained g aircraft with 254 control pilots. The participating nations divided the tasks of scientific methods, protocol production, quality control, data management, statistical analysis, and manuscript production. This was an enormous study which was completed in 6.5 years. The sample size to conduct this study did not exist in any single country. This study could never have been performed without AGARD sponsorship, and statistical significance could never have been reached without the NATO sample size. The study concluded, that for current aerospace systems and life support systems, there was no evidence that repetitive high sustained $+g_Z$ exposure induced any pathological changes in the heart. Many lessons regarding organization, protocol production, data management, and quality control were learned. The extensive protocol, which has already been published, and the study results, which are currently in press, represent templates from which many collaborative NATO life sciences projects could be patterned. The lessons learned by the AGARD AMP were as valuable as the scientific answer itself.

There are lingering concerns in the NATO Air Forces about possible degenerative joint and disk disease of the axial spine, produced or aggravated by long-term repetitive high sustained $+g_Z$ exposure. This issue remains unresolved. There are the usual problems of the frequent occurrence of abnormal imaging findings in the "normal" unexposed population. This observation has led some to conclude that a scientific study is not feasible. However, the crucial scientific issue is not "who is normal?". The crucial scientific issue is whether findings are overrepresented in exposed persons when compared to unexposed persons in a well-controlled study of adequate sample size. Large sample sizes are required to detect small differences. The "normal" issue is not an insurmountable problem--it simply dictates a larger sample size--a problem which can be defined and solved. Disagreements about what represents a "case" of significant cervical degenerative disease is a valid issue, but it is not a contra-indication to doing the study. Inter- and intra-observer variability in the interpretation of tests was thoroughly studied by the NATO Echocardiographic Working Parties. Such problems are not insurmountable; they simply dictate the sample size needed to find the difference if a difference indeed does exist. It seems clear that the concerns regarding high performance flying and the axial spine, as well as the vestibular system, will not be solved unless by NATO. Perhaps no collaborative study could have been more technically demanding than two-dimensional Doppler echocardiography. If it can be done for the heart, it can be done for other body systems. The alternatives to a large denominator NATO study will be the continuous publication of small denominator, descriptive studies with no control groups. Based upon the success of the NATO Echocardiographic Working Groups, and the lessons learned in the conduct of multinational studies, I have no doubt that NATO is fully capable of conducting true multinational collaborative scientific projects of adequate sample size. Not only do I see NATO as capable of doing such critical work--I see NATO, in many instances, as the only way to perform such projects. I would urge NATO, as it revamps the scientific mission, to carefully consider a true collaborative mission in the conduct of aircrew research.

III. Cardiovascular Physical Standards for High Performance Pilots

Long-term epidemiological studies of cardiovascular conditions are essential for the evolution of physical standards for both non-high performance and high performance pilots. However, epidemiological studies, performed at 1g, do not address the acute effects of $+g_Z$ acceleration. The effect of $+g_Z$ acceleration on preexisting disease states such as minimal coronary artery disease, mild valvular disease, and ventricular arrhythmias is unstudied. In many instances, fighter pilots have not benefited from physical standards advances because of the information void regarding the above clinical conditions under $+g_z$. Virtually all of the gravitational hemodynamic research in NATO has been directed toward countermeasures. In several areas of clinical aviation cardiovascular standards, we are at a standstill because of this information void. We are at least a decade behind in this critical area of aircrew standards research. The critical hemodynamic information must come from experimentally produced conditions in non-human primates. It is time for the clinical community to clearly articulate this need to our excellent basic sciences laboratories. The fighter pilot has not been well served by this void in both technology and hemodynamic data. Advances in high performance standards cannot progress without a highly structured hemodynamic initiative, which is a highly technically demanding and expensive project. It is time for NATO to formulate a plan. Too many $6 million pilots are still being grounded because of the information void in mild subclinical cardiovascular disorders, many of which would undoubtedly become waiverable if the gravitational hemodynamics were understood.

IV. Evaluation of Pharmacological Agents for Aeromedical Use

For the five-year period spanning 1992-1996, there were 30 human drug testing publications in *Aviation Space and Environmental Medicine*. This is not the only aerospace medical journal, but it is a widely followed international publication.

Table 9

Human Drug Testing Publications*

N=30

Motion sickness/space adaptation	9
Chemical defense	6
Clinical	6
Circadian/performance	5
Diving/Altitude	2
Thermal	2

**Aviation, Space, Env. Med   1992-1996*

Table 9 lists the category of drugs which were studied. Motion sickness and chemical defense agents were most frequently represented, followed by clinical and circadian performance studies.

Table 10

Human Drug Testing Publications

Scopolamine/Atropine	7
Pyridostigmine	4
Zolpidem/Triazolam	3
Benadryl/Hismanal	2
Phentoin	2
Amphetamine	2
Mefloquin	1
Propanalol	1
Modafanil	1
Promethazine	1
Dexamethasone	1
Captopril	1
Reglan	1
Ginko Biloba	1
Melatonin	1
Cinnarzine	1

Table 10 enumerates the individual drugs which were tested, with motion sickness and chemical defense agents dominating the list, with soporifics the next most commonly studied agents. From a clinical standpoint, it is of concern that only one antimalarial, one antihypertensive, and no lipid agents were tested. While several drugs have been studied from more than one standpoint, there is no unifying body of information which would document the broad aeromedical acceptability of a single drug in terms of multiple body systems. However, the issue for the flight surgeon is: Can the aircrew member fly and perform while taking this drug? Have the side effects been assessed in a population which is exposed to high levels of mental and physical stress, hypoxia, acceleration, thermal stress, sleep deprivation, and the rigors of escape and evasion? More likely, our knowledge of the drug comes from the clinical literature, tested on the wrong population, under the wrong conditions, with the wrong endpoints. The flight surgeon wants to know answers which can only come from full-scale aeromedical drug evaluations, before the drug is released for operational use in thousands of NATO aircrew members. Table 11 enumerates the answers required.

Table 11

Full Scale Aeromedical Drug Evaluation

- Determination of drug efficacy
- Cardiovascular effects
  - Arrhythmia's
  - Hemodynamics, gravitational effects
- Vestibular effects
- Psychomotor effects, performance
- Neurophysiological effects
- Responses under hypoxia
- Drug interactions
  - Compatibility with other aeromedically approved drugs

It is very difficult to find a drug which has been evaluated in all of the desired areas. It is possible that a candidate drug may not require evaluation in every venue, but such a decision should be a conscious, well-thought out judgment, not a decision by default. Table 12 lists four drug categories for which a broad consensus of clinical need exists in the aviation community.

Table 12

Drug Requirements in Clinical Aerospace Medicine

- Lipid lowering drugs
- Antihypertensives
- Antimalarials
- Circadian/performance enhancement drugs

Lipid lowering drugs, antihypertensives, antimalarials, and circadian/performance enhancement drugs are critical to the management of the aviator's health. Why have no drugs, in any category, been evaluated in the depth and breadth required for aeromedical purposes? I believe that we all know the answer--the resource issue again. When I was the Chief of the Aeromedical Consultation Service at USAFSAM, our mean strength was 170 personnel, and 70% of our time was completely subscribed in clinical evaluations. We estimated the resources required to do a full clinical evaluation of a candidate drug. Studies must be performed before and after drug administration. Follow-up studies must be scheduled over time to detect late or intermediate effects, and yet serial studies must be spaced out at intervals great enough to preclude learning or training effects. And, multiple variables require a large sample size. We estimated a 4-6 month commitment of our technical resources to completely study a single drug--resources which, in the best of times, we could not assign to this task. This is a serious situation. Heavily subscribed clinical activities cannot devote enough dedicated resources to such pursuits, nor is the situation apt to improve as NATO's aeromedical centers come under continuing financial and manpower pressures.

Table 13
Status of Aeromedical Drug Evaluation

- Excellent work has been done
- Sample sizes usually quite small
- Virtually no full scale drug evaluations for all aeromedical concerns
- Interaction with other mission essential drugs not addressed

Table 13 summarizes the current status of aeromedical drug testing in NATO. Excellent work has been done, and these observations should not diminish the superb system specific drug research already accomplished. Indeed, many centers have very mature investigation facilities in one or more of the relevant disciplines--neurophysiology in one center, visual sciences in another, cardiovascular medicine in another, biodynamics in another, human performance in another, and altitude physiology in yet another center.
If we in NATO are to meet our requirements, it seems clear that we must, in a central fashion, organize and coordinate the parallel investigation of a candidate drug in a battery of NATO laboratories, both military and civilian, which will function as centers of excellence in a discipline-specific fashion. The sheer number of candidate drugs outstrips the available resources of individual NATO members, both from a technical and from a sample size standpoint. In general, aerospace medical studies are plagued by small denominators, with confidence limits often not stated. Is it not time for NATO to mobilize and organize our drug testing resources into a multinational collaborative approach? Is it not time for NATO to take advantage of the extraordinary sample size which offers unparalleled statistical power?

Figure 2 outlines the possible evolution of a multinational drug testing protocol in NATO. The identification and prioritization of candidate drugs should ultimately lead to the establishment of a NATO drug testing group composed of NATO life scientists, both military and civilian, both clinical and basic scientists. A candidate drug should be initially assigned to a discipline-specific laboratory. Does the drug actually do what we want done? Otherwise, further investigation is not warranted. If efficacy is established, the candidate drug is then evaluated simultaneously in a parallel fashion in multiple NATO venues.

Figure 2
Evaluation of a Multinational Drug Testing Protocol in NATO

Identification of mission essential drug requirements by NATO flight surgeons

↓

Generation of a prioritized list of mission essential drug candidates

↓

Establishment of a NATO drug testing group, composed of NATO life scientists--military and civilian, clinical and basic scientists

↓

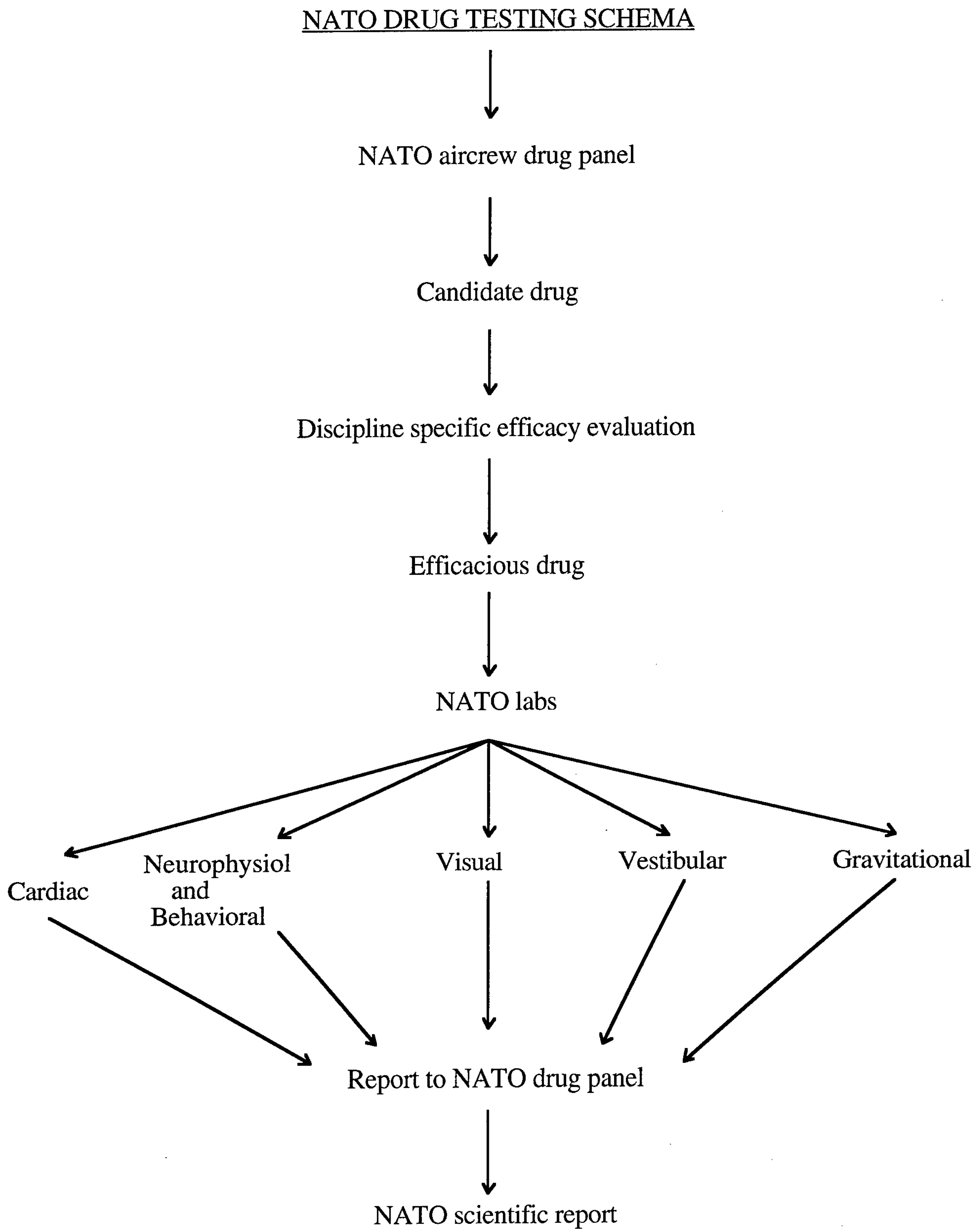
Assignment of a drug to a discipline specific laboratory for an initial efficacy study--does the drug actually do what we ant done?

↓

If efficacy is established, the candidate drug is then evaluated simultaneously in a parallel fashion in multiple NATO venues

Figure 3 represents a drug testing schema, emphasizing parallel testing.

Figure 3


NATO DRUG TESTING SCHEMA
NATO aircrew drug panel
Candidate drug
Discipline specific efficacy evaluation
Efficacious drug
NATO labs
Cardiac
Neurophysiol and Behavioral
Visual
Vestibular
Gravitational
Report to NATO drug panel
NATO scientific report

SUMMARY

As the NATO alliance enters into a new era, with new roles and new missions, a new R&D structure will emerge. AGARD has been a splendid organization, existing at the heart of the alliance. It seems that NATO must now move beyond an information sharing and advisory role to a sponsor of multinational scientific projects. It is time to take advantage of the combined sample size in order to reach significant conclusions sooner and with greater confidence. It is time to organize our centers of excellence into a collaborative mode in order to assure that the human subsystem is both affordable and effective. In several key areas of aerospace medical research, there is no alternative to the NATO sponsored multinational project.

The Shape of Things to Come: Revolution in Engineering Anthropometry

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1. SUMMARY

Even after discovering the world was not flat, map makers were limited to representing our three-dimensional (3-D) world on a flat piece of paper. This was fine for small regions. For large regions, however, distortions became obvious; continents were misshapen, enlarged or shrunken.

Like the earth, the human body is covered with ridges, hills and valleys and is anything but flat. Scientists attempting to map the body face the same difficulty with distortions that cartographers do. For engineering purposes, researchers measure the 3-D body, but until now they have used only one- or two-dimensional tools. They have been forced to change back and forth from 3-D to 2-D to create the products. This paper describes the design impact of the limitations with traditional tools for human body measurement and illustrates the future potential of 3-D surface anthropometry technology on the engineering of aerospace systems.

2. INTRODUCTION

In a 3-D Computer Aided Design (CAD) environment, there is a need for 3-D representations of people. Until now, modelers have been forced to construct the 3-D people from disconnected, generally one-dimensional measures. It made modeling a time consuming, costly, as well as inaccurate process. Many different contours could fit the same data sets; in other words, there was no unique 3-D solution to a given set of data. Perhaps worst of all, there was no way to quantify the accuracy (or inaccuracy) of the 3-D model.

It should not be surprising, therefore, that modeling inaccuracy contributed to large errors in crew station accommodation, such as those shown in figure 1 below. The crew members in the pictures are among those for whom the crew stations were designed. Not only did engineers have too little information to design properly, but they also had too little to realistically visualize the human system interface. As a result, qualified pilots are either: 1) unable to fly a given aircraft or 2) are operating under less than ideal conditions with resulting performance and safety degradation.

Until now, the time required to model and the lack of a unique contour to fit a given data set made customization options unfeasible. Inaccuracy of the 2-D to 3-D translation wasted money in too many sizes and retrofits or alterations required. Inaccuracy compromised fit for many, and subsequent individual and mission performance suffered.

New technology developments in 3-D Surface Anthropometry are radically changing all this. In fact, it has been said that these advances represent a paradigm shift in the field of engineering anthropometry which will change forever the way equipment is designed for people.

3. NEW TECHNOLOGY BRINGS OPPORTUNITIES

Unique, well defined, and fast 3-D characterization of individuals is now possible. This makes customization or made-to-measure products feasible for the first time for many types of items. It also permits direct importing of 3-D characterizations into many CAD or illustration systems for fast evaluation of crew station design concepts. Good individual characterizations make it possible to evaluate and adjust biomechanical human models to more appropriately represent populations. But perhaps the biggest advantage is the ability to both quantify and visualize fit.

Paper presented at the AGARD Symposium on "Future Aerospace Technology in the Service of the Alliance", held at the Ecole Polytechnique, Palaiseau, France, 14-17 April 1997, and published in CP-600 Vol. 1.

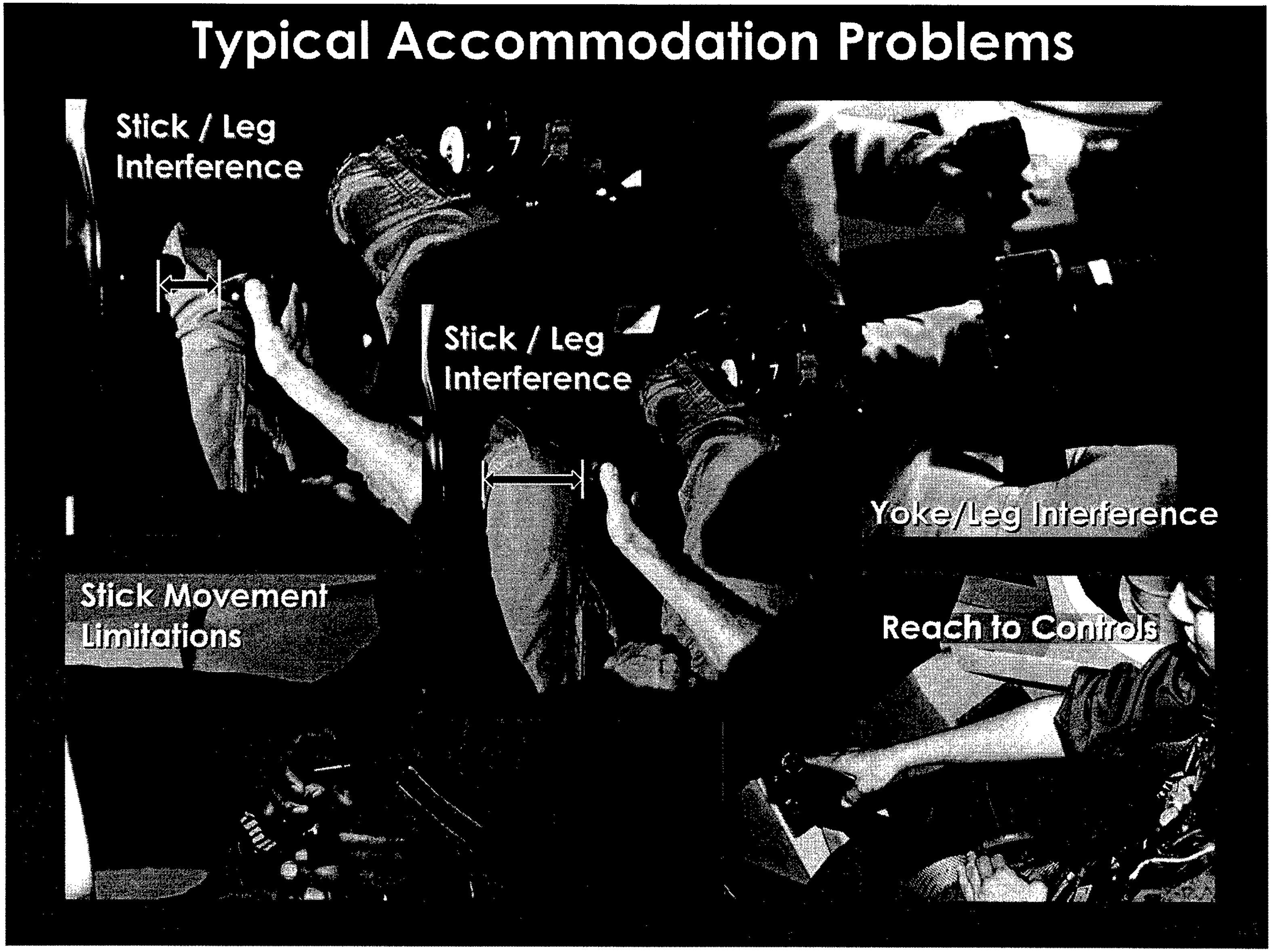

Figure 1. Aircraft accommodation problems in past.

Figure 2 shows the fit of a person in a flight suit. It was created using two 3-D scans of the same person and a software package we created called INTEGRATE© (Burnsides et al 1996). The package permits the registration and measurement of multiple 3-D digital objects. Not only can we see the person in the flight suit, we can also measure distance or create enclosed volumes etc. between the two objects.

This ability to quantify fit is a vital step toward developing customized fit for a wide variety of items. Some of the advantages of this approach were recently demonstrated in a burn mask project (Whitestone, 1994). In this effort, masks for promoting healing and reducing scarring for burn victims were created using two different types of rapid prototyping technologies, numerically controlled milling and stereolithography. This process had previously been done by making a plaster cast of the face, creating a plaster form, and then vacuum forming.

The photo in figure 3 shows a difference map of a person's face versus his mask. These measurements of the differences demonstrated that the digital process was not only faster but also resulted in a more accurate reproduction of the face. Furthermore, it has the advantage of permitting controlled adjustments in the digital state to make the mask tighter or looser in areas where it is needed.

This type of customization process can be applied to many clothing and equipment items in the future. We are now using the same techniques to investigate processes for customization of a positive pressure oxygen mask.

The process of digital registration of the oxygen mask to the face is illustrated in figure 4. The mask is connected to the surface of the face digitally and a "solid model" (or enclosed volume) is digitally constructed. Stereolithography is then used to transform the solid model into a dipping form for the soft rubber portion of the mask. Just as with the burn mask, the digital form requires some tightening and loosening adjustments in some areas to make the mask fit, because the original face shape is not the ideal mask shape. For this part of the process to be both accurate and fully automated, the areas that need to be adjusted must be determined through testing and statistical algorithm development from the test results.

Customization can lead to better quality fit and improved performance. In addition, given the new measurement technology, there can also be significant cost benefits to customization as an alternative to pre-set sizes. Sizing is essentially building an item to fit clusters of people. Some people in a size get a better fit than others, with people getting a poorer and poorer fit as they move away from the center to the edges of sizes and groups of sizes. The closer together the sizes and the smaller the size "bins," the more sizes are needed to cover the population and the fewer people between sizes who get a poor fit. If many sizes are needed to get the required level of fit for effective performance it can get very expensive to produce, stock and logistically track the item.

The graph in figure 5 shows the diminishing return for adding sizes at the end of the distribution. The farther away from the center (represented here by the median or 50th percentile), the greater the size change needed to accommodate the same percentage of people. For example, the stature range needed to accommodate the 9% between the 1st and 10th percentiles is from 58.5 to 61.00 inches, a range of 2.5 inches. Yet the stature range to accommodate the 10% who fall between the 40th and 50th percentiles is only 1/2 inch.

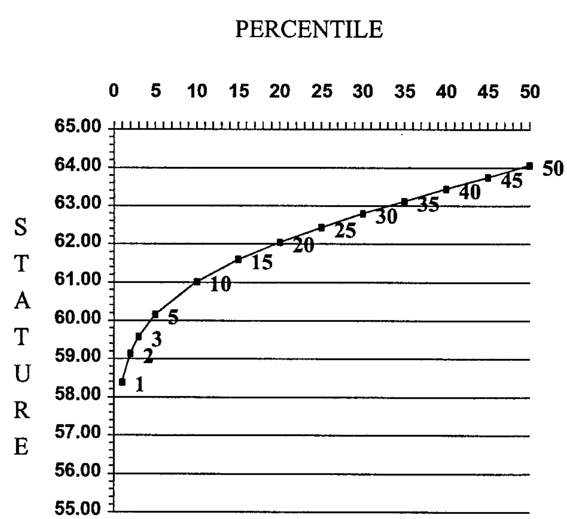

Figure 5. Plot of stature percentiles.

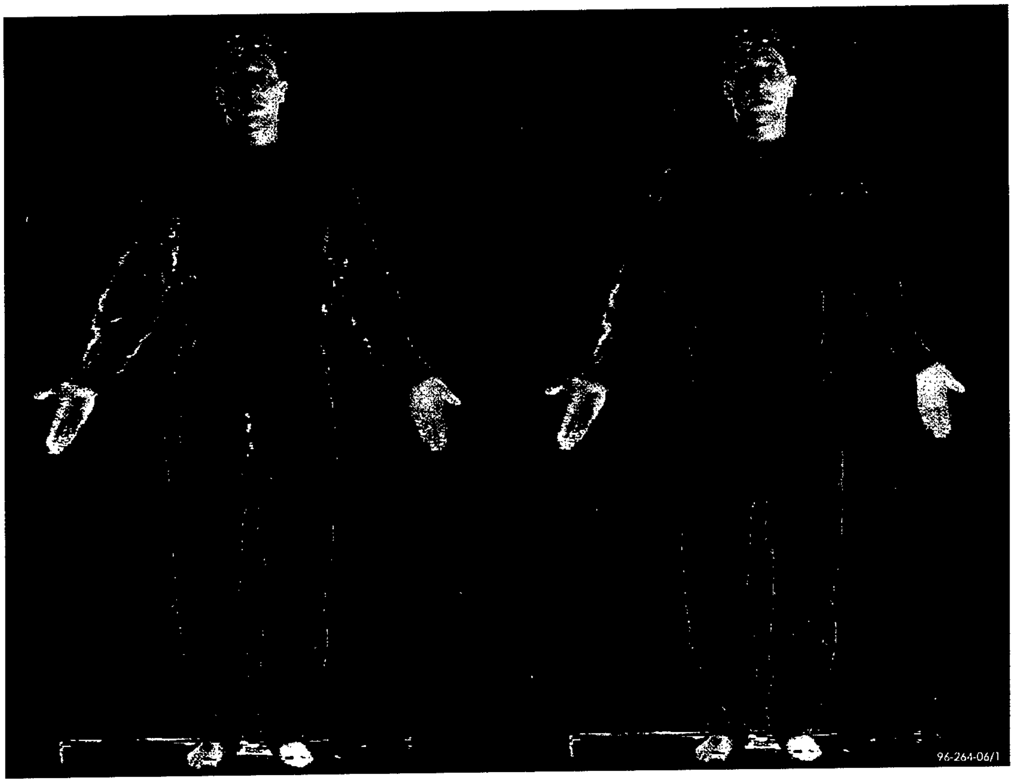

Figure 2: Two scans of subject, one in scanning garment and one in flight suit.

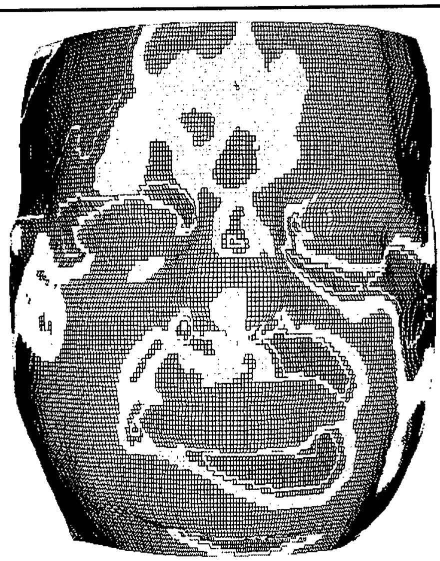

Figure 3: A difference map between a subject's face and a form fitting mask.

Figure 4: Digital registration of an oxygen mask to an individual's face.

Sizes at the extremes actually accommodate very few people. If a customization option is available, it could be cheaper to customize than to produce and stock these sizes.

Customization can also be a cost effective way to accommodate minority groups with good quality. Figure 6 illustrates typical bivariate male and female body size distributions. Note that the spread of body size variability is the same for each sex. This indicates that the same number of sizes will be needed to accommodate 99% of women as needed to accommodate 99% of men. For example, for a flight suit it was determined that 18 sizes were needed to fit 99% of the population of male pilots and that 18 sizes were also needed to accommodate female pilots.

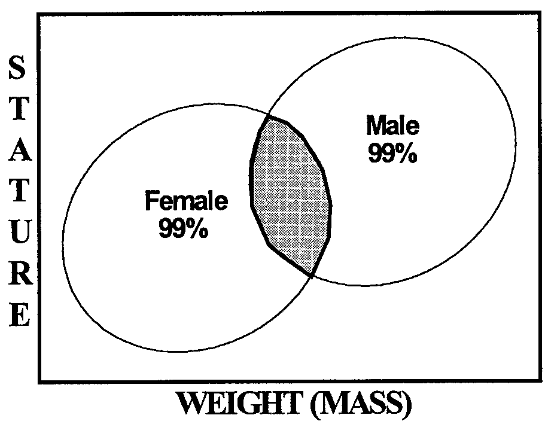

Figure 6. Illustration of typical anthropometric distributions.

Also note that the overlap between men and women is only a small sector. This indicates that only a few of the sizes might be shared. In the flight suit example, perhaps twelve sizes beyond the male 18 may be needed to accommodate the female pilot population. If that population is a minority comprising only 1 percent of the overall pilot population, it will mean stocking 12 sizes to accommodate less than 1 percent. Many of these items are likely to exceed their shelf life before they are ever needed. In instances such as this, an effective customization process could very likely be the cheaper option.

Since rapid manufacturing technologies are also coming of age, it is possible that the clothing store of the future might resemble the store shown in figure 7. You could be scanned once and keep your scan on file at your favorite companies. You could then try on different clothing in a virtual environment, selecting style, color, fabric, and even the pattern of the weave. You would change in and out of the various options nearly instantaneously without having to actually change clothes at all. In fact, once your scan was on file, youwould not actually go to a physical store location but could conceivably try on clothing from the comfort of your living room.

After making your selections you could have your clothing produced in 3-D, completely bypassing the flat pattern process. The translation errors which result from repeated 2-D to 3-D translations are thereby avoided, making certain that what the you see is what you get. Your custom clothing could be ready for pick-up or delivery in a matter of hours or minutes.

For the aircrew members of the future, after scanning, their entire equipment ensemble could be customized or "customerized" (adapted to the person but not necessarily completely created from scratch) in a few hours. The crew system design may utilize equipped virtual people in 3-D virtual space, with the ability to individualize the crew station. We may be able to get into our virtual gear and climb into our virtual crew station to try it out. Possibly, crew stations could be designed to adjust automatically to our bodies, gear and personal adjustment preferences to give us optimal performance and safety. This new technology has the potential to really put the crew into crew system design.

Automated, quantified, and electronic advanced anthropometry and anthropometric accommodation will be accessible worldwide. With new information systems technology, this can improve readiness and NATO inter-operability. Information systems will be able to indicate which body sizes and shapes are best for which aircraft, how to configure the aircraft, or what equipment to use to optimize the system for a given individual, etc. in a matter of minutes.

The first 3-D surface anthropometry survey for NATO is now in the preliminary stages. The plans are to measure approximately 15,000 people in 3 countries: the United States (largest population), The Netherlands (tallest

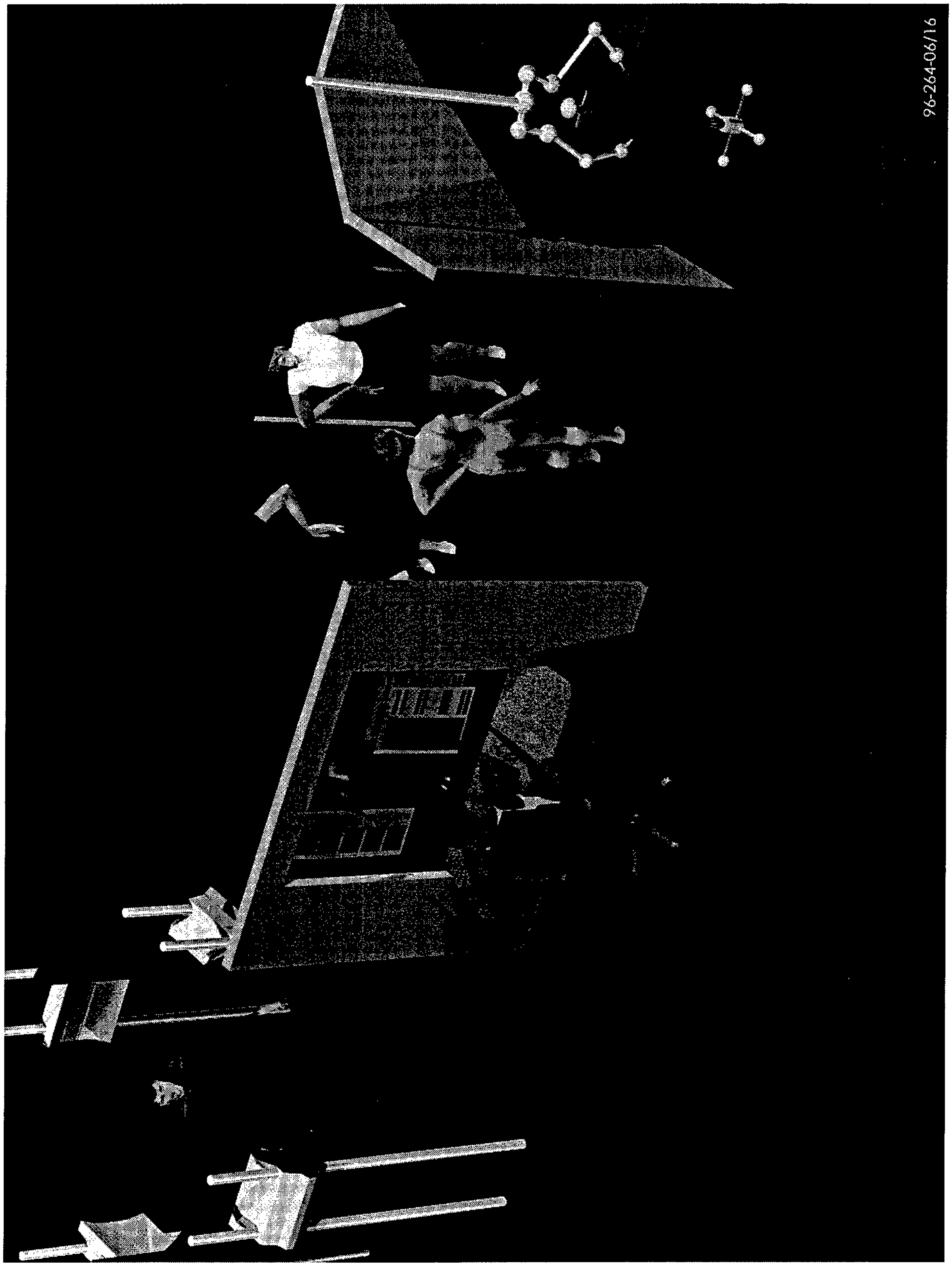

Figure 7. A vision of the clothing store of the future.

population) and Italy (one of the shortest populations). This survey was initiated by an AGARD project under AGARD/AMP Working Group 20, on 3-D Surface Anthropometry. For more information about this or other CARD Lab projects visit our Web Site at www.al.wpafb.af.mil/~cardlab.

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REPORT DOCUMENTATION PAGE

1. Recipient's Reference	2. Originator's Reference	3. Further Reference	4. Security Classification of Document
	AGARD-CP-600 Volume 1	ISBN 92-836-0047-9	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

Future Aerospace Technology in the Service of the Alliance:
Affordable Combat Aircraft

7. Presented at/sponsored by

The AGARD Symposium on "Future Aerospace Technology in the Service of the Alliance" held at the Ecole Polytechnique, Palaiseau, France, 14-17 April 1997.

8. Author(s)/Editor(s)	9. Date
Multiple	December 1997

10. Author's/Editor's Address	11. Pages
Multiple	310

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

Fighter aircraft	Combat effectiveness	Flight crews
Development	Operational effectiveness	Mission profiles
NATO forces	Aeroelasticity	UAV (Unmanned Aerial Vehicle)
Procurement	Airframes	Human factors engineering
Transport aircraft	Stealth technology	Anthropometry
Helicopters	Avionics	Cockpits
Cost analysis	Aircraft engines	Ditching (landing)
Design	Vertical takeoff aircraft	Reviews

14. Abstract

One of three volumes containing the unclassified papers presented at a conference on "Future Aerospace Technology in the Service of the Alliance" organised by AGARD (NATO's Advisory Group for Aerospace Research and Development) at Palaiseau, near Paris, France, 14-17 April 1997. The conference took the form of three parallel symposia and three plenary sessions.

This volume contains the papers from the three plenary sessions:

- Future Directions in Aerospace Systems
- Future NATO Trends and Mission Scenarios
- Human Machine Interaction in the Future

and the symposium on "Affordable Combat Aircraft", which had sessions on:

- Affordability of Procurement
- Combat Effectiveness
- Affordability of Ownership
- The Human Element

Volume 2 contains the papers on "Mission Systems Technologies".

Volume 3 contains the papers on "Sustained Hypersonic Flight".

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(membre de la Corporation St-Joseph)
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Printed by Canada Communication Group Inc.
(A St. Joseph Corporation Company)
45 Sacré-Cœur Blvd., Hull (Québec), Canada K1A 0S7

ISBN 92-836-0047-9