ADVANCES IN AFFORDABLE MATERIALS FOR AEROSPACE

BY

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ABSTRACT

This article reviews the status of aerospace materials currently under development or moving to application and assesses the difficulties inherent in their transition from research to commercial use, in particular those factors affecting affordability. The article then speculates upon future possible trends in aerospace structures and on the consequences for advanced materials.

Introduction

Examples will be given in this article of some of the factors driving research programmes aimed at materials developments and that subsequently control their embodiment into commercial projects, in particular, affordability. This will be attempted by specific references to the status of developing aerospace materials including new alloys, metal matrix composites, polymeric composites and trends towards more affordable systems identified by the UK Foresight Challenge. Finally, in light of the current situation, a speculative look is taken at future aerospace structures and the consequential requirements for aerospace materials.

It is first necessary to consider the driving forces for the application of new materials in the military field. These and other elements of the process can be simplified into three interdependent issues namely:

(*a*) Improvement in aircraft or system performance, e.g. range, payload, speed etc.
(*b*) Reductions in cost, e.g. cost of acquisition and operation.
(*c*) Improvements in survivability, crashworthiness and ballistic performance.

Whilst the generation of research and development is relatively without risk, the translation of new concepts, materials and ideas into commercial reality is currently dominated by the cost-effectiveness of the proposal. This can be viewed in terms of the cost of acquisition including qualification and manufacture and in terms of the subsequent operating cost associated with application of the end product. It seems clear that, although there is a continuous drive in the aerospace world for new materials developments, there are many negative aspects and significant costs associated with them and they are undertaken at risk.

Background

For nine decades the UK has played its part in the advancement of the international aerospace industry both for military and civil applications. Developments have often occurred in small incremental steps but, at times, they have been revolutionary. For example, the use of stressed aluminium alloy skins could be described as revolutionary but airframes could still be produced today using the original aluminium-copper alloys developed in

1908 with but a quantifiable weight penalty. Similarly, the current generation of advanced gas turbine engines would not exist at all without utilizing the modern titanium and nickel superalloys but, since their initial selection, progress has occurred incrementally.

Detailed considerations of the application of particular materials to any selected project tend to become contentious. Typically, to minimize risk, new structural projects will tend to be based on proven materials and new materials may well be first proven on an established airframe undergoing an updating. There are examples, however, of new materials being applied to whole new concepts such as the Stealth B2 Bomber with, of course, exceptionally high unit costs. Nevertheless, if a suitable perspective is chosen, it can be seen that very major changes have occurred to the structural materials employed over these decades by combination of revolutionary and incremental improvements.

For the airframes of combat aircraft, military and civil transports, a progression from the extensive use of non-metallic materials into the stressed metallic airframe and then to the current hybrid mixtures of metals and the now conventional polymeric composites can be traced. Currently, improved alloys, metallic and polymeric composites are emerging for the next generations of hotter, faster airframes and missile systems. Within these major changes in materials selection, new aluminium alloys have emerged, notably those based on aluminium-zinc alloys during WW2 and the aluminium-lithium series during the 1980's producing a gradual progression that can be illustrated (Fig.1) by increases in mechanical performance[1]. Titanium alloys

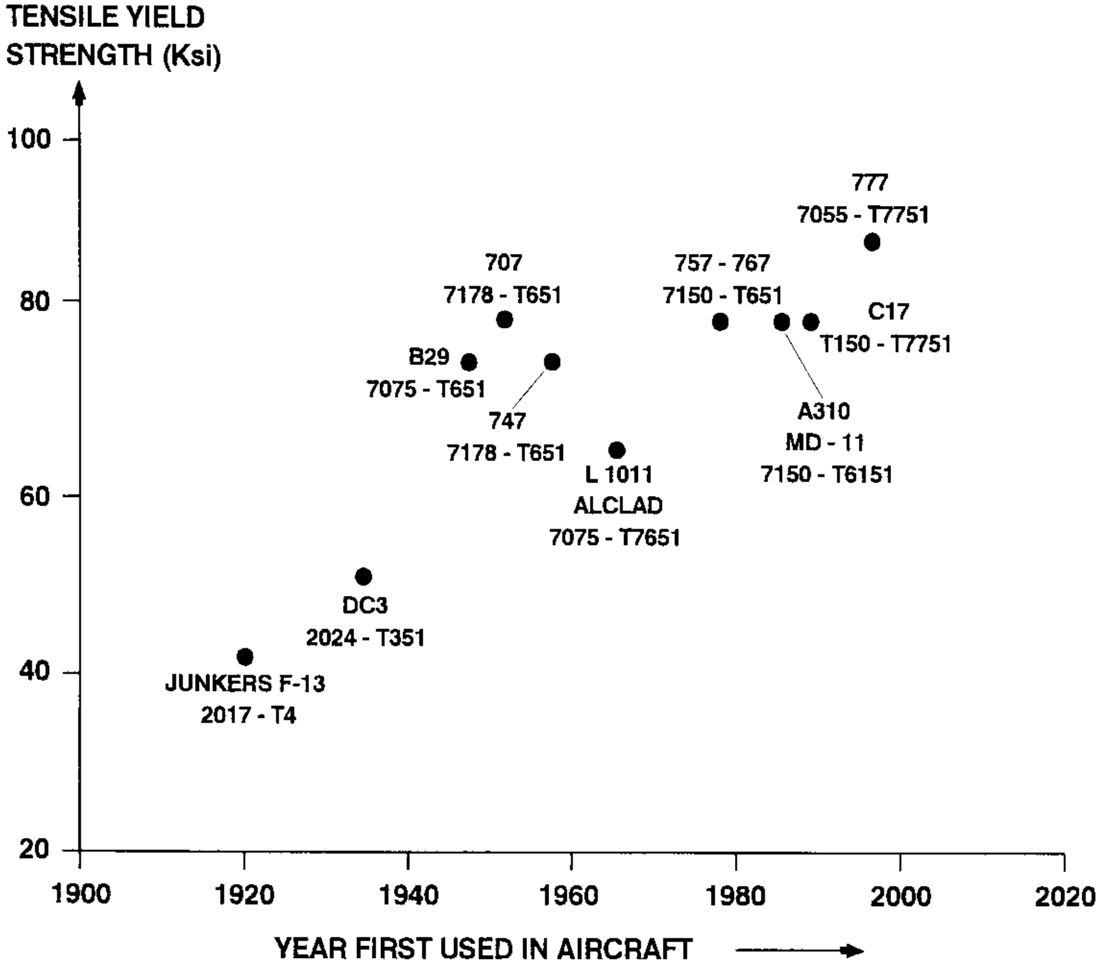

Fig 1. - The gradual but significant progress in Aerospace Alluminium Alloys. After Rioja[1]

were adopted extensively during the 1970's with the dominant use of Ti-6Al-4V still heavily employed in the most advanced military combat aircraft such as TORNADO, EF2000 or the F22. Polymer composites appeared in much the same time-frame as the titanium alloys and have achieved acceptance for most military projects in some form or another, mostly based upon the use of glass and carbon fibre reinforcement of epoxy polymer matrices. Step advances for the polymer composites have occurred with the introduction of ranges of tougher structures based on aramid and polythene fibres or mixed thermosetting and thermoplastic matrices and with the gradual advancement of the performance of the fibres themselves as illustrated (FIG.2) for carbon fibre[2].

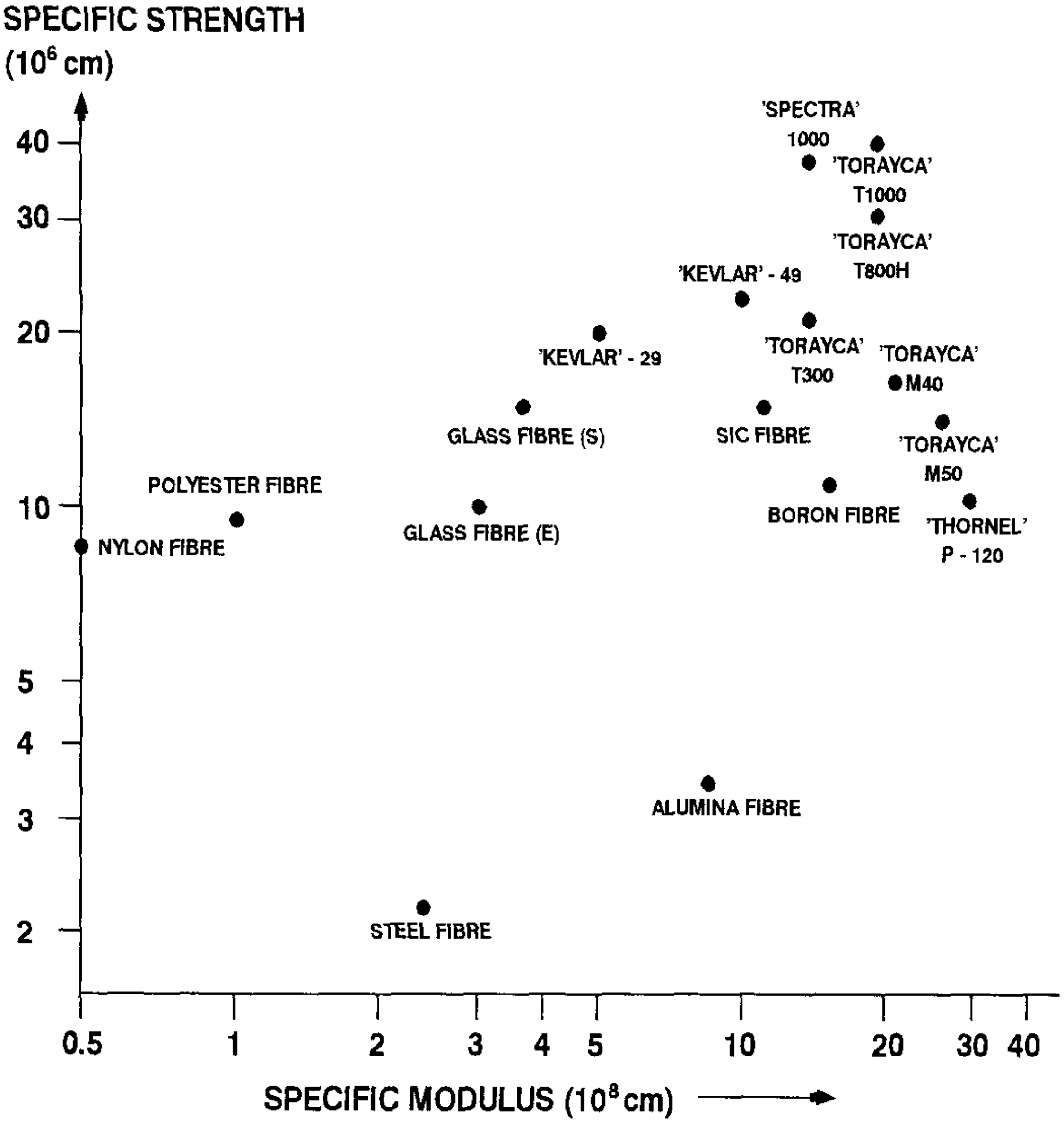

FIG.2. - THE RELATIVE PERFORMANCE OF FIBRES USED IN POLYMER COMPOSITES. AFTER HIRAMATSU AND NISHIMURA[2]

Aero-engine materials have progressed from the use of iron and aluminium based alloys in radial and in-line piston engines through the necessary introduction of nickel alloys such as Nimonic 80 during the 1940's for the first gas turbines. These in turn have progressed through the wrought and cast precipitation hardening versions including the nickel single crystal blades to the air cooled blades that currently operate in gas streams at temperatures above their melting points. The progression in this technology can be illustrated (FIG.3).

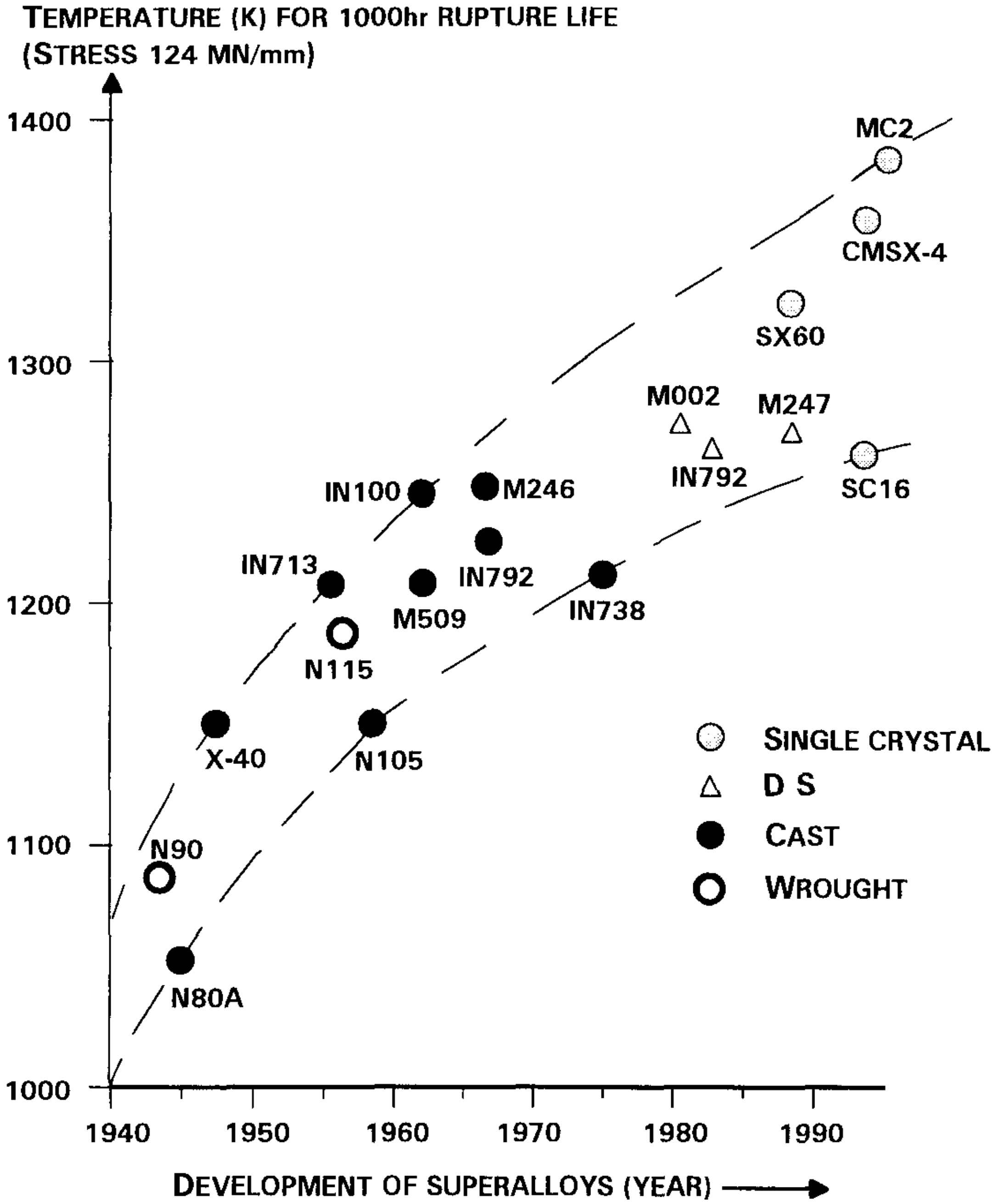

FIG.3 - THE EVOLUTION OF CREEP-RESISTANT NICKEL SUPPERALLOYS. AFTER HARRISON AND WINSTONE[3]

Titanium alloys replaced high temperature aluminium alloys such as the 2618 or RR58 alloys initially used for the cooler fan and compressor components of early gas turbine engines. An aborted attempt to use polymer composites for large fan blades was superseded by the hollow superplastically formed and diffusion bonded titanium alloy variants. The very large polymer composite fan blade has now reappeared for potential application to future very large engines, although now supported by titanium structure. The titanium alloys in use have also improved in strength and strength at temperature[4] (FIG.4).

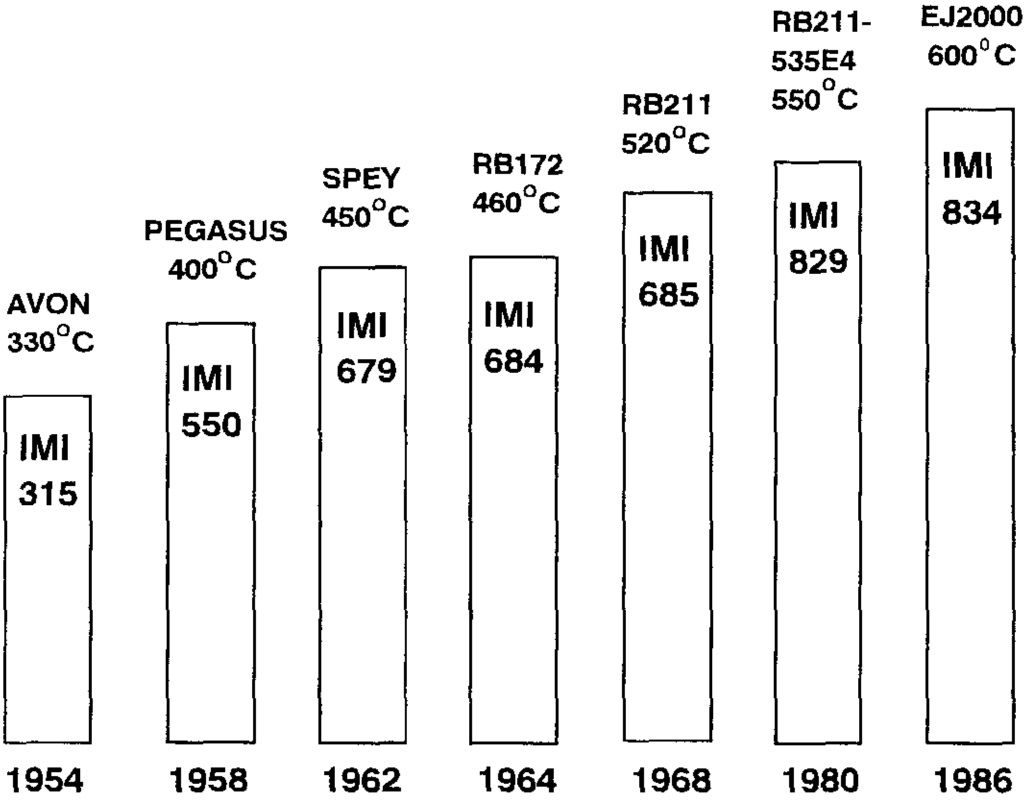

FIG.4 - THE EVOLUTION OF TITANIUM ALLOYS USED IN UK AEROSPACE. AFTER FARTHING[4]

Whilst a very clear trend can be seen in improving technology or capability throughout this background, it needs to be clearly stated that at the same time there has been an escalation in costs that has run ahead of commercial inflation, reflecting the increasing sophistication of the system. The illustration presented by JAGGER[5] illustrates this effectively (FIG.5) but does not include the phenomenal cost increases associated with systems such as the B2 bomber. Hidden behind these increased costs has been an unacceptable trend towards much increased developmental timescales associated with the increased complexity of the systems. Although, as will be seen, the impact of new materials on systems affordability is minor, the overall pressure for reducing costs and compressed timescales can create a reaction to materials advances.

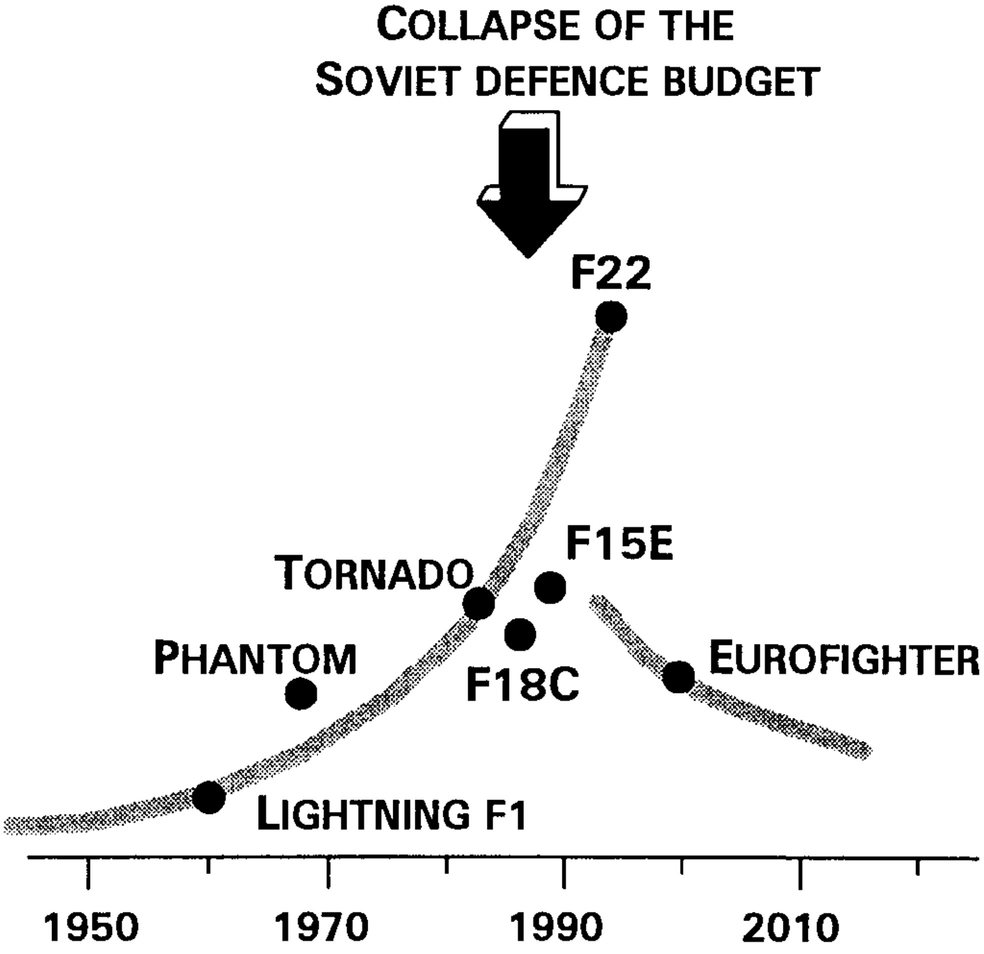

FIG.5 - MILITARY AIRCRAFT CAPITAL COST TRENDS. AFTER JAGGER[5]

Enhancement to vehicle performance

Previously, it has been the case that the performance of military systems has been the dominant factor, there being no place for second best. It should be stated here that there are real arguments for the maintenance of technology at the leading edge for systems that have a critical impact on military performance. In the author's opinion, following foresight judgement, this transposes into lighter, higher performance materials and those with higher temperature capabilities. In addition to these real incentives for the selective enhancement in performance of military combat and transport aircraft there are different, but equally demanding ones, for the civil transport field.

Reduction in structural mass

In terms of combat aircraft the speed of climb, flight and turn, the fuel and payload masses, rates of fuel burn, observability and survivability are obvious issues. Many, but not all, of these are determined by total allowable aircraft mass and, hence, reduction in 'parasitic' structural mass is a major driver. For engines the thrust to mass ratio is a key issue and, remembering that thrust is limited by the maximum thermal capability of the materials employed, the current drive combines mass reduction by the use of advanced materials with increases in operating temperatures and hence increased thrust.

Transport aircraft performance can be measured in terms of the cost of transport per passenger or load—mile. In reviewing the impact of new technologies on the likely gains in reduced fuel consumption for a large transport fleet, Swihart revealed[6] that advanced materials and structural designs had a significant part to play. But the impact of the new materials would be relatively small in comparison to the impact of improved engine performance or enhanced aerodynamics (Fig.6). In these studies of the performance of large fleets of aircraft, reasonably meaningful data can be accumulated to indicate the value of reduction in airframe parasitic mass and consequently fuel burn. Thereby, a measure of the value of a new material can be gained especially when incremental changes are made.

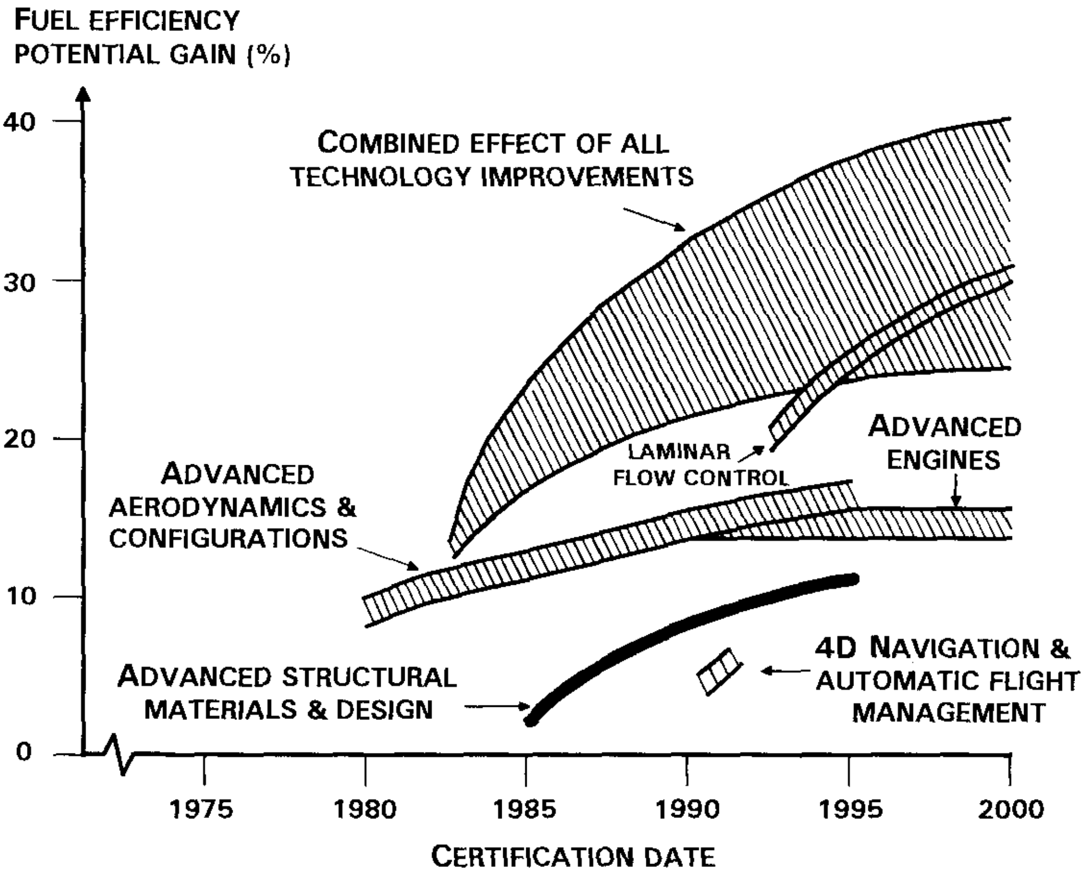

Fig.6 - The impact of advancing technologies including structural materials on transport fuel efficiencies. After Swihart[6]

Higher temperature airframe developments

Enhancement of performance envelopes can be illustrated by the application of new materials at elevated temperatures for airframe, aero-engine and advanced missiles. For example, the instantaneous temperatures experienced in the skin of a generic missile are shown[7] to be beyond the immediate capability of conventional aluminium alloys or polymeric composites. But there is a significant prospect for the development of improved light alloy systems and new higher temperature polymeric composite matrices (Figs 7&8).

In terms of airframe requirements, there has appeared recently a case for the development of a second-generation supersonic transport aircraft, a Concorde replacement. An issue relevant to both military and civil operations since the appearance of a new fleet of long range high speed transport aircraft has military implications in its own right. But additionally, the challenges derived from the need for new materials and efficient structures

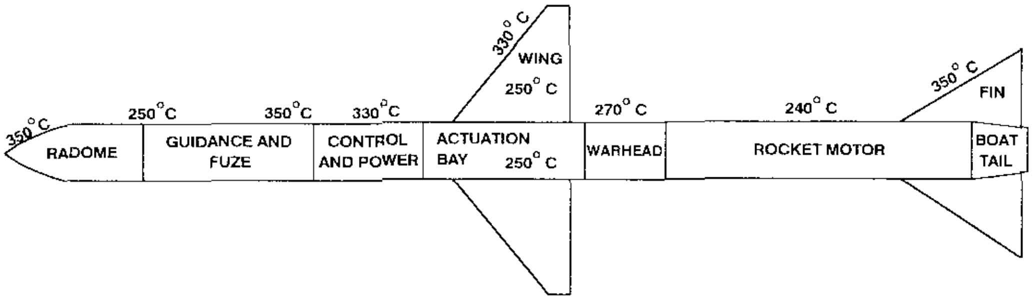

FIG.7 - MAXIMUM TEMPERATURE REQUIREMENTS FOR A GENERIC MEDIUM RANGE MISSILE. AFTER CHAMBERLAIN.[7]

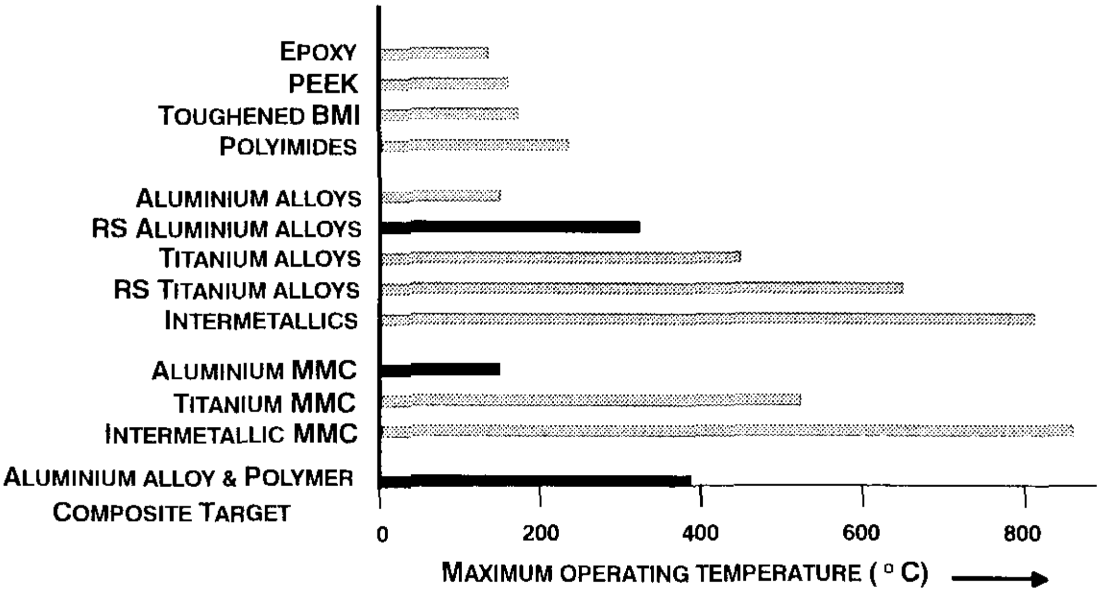

FIG.8 - TARGET AND PRESENTLY ALLOWED MAXIMUM OPERATIONAL TEMPERATURES

impact on the development of future military aircraft, where the use of vectored thrust and operation at high speed impart a similar requirement to withstand severe cycles in temperature, although for more limited timescales.

It has already been indicated that increases in payload and range are critical to the success of a new project just as could be high temperature performance in increasing an aircraft's operating envelope. Considering these aspects simultaneously, advanced materials may also be of direct benefit in extending the range of an aircraft with a prescribed payload. For example,[8] for the next generation of supersonic transport flying at Mach 2.5, conventional aluminium or titanium alloys may not produce a structure light enough to allow sufficient range to cover the Pacific routes. New materials, whether polymeric or metal composites or advanced alloys must simultaneously produce weight reduction and high temperature performance to produce a viable aircraft. If insufficient weight saving is achieved or high temperature performance proves inadequate, the aircraft may not be commercially viable.

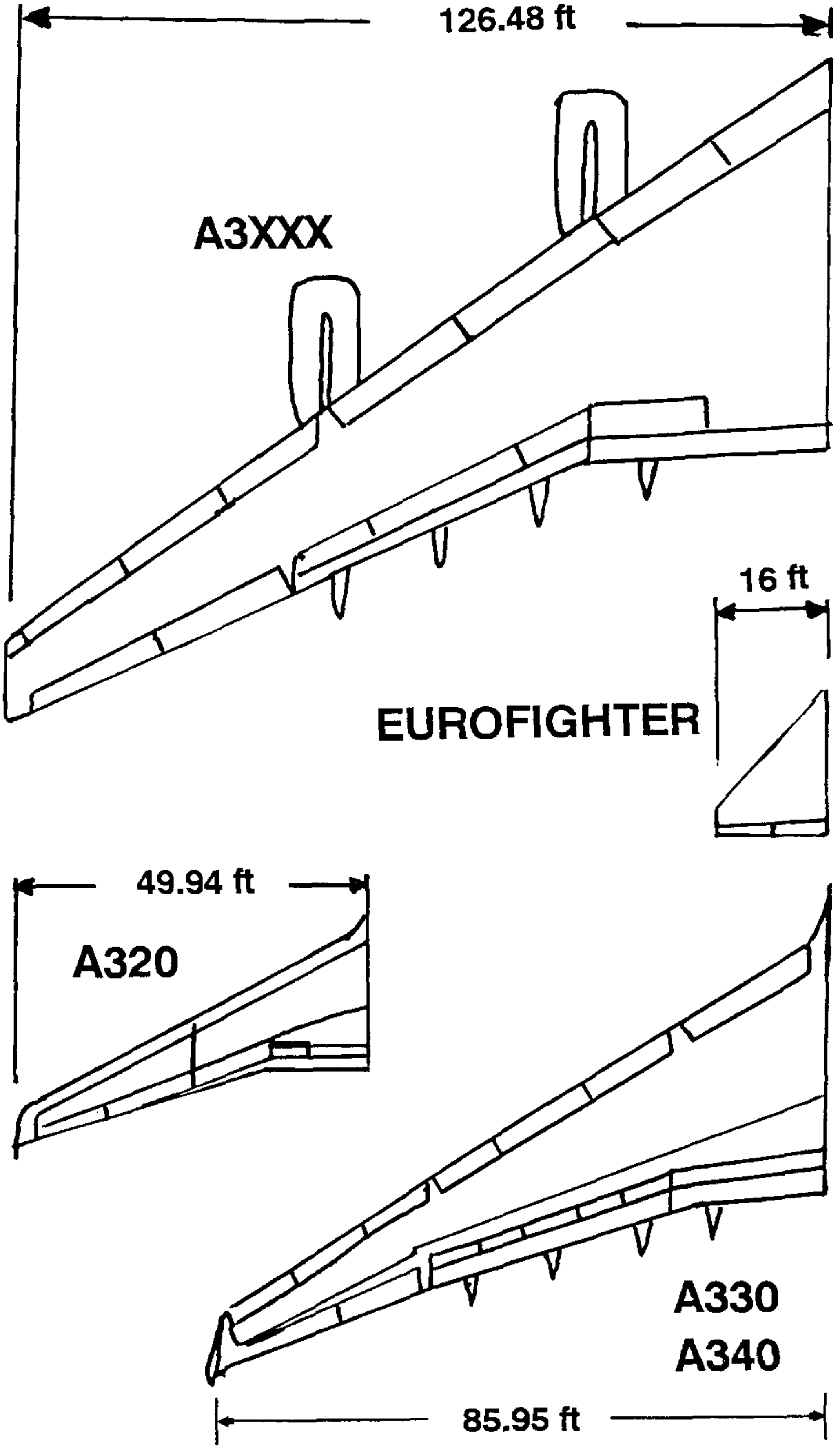

Fig.9 - Relative sizes of civil and military transport wings, identifying a challenge for future materials' suppliers.

Courtesy of BAe Airbus Ltd

The very large airframe

For the civil transport market increasing aircraft size has become important. Plans are announced to design and build exceptionally large aircraft (FIG.9) capable of carrying perhaps 800 passengers and obviously the infrastructure changes required to accommodate such large aircraft are of major importance. However, such large aircraft will require some critical issues in material production to be addressed. For example, the intended wing span will approach 80 metres and structural efficiency would demand that ideally, whether metallic or composite, pieces of material perhaps over 30 metres long would be required, or one or more wing joints will have to be employed. Currently wing covers are typically constructed from single lengths of rolled or extruded aluminium alloy perhaps 20 metres in length. This extension will require significant capital investment whether the choice is for an enlarged aluminium alloy plant or extremely large composite facilities. Indeed, since composites can produce lighter structures when specific stiffness is the issue, and metallic materials are more efficient for strength requirements, it may be that future large wings may well be hybrid. In any event, the major demand for new materials in large structures should provide a strong incentive for the materials industries. Similar trends can be found in the military transport aircraft where the wing structures of large transports such as the GALAXY and C17 aircraft are similarly constructed from exceptionally large planks. Clearly, if the civil market invests in capital equipment to support these developments in scale, then the military manufacturers will benefit by access to such technology and investment.

Developing requirements for aerospace gas turbines

The requirements for materials employed in gas turbines engines parallel those applicable to the airframe construction with a continuing drive to reduce parasitic mass but now with a distinct emphasis on the need to derive new materials that will operate at ever increasing temperatures. This is because the thermodynamic efficiency of a gas turbine engine is increased as the working temperatures and pressures are increased reducing specific fuel consumption and increasing thrust to weight ratios. Current military gas turbine engines achieve a thrust to weight ratio approaching 10:1 but the perceived needs for future offensive and combat aircraft require this ratio to be doubled as a longer term goal. Targets for improvement include combinations of weight reduction, reduced engine diameters with reduced numbers of stages to achieve mass and cost reduction, with increased pressure ratios and turbine entry temperatures to effect thrust improvements. Since the increasing operating temperatures required to increase thrust will be limited by the high temperature performance of existing and developing materials, weight reduction by materials development must also remain a major issue.

The property requirements for components of the gas turbine are equally varied as those seen for an airframe. Cooler compressor areas will tend to be dominated by corrosion, erosion, impact and fatigue considerations. Creep and corrosion resistance will dominate the requirements for turbine blades operating at high temperatures primarily because the stresses, necessarily limited by creep resistance, are too low to cause fatigue problems. Whilst the turbine disc on which they are mounted are cooler in operation, more highly stressed and therefore are again fatigue critical.

To meet these challenges, two types of activity run part in competition and part in parallel with attempts to increase operating temperatures and or to reduce parasitic mass. These activities include the derivation of:

- New materials, based primarily on nickel superalloys and on tough engineering ceramics, to operate efficiently at increasingly elevated temperatures.
- New alloys, metal composites and ceramics designed to reduce parasitic mass in components operating at higher temperatures than may be achievable currently.

The status of these materials is addressed subsequently.

Reduction in costs of acquisition and ownership

A current trend with all new materials being embodied in military and civil projects is the minimization of both initial cost and cost of ownership. Weight savings achieved by the use of modern materials can reduce fuel burn, thereby saving on running costs, or can increase the proportion of the total structural mass that is payload. Materials improvements can generate reductions in Direct Operating Costs (DOCs) of a sizeable extent exemplified by a Lockheed NASA study[9] where a $40M annual saving is generated in a small fleet of 23 medium range transport aircraft by the application of advanced aluminium alloys.

However, whilst these improvements may lead to a reduction in the cost of ownership, any premium associated with an initially increased cost of new materials must be taken into account. It will be seen in the example to follow that the cost of embodiment of either aluminium-lithium alloy or polymer-based composite is recovered successfully only if sufficient weight saving is achieved to reduce structural mass and fuel burn.

Consider, for example, the relative costs and weight savings offered by new materials viewed from the somewhat opposing perspectives of an airframe manufacturer and the aircraft operator. In general terms new materials offer weight savings normally at increased cost (FIG.10). For example, generally, fibre reinforced polymeric composites offer higher weight savings than new metallic materials but at a potentially higher cost. Superplastic Forming (SPF) coupled with Diffusion Bonding (SPF-DB) appears to combine cost and weight saving but is more limited in applicability in terms of the size of component that can be manufactured. The average weight savings that are offered by improved aluminium-lithium alloys and carbon fibre reinforced polymers appear similar, although the composites have greater absolute potential. To judge the impact of the balance between weight savings achieved and the extra costs of new materials requires slightly more detailed consideration.

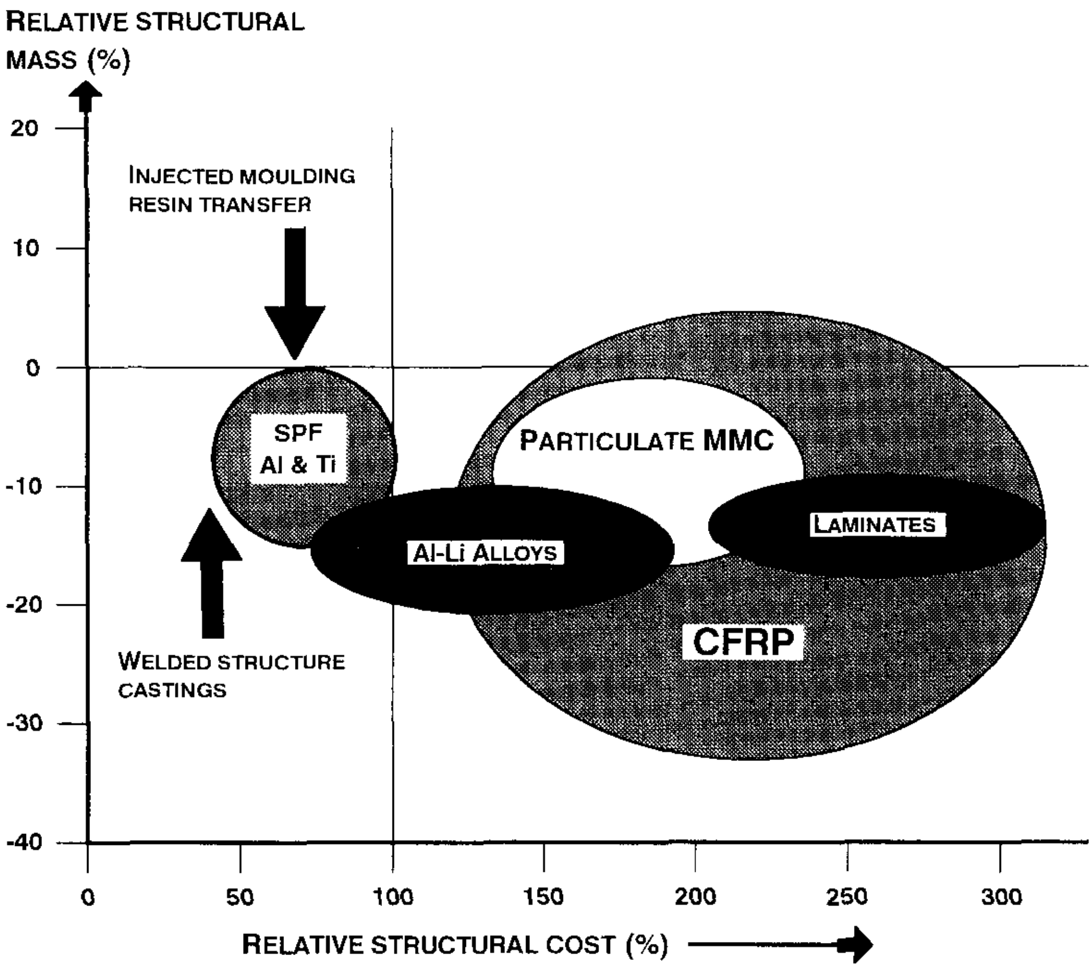

FIG.10 - RELATIVE COSTS AND WEIGHT SAVINGS FOR CURRENT AND FUTURE STRUCTURAL MATERIALS AND TECHNOLOGIES

Following the work of EVANS and JONES[10] it can be seen that the fuel savings offered to the operator achieved by the use of these new materials will offset the initial premium in materials cost here shown for a wing box (FIG.11) considering only aluminium-lithium for the present. An initial premium for the use of the new alloy of times 3 in comparison with previous aluminium alloys is unlikely to be recovered in under ten years even if a full 12.5% weight saving is achieved. If the premium for the use of the new material is reduced, even to a factor of 2.5, then the recovery period is much reduced and the dependency on weight saving is reduced. However, a major factor is the price of fuel. At a standardised price of $1 US per gallon, weight saving is unattractive but at $2 per gallon the reduction in fuel burn becomes a major driving force for weight reduction and the embodiment of new materials. Irrespective of the detailed arguments justifying this analysis, it seems that in assessing the risk of undertaking a new materials development and qualification, the manufacturers have to consider the world price of fuel and political stability perhaps almost more than the technical advantages of the material.

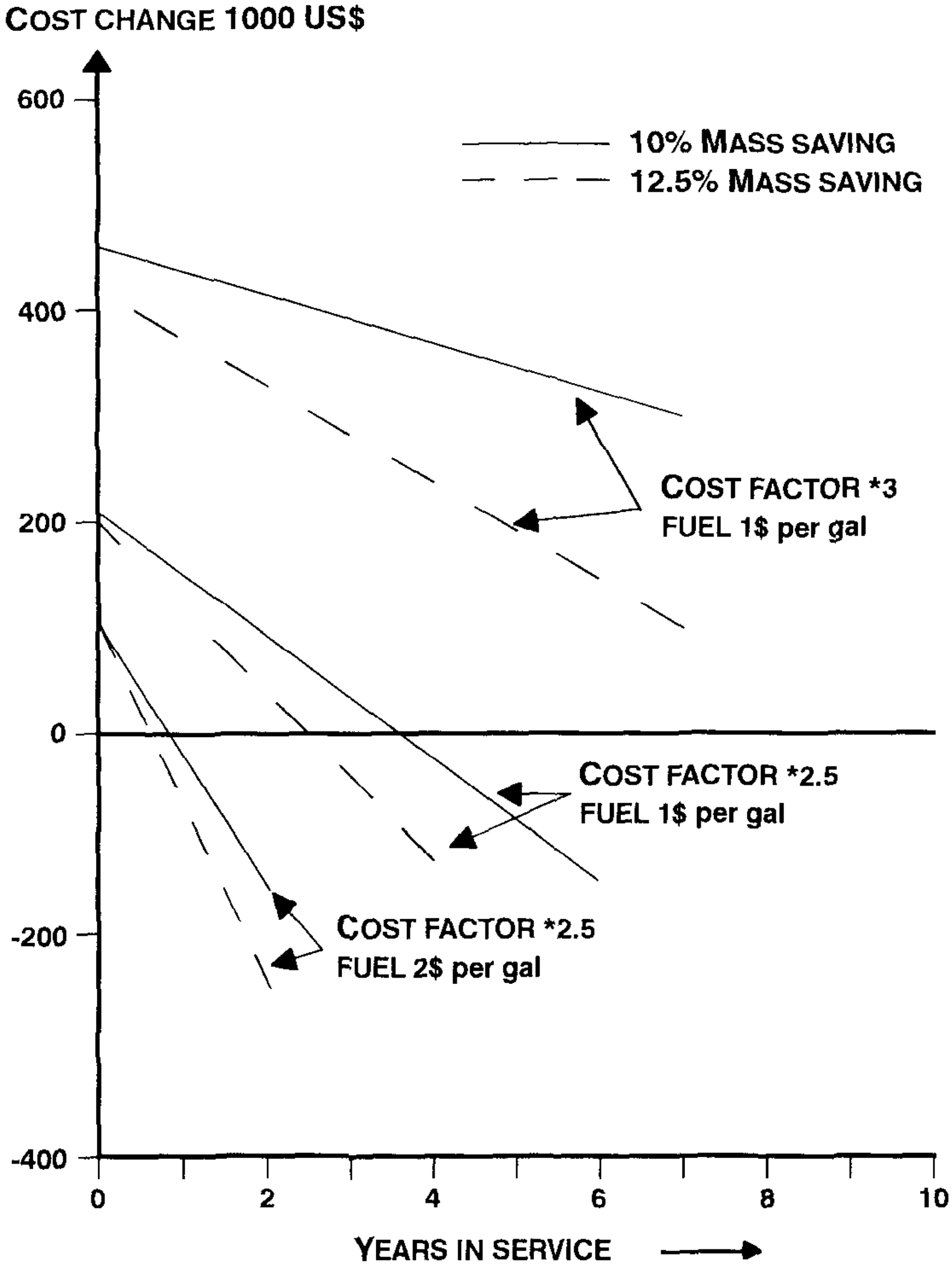

FIG.11 - THE IMPACT OF COST, FUEL PRICE AND MASS CHANGES ON THE OPERATIONAL COST OF A TRANSPORT AIRCRAFT WING BOX. THE USE OF ALUMINIUM-LITHIUM ALLOYS AT 2.5 AND 3 TIMES THE COST OF ALUMINIUM ALLOYS NOW USED ARE ASSUMED

Extending the argument to consider the greater risk involved in the embodiment of fibre reinforced polymeric materials in the same wing box now considered from the operators view point of the accumulation of reductions in direct operating costs. It can be seen (FIG.12) that the higher initial outlay for the polymeric materials requires a higher weight saving to be achieved to offset the initial outlay, now taken as a depreciation factor in the DOC, in a sensible period. To achieve approximately the same recovery period to the point of a net reduction in accumulated DOCs, the composite material has to pro-

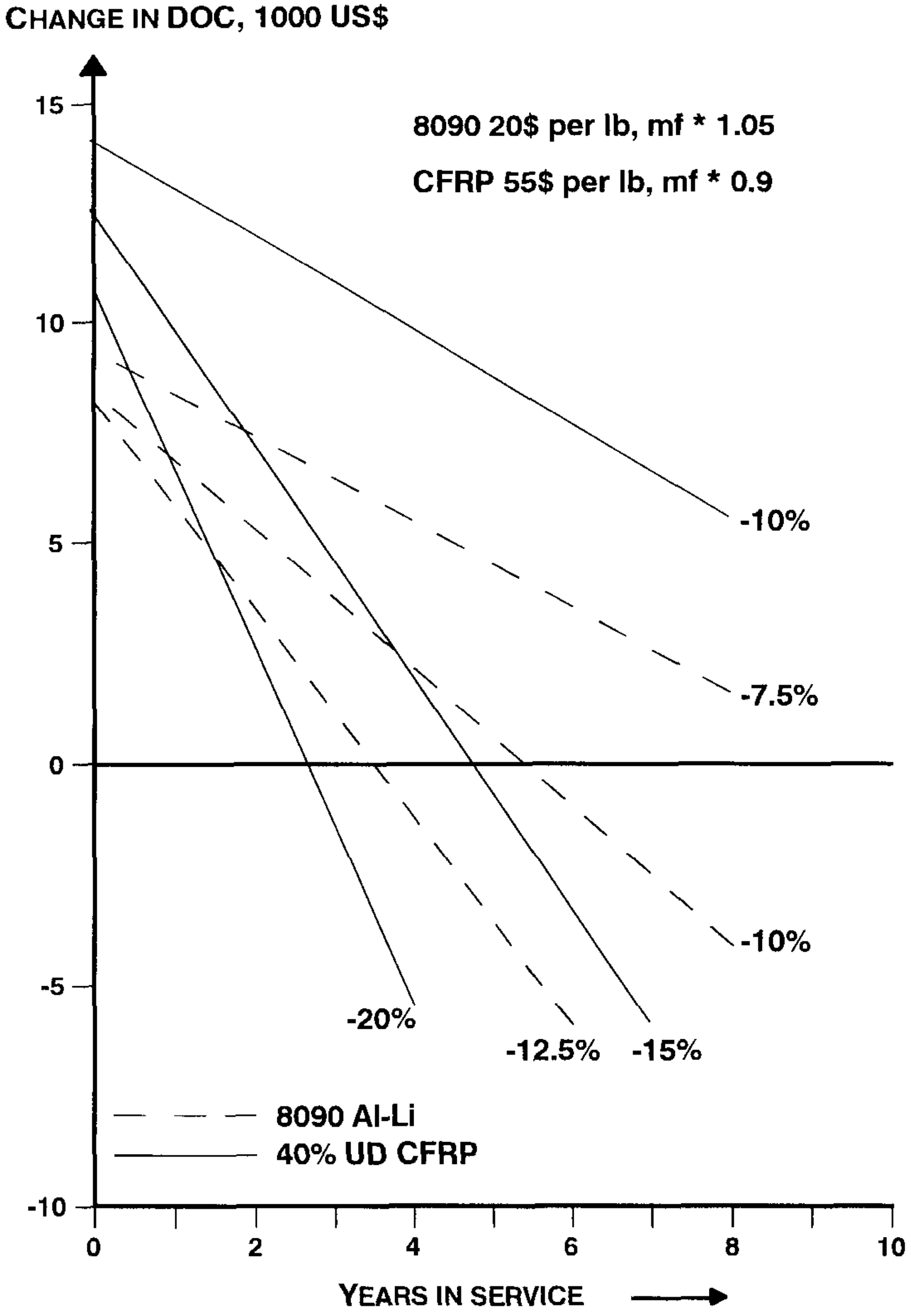

FIG.12 - COMPARATIVE SAVINGS IN DIRECT OPERATING COSTS FOR CARBON COMPOSITE AND ALUMINIUM-LITHIUM ALLOYS USED IN A TRANSPORT AIRCRAFT WING BOX FLYING 3000 HOURS PER YEAR[10]

duce a weight saving 50% greater than that achieved with aluminium-lithium alloys. Smaller weight savings with comparatively cheaper conventional alloy developments produce an even more powerful argument for reducing the risk and remaining with conventional alloys whilst fuel prices remain low.

The impact of maintenance costs

For both civil and military aircraft, the costs associated with maintenance and operation will be at least two to three times greater than initial purchase values and this trend will be magnified by the need to extend future operational lives for military equipment (FIG.13). A distinct difference may be found between the distribution of operating costs for military and civil aircraft because, with relatively low utilization of military aircraft, fuel burn becomes of less importance than weapons and avionic systems up-grade, maintenance and repair. Indeed, in the context of the impact of materials and structures on the cost of new combat aircraft, it can be seen that the cost of materials has a very small influence on the overall cost of the system. But the cost of maintenance of the airframe and engine structures is most significant.

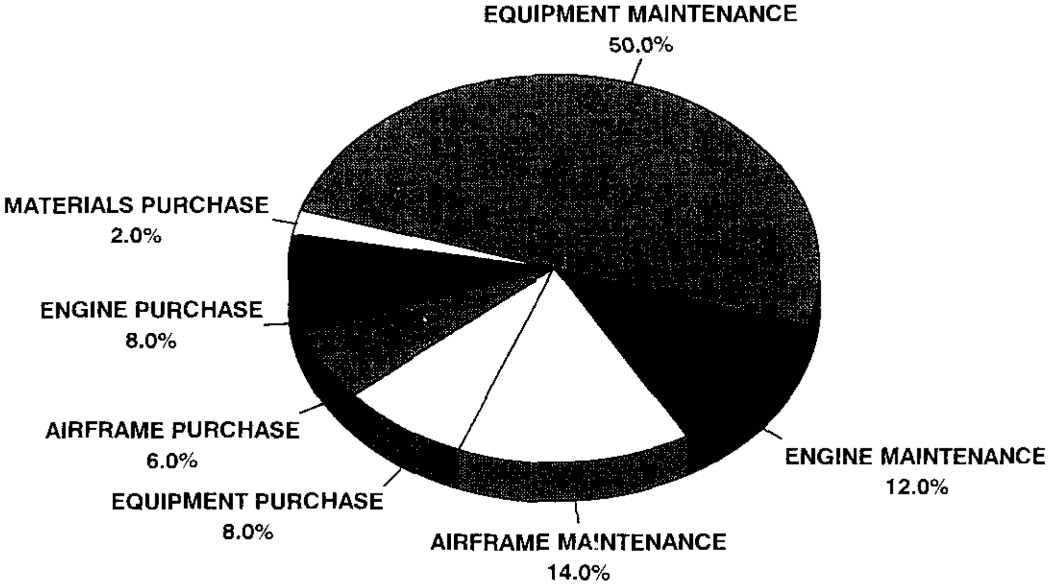

FIG.13 - RELATIVE ACQUISITION AND MAINTENANCE COSTS FOR COMBAT AIRCRAFT, SHOWING THE SMALL INFLUENCE OF MATERIALS' COST

Additional to simple arguments related to fuel burn or payload, mass reduction in an airframe or the rotating parts of a gas turbine can reduce the acceleration induced loads, which in turn can lead to an increase in fatigue life. Moreover, new materials such as aluminium-lithium alloys or metal matrix composites can be employed purely because of their improved resistance to fatigue cracking and enhanced levels of damage tolerance, whilst polymeric composites can be used to offset the damage caused in corrosive environments. For example, in general terms, lightweight alloys have been employed very extensively in aerospace to reduce parasitic mass and the developments of the last two decades have been orientated towards the enhancement of performance in service by the reduction in fatigue damage rates or sensitivity to corrosion problems. With aluminium-lithium alloys there appears to be the possibility to both reduce the parasitic mass of the structures to which they are applied and to improve performance in service. For example, the use of aluminium-lithium alloy is being made in the fuselage frames of the F16, currently undergoing mid-term enhancements, with up to a five fold increase in fatigue life being achieved for this critical application, with a concomitant mass reduction being a further bonus. In consequence, it may be that, whilst the risk and cost of the application of new materials is born by the airframe manufacturer, the major benefit of the application of fibre reinforced polymer composites, or aluminium-lithium, is gained by the operator with a reduction in operating costs stemming from reductions in the rates of fatigue or corrosion damage. But these potential advantages may be difficult to quantify, and therefore to sell, before service experience is obtained.

Repair technology

Further examples of the influence of materials choice on operating costs can be found. For example, during the long development of carbon fibre reinforced polymeric composites, insufficient attention was given in the early stages to the consequences of embodiment on the operating costs of the final users with especial reference to the cost of repair. Following the paper presented by THORBECK,[11] it can be seen (FIG.14) that repair costs for composite structure can exceed those for conventional metallics by a factor of at least 2. In the event of the need to replace entire items containing significant damage levels such as a complete fin, the re-investment required to replace the damage item cannot be seen to be sufficiently offset by the relatively modest fuel burn reductions. This has resulted in a regression towards the cheaper metallic structures, at least whilst fuel prices remain low or emphasis is placed on more affordable maintenance costs. Whilst this technical risk could perhaps have been foreseen earlier, its effects on the market share obtained by composites would have proved impossible to predict. The lesson here is that the ultimate customers for the new material, namely the operators, were not involved in the early stages of risk analysis. Although it is arguable whether negative opinion of this sort would have had any impact at all on a development as radical as carbon fibre reinforced plastic. Analogous comment can be made on the potential difficulties in repair of aluminium-lithium alloys and particularly on the impact of the appearance of lithium in the aluminium scrap cycle.

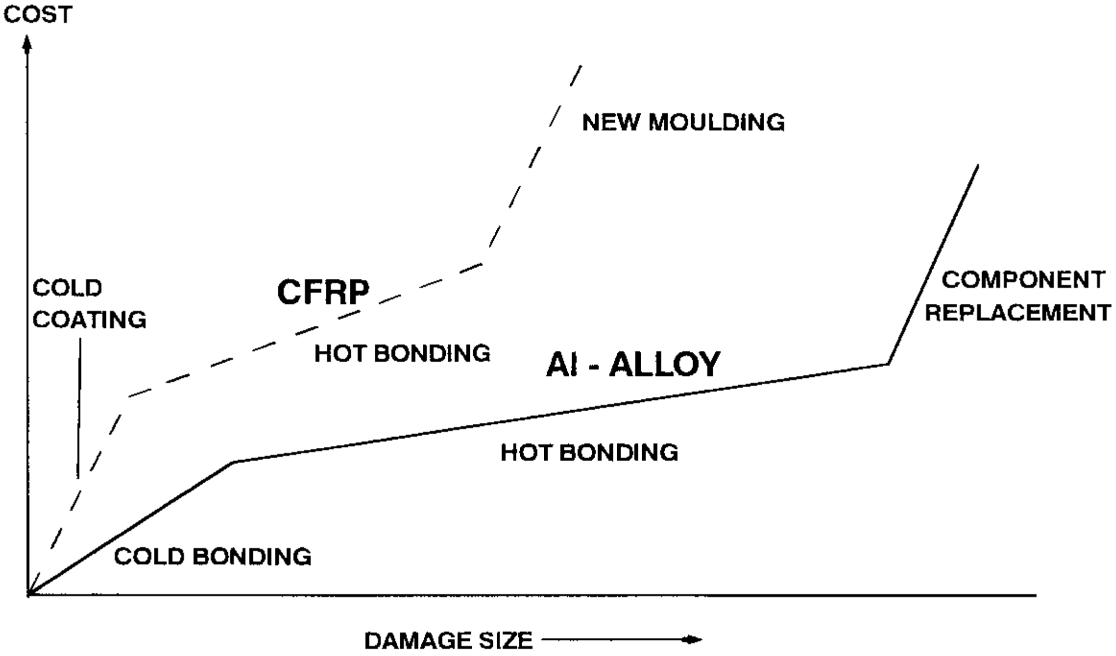

FIG.14 - THE RELATIVE COSTS OF REPAIR OF CARBON-FIBRE-REINFORCED PLASTIC AND ALUMINIUM ALLOY STRUCTURES. AFTER THORBECK[11]

Market issues

The perceptions of the materials suppliers may well be different from those of airframe manufacturers. The major supply companies active in the aerospace materials field traditionally undertake developments. It would seem that a prime driver for these suppliers is the retention or enhancement of market share. Arguments may be raised on the apparent competition between light

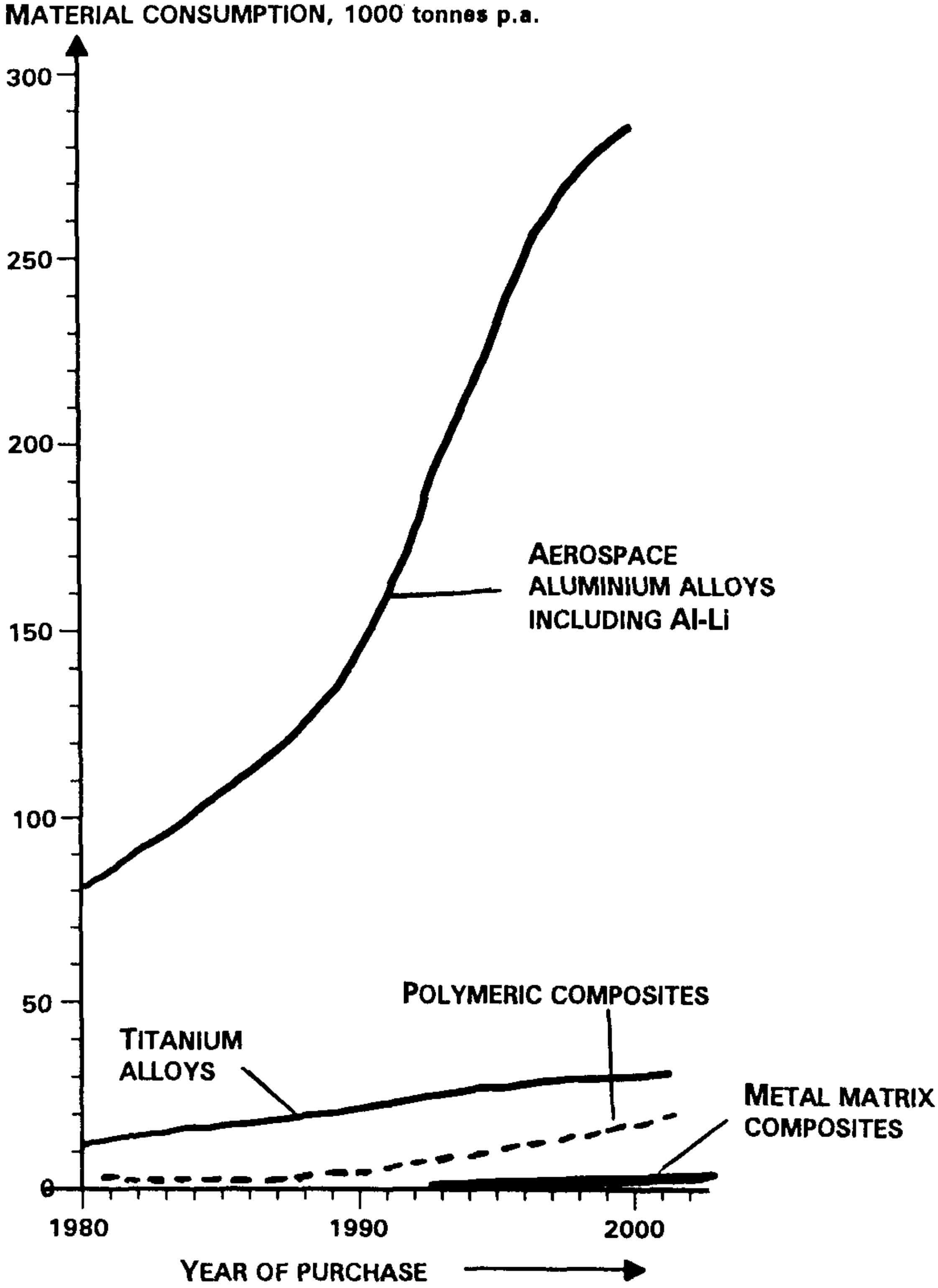

FIG. 15 - THE PROJECTED GROWTH OF MATERIALS USED IN AIRFRAME CONSTRUCTION

alloys titanium alloys and polymeric composites in the structural airframe market. Recent trends in the USA with significant quantities of titanium (and aluminium alloys) being used in the F22 may herald a return in the use of titanium in combat aircraft. Nevertheless, future combat aircraft are indeed hybrid in their materials and presently show roughly equal proportions of conventional polymeric composites and conventional metals. The perceived risk of lost market has undoubtedly been a factor driving aluminium alloy manufacturers to invest in new alloys and in metal matrix composites. A careful risk analysis may well have revealed that the consumption of material is dominated by the building of large fleets of large aircraft. The dominant use of aluminium alloys in major transport aircraft, when integrated with the general trends towards larger, cheaper airframes would have indicated (Fig.15) that the growth in the consumption of aluminium alloys was assured. Equally, the increasing penetration of composites into the smaller but very valuable market such as combat aircraft also produces growth (Fig.16). That is, there is clearly room for both technologies. The key issue is that to justify plant installation or enhancement a significant commercial market must be found for the materials suppliers.

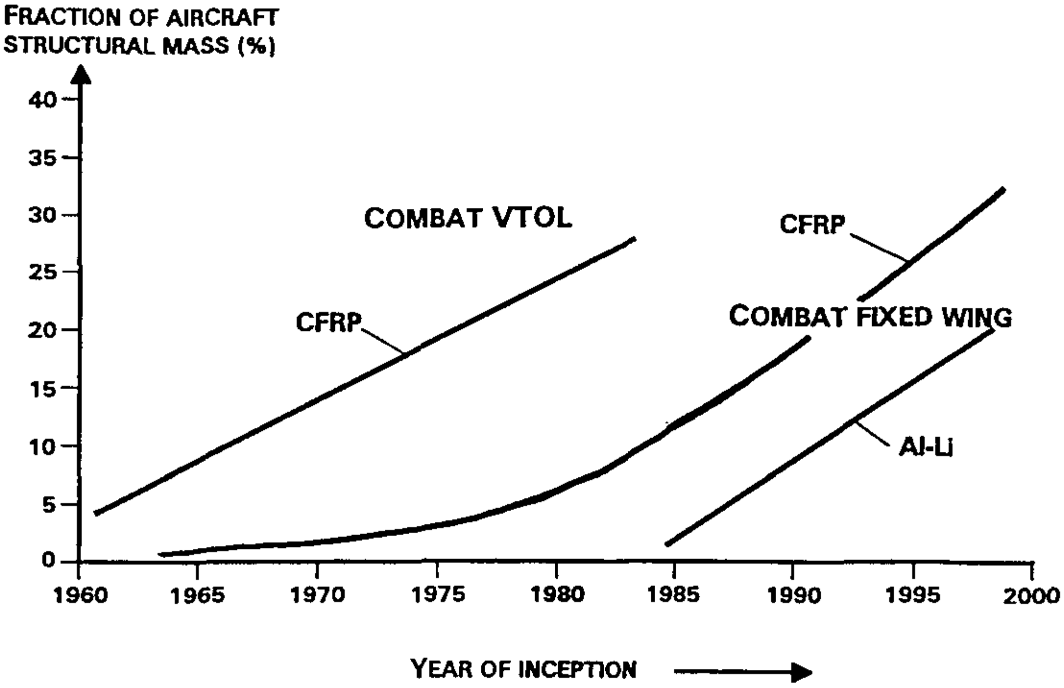

Fig.16 - The growth in the use of fibre-reinforced polymer composites in the primary structures of military aircraft and the emerging trends for aluminium-lithium alloys

The status of current materials

New materials aimed at military aerospace application, such as aluminium-lithium alloys or fibre reinforced composites, are now being adopted partly due to research in the Structural Materials Centre. These also include particle and fibre reinforced metal matrix composites based on aluminium, magnesium and titanium alloys and more exotic mechanically alloyed and powder materials. The application of titanium alloys in combat aircraft is showing a resurgence although a drive towards cost effective manufacture tends to limit alloy choice to traditional variants. Nickel superalloys and ceramics continue to make incremental improvements. New polymer matrices are appearing with enhanced toughness and higher temperature performance whilst new fibres and fibre concepts continue to be derived.

Developments in aluminium alloys

Although aluminium alloys have dominated the construction of military and civil airframes since the inception of the stressed metallic airframe in WW2, it should not be assumed that they are fully developed as a continuous stream of step improvements continues to be achieved. These include:

- Improved high strength aluminium-zinc based alloys (7000 series)
- Better damage tolerant aluminium-copper and aluminium-magnesium-silicon alloys (2000 and 6000 series)
- The more novel aluminium-lithium and aluminium-beryllium variants.

High strength aluminium-zinc alloys

There has been a steady progression of the development of the aluminium-zinc-magnesium-copper alloys (7000 series). They are used primarily in compressively loaded structures such as upper wing skins but also for internal ribs, frames and landing gear, typified by adoption for F22 and evaluation for use on FLA and next generation combat aircraft. The drive for increased compressive strength in upper wing skin material leads to ever increasing levels of applied stresses to maximize weight saving such that good fatigue strength and fracture toughness become increasing important. Additionally, problems that beset the early use of the 7000 series alloys with poor exfoliation and stress corrosion resistance must be shown to be overcome. Techniques such as double ageing practices, controlled combinations of heating rates and mechanical deformation between quenching and ageing and the use of the so called reversionary ageing practices has enabled strength, fracture toughness and corrosion resistance to be increased simultaneously. This can be well illustrated by Alcoa data (FIGS 1 and 17).

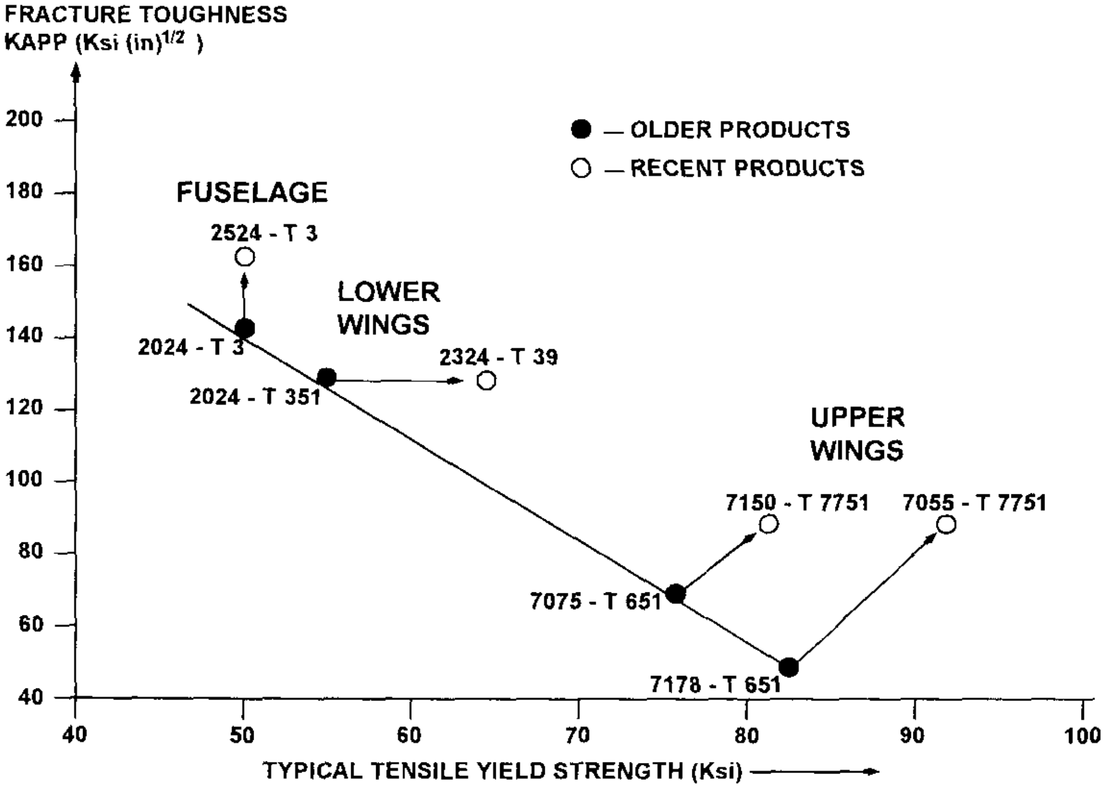

FIG.17 - ALCOA DATA FOR INCREASES IN THE TOUGHNESS AND STRENGTH OF IMPROVED ALUMINIUM ALLOYS[1]

High corrosion resistance is always at a premium to maintain long maintenance-free service intervals. Major strides were made against stress corrosion attack by minimizing internal stress levels through combinations of controlled quenching for irregular shapes such as forgings and controlled stretching after quenching for plates, extrusions and sheet of regular cross section. High temperature ageing was then found to impart high levels of natural resistance to stress corrosion by developing solute depletion close to grain boundaries whilst double ageing and more complex treatments were derived to achieve strength, corrosion resistance and fracture toughness simultaneously.

Clearly, if future military aircraft can adopt these new treatments applied to established alloys they may benefit simultaneously from improved performance and improved maintainability via a low cost low risk route.

The damage tolerant aluminium-copper alloys

Traditionally, the 2000 series aluminium-copper and aluminium-copper-magnesium alloys have been used for applications requiring damage tolerance. Damage tolerance here can be taken to be considered as the beneficial combination of very high fracture toughness and very low rates of fatigue crack propagation particularly under loading spectra containing the occasional high tensile load. From early development and steady evolution, naturally aged 2000 series alloys have come to dominate this type of application in both fuselage skin and lower wing covers. In both, the strength of the material has been generally less important than its damage tolerance and stress levels are, in the main, set to achieve satisfactory fatigue lives. In the case of the fuselage sheet skin material, sufficient fracture toughness has been required to enable the fuselage to withstand a crack two frame bays in length at maximum service pressure. The improvement achieved in increasing the plane stress fracture toughness of 2524-T3 is illustrated (FIG.17) using Alcoa data. As damage tolerance has improved progressively by minimizing levels of impurity elements, by improved fabrication practice to optimize grain structures, and by the use of cold working of fastener holes to maximize fatigue strength, so working stress levels have been increased to save weight. This has resulted in a need to increase the yield strength of materials used in lower wing skins to offset yielding, illustrated by the application of 2324-T39 in FIG.17.

Again if damage tolerance can be improved simultaneously with improved strength using an established alloy system, improvements in both performance and maintainability are achievable for minimal extra cost. The improvement in fatigue and corrosion resistances indicated for these two major alloy types is vital if the trends in extended aircraft lifetimes are to persist. For example, as an indication of such exacting requirements, it is now projected that certain North American military aircraft will remain in service for sixty years.

Aluminium-lithium alloys

Recent years have seen the emergence of aluminium-lithium alloys offering typically up to 10% density reduction and 15% increase in stiffness coupled with significant improvements in damage tolerance particularly achieved by improvements in resistance to the growth of fatigue cracks. The first generation of new aluminium-lithium alloys, such as the Al-Mg-Li alloy, 1420, developed in Russia, and the Al-Li-Cu-Mg alloy, 8090, developed in the UK are now in service in major military and space structural applications. 8090 has been qualified for EF 2000 and is built into prototype aircraft, but has yet to be embodied for production airframes primarily because of cost. The alloy has being extensively adopted on MERLIN. Studies in the USA are centred on the use of more dilute and weldable aluminium-lithium alloys with improved fracture toughness such as the Al-Cu-Li alloy 2097. Applications include space shuttle fuel tanks, where weight reduction is at a premium, and the fuselage frames of the F16, where a five-fold increase in fatigue life is predicted from the replacement of 2124.

Improvements have been affected over the last decade in the performance of aluminium-lithium alloys by the eradication of some of the persistent problems hampering their application. These have been achieved partly with the development of a second generation of more dilute alloys and partly by improved control of microstructure. Principal areas for activity within the SMC have centred on:

- Factors causing scatter in short transverse fracture toughness in thick sections
- The maximization of in plane toughness for sheet products
- Improvements to thermal stability.

Since growing use of these new alloys is being achieved, work now proceeds on a second generation of alloys for further application. Two themes are emerging, one being property enhancements, the other extensive reduction in the cost of structures embodying aluminium-lithium alloys. It may be noted that the damage tolerant variants of the aluminium-lithium alloys now being studied in the UK have higher fracture toughness and fatigue crack growth resistance in sheet than even these improved 2000 series alloys, but at a slightly lower level of strength

Attention in the UK is concentrated on the derivation and optimization of a high strength variant with maximum weight saving potential in military applications. In particular, material with high compressive performance is sought for undercarriage, spar and wing plank applications. Progress to date has been good. However, it can be seen above that a significant factor is the cost of the material *per se.*

Lower cost alloys and production methods

To reduce the cost of aluminium alloy structures, two approaches may be considered. Of course cheaper alloys may be selected but, as a general trend, technical requirements are increasingly exacting and consequently attract price increases. A second approach is to develop lower cost semi-fabrication and final assembly techniques. For example, stringers or stiffeners may be integrally extruded in sheet (FIG.18) to obviate built-up structure or welding may be employed. These changes in fabrication may require alloys to be derived and optimized to enable the technology. For example, the high performance aerospace variants of the aluminium-copper and aluminium zinc series have traditionally been regarded as poor in terms of weldability. This issue is being addressed especially with the emergence of improved welding technology.

As an example of a potentially cheaper material, aluminium alloys precipitation hardened by Mg_2Si have been in general use including aerospace for decades. Recently, interest in this system has increased for several reasons. Firstly, they appeared to offer potential for reduction in initial cost being potentially cheaper than aluminium-copper alloys having replaced the expensive copper addition. Secondly, being weldable, they appear to offer the potential to reduce manufacturing costs and, finally, variants with improved property levels have appeared typified by the ISO 6013 alloy. Somewhat surprisingly, the damage tolerance of the 6000 series alloys has been shown to at least match that of the incumbent 2000 series alloys in terms of sheet fracture toughness and resistance to fatigue crack growth.

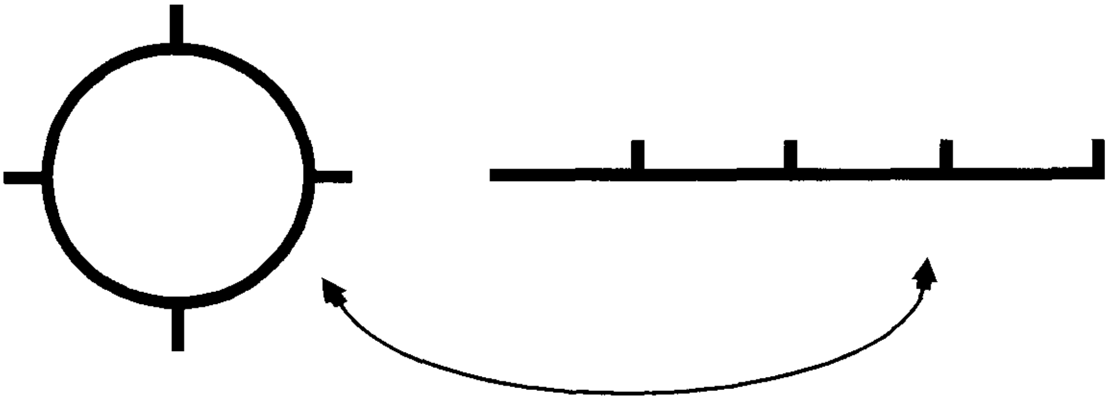

FIG.18 - THE PRINCIPLE OF THE LARGE STRINGER-REINFORCED PANELS PRODUCED INTEGRALLY BY EXTRUSION

A particularly interesting feature is the possibility being studied to weld integral stiffeners to sheet 6000 alloys for future fuselage structure. In similar vein, SMC has tested extruded sheet of both 6000 series and aluminium-lithium with integral stiffeners in the extrusion. Both the fracture toughness and the fatigue crack growth resistance proved to be more than acceptable.

Cost reduction using aluminium-lithium alloys may seem a difficult task because of the inherently high cost of lithium until certain critical features are revealed. For example, the alloys can be successfully welded and have been applied extensively to the structure of CIS combat aircraft and to the US Space Shuttle fuel tanks in the welded state. Whilst 50% cost reductions for the initial structure may be achieved by welding, the impact of this type of structure on sustainability and cost of ownership must be carefully considered.

A second major feature for cost reduction in aluminium-lithium involves the use of creep forming technology typically used on metal combat aircraft wings with conventional aluminium-copper alloys. Creep forming involves pre-setting the wing plate material to the wing curvature and then using the artificial ageing cycle of the aluminium heat treatment to creep the material permanently to shape. Alternative methods with metallic wing planks involve either complex machining operation or the use of shot blasting. Creep forming is efficient in that it involves two operations simultaneously and in particular it can produce the deep curvatures in very large structures required in modern high lift wing forms. However, aluminium-lithium alloys of the 8090 type have a particular advantage in that they have been shown to possess the correct balance of damage tolerant properties when artificially aged, whilst damage tolerant aluminium-copper alloys are not normally aged artificially.

Higher temperature airframe alloys

There persists a barrier to the application of materials at elevated temperature. When operating temperatures of airframe, or missile, skins exceed approximately 150 to 200°C aluminium alloys or polymeric composites tend to be replaced by titanium alloys increasing cost significantly. If light alloys or composites can be improved in this respect the use of titanium or other heavier materials can be obviated saving cost and weight.

For this reason powder metallurgy aluminium alloys are being evaluated at temperatures up to 450C. Close control of the composition of the atomising gas coupled with sieving and gas classification techniques in powder atomisation allows the production of fine spherical powders to pre-selected sizes. These can be readily mixed, whilst the relatively rapid quenching rates (circa

10^4K s^{-1}) of the powder process allows the retention of supersaturation of normally insoluble elements. Perhaps more importantly, the powder route lends itself to the use of mechanical alloying techniques for materials fabrication. Alloy compositions currently being pursued are demonstrating thermal stability at temperatures as high as 450°C with satisfactory levels of strength at ambient temperatures (FIG.19) but still presently with inadequate strength at temperature. Research is aimed at the derivation of compositions and microstructures that optimize the need for high temperature ductility during fabrication with maximum creep strength and strength at service temperatures. A strong tradition persists in the use of compositions that produce fine dispersions of thermally stable precipitates typified by the combination of iron, vanadium and silicon in the ISO 8009 alloy. However, many of these systems can show a temperature range in which embrittlement occurs by the precipitation of very fine phases in matrix and grain boundaries.

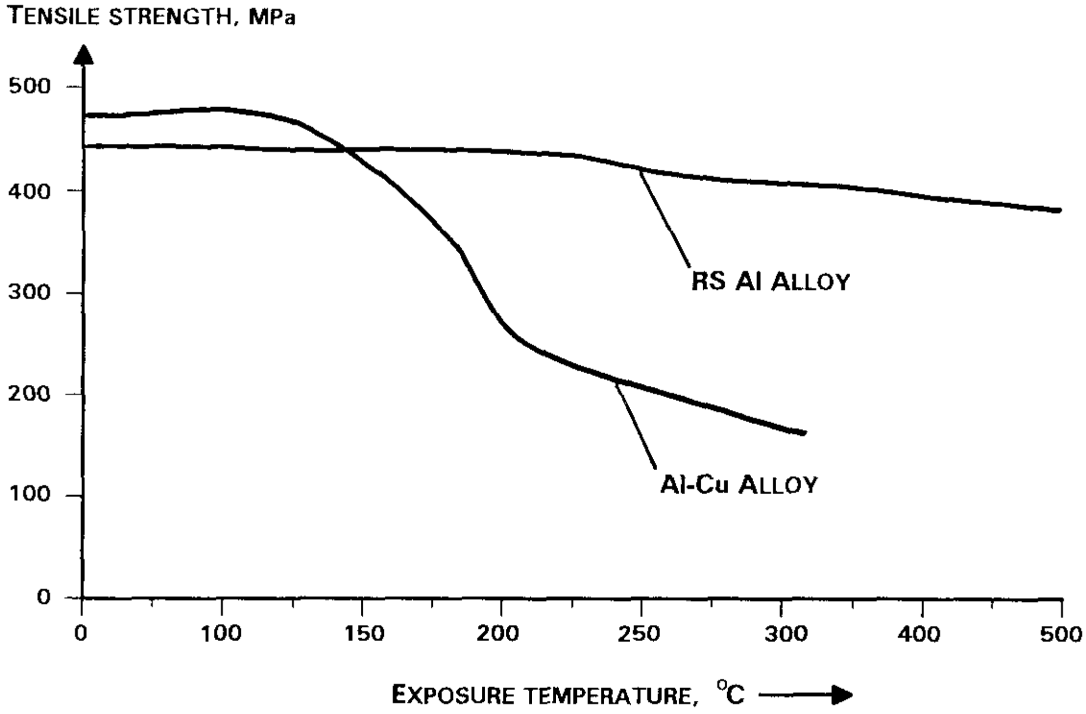

FIG.19 - RECOVERED STRENGTHS OF RAPIDLY SOLIDIFIED, UNREINFORCED ALUMINIUM ALLOYS

If temperatures are envisaged that are higher than can be sustained with light alloys or polymer composites, the traditional choice has been an aerospace titanium alloy. An issue of some importance is that titanium is electrochemically more compatible with carbon fibre reinforced polymers than aluminium alloys and is therefore being chosen for hybrid metal—composite structures to circumvent corrosion problems associated with the use of aluminium. Developments in North America are using aluminium and titanium plate structures explosively bonded to form a hybrid frame with the titanium element carrying high loads in the fatigue prone areas and the aluminium component minimizing weight and cost where minimum gauge and shear strength are required.

Higher temperature engine alloys

Titanium alloy usage has centred on the $\alpha+\beta$ alloys such as Ti-6Al-4V or Ti-6Al-2Sn-4Zr-2Mo in wrought forms and on commercially pure material or Ti-6-4 in cast forms. Although there is a large range of titanium alloys potentially available,[12] considerations of cost, castability, fabricability and weldability have tended to limit the choice for most applications. Features, such as the need to heat-treat the more complex alloys after welding or diffusion bonding, have had a critical influence on materials selection.

However, the substantial incremental increases in performance of the titanium alloys and titanium based intermetallics in the UK should not be underestimated. Maximum service temperatures were illustrated previously, but it may be noted that the step change from the standard Ti-6Al-4V alloy to Ti-4Al-4Mo-2Sn-0.5Si (IMI 550) not only adds strength at room temperature but also a 100C increase in maximum operating temperature. The further step to the near α alloys like Ti-5.8Al-4Sn-3.5Zr-0.7Nb-0.5Mo-0.3Si-0.05C (IMI834) illustrates the complex alloy chemistry required to increase the maximum operating temperature to approaching 600°C.

Intermetallic alloys appear to offer a further extension in operating temperature, although the maturity of these materials is not as advanced as the complex titanium alloys. Intermetallic systems are based, in the main, upon titanium aluminides centred on super aα2, TiAl and Ti_2Al-Nb, hexagonal close packed, tetragonal and orthorhombic phased compounds with complex chemistries adjusted to attempt to impart satisfactory room temperature ductility and toughness coupled with high temperature strength and creep resistance by the generation of fine duplex or complex microstructures.

The derivation of new nickel superalloys for high temperature turbine application and the associated manufacturing technologies can be traced from the inception of the gas turbine using Nimonic 80 in the 1940's. Step changes can be seen with the introduction of cast alloys during the 1960's, to be followed by the use of directional solidification and then single crystal developments. The principal aim has been to improve resistance to creep damage at temperatures approaching 1100°C. Hence the recent emphasis on control of grain structure to maximize creep strength through casting processing. Target operating temperatures beyond the currently achievable maxima of approximately 1100°C would appear to require the use of ceramic-based materials probably employing fibre reinforcement, yet to be discussed. Of course, the engineering technology has kept pace with the materials developments, for example the introduction of internally cooled blades allows their operation in hot gas streams, at temperatures above the melting point of the blade alloy.

Affordable titanium structures

The application of titanium based materials is closely linked to cost effective manufacturing technologies. The inherently high price of titanium, based on current extraction and alloying technologies and its relative scarcity makes it unattractive for general structure. However, when the ability to superplastically form the material, with or without diffusion bonding and the excellent weldability of the simpler alloys is taken into consideration, titanium structures become highly competitive. Recent trends have seen a resurgence in the use of titanium alloys especially when weight reduction is required by replacement of steel components or strength is required at temperatures higher than can be sustained by an aluminium alloy or polymer composite. The wide chord fan blade and EUROFIGHTER foreplane provide good examples of this technology reaching application. One exciting trend that may develop is the qualification of sources and extraction methods for reduced cost titanium. This includes the potential use of CIS material.

Metal matrix composites

To extend further the performance of metals, work has continued on the derivation and extension of a family of metal matrix composites. In a metal matrix composite, use is made of ceramic reinforcements in the form of fine particles, fine fibres or continuous monofilaments to reinforce matrices typically of aluminium, magnesium, titanium, nickel or iron. The inclusion of the ceramic reinforcement imparts much increased stiffness to the composite with a significant increase in strength and in certain cases very much enhanced strength at temperature. The use of particulate or randomly aligned multi-filament tows produces a composite with isotropic properties. Alignment can be achieved with multi-filament and mono-filament variants to tailor properties anisotropically enabling greater optimization of the structure to save weight.

To fabricate the composites, use is made of liquid metal processes, such as squeeze casting or liquid metal injection, powder technologies and mechanical alloying with hot isostatic pressing for consolidation. In the case of alloys reinforced with SiC monofilaments, a key element is the ability to be able to superplastically form and diffusion bond the matrix material.

There are major benefits for aircraft structure in the use of material with increased specific stiffness because approximately half of the structural mass may be limited by stiffness requirements. Composites based on aluminium alloys reinforced by ceramic particles or chopped fine fibres typically of silicon carbide or alumina show increasing stiffness and strength with increasing levels of reinforcement (FIG.20) but this is at the cost of reducing toughness and ductility. Maximum additions for aerospace engineering products tend to be approximately 25% to 30% by volume although additions of up to 60% can be achieved for other types of application.

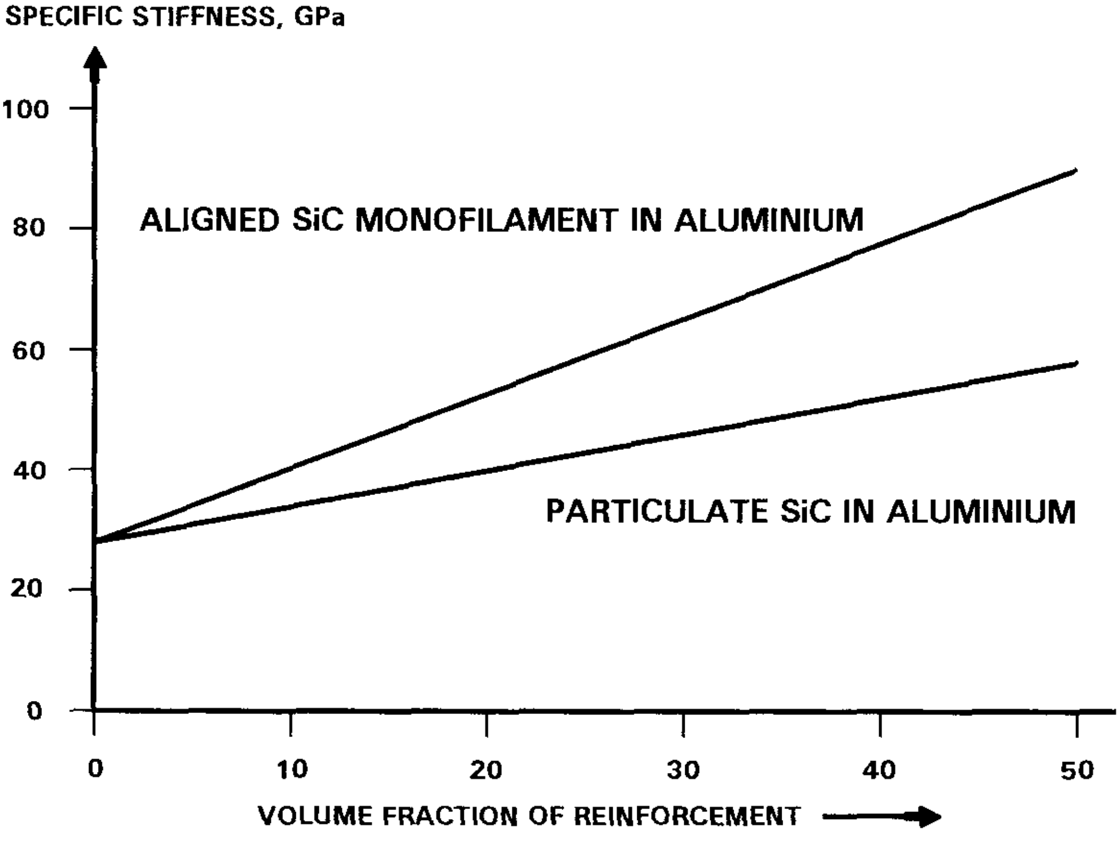

FIG.20 - THE INCREASE IN STIFFNESS FROM REINFORCING ALUMINIUM ALLOYS WITH ALIGNED MONOFILAMENTS OR PARTICULATE SILICON CARBIDE

Recent detailed studies and worked examples have revealed that particulate reinforced composites based on aluminium alloys can provide matching specific strengths, stiffness and damage tolerance to polymeric composite components at competitive cost. As a result there has been a growing interest in their application to stiffness critical components typified by the floor support beam for a transport aircraft, rotor head components (FIG.21), crashworthy crew seat struts, drive shafts and struts etc. These are basically small components where the combination of strength, stiffness and wear resistance can be put to good purpose. Early production applications have been achieved in the USA with, for example, the use of particulate reinforced aluminium alloy for the skins of ventral fins on the up-dated F16.

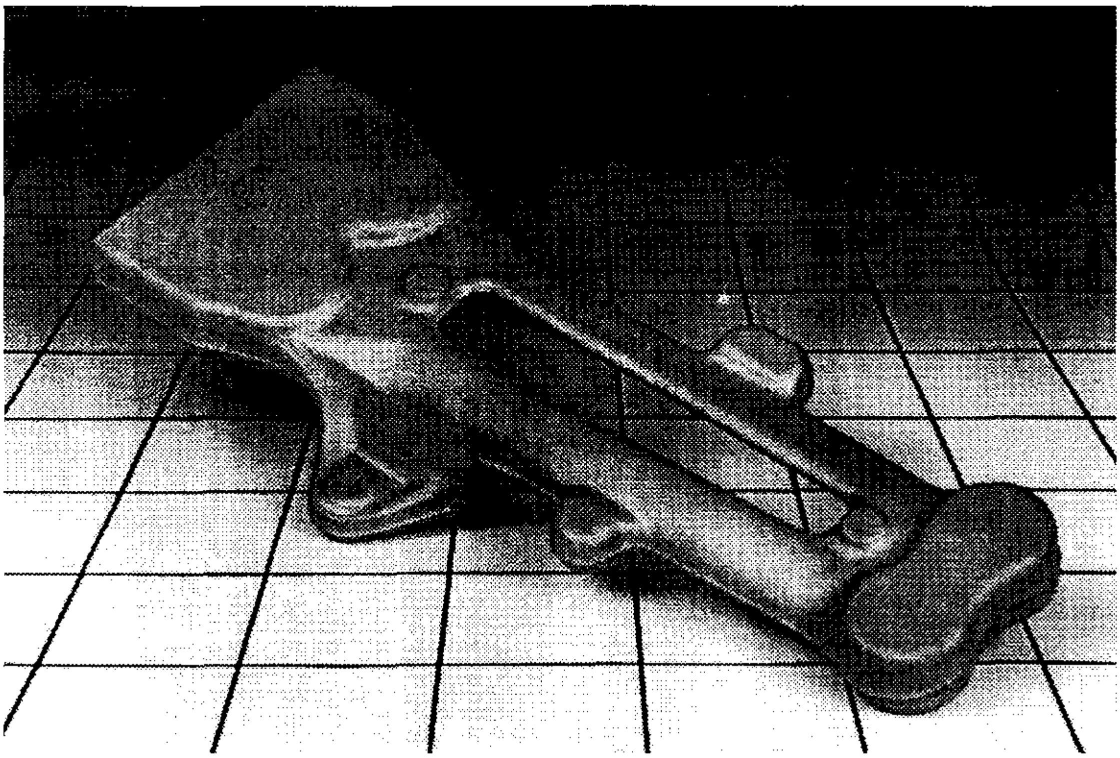

FIG.21 - ROTOR BLADE SLEEVE IN PARTICULATE METAL MATRIX COMPOSITE

COURTESY OF AEROSPACE METAL COMPOSITES

Multi-filament metal matrix composites

There remains further potential to enhance metal composites performance with the use of randomized or aligned fibre reinforcement. Multi-filament composites, typically consisting of tows of fine fibres of alumina or carbon in aluminium have been developed. Currently, manufacturing technology favours the use of a 'squeeze casting' technique ensuring the consolidation of the solidifying metal under significant pressure but also embodying the need to carefully control the delivery of molten metal through fibre pre-forms. Accurate fibre placement and minimization of fibre 'swim' is achieved by proprietary techniques. The use of randomly oriented aluminia fibres incorporated in a series of aluminium casting alloys is now being adopted progressively for components such as pistons for military diesel engines, where the demand for stability at elevated temperatures, control of thermal expansion, wear resistance and high temperature fatigue strength matter. For this type of application, rapid production methodologies are essential to maintain high levels of cost effective manufacture. The casting-squeeze casting technique described lends itself to this form of automated production but is naturally limited to relatively small components.

For a higher level of structural optimization, potentially affordable in the aerospace and defence markets, emphasis has been placed on the use of aligned fine fibre tows containing alumina, silicon carbide and graphite fibres with typical individual diameters below 10µm and reinforcement again incorporated again by liquid metal and squeeze casting techniques. Many potential applications are being addressed for small components such as missile parts including control fins.

Monofilament Reinforced Metal Matrix Composites in aeroengines

There are potential applications for aluminium and titanium alloy components selectively reinforced with continuous monofilaments, especially when there are requirements for use at high service temperatures in aeroengine components. In these composites, a single fibre or monofilament typically of silicon carbide, 100µm or more in diameter, is distinguished from a tow of fine fibres described above. Monofilaments up to 25Km in length are currently produced by chemical vapour deposition typically of boron or silicon carbide ceramic around either a tungsten wire or a single carbon fibre, as opposed to spinning tows of fine ceramic multi-filaments.

The monofilament composites are capable of very high specific strengths and stiffness in the direction of fibre alignment especially at increased operating temperatures (FIG.22). However, the current price of the monofilament alone is in the region of £8,000/Kg.[13, 14]

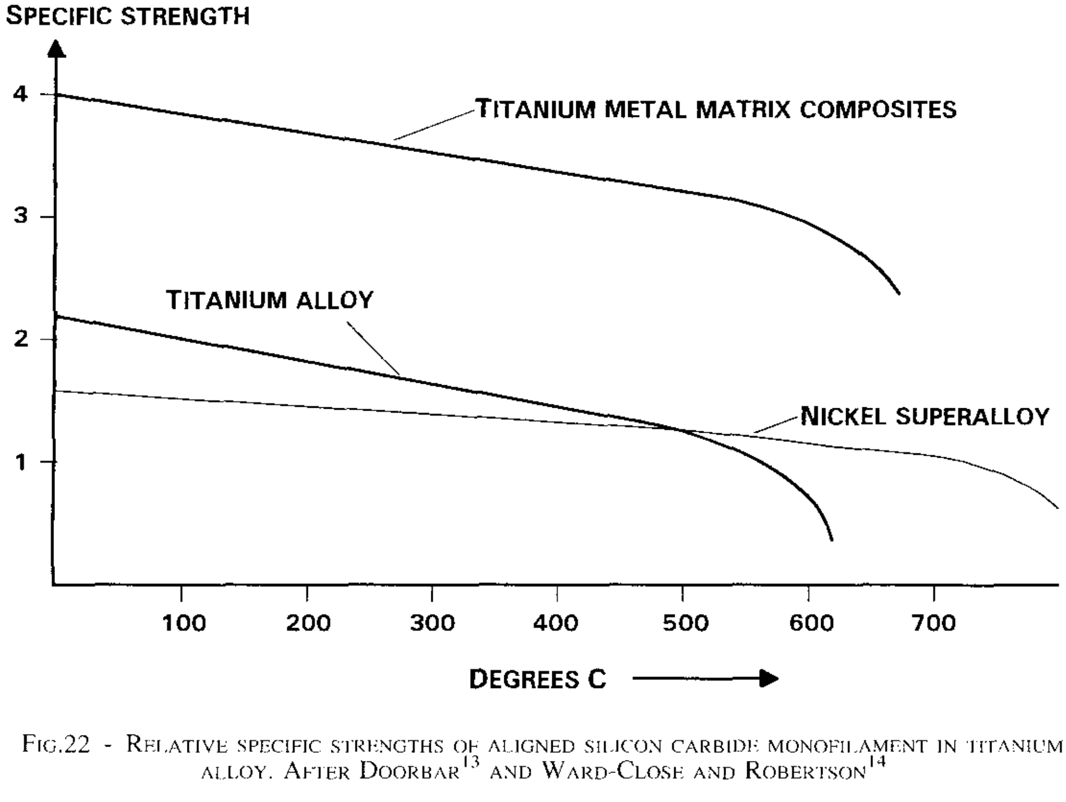

FIG.22 - RELATIVE SPECIFIC STRENGTHS OF ALIGNED SILICON CARBIDE MONOFILAMENT IN TITANIUM ALLOY. AFTER DOORBAR[13] AND WARD-CLOSE AND ROBERTSON[14]

Selective reinforcement of aluminium alloys, titanium alloys and several fabrication routes can achieve intermetallic alloys. These include the diffusion bonding of packs of aligned monofilaments between sheets of alloy foil or similar packs infilled with alloy wires. Alternatively, filament wound structures can be produced using monofilament coated with the requisite matrix alloy and consolidated again by diffusion bonding. The two most common approaches for coating monofilament are based upon plasma spraying during filament winding of the fibre or the use of physical vapour deposition of matrix material around individual fibre before filament winding and consolidation.

A sustained drive for high temperature metal matrix composites based on silicon carbide monofilaments in titanium alloys is aimed at achieving higher engine thrust to weight ratios. Typified by a drive to increase thrust to weight on military engines from circa 10:1 to approaching 20:1. Inclusion of these metal composites into structures such as an integrally bladed compressor discs is predicted by DOORBAR[13] to reduce rotating mass of the 'BLING' by up to 70% and is critical upon the high temperature performance of the new composite material. Here the term 'BLING' is used to describe an integrally bladed ring, differentiating it from blades mounted conventionally on discs using fir tree fittings.

Composites of this form are intended to be used for the selective reinforcement of structures since, presently, the high cost of the base material would tend to preclude large scale usage or general application within a component except perhaps for the most expensive weight critical space structures. However, significant potential for application can be found in the aeroengines (FIG.23) of the future where weight reductions and performance increases have been identified for a range of components such as low pressure compressor blades and vanes, compressor and turbine blings, turbine shafts, compressor casings etc. The general intention would be to apply monofilament reinforcement to relatively standard titanium alloy matrices for lower temperature applications such as the shafts, casings and low pressure rotating machinery with intermetallic alloy matrices being used for the higher temperature turbine areas. At present the performance of monofilament reinforced metal composites is being assessed in prototype engine components with cost of manufacture very much in mind.

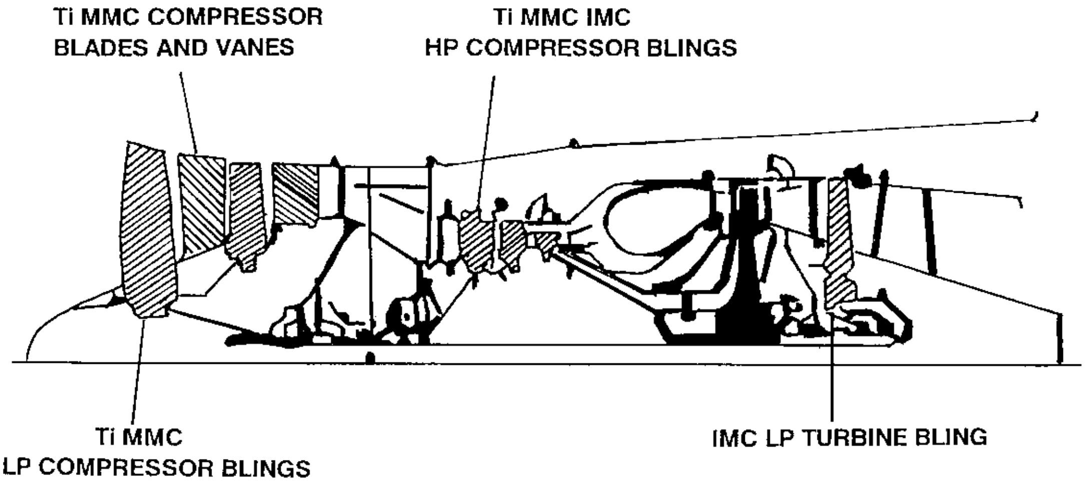

FIG.23 - SOME OF THE POTENTIAL APPLICATIONS FOR REINFORCED TITANIUM ALLOYS IN FUTURE COMBAT AERO-ENGINES. AFTER DOORBAR [13]

Ceramics and ceramic composites

Monolithic ceramics and composites based on ceramic matrices offer a powerful balance of properties. This stems from their covalently bonded structures with exceptional capability at high temperature in terms of strength, stiffness, hardness and wear resistance coupled with relatively low density making their choice seemingly inevitable for high temperature applications, typically in gas turbine components. However, lack of ductility, fracture toughness and resistance to shock held back structural application until the advent of toughened materials during the 1980s, although use of ceramic coatings has long been made for critical wear and temperature resistant surfaces.

Typical monolithic ceramics include those based on alumina and alumina-silica mixtures with toughening achieved by the inclusion of up to 20% by volume silicon carbide as fine whiskers to produce a composite. Fracture toughness levels approaching $10 MPam^{1/2}$ have been achieved. However, inconsistency in properties and fears of the health risks associated with fine whiskers are limiting structural application.

A key step towards inherently higher toughness has been the development of fine grained polycrystalline material whether in alumina or zirconia. A second key step has been to toughen zirconia with stabilising oxides such as magnesia, or yttria that prevent high temperature phase changes. This has formed the basis for a wide range of engineering ceramics with mixtures of tetragonal zirconia in cubic zirconia (PSZ) or alumina (ZTA) or fine grained polycrystalline zirconia itself (TZP). Mechanical properties are shown in Table 1,but it should be noted that strength and toughness of these toughened materials deteriorates as temperatures of 1000°C are approached limiting high temperature applicability.

TABLE 1—*Relative properties for selected ceramics in sintered form*

Ceramic	**Density g/cc**	**Elastic Modulus GPa**	**Flexural Strength at 25°C MPa**	**Estimated max temp °C**
Alumina	4.0	400	550	900
Silicon carbide	3.1	300	380	1400
Silicon nitride	3.1	240	420	1000
Toughened zirconia	5.7	210	600	900
Alumina/SiC whiskers	3.7	380	640	900

A further class of engineering ceramic materials is loosely described as 'non-oxide ceramics' comprising systems based on silicon carbide, silicon nitride and the sialons. Again use of whiskers or short fibres of silicon carbide or nitride achieve toughening. Having lower coefficients for thermal expansion than the oxides, these materials appear more attractive for high temperature engine applications where thermal shock is critical.

It should be noted that fibre and monofilament reinforced ceramic matrix composites may extend the toughened ceramic concept by allowing anisotropic strengthening with the use of aligned fibres typical of a metal or polymer matrix composite. Glass or silicate based composites, carbon/carbon and silicon carbide/silicon carbide combinations all appear to offer exceptional properties at temperature with increased toughness achieved by crack deflection and fibre pull-out mechanisms imparted by the fibre reinforcements.

Although to a large extent the application of these developing ceramic materials in airframe and engine structural applications is still awaited, the significant contribution of early systems such as carbon/carbon in aircraft disc brakes and carbon/carbon or silicon carbide/silicon carbide rocket engine nozzles points to the potential for extensive use in the future.

Polymers and polymeric composites

Fibre reinforced polymer composites will undoubtedly find extensive application in future aerospace structures. Now regarded as conventional materials, in the sense that it is more than thirty years since the early forms of carbon fibre reinforced epoxy were evaluated for aerospace applications and were first adopted for use in sports goods, fibre reinforced polymeric materials have been continually improved over this period.

Major phases of significance can be recognized in the use of glass fibre composites for radar transparent covers and the early use of boron monofilaments in epoxy resins. These are typified by application in the tail structure of the F15 EAGLE, followed by the adoption of high strength and stiffness carbon fibre reinforcement in the GR5. Separately, the use of aramid intermediate and high modulus fibres has become common place in many secondary structure applications, where toughness and durability have been the key issues. Fibre properties are compared in Table 2.

TABLE 2—*Relative fibre properties*

Fibre	Tensile modulus GPa	Tensile strength GPa	Density g/cc	Specific modulus	Specific strength
Ultra-high modulus carbon	725	2.2	2.15	336	1.02
Intermediate modulus carbon	310	5.2	1.8	170	2.9
Medium modulus carbon	235	3.8	1.8	130	2.1
R/S Glass	85	4.5	2.52	35	1.8
E Glass	69	2.4	2.54	27	1.0
Boron	400	3.5	2.6	155	1.4
Silicon carbide	400	4.0	3.4	120	1.2
Aramid	125	3.6	1.45	85	2.5

Carbon fibre based on pyrolysed polyacrylonitrile precursor has been adopted for structures of high mechanical integrity, typified by wing structures for current combat aircraft. Offering similar stiffnesses to aluminium alloys in a typical near isotropic composite, the primary advantage of the polymer-based material has been reduced density affording weight savings in structures dominated by stiffness requirements.

The last decade has seen increased utilization of hybrid materials in which fibre types are selected and mixed to balance the requirements for strength, stiffness, toughness and impact resistance and most recently control of signature. Moreover, the last decade has also seen the emergence of new fibres with further improved mechanical properties such as increased modulus and failure strains reflected by increased usable tensile strengths. Indeed it should not be assumed that fibre and polymer developments per se have ceased. For example, new fibres appear regularly with extended mechanical properties. Typical new arrivals could be illustrated by the ultra high performance Nexel alumina fibres, ultrahigh molecular weight polyethylene, hollow glass and carbon fibres, ultra high performance silicon carbide fibres and monofilaments and ultimately, perhaps, diamond fibre. Some of these developments have been driven purely by mechanical property improvement. Others such as the hollow carbon and glass fibres (FIG.24A&B) have interesting possibilities for SMART material applications in which the hollow core of the fibre may be ultimately used for the inclusion of strain sensing and reactive materials and potentially self-repairing matrix materials.[15]

The greater application of fibre reinforced composites has continued to be hampered by a few key problems. These can be simplified to fundamental difficulties in the use of what is currently, essentially, a two-dimensional material, limitations imposed by minimum gauge requirements and the all pervading issue of cost effectiveness.

Affordable composite structures

Since improvements in the technical performance of the polymer composite may be constrained by the issues of third axis properties, emphasis is being currently placed on the cost-effective manufacture of structure with three-dimensional capability. Progression from mechanically fastened composite skins attached to metallic and pre-cured composite substructures, through adhesively bonded structures to the current co-cured combinations of skin and substructure has produced steady improvements, although mechanically fastened removable covers will remain a requirement for many applications. Further developments already taken to demonstrator stages include the use of stitched three dimensional structures, three dimensional woven fibre architectures and the use of woven fibre laminates bonded or mechanically fastened.

Cost reduction developments have recognized that the use of autoclave bonding of pre-preg laminates is unlikely to be affordable for transport applications or large structures in general. Developments are therefore being directed at techniques such as resin transfer moulding, resin injection, the use of adhesive films and non-crimp fibre fabrics. Thermo-plastic matrix composites may offer possibilities for techniques such as diaphragm forming and the use of superplastic metal membrane forming at least for smaller components. An issue in all of these techniques will be the cost of tool design and manufacture and in particular the need to accurately predict material performance and structural compliance electronically to minimize production development costs.

It was illustrated earlier that adoption of polymer based composites might produce significant increase in the cost of new structures but a reduction in subsequent service costs. Achieving an accurate appreciation of both initial and lifetime costs against a background of ever changing application requirements is a very major challenge. However, the adoption of increasing levels of sophistication in electronic product definition and life modelling may allow designers to simulate the effects of selections and changes very rapidly aiding the optimization process.

Polymers and higher temperature polymers

The two basic forms of polymers used monolithically and as matrices for polymer composites are based on either a thermosetting or thermoplastic principles. Thermosetting materials require polymerisation to be generated in the base material by addition of a curing agent and, usually, application of an elevated temperature. The material so formed is set in its final shape. Typical thermosetting matrices include epoxy, polyimide (bismaleimide) polyester

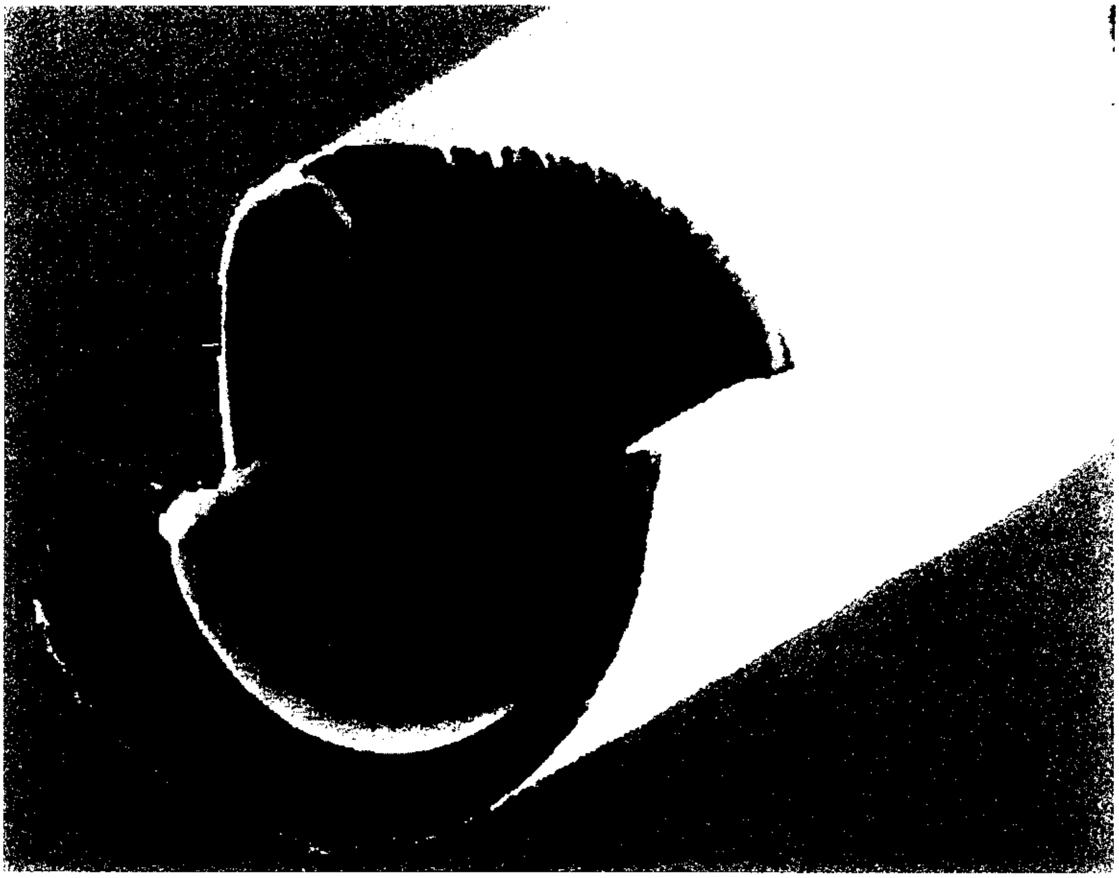

FIG.24A - HOLLOW CORED CARBON FIBRE. AFTER CURTIS[15]

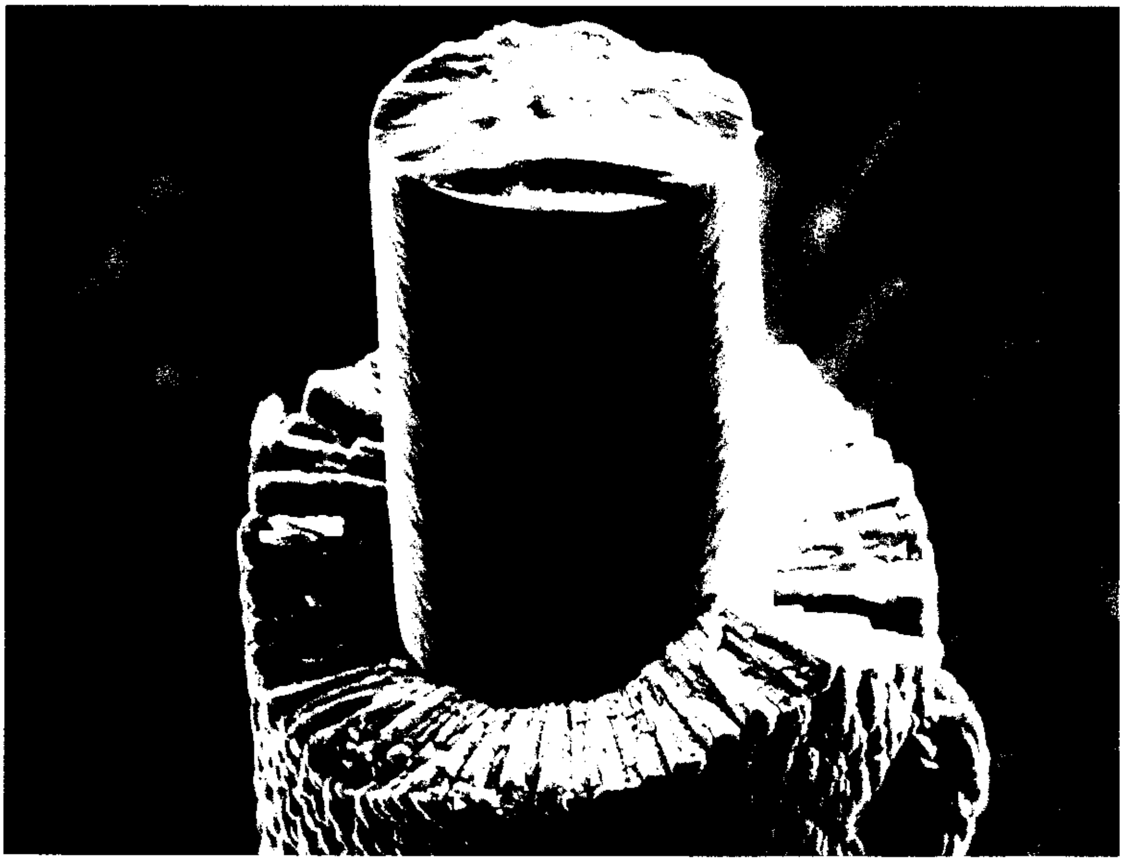

FIG.24B - SILICON CARBIDE MONOFILAMENT COATED WITH TI ALLOY. AFTER WARD-CLOSE[14] and phenolic resins. Thermoplastic materials are fully polymerised ab initio and are set to shape at elevated temperatures where they are softened or even melted being capable of repeated thermal cycles. Typical thermoplastic materials include Polyether Ether Ketone (PEEK), Polyether Imide (PEI), Polyphenylene Sulphide (PPS) and polyarylene sulphone.

There are materials that are thermoplastic in nature but that require a chemical reaction initially to polymerise such as the semi-thermoplastic polyimides. Many of the thermoplastics are semi-crystalline in nature and possess better toughness and chemical resistance than thermosetting materials. A recent trend has been the derivation of hybrid mixtures of thermosetting and thermoplastic materials to achieve ease of application and increased toughness simultaneously.

A major issue of significance to future application, especially in the gas turbine, is the limiting temperature of operation achieved by the matrix of polymer composites, typified by the maximum hot-wet operating temperature allowable. Table 3 lists the typical maximum operating temperatures of selected systems. Notable are the thermo-setting polyimides and the semi-thermoplastic polyimides with maximum operating temperatures in excess of 200°C. The key problem is to balance a high glass transition temperature, necessary for high temperature service against the minimization of thermally induced micro cracking during initial setting. New materials are emerging from the USA that have significant promise in this respect.

TABLE 3—*Typical maximum hot/wet operating temperatures*

Matrix polymer	**Type**	**Max hot/wet limit C**
Epoxy	Thermoset	120
Polyimide (bismaleimide)	Thermoset	220
Polyimide	Semi-thermoplastic	260
Polyether ether ketone (PEEK)	Thermoplastic	120
Polyetherimide	Thermoplastic	120

As a general trend, the matrix materials for high temperature application are significantly more expensive than those used in general low temperature applications. However, they may meet a requirement that otherwise would require the use of an expensive titanium based metallic solution.

Discussion

It has been the intention in this article to review the state of development of emerging materials for military aerospace applications with specific comment being addressed to cost of manufacture and ownership. It may have become apparent that cost in acquisition and ownership are relative and two distinct trends emerge.

If a new material is more expensive than the incumbent that it is intended to replace, to be cost effective, improvements must be made in utilization or in reduction of costs associated with fabrication of the material into the structure. Research has identified means to increase utilization and to embody more effective manufacturing for example in the current re-investigation of the welded airframe.

However, there is the further possibility that if a new material can match the technical performance of a 'more exotic' material then it can be cost effective. Thus, if expensive polymer or metal matrix composites with the appropriate stiffness and high temperature strength can match the performance of the intrinsically more expensive titanium alloys, both performance increase and cost reduction can be achieved.

Future trends

It is extremely difficult to extrapolate current trends in aerospace materials development much beyond the next decade and any such extrapolation must be regarded as pure speculation. In this light the more obvious trends dictating the immediate future can be separated from longer-term issues. Immediate trends may be summarized as:

- Improving performance
- Reducing costs
- Improving the environment
- Sharing commercial risks.

Airframes and engines will continue to benefit from reduction in parasitic mass. Systems such as landing gear will require to be reduced in weight and, if possible, volume simultaneously, posing major challenges for engineering with improved materials including, perhaps, a move away from steel towards a titanium alloy base. Undoubtedly a major challenge for improved performance is raised by the requirements of future airframes and engines to accommodate increased operating temperatures. Large structures such as a new supersonic transport aircraft are contemplated that from their sheer size, costs and risks, must be produced in near conventional materials, optimized for the high temperature requirement. Combat aircraft and missiles will fly faster or employ vectored thrust techniques demanding the derivation and application of weight efficient materials with enhanced high temperature performance. Engines continue to reduce in size but increase in thrust. To achieve the 20:1 thrust to weight ratios in the compact engines required for military aircraft of the future requires the combination of all the new materials technologies outlined in this article.

Cost effective manufacture of transport and combat airframes, aerospace structures and aero-engines is a major current theme moving towards more affordable structures. This issue will have a major influence on the potential for utilization of materials such as fibre-reinforced composites and aluminium-lithium alloys. Unless the costs of built-up structure utilizing these expensive materials can approach those of the incumbent materials there is little hope for their embodiment on a large scale. To reach this objective, demonstrator programmes investigating low cost manufacturing routes for large composite and metallic structures are now in planning, if not, under way. It is critical to the success of the Foresight Approach that these initiatives succeed. Cost effective manufacturing processes have been considered in passing throughout this article, but these are matters in which the UK capability has been traditionally underdeveloped. Present trends are towards modular or unitized structures maximizing commonality in terms of materials, process and units of built-up structure. Techniques that minimize parts counts are being researched for both metallic and polymer composite systems exemplified by current interest in welded metallic airframes.

Reduction of service lifetime costs is a major issue. If the lifetime service and repair cost of a combat airframe is two to three times that of the initial purchase, more will need to be done to model and control lifetime performance and to select materials with improved fatigue and corrosion resistance. This aspect can reverse the trend towards materials with lower initial and manufacturing costs. For example, the introduction of cost effective manufacture of woven 3D composite structures may affect fatigue life adversely.

A trend that is emerging is for hybridisation of materials to accommodate multiple requirements simultaneously such as:

- Low observability
- High specific mechanical performance
- Longevity in resisting corrosion and fatigue
- Enhanced thermal properties including strength at high temperatures.

This may well require functionally graded materials. For example, the SMC are developing aluminium alloys clad with layers of ceramic-rich metal matrix composites. Additionally, metal composites clad by a loaded thermoplastic membrane are becoming a reality.

Protecting and conserving the environment is an issue of ever increasing importance. The effects of emissions from aircraft engines may well limit speeds and altitudes in the short term and will continue to provide pressures for higher temperature materials to enable turbine entry temperatures to be further increased reducing fuel burn and emission levels simultaneously. More attention is being applied currently to scrap and waste matters such as the:

- Replacement of the use of cadmium and chromate for corrosion protection
- Reduction of the levels of volatile substances in surface finishes and paints
- Complete eradication of halon fire suppressants following the Montreal Protocol.

An ability to recycle the materials used in aerospace structures may even become a requirement that will affect the use of current polymers and alloys. In the same vein, the method of ultimate disposal of a material will become a requirement for consideration during development.

For the far future, a trend continues to emerge in which there is a steady separation of the needs of military equipment from those for transportation. To be efficient in reducing service costs, transport aircraft will continue to grow in size and range. In contrast, for example, the development of unmanned military systems may be a simple extension of present capability. Without the encumbrance of the human physiology, sensitive as it is to acceleration and environment, and the continuous need to train flight crews, speeds and turn rates may be increased significantly, structural loadings increased and system flight lifetimes reduced dramatically to enable much more efficient use of the airframe materials. The structures themselves will become smaller and smaller with increased thrust to weight engines compacted in reducing volumes and miniaturised electronic and control systems. A system proved electronically for use in military emergency may only need to be flown in anger but a few times such that all requirements for damage tolerance and longevity are forgone and service costs much reduced. Structurally, these developments will change the nature of materials and processes employed quite dramatically. Whole body castings, welded metallic structures and injection moulded thermoplastics or derivatives thereof would seem to offer cost effective solutions. Manufacturing trends in the cost-conscious automobile industry maybe adopted. Even the re-utilization of welded pressed sheet structures may occur as these are consistently cost and weight efficient.

Since the use of ever increasingly efficient electronic systems seems inevitable, reliance on advanced materials may well diminish. For example, the present emphasis on control of observability may well become dominated by the electro-mechanical behaviour of materials with measures and counter measures achieved without resort to passive materials-based solutions. On the other hand, SMART materials and processes applied to engineering problems such as the alleviation of flutter, adaptive lift geometries, or damage sensing structures will require new materials with optimized electrical and mechanical properties.

If there is to be a trend, it must be that application of aerospace materials will become a holistic process combining materials and process routes with prediction of engineering and market performance with developments preordained by electronic modelling. Whatever, the trends that emerge, whether it is the greater application of more robust marketable materials to aerospace structures, the greater use of predictive modelling, or the continued derivation of specialised materials for highly optimized structures, the critical role of the materials scientist will persist in the aerospace industry.

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