

NASA Technical Memorandum 80231

COMPOSITE COMPONENTS ON COMMERCIAL AIRCRAFT

(NASA-TM-80231) COMPOSITE COMPONENTS ON
COMMERCIAL AIRCRAFT (NASA) 24 p
HC A02/NP A01 CSCL 11D

880-18109

Unclas

63/24 47406

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March 1980



NASA

National Aeronautics and
Space Administration

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COMPOSITE COMPONENTS ON COMMERCIAL AIRCRAFT

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SUMMARY

The technology development of advanced composite structures has progressed to the point where commercial aircraft manufacturers are making production commitments to composite structure for future aircraft and modifications to current production aircraft. NASA has been active in sponsoring flight service programs with advanced composites during the past 10 years. Approximately 2.5 million total composite component flight hours have been accumulated since 1970 on both commercial transports and helicopters. Design concepts with significant mass savings were developed, appropriate inspection and maintenance procedures were established, and satisfactory service was achieved for the various composite components. Also, a major NASA/U.S. industry technology program to reduce fuel consumption of commercial transport aircraft through the use of advanced composites has been undertaken. Ground and flight environmental effects on the composite materials used in the flight service programs supplement the flight service evaluation.

INTRODUCTION

Advanced composite aircraft structures have the potential to reduce airframe structural mass by 20 to 30 percent, reduce fuel consumption by 10 to 15 percent, and thus reduce the direct operating costs to the airline operator. The U.S. Government and industry have been developing advanced composites technology for the past 15 years. This technology has matured to the point where commercial aircraft manufacturers are starting to make production commitments to this new class of materials.

The NASA Langley Research Center has been instrumental in the development of advanced composite structures primarily for commercial aircraft. Flight service evaluation programs were initiated in the early 1970's to develop confidence in the long-term durability of advanced composites in actual aircraft operating environments. Concurrent with the flight evaluation of structural composite components, NASA initiated programs to determine the outdoor environmental effects, the effects of aircraft fuels and fluids, and the effects of sustained stress on several thousand composite test coupons.

In 1975, NASA initiated an extensive aircraft energy efficiency (ACEE) program to improve the efficiency of commercial transport aircraft through the development and application of advanced technologies such as advanced composites. The objective of the ACEE program is to accelerate the development of advanced technologies to the point where U.S. commercial transport manufacturers can economically incorporate the technology into their production aircraft. Six components, three secondary structures, and three primary structures, are presently under development.

The purpose of this paper is to outline some of the NASA/U.S. industry composite programs and report on the service experience gained with numerous composite components during the past decade.

NASA FLIGHT SERVICE PROGRAMS

NASA recognized the need to build confidence in the long-term durability of advanced composites to allow aircraft manufacturers and operators to make future production decisions. NASA initiated a systematic program for the design, fabrication, test, and flight service evaluation of numerous composite components that will provide the necessary confidence. Early applications were for selective reinforcement of military aircraft structures [1 to 6] but major emphasis was placed on evaluating advanced composites on commercial transport aircraft [7 to 13]. Commercial aircraft were chosen because of their high utilization rates, exposure to worldwide environmental conditions, and systematic maintenance procedures.

A typical NASA flight service program takes approximately 3 years for component development, detail design, fabrication, and ground testing and 5 years or more for service evaluation. In some cases, selected components are periodically removed from service for residual strength testing. In addition to component evaluation, environmental tests on small coupons are conducted throughout the flight evaluation program. These tests generally include outdoor and controlled laboratory exposure tests, thermal cycling, and exposure at airline terminals and at Langley Research Center.

Component Description

The composite components currently being evaluated in the NASA flight service programs are shown in Figure 1. All components shown have been in service except for the Bell 206L helicopter doors and fairing which are being fabricated. Details of the current and planned flight service evaluation components are shown in Figure 2. The first flight service program involved reinforcement of a U.S. Army CH-54B helicopter tail cone with unidirectional boron/epoxy [1 and 2]. Boron/epoxy strips bonded to the tail cone stringers increased the tail cone stiffness and reduced the structural mass by 14 percent. Eighteen Kevlar/epoxy fairings are being evaluated on three Lockheed L-1011 aircraft [7 and 8]. Solid laminate and Nomex honeycomb sandwich panels were installed as a direct replacement for production fiberglass parts. An average mass saving of 26.8 percent compared to the fiberglass panels was achieved.

The largest number of components is being evaluated on Boeing 737 aircraft [9 and 10]. One hundred and eight graphite/epoxy spoilers have been installed in sets of four by six different commercial airlines on 27 aircraft for worldwide flight service. The spoilers are constructed with graphite/epoxy upper and lower skins, corrosion resistant aluminum honeycomb core, aluminum spar and hinge assemblies, and fiberglass closure ribs. The finished spoilers are 35 percent composite and are 16.9 percent lighter than the standard production aluminum spoilers. Two boron/epoxy-reinforced aluminum center-wing boxes are in service with the U.S. Air Force on C-130 transport aircraft [3 to 6]. Boron/epoxy bonded to the covers on both the wing planks and hat-section stringers resulted in an increased fatigue life and a 10 percent mass saving. Three boron/aluminum aft pylon skin panels are in service on three DC-10 aircraft [11]. These panels are subjected to elevated temperatures and high-intensity acoustic loading as a result of their proximity to the center engine. A mass saving of 27.3 percent compared to baseline titanium was achieved.

Nine graphite/epoxy DC-10 upper aft rudders are in service on seven commercial airlines [12 and 13]. These multi-rib stiffened rudders weigh 32.9 percent less than standard production aluminum rudders. An important aspect of the DC-10 graphite/epoxy rudder program was the development of a cost competitive manufacturing procedure to allow a single oven cure cycle for the total structural box. The process selected is identified as the "trapped rubber" process and is shown in Figure 3. The process begins with the layup and densification of the right and left side skin panels and pre-forming the spars and ribs. The front spar web has lightening holes that permit the spar to fit over internal metal mandrels of the tool. The mandrels are centered in the cavity formed by adjacent ribs and the skins. Each mandrel is surrounded by carefully sized blocks of silicone rubber that fill each cavity. Once all the ribs are located, the outer skins are installed and heavy steel plates are attached to the tool to form a closed system. The tool is rolled into an oven where temperature is increased at specified rates and the rubber expands against the graphite/epoxy to develop the desired cure pressures. Once the cure cycle is completed, the tools and silicone rubber are removed and the finished structural box is ready for installation of standard aluminum alloy hinges and actuator fittings and the standard glass/epoxy leading and trailing edge members and tip assembly. Additional details on these NASA flight service components can be found in [14].

The most recent flight service program involves installing 40 shiheets of Kevlar/epoxy doors and fairings on Bell 206L commercial helicopters. The composite components are being fabricated and flight service will begin in late 1980. Three design concepts - stiffened foam sandwich, stiffened skin, and honeycomb sandwich - as shown in Figure 4, will be evaluated. An overall mass saving of 25.9 percent compared to the production components is estimated. The helicopters will operate in diverse environments in Alaska, Canada, and the U.S. Gulf Coast. Coupons exposed to ground and flight environments will be tested at specified intervals to determine effects of the various helicopter operating environments on material strength. Also, selected components will be removed from service and tested to failure to compare residual strength with original strength.

Sikorsky Aircraft has committed to extensive use of secondary and primary Kevlar/epoxy and graphite/epoxy structural composites in their S-76 commercial helicopter. NASA Langley Research Center and Sikorsky are planning a joint program to determine the long-term durability of composite components on the S-76. The objective of the NASA/Sikorsky program is to determine the effects of realistic operational service environments on typical composite helicopter structures. Fourteen tail rotors and four horizontal stabilizers such as those shown in Figure 5 will be removed from helicopters after up to 10 years of operational service. The tail rotor has a laminated graphite/epoxy spar with a glass/epoxy skin. The horizontal stabilizer has a Kevlar/epoxy torque tube with graphite/epoxy spar caps, full-depth honeycomb sandwich core, and Kevlar/epoxy skins. The two composite components have a total mass of 24.7 kg. Static and fatigue tests will be conducted on the components removed from service and the results will be compared with baseline certification test results. In addition, several hundred composite coupons exposed to the outdoor environment will be tested for comparison with the component test results.

Flight Service Summary

A total of 142 composite components have been in flight service with 17 different operators, including foreign and domestic airlines, the U.S. Army, and the U.S. Air Force. The NASA flight service program was initiated in 1972 to determine the long-term durability of boron, Kevlar, and graphite composites in realistic flight environments. Nearly two million component flight hours have been accumulated with the high time aircraft having 17,718 hours as shown in Figure 6. The boron/epoxy reinforcement in the CH-54B helicopter has been in service the longest, over 7 years, but it has been flown very little compared to the other types of aircraft. This CH-54B helicopter was removed from flight service in October 1979 when it was damaged by a tornado. The graphite/epoxy in one of the DC-10 upper aft rudders has been acquiring flight service time at the greatest rate of any of the components listed in Figure 6, a rate of over 300 hours per month. The graphite/epoxy in the 108 spoilers on the Boeing 737 airlines has accumulated the greatest total component flight hours, 1,438,000 in 6 1/2 years. The high-time spoiler has 17,500 flight hours and approximately two-thirds of the spoilers have accumulated over 10,000 flight hours.

The large number of spoilers with graphite/epoxy skins allows planned retrievals from flight service without seriously impairing the total exposure. Six spoilers are selected at random for removal from service annually, two of each of three material systems used in fabricating the spoilers. These spoilers are shipped to Boeing for ultrasonic inspection. Three of the spoilers are returned to service after inspection and three are tested to failure to compare residual strengths with the strength of 16 new spoilers that were tested early in the program. Results of these tests are shown in Figure 7. After 5 years of service, the strengths for the individual spoilers generally fall within the same scatter band as was defined by strengths of the new spoilers. These results indicate essentially no degradation in strength after the 5 year period of service.

In addition to structural tests of the spoilers, tests are conducted to determine absorbed moisture content of the graphite/epoxy skins. The moisture content in the graphite/epoxy spoilers is determined from plugs cut near the trailing edge as shown in Figure 8. The plugs consist of aluminum honeycomb core, two graphite/epoxy face sheets, two layers of epoxy film adhesive, and two exterior coats of polyurethane paint. About 90 percent of the plug mass is in the composite faces, including the paint and adhesive. The moisture content is determined by drying the plugs and recording the mass change. The data shown in Figure 8 for plugs removed from three spoilers after 5 years service indicate moisture levels in the graphite/epoxy skins ranging from 0.66 to 0.75 percent for T300/5209, T300/2544, and AS/3501 material systems. Apparently, these moisture levels have not affected the room temperature strengths of the spoilers as shown in Figure 7.

Inspection and Maintenance

The composite components in the NASA flight service evaluation program are being inspected at periodic intervals to check for damage, defects, or repairs that may occur during normal aircraft operation. The maintenance data shown in Figure 9 were reported by the aircraft manufacturers who fabricated the various components. The composite components are being inspected by the aircraft operators and manufacturers and in most cases both visual and ultrasonic inspection methods are being used.

Minor disbonds have been found under small portions of the CH-54B boron/epoxy reinforcement. These disbonds were small and did not require repair. The Kevlar/epoxy fairings on the L-1011 aircraft are visually inspected annually. Minor impact damage from equipment and foreign objects has been noted on the wing-to-body Nomex honeycomb sandwich fairings. Fiber fraying, characteristic of Kevlar, and fastener hole elongations have been noted on all the Kevlar/epoxy fairings but no repair has been required. The 737 graphite/epoxy spoilers are inspected annually by Boeing and any defective spoilers are returned to Boeing for repair. Infrequent minor damage has occurred which included a mechanical interference problem and front spar exfoliation-corrosion damage. The spar exfoliation-corrosion was caused by accidental breaching of the corrosion-inhibiting system prior to final bonding of the graphite/epoxy skins during the fabrication process. Visual, ultrasonic, and destructive testing have found no evidence of moisture migration into the aluminum honeycomb core and no core corrosion.

The boron/epoxy-reinforced C-130 wing boxes are inspected every 6 months and no defects have been detected after more than 5 years of service. The boron/aluminum aft pylon skins on the DC-10 aircraft are inspected annually and minor surface corrosion has been reported on one panel. This corrosion is believed to have been caused by improper surface preparation during fabrication of the panels. The graphite/epoxy rudders on the DC-10 are visually inspected every 3 months and ultrasonically inspected every 12 months. Minor rib-to-skin disbonds have been detected on two rudders but repairs are not required. These minor disbonds may have been caused by thermal stresses during cooldown after the manufacturing cure cycle. Overall, excellent performance has been achieved with the NASA flight service composite components.

AIRCRAFT COMPANY FLIGHT SERVICE PROGRAMS

Component Description

The U.S. commercial aircraft manufacturers have installed numerous advanced composite components on aircraft for flight service evaluation. The objective of these programs is to determine the reliability and maintainability of composite components under normal airline fleet conditions. The composite components developed by the U.S. commercial transport manufacturers are indicated in Figure 10. Some of the components were designed as direct replacements for production fiberglass parts while other components were new designs to replace metal production parts.

Boeing has installed about 118 m² of graphite/epoxy floor panels on each of 30 B-747 aircraft. These panels have a mass of 312.5 kg which represents a mass saving of 30.8 percent compared to production fiberglass panels. Boeing also has two boron/epoxy foreflaps installed on B-707 aircraft. The foreflap as shown in Figure 11 is an aluminum honeycomb monocoque shell which replaced the rib-and-skin production design. The shell structure is closed out with fiberglass end ribs and titanium plates for attachment to the flap carriage. A mass saving of 25.3 percent was achieved.

The Douglas Aircraft Company has designed and fabricated several graphite and Kevlar composite components for service on DC-9 and DC-10 aircraft. Sketches of some of the components are shown in Figure 12. The types of structures being evaluated include panels, beams, doors, and engine nacelle structures. The largest component is a Kevlar/epoxy nose cowl for the DC-9 which has a mass of 73.9 kg. The cowl has a Kevlar/epoxy outer barrel with an aluminum honeycomb sandwich inner barrel for a mass saving of 16.6 percent.

The Lockheed California Company has made extensive applications of Kevlar/epoxy on their L-1011-500 aircraft. As shown in Figure 13, numerous fiberglass parts have been replaced by 1134 kg of Kevlar/epoxy for an average mass saving of 24.4 percent. Most of the applications are for secondary components such as panels, doors, trailing edge wedges, and fairings. In addition, numerous interior structures such as ceiling panels and stowage compartments are fabricated with Kevlar composites. Lockheed has four large graphite/epoxy cowl doors installed on L-1011 aircraft. These doors, shown in Figure 14, have graphite/epoxy skins with aluminum honeycomb core. These doors were developed by Rolls-Royce for the L-1011 engines and production is planned for early 1980. A set of doors has a mass of 94.3 kg which represents a 22.1 percent mass saving compared to the aluminum production doors. Lockheed also has a small laminated I-beam floor post in service on an L-1011 aircraft which represents a 23.5 percent mass saving.

Flight Service Summary

As indicated in Figure 15, the 56 company-developed composite components currently in service on a variety of commercial transport aircraft have accumulated over 600,000 flight hours. Boeing has accumulated 496,000 successful flight hours during the last 9 years on graphite/epoxy floor panels installed on 30 B-747 aircraft. Similar floor panels are now provided as customer options to save considerable mass compared to the standard fiberglass floor panels. Douglas has accumulated about 45,000 component flight hours on their DC-9 and DC-10 composite components. The high-time component is the Kevlar/epoxy nose cowl on the DC-9 which was installed in 1976 and has 9,000 flight hours. Lockheed started delivery of their L-1011-500 aircraft in April 1979; hence, not many flight hours have been accumulated on their Kevlar/epoxy production components. However, these components are expected to accumulate about 2,500 flight hours per year. Lockheed has accumulated almost 10,000 hours on four graphite/epoxy cowl doors and almost 18,000 hours on a graphite/epoxy floor post.

The aircraft companies have reported excellent service performance with all their composite components. The success of the NASA and industry flight service programs has led to large commitments of secondary composite components on future commercial aircraft. Continued success of these programs will lead to the introduction of primary composite components in the commercial airline fleet which will translate into improved fuel economy.

COMPOSITES ON COMMERCIAL HELICOPTERS

The commercial helicopter industry is starting to make use of advanced composites to save structural mass and thus increase helicopter range and payload. Sikorsky Aircraft has been the major user of advanced composites on both commercial and military helicopters. The most widely used composite material is Kevlar/epoxy, primarily because it costs less than graphite/epoxy. The Sikorsky S-76 commercial helicopter makes extensive use of Kevlar and graphite composite structure as shown in Figure 16. Over 115 kg of Kevlar/epoxy primary structure, secondary structure, and non-structural applications are currently in production on the S-76. Sikorsky chose Kevlar/epoxy because of its combination of mechanical properties, intermediate costs, and formability similar to fiberglass. Also, successful flight service experience of Kevlar/epoxy secondary structures on a Sikorsky CH-53D marine helicopter helped establish the necessary confidence required to enter into commercial production.

Kevlar/epoxy components account for approximately 45 percent of the wetted external surface of the S-76. Applications include the horizontal stabilizer, main-rotor blade-tip caps, canopy, radome, cabin doors, forward and aft engine fairings above the cabin, landing gear and baggage compartment doors, and internal non-structural items. Graphite/epoxy and Kevlar/epoxy hybrids are used in selected components to improve strength and stiffness. Several of the composite components are shown in Figure 17. In most hybrid applications the graphite carries the primary bending loads and the Kevlar carries the shear loads. An example is shown in Figure 18 for a horizontal stabilizer where uniaxial graphite/epoxy carries bending loads in spar caps and cross-ply Kevlar/epoxy basically carries shear loads. The application of graphite/epoxy in the tail rotor spar takes advantage of the superior fatigue characteristics of this material for a primary, dynamic structural component. The composite components have been flying for over 2 years on three S-76 prototypes with no major malfunctions. The first commercial delivery of the S-76 helicopter was in February 1979. As of December 1979, 27 S-76 helicopters have been delivered and a total of 5450 successful flight hours have been accumulated on the composite components.

Boeing-Vertol has an extensive development program underway to place Kevlar and graphite composite components into production on Boeing 234 commercial helicopters. Primary emphasis is on extending the range of the helicopter through the use of Kevlar-graphite hybrid fuel pods as shown in Figure 19. Other graphite and Kevlar components include doors, fairings, cabin floor, and support beams. The Boeing 234 helicopter is scheduled to enter commercial service in early 1981.

Bell Helicopter is using advanced composites in crew seats on the Bell 222 commercial helicopter. The seat shown in Figure 20 uses Kevlar skins and aluminum honeycomb in sandwich construction for the bucket and a graphite/epoxy energy attenuator tube as part of the seat support structure. Twelve model 222 helicopters have been delivered with two lightweight energy-absorbing crew seats in each aircraft.

NASA AIRCRAFT ENERGY EFFICIENCY PROGRAM (ACEE)

Since 1975, NASA has been sponsoring an extensive program to improve the efficiency of current commercial transport aircraft through the development and application of several technologies that could reduce fuel consumption on new aircraft by up to 50 percent. Advanced composite structures alone have the potential to reduce fuel consumption by 10 to 15 percent. The broad objective of the composites part of this program is to conduct research to provide the technology and confidence so that commercial transport manufacturers can commit to production of composites in their future aircraft. Composites technology is being developed for large secondary structures and medium primary structures. As shown in Figure 21, the technology readiness dates are to make such commitments for secondary structures in the 1980-1985 time frame and for primary structures in 1985-1990. Verification of design methods and cost competitive manufacturing processes are required to determine technology readiness. Confidence in composite structures is being developed through durability tests that lead to warranty of the aircraft, cost verification through manufacture of multiple components in the production mode, FAA certification, and airline acceptance.

Composite Secondary Structures

Each of the three major U.S. commercial transport manufacturers are under contract to NASA to design, fabricate, and test major secondary composite components as shown in Figure 22. Douglas has completed fabrication of additional graphite/epoxy DC-10 upper aft rudders using cost-effective fabrication and tooling methods, Boeing has fabricated graphite/epoxy elevators for the B-727 and Lockheed is fabricating graphite/epoxy ailerons for the L-1011. Several shipsets of these components will be placed into airline service for evaluation.

All of the ACEE composite secondary components are large enough to present manufacturing problems that may be encountered in constructing many other aircraft structures. Details of the three graphite/epoxy secondary components are summarized in Figure 23. The L-1011 aileron is about 1.2 m wide by 2.4 m long and has a mass of 45.4 kg. The composite design features a syntactic-core sandwich with graphite/epoxy face sheets. The total number of ribs has been reduced from 13 for the aluminum aileron to 10 for the composite aileron, the number of parts has been reduced from 398 to 205, and the number of mechanical fasteners has been reduced from 5253 to 2574. A mass saving of 28.5 percent is projected for the composite aileron. Some of the construction details are shown in Figure 24 for an aileron located in the assembly fixture. The upper surface, ribs, and spars are permanently fastened using titanium fasteners, whereas, the lower surface, trailing edge wedge, and end fairings are attached with removable fasteners. Analysis indicates that the composite design is cost competitive with the production aluminum aileron. Twenty-two composite ailerons will be fabricated to establish a good basis for projecting costs. Upon completion of aileron fabrication and detailed manufacturing analysis, a production decision will be made by Lockheed.

The graphite/epoxy upper aft rudder for the DC-10 is 0.8 m wide by 4.0 m long and has a mass of 30.3 kg. The composite design features multi-rib construction with two spars. As discussed previously, the structural box is manufactured as a single cocured unit and represents a 26.8 percent mass saving compared to the production aluminum

rudders. An additional 11 rudders have been manufactured under the ACEE program to develop more efficient manufacturing methods and to obtain quantitative cost data. The rudders have been FAA certified and Douglas is considering fleet production of the graphite/epoxy rudders for new DC-10 aircraft.

The graphite/epoxy elevator for the B-727 is 0.9 m wide by 5.8 m long and has a mass of 89.4 kg. The elevator design is dictated primarily by stiffness requirements and makes efficient use of graphite/epoxy Nomex honeycomb sandwich skins to carry normal pressure and in-plane shear loads. The upper and lower skins are attached to the substructure with titanium fasteners. With this design, most of the interior ribs used in the production elevators are eliminated and a mass saving of 23.6 percent has been achieved. Since the elevator is mass-balanced, additional mass saving can be effected through the use of graphite/epoxy. Eleven elevators have been fabricated to verify cost projections and FAA certification has been received. Five shipsets of graphite/epoxy elevators will be placed into airline service for evaluation. Four shipsets of assembled graphite/epoxy elevators are shown in Figure 25. Boeing is considering fabrication of up to 25 additional shipsets of elevators to establish manufacturing learning curves.

Composite Primary Structures

Each of the three major U.S. commercial transport manufacturers are also under NASA contract to design, fabricate, and test medium-sized primary composite components as shown in Figure 26. Douglas and Lockheed will fabricate graphite/epoxy vertical fins for the DC-10 and L-1011, respectively, and Boeing will build horizontal stabilizers for the B-737. The ACEE composite primary components are more complex than the secondary components and thus present a greater design and manufacturing challenge. Details of the three graphite/epoxy primary components are summarized in Figure 27.

The composite L-1011 vertical fin is about 2.7 m wide by 7.6 m long and has a mass of 272.2 kg. The structural configuration consists of cocured hat-stiffened skins, cocured I-beam stiffened front and rear spars, and multiple ribs. Using this design approach a mass saving of 30.1 percent is projected. The tooling for the stiffeners consists of inflatable silicone rubber bladders to provide internal pressure, exterior caul plates, and a vacuum bag. The entire skin panel is cured in an autoclave under pressure and elevated temperature. Upon completion of the cure, the inflatable bladders are easily removed from the stiffener cavity as shown in Figure 28. Three L-1011 fins will be fabricated to validate manufacturing cost projections.

The graphite/epoxy vertical stabilizer for the DC-10 is 2.4 m wide by 7.6 m long and has a mass of 350.3 kg. The design configuration selected for the DC-10 vertical fin consists of Nomex honeycomb sandwich skins, four I-beam spars with sine-wave webs, and multiple sine-wave ribs. Titanium lug fittings are cocured into the spar caps to provide root-end attachments. The ribs and spars are joined by adhesive bonded angle clips and the skins are mechanically fastened to the substructure with titanium bolts. A mass saving of 22.8 percent is projected using this design concept. Seven DC-10 vertical stabilizers will be fabricated to obtain manufacturing cost data.

The graphite/epoxy horizontal stabilizer for the Boeing 737 aircraft is 1.2 m wide by 5.2 m long and has a mass of 91.6 kg. The design selected consists of cocured integrally stiffened skins, laminated front and rear spars with titanium lug attachments, seven inboard Nomex honeycomb ribs, two closure ribs, and a laminated trailing-edge beam. The honeycomb ribs have cutouts to allow passage of the continuous skin stiffeners as shown in Figure 29. Assembly of the structural box is accomplished with titanium mechanical fasteners. With this design configuration, a mass saving of 22.9 percent is projected. Eleven B-737 horizontal stabilizers will be fabricated to verify predicted manufacturing learning curves.

Ancillary Test Plan

Numerous ancillary tests are being conducted by the ACEE contractors to verify design procedures, provide design allowables data, and provide data in support of certification requirements. The tests vary in size and difficulty from small static coupons to large combined-load subcomponents. Some of the tests are shown schematically in Figure 30. As indicated, mechanical tests such as panel compression, root-end load transfer, impact damage, rib-to-skin attachments, and lap joints are being conducted. Most of these tests are conducted at room temperature or at elevated temperature with and without moisture conditioning. Additional details of the NASA ACEE composite structures program can be found in [15].

NEAR-TERM PRODUCTION PLANS

Advanced composites technology has been developed to the point where U.S. commercial aircraft manufacturers are starting to make production commitments to these materials. Success of the flight service evaluation programs and technology developments under the NASA ACEE composites program has led Boeing to plan extensive use of advanced composites on their new B-767 aircraft. As shown in Figure 31, most of the control surfaces, including rudders, elevators, spoilers, and ailerons, will be built with graphite/epoxy composites. Graphite-Kevlar hybrids will be used in numerous structures

such as leading and trailing edge panels, cowl components, landing gear doors, and fairings. Replacement of standard fiberglass parts with Kevlar and graphite composites will result in mass savings of up to 30 percent.

Lockheed has made extensive production commitments to Kevlar/epoxy secondary structures on the L-1011-500 as discussed previously. Design studies are currently underway to investigate potential graphite/epoxy structure applications on the L-1011 aircraft. Components being studied include the vertical fin, rudders, elevators, ailerons, flaps, doors, and floor beams and posts. As shown in Figure 32, graphite/epoxy applications being studied have a mass of 2560 kg which represents a 26 percent mass saving compared to the current production components. At the conclusion of these studies Lockheed will be in a position to make future production decisions provided the composite components are economically feasible.

Douglas is also conducting studies to determine the economic feasibility of committing to production of numerous composite components on their DC-10 aircraft. Some of the potential components as shown in Figure 33 include graphite/epoxy vertical stabilizers, rudders, elevators, spoilers, and ailerons. Other graphite/epoxy components include doors, panels, beams, and nacelle structure. Potential Kevlar/epoxy components include extensive fairings, tail cone, and nose cowl structure.

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ENVIRONMENTAL EFFECTS ON COMPOSITES

In conjunction with the flight service evaluation of composite components, approximately 17,000 composite specimens are being tested to determine the long-term environmental effects on composites. Epoxy matrix composites inherently absorb moisture from the surrounding environment and ultraviolet radiation can attack the molecular structure of polymeric materials. This combination of moisture, elevated temperature, and ultraviolet radiation can reduce the mechanical properties of composite materials. Mechanical property tests are being conducted on small specimens to determine the effect of these environments on the strength of several composite material systems. Specimens are being exposed worldwide to outdoor ground environments, to indoor controlled laboratory environments, and real-time flight exposure.

The worldwide ground exposure specimens are mounted in racks which are deployed on roofs of airline buildings at a number of airports around the world to receive maximum exposure to the airport environment. Racks are located in Germany, Brazil, New Zealand, Hawaii, and several locations within the continental United States. The exposure racks contain several different graphite and Kevlar composite material systems. Figure 34 shows a typical exposure rack, the various specimen configurations and the worldwide exposure locations. Tests performed include short beam interlaminar shear, flexure, compression, and tension. Most of the deployed specimens are unstressed. However, three racks have been deployed with tensile specimens under sustained load. Two distinct sets of composite specimens have been deployed. One set is unpainted to provide maximum exposure of the matrix materials and a second set of specimens is painted with standard aircraft polyurethane paint to protect the matrix from direct ultraviolet radiation exposure. Specimens are periodically removed from the racks and shipped to NASA Langley for mechanical property testing. The specimens are weighed to determine mass changes associated with moisture absorption and weathering. The specimens are tested to failure to compare residual strengths with baseline control specimens with no prior environmental exposure. Specimens are removed from the racks for testing after 1, 3, 5, 7, and 10 years exposure.

The moisture contents for four graphite/epoxy material systems and two Kevlar/epoxy material systems have been determined after 3 years outdoor environmental exposure. Data shown in Figure 35 for specimens removed from racks at six different exposure sites indicate moisture contents ranging from about 0.5 percent to 2.0 percent. Additional moisture data will be collected after 5, 7, and 10 years exposure. The effects of absorbed moisture and ultraviolet radiation on composite mechanical properties have been determined after 5 years outdoor exposure at six locations. The room temperature residual flexure strengths for six composite materials are shown in Figure 36. Most of the test data fall within the scatter band for the baseline strength of unexposed specimens. These results indicate essentially no degradation in the flexure strength of the six composite materials after 5 years outdoor exposure. Results from shear and compression tests indicate strength reductions of up to 15 percent after 5 years exposure. Since these properties are more matrix dominated than are the flexure properties, shear and compression properties are normally more sensitive to absorbed moisture.

To consider the possible influence of constant stress during the outdoor exposure, tensile specimens are being exposed at NASA Langley Research Center and San Francisco Airport with a sustained stress of 40 percent of the original ultimate strength. Test results for T300/5208 graphite/epoxy laminates are shown in Figure 37. Quasi-isotropic laminated tensile specimens have been tested after 1, 3, and 5 years exposure for both stressed and unstressed conditions. Essentially no difference between strength of stressed and unstressed specimens and no degradation in tensile strength was found for any condition.

Another type of environmental exposure that must be considered is the interaction of composite materials with long-term exposure to aircraft fuels and hydraulic fluids. Under NASA contract, the Boeing Company is conducting a series of exposures of composite materials to JP-4 jet fuel, Skydrol, fuel-and-water mixture, and a fuel-and-air cyclic environment. Results for T300/5209 tensile specimens with [$\pm 45^\circ$] ply orientations are shown in Figure 38. A maximum degradation of 10 percent in the tensile strength occurred after 5 years exposure to the fuels and fluids indicated. However, Kevlar/2544 exhibited a 40 percent loss in short beam shear strength when exposed to fuel/water immersion.

The most recent NASA Langley Research Center environmental exposure program involves flight exposure of composite specimens on scheduled airlines. Moisture absorption in flight is being determined for composite specimens mounted on the Boeing 737 aircraft. Unstressed exterior exposure is obtained with specimens mounted on the top and bottom surfaces of the flap track fairing cone as shown in Figure 39. Interior stressed and unstressed exposure is obtained with specimens mounted in an aft fuselage vented compartment. The exterior specimens were deployed first and moisture absorption data have been obtained after 18 months of flight exposure. Composite mass change for three graphite/epoxy material systems is shown in Figure 40 for specimens removed from the exterior surface of three commercial airlines which operate in distinct climatic conditions. Specimen mass varied with seasonal weather variations, with mass change being most pronounced in the temperate regions having wide seasonal variations than in the tropical region having a more uniform year-round climate. The T300/5209 system experienced somewhat less mass gain than did the T300/5208 and AS/3501 systems. Maximum mass gain in any climate was only slightly greater than one percent. Mass changes such as these result from moisture absorption, drying, and ultraviolet radiation, all of which could have cumulative damaging effects on composites. These tests will be conducted over a period of several years to determine saturation levels and the repetitive nature of the seasonal variations. The results of these tests will be compared with outdoor ground environmental test results and indoor controlled laboratory results. Methodologies for predicting environmental behavior are being systematically developed during a comprehensive 10-year program. Additional details of the NASA Langley environmental effects programs can be found in [16].

CONCLUDING REMARKS

Excellent experience has been achieved with approximately 200 composite components in flight service for 2.5 million total component hours.

No significant degradation has been observed in residual strength of composite components or environmental exposure specimens after 5 years service or exposure.

Technology is being developed that will lead to extensive production of advanced composites in future aircraft.

Confidence in advanced composites technology is being developed to the extent that commercial transport and helicopter manufacturers have made production commitments to composites for selected components.

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ACKNOWLEDGEMENT

Portions of the data reported herein were obtained from U.S. commercial transport aircraft and helicopter manufacturers. Several NASA researchers participated in developing the data reported for the NASA composites program. The author gratefully acknowledges these contributions.



Figure 1. NASA flight service composite components.

COMPONENT	COMPOSITE MATERIAL	STRUCTURAL CONFIGURATION	BASELINE MASS, kg	COMPOSITE MASS, kg	MASS SAVINGS, %
CH-54B TAIL CONE	BORON/EPOXY	REINF. AL	209.5	180.	14.0
L-1011 FAIRINGS	KEVLAR/EPOXY	NOMEX H/C AND SOLID LAMINATE	13.8	10.1	26.8
B-737 SPOILER	GRAPHITE/EPOXY AND GLASS/EPOXY**	AL H/C SAND.	7.1	5.9	16.9
C-130 CENTER WING BOX	BORON/EPOXY	REINF. AL	2240.0	2017.0	10.0
DC-10 AFT PYLON SKIN	BORON/ALUMINUM	SOLID LAMINATE	2.2	1.6	27.3
DC-10 UPPER AFT RUDDER	GRAPHITE/EPOXY AND GLASS/EPOXY	RIB-STIFFENED SKIN	41.4	27.8	32.9
206L DOORS AND FAIRING	KEVLAR/EPOXY	NOMEX H/C, STIFFENED SKIN, AND FOAM SAND.	10.8	8.0	25.9
S-76 TAIL ROTOR AND HORIZ. STAB.	GRAPHITE/EPOXY, KEVLAR/EPOXY, AND GLASS/EPOXY	SOLID LAMINATE AND NOMEX H/C SAND.	24.7	24.7	N/A

Figure 2. Details of NASA light service components.

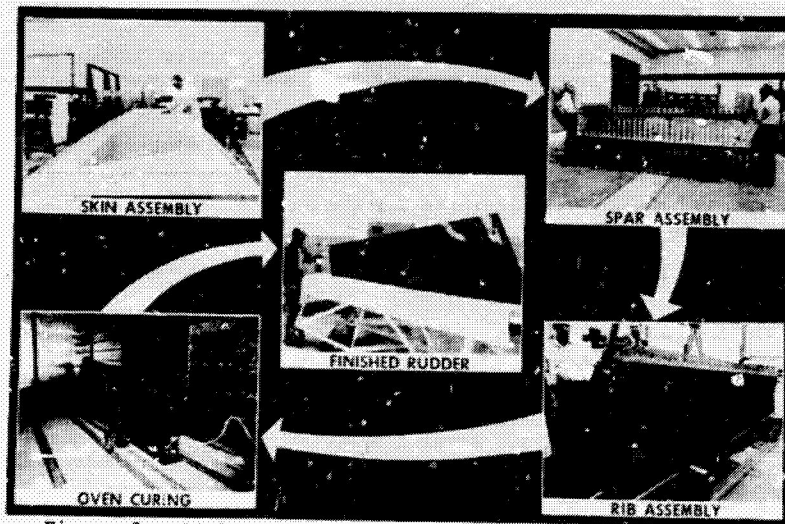


Figure 3. DC-10 upper aft rudder manufacturing sequence.

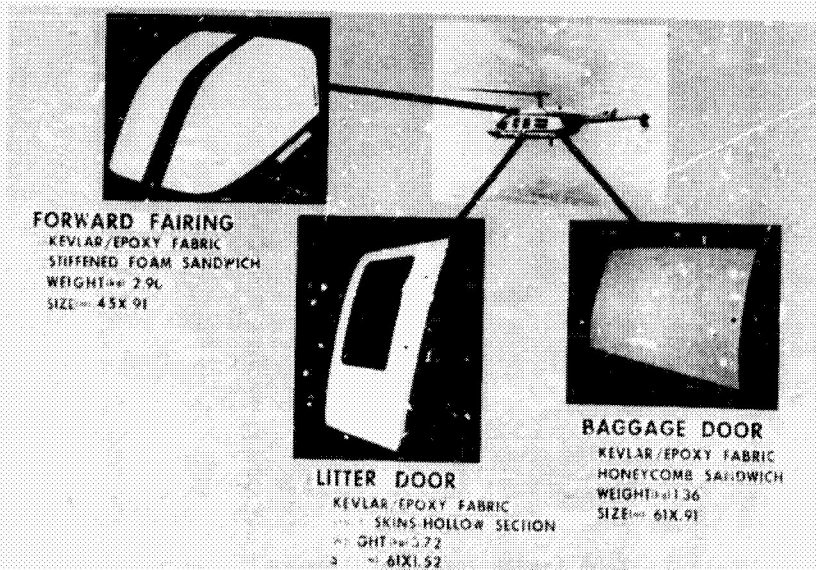


Figure 4. Bell 206L helicopter composite components.



Figure 5. Sikorsky S-76 helicopter composite components.

AIRCRAFT, COMPONENT	TOTAL COMPONENTS	START OF FLIGHT SERVICE	CUMULATIVE FLIGHT HOURS	
			HIGH TIME AIRCRAFT	TOTAL COMPONENT
CH-54E TAIL CONE	1	MARCH 1972	1,140	1,140
L-1011 FAIRING PANELS	18	JANUARY 1973	17,718	282,870
737 SPOILER	108	JULY 1973	17,500	1,436,000
C-130 CENTER WING BOX	2	OCTOBER 1974	3,840	7,650
DC-10 AFT PYLON SKIN	3	AUGUST 1975	11,880	35,300
DC-10 UPPER AFT RUDDER	10	APRIL 1976	14,470	92,800
GRAND TOTAL	142			1,857,760

Figure 6. NASA composite structures flight service summary.

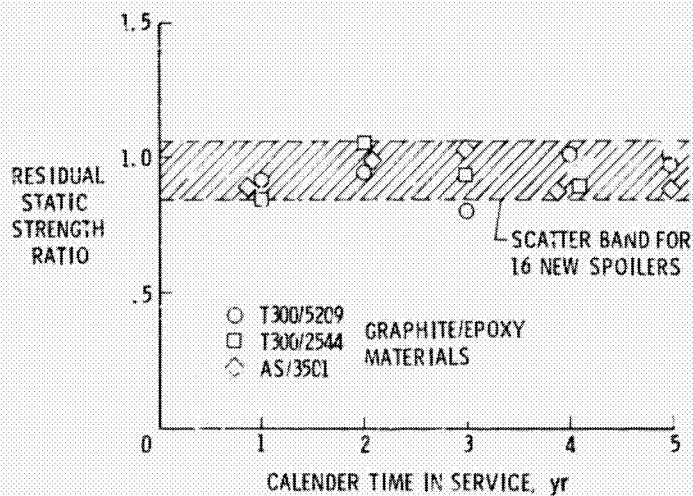


Figure 7. Residual strength of graphite/epoxy spoilers.

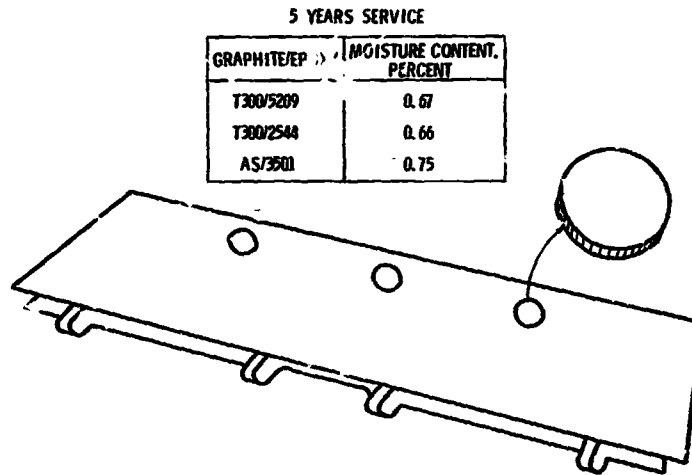


Figure 8. Spoiler moisture levels determined from plugs.

COMPONENT	INSPECTION INTERVAL, months	INSPECTION METHODS	STATUS
CH-54B TAIL CONE	2	VISUAL ULTRASONIC	MINOR DISBONDS NO REPAIR REQUIRED
L-1011 FAIRING PANELS	12	VISUAL	MINOR IMPACT DAMAGE, FIBER FRAYING AND HOLE ELONGATIONS
737 SPOILER	12	VISUAL ULTRASONIC	INFREQUENT MINOR DAMAGE REPAIRED AT BOEING
C-130 CENTER WING BOX	6	VISUAL ULTRASONIC	NO DEFECTS AFTER MORE THAN 5 YEARS SERVICE
DC-10 AFT PYLON SKIN	12	VISUAL	MINOR SURFACE CORROSION ON ONE SKIN
DC-10 UPPER LEFT RUDDER	3, 12	VISUAL ULTRASONIC	MINOR RIB-TO-SKIN DISBOND ON TWC RUDDERS

Figure 9. NASA composite component inspection and maintenance results.

COMPONENT	COMPOSITE MATERIAL	STRUCTURAL CONFIGURATION	*BASELINE MASS, kg	*COMPOSITE MASS, kg	MASS SAVINGS, %
B-747 FLOOR PANELS	GRAPHITE/EPOXY	NOMEX H/C SAND.	451.3	312.5	30.8
B-707 FOREFLAP	BORON/EPOXY	AL H/C MONOCOQUE SHELL	9.1	6.8	25.3
DC-10 VERT. STAB. T.E. PANEL	GRAPHITE/EPOXY	HAT-STIFFENED	1.0	0.8	20.0
DC-10 FLOOR BEAM	GRAPHITE/EPOXY	LAMINATED I-BEAM SECTION	14.5	10.9	24.8
DC-9 COWL DOOR	KEVLAR/EPOXY & GRAPHITE/EPOXY	AL H/C FRAME STIFFENED	65.3	50.4	22.8
DC-9 NOSF COWL	KEVLAR/EPOXY	AL H/C INNER BARREL	100.7	73.9	26.6
DC-9 TAIL CONE	KEVLAR/EPOXY	NOMEX H/C SAND.	34.0	27.7	18.5
L-1011 PANELS, DOORS, T.E. WEDGES & FAIRINGS	KEVLAR/EPOXY	NOMEX H/C SAND. & SOLID LAM.	1500.0	1134.0	24.4
L-1011 COWL DOOR	GRAPHITE/EPOXY	AL H/C SAND.	121.1	94.3	22.1
L-1011 FLOOR POST	GRAPHITE/EPOXY	LAMINATED I-BEAM	1.7	1.3	23.5

*COMPONENT MASS PER AIRCRAFT

Figure 10. Details of aircraft company composite components.

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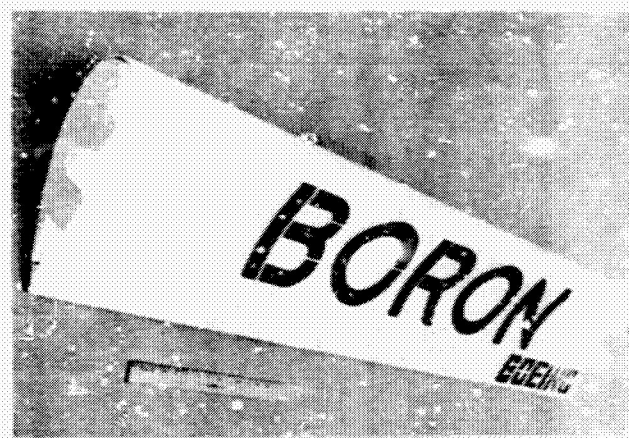


Figure 11. Boeing 707 boron/epoxy foreflap.

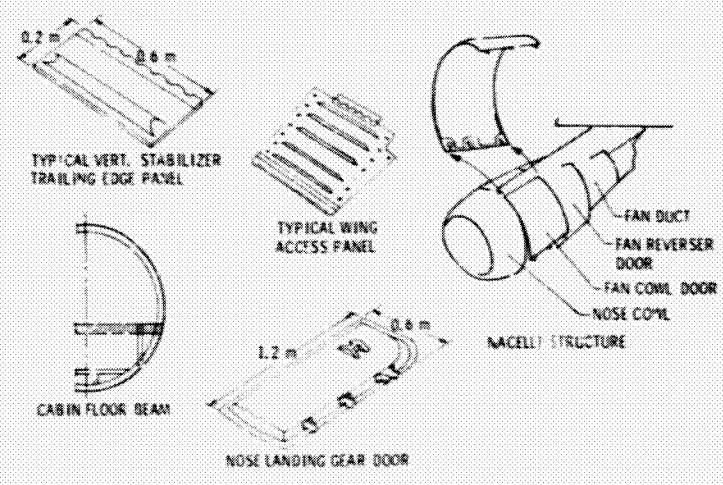


Figure 12. Douglas flight service composite components.

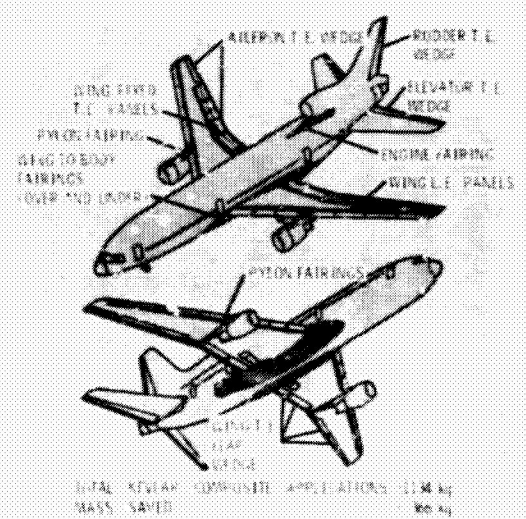


Figure 13. Lockheed L-1011 Kevlar/epoxy composite applications.



Figure 14. Lockheed L-1011 graphite/epoxy cowl door.

COMPONENT	TOTAL COMPONENTS	START OF FLIGHT SERVICE	CUMULATIVE FLIGHT HOURS	
			HIGH TIME AIRCRAFT	TOTAL COMPONENT
B-747 FLOOR PANELS	30 A/C	APRIL 1970	33,000	495,000
B-707 FOREFLAP	2	MAY 1970	17,500	35,000
DC-10 VERT. STAB. T.E. PANEL	5	JANUARY 1978	5,340	22,400
DC-10 FLOOR BEAM	3	MAY 1979	1,560	2,600
DC-9 COWL DOOR	4	AUGUST 1978	3,500	10,300
DC-9 NOSE COWL	1	MAY 1976	9,000	9,000
L-1011 PANELS, DOORS, T.E. WEDGES & FAIRINGS	6 A/C	APRIL 1979	1,890	8,160
L-1011 COWL DOOR	4	DECEMBER 1978	2,600	9,660
L-1011 FLOOR POST	1	JANUARY 1972	17,900	17,900
GRAND TOTAL	56			611,040

Figure 15. Flight service summary of aircraft company composite components.

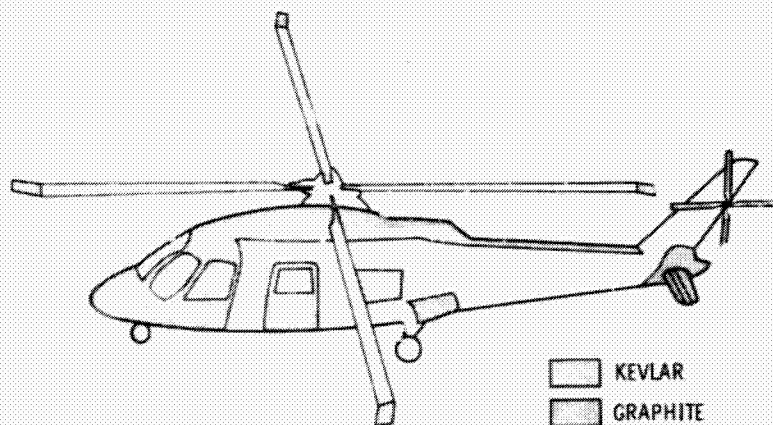


Figure 16. Sikorsky S-76 helicopter composite applications.



Figure 17. S-76 composite applications.

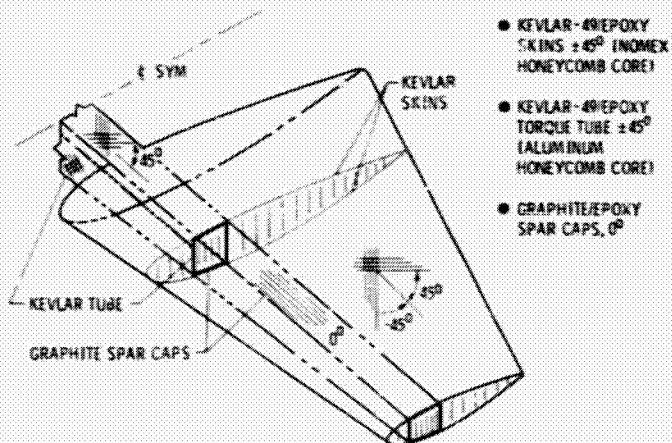


Figure 18. S-76 composite horizontal stabilizer.

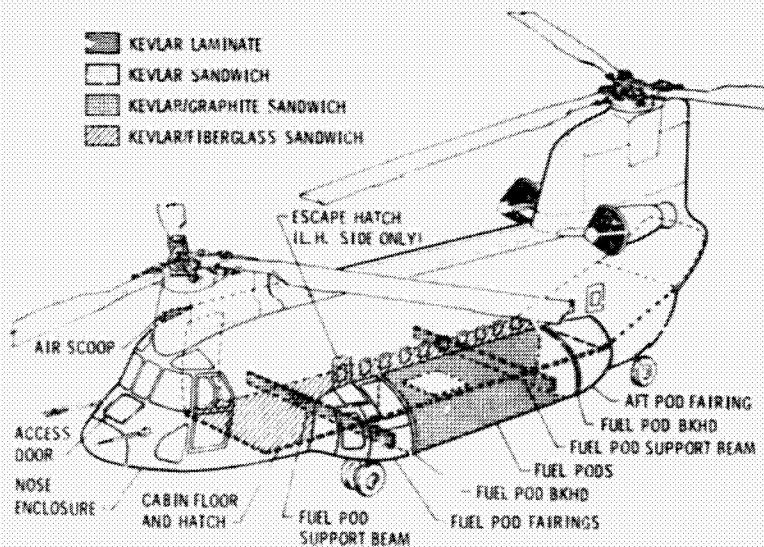


Figure 19. Boeing 234 helicopter composite applications.

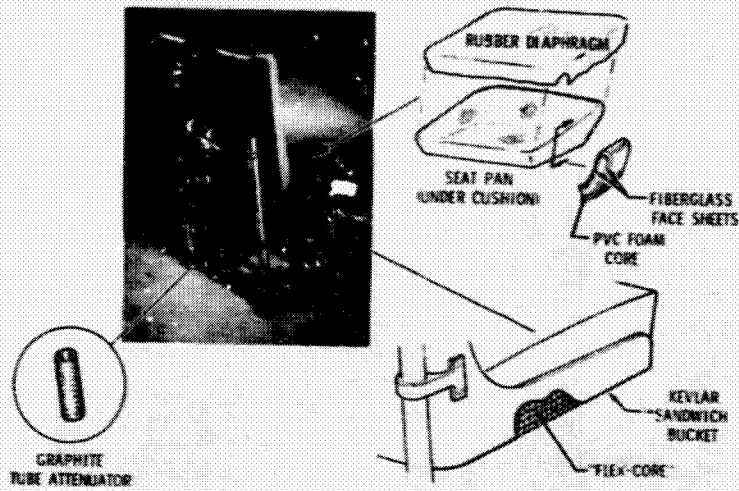


Figure 20. Bell 222 composite crew seat.

OBJECTIVE

PROVIDE THE TECHNOLOGY AND CONFIDENCE SO THAT COMMERCIAL TRANSPORT MANUFACTURERS CAN COMMIT TO PRODUCTION OF COMPOSITES IN THEIR FUTURE AIRCRAFT:

SECONDARY STRUCTURE - 1980 TO 1985

PRIMARY STRUCTURE - 1985 - 1990

TECHNOLOGY

- DESIGN CRITERIA, METHODS AND DATA
- QUALIFIED DESIGN CONCEPTS
- COST COMPETITIVE MANUFACTURING PROCESSES

CONFIDENCE

- DURABILITY/WARRANTY
- QUANTITY COST VERIFICATION
- FAA CERTIFICATION
- AIRLINE ACCEPTANCE

Figure 21. NASA ACEE composite program.

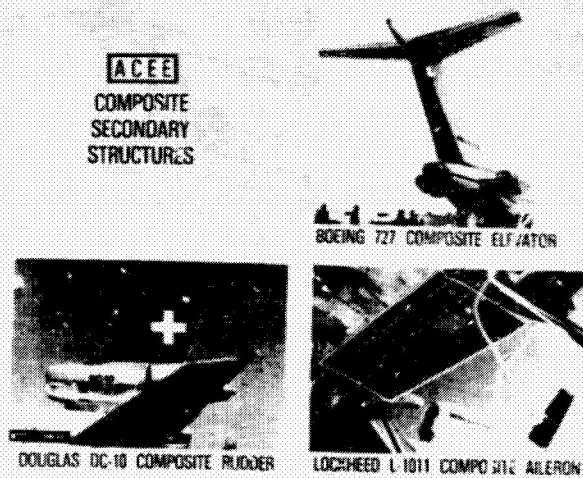


Figure 22. NASA ACEE composite secondary structures.

COMPONENT	L-1011 AILERON	DC-10 RUDGER	B-727 ELEVATOR
SIZE, m	1.2 x 2.4	0.8 x 4.0	0.9 x 5.8
BASELINE METAL MASS, kg	63.5	41.4	117.0
COMPOSITE MASS, kg	45.4	30.3	89.4
MASS SAVING, %	28.5	26.8	23.6
QUANTITY TO BE FABRICATED	22	11*	11*
CERTIFICATION	MID-1980	YES	YES
PRODUCTION	UNCERTAIN	PENDING	UNCERTAIN

*FABRICATION COMPLETED

Figure 23. Details of NASA ACEE composite secondary components.

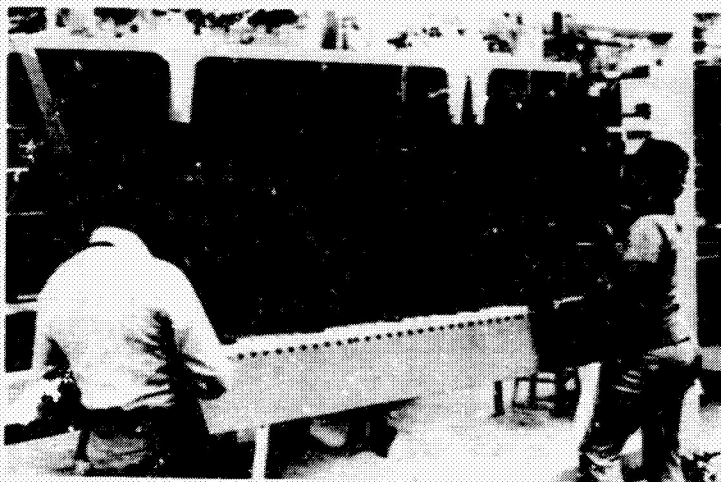


Figure 24. Assembly of Lockheed L-1011 composite aileron.

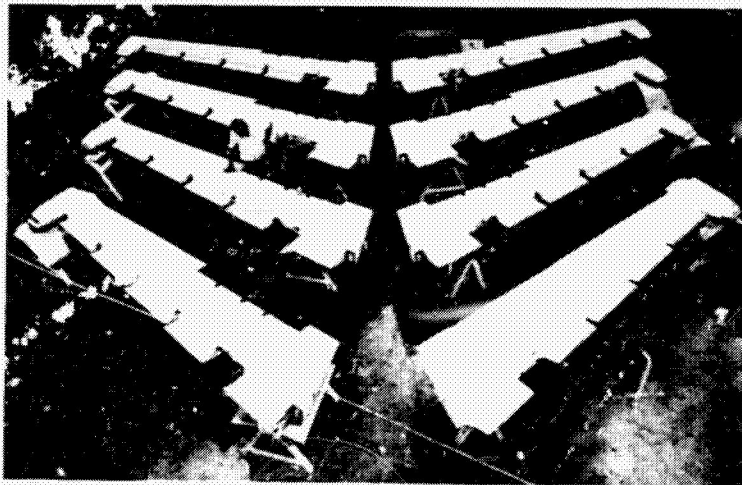


Figure 25. Boeing 727 graphite/epoxy elevators.



Figure 26. NASA ACEE composite primary structures.

COMPONENT	L-1011 VERT. FIN	DC-10 VERT. STAB.	B-737 HORIZ. STAB.
SIZE, m	2.7 x 7.6	2.4 x 7.6	1.2 x 5.2
BASELINE METAL MASS, kg	389.2	453.6	118.9
COMPOSITE MASS, kg	272.2	350.3	91.6
PROJECTED MASS SAVINGS, %	30.1	22.8	22.9
QUANTITY TO BE FABRICATED	3	7	11

Figure 27. Details of NASA ACEE composite primary components.

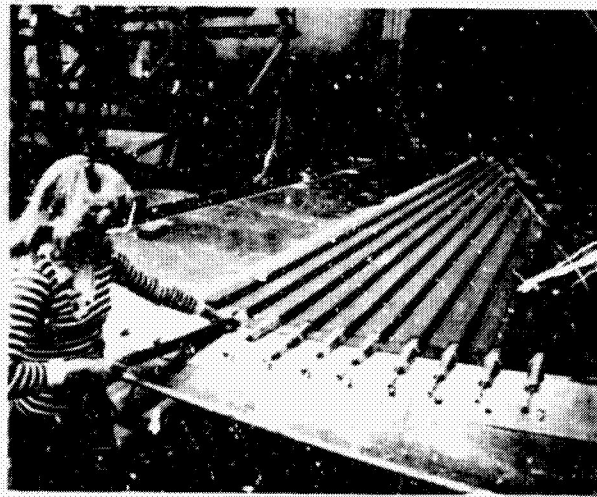


Figure 28. Graphite/epoxy skin panel for Lockheed L-1011 vertical fin.

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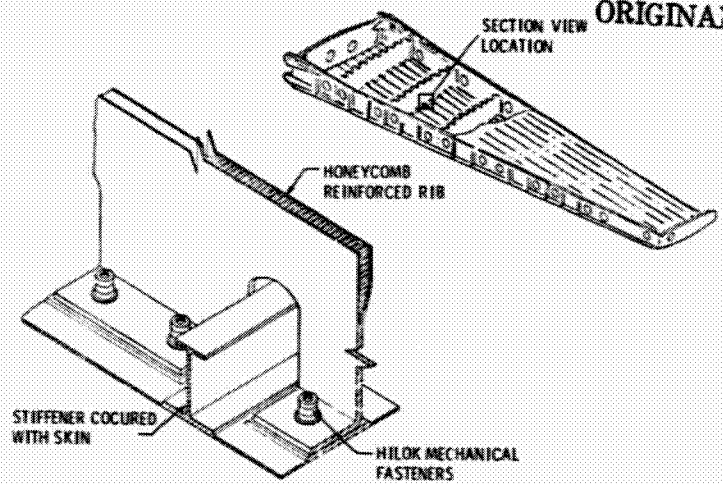


Figure 29. Boeing 737 composite stabilizer assembly.

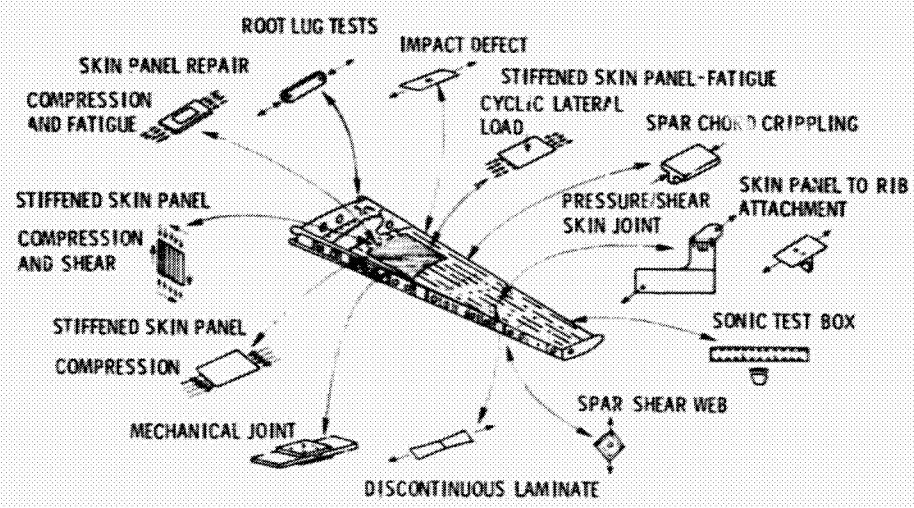


Figure 30. NASA ACEE composites ancillary tests.

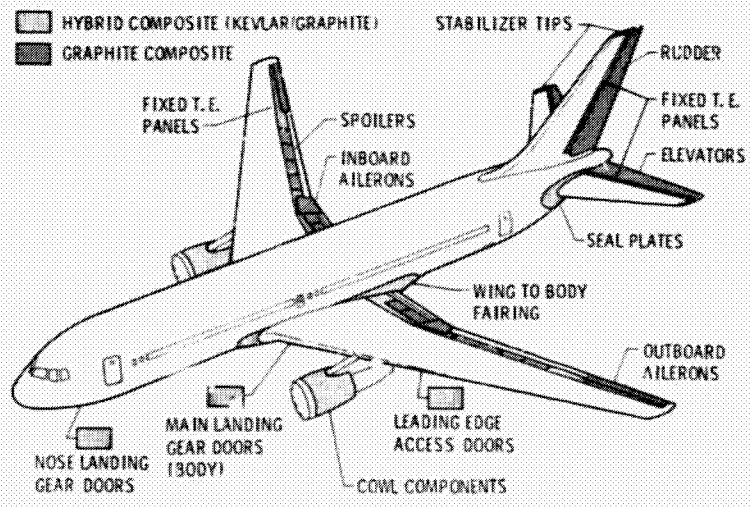
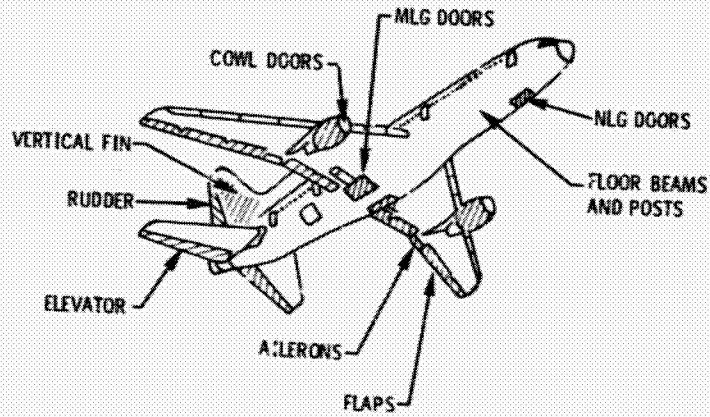


Figure 31. Boeing 767 composite applications.



TOTAL GRAPHITE/EPOXY COMPOSITE APPLICATIONS - 2560 kg
 MASS SAVED - 915 kg

Figure 32. Potential composite structure applications on Lockheed L-1011.

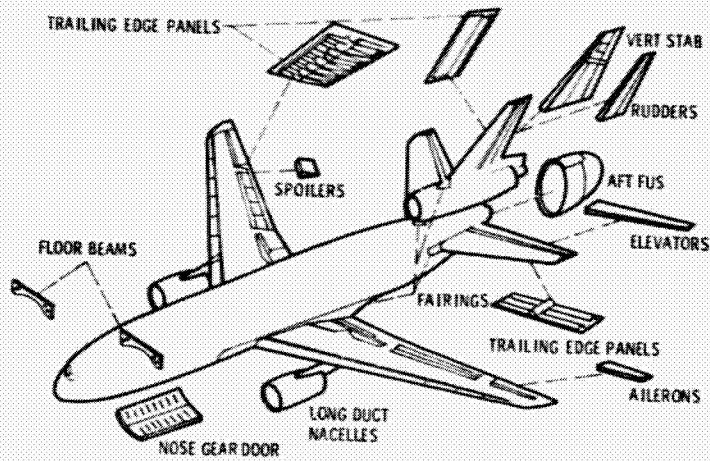


Figure 33. Potential composite structure applications on Douglas DC-10.

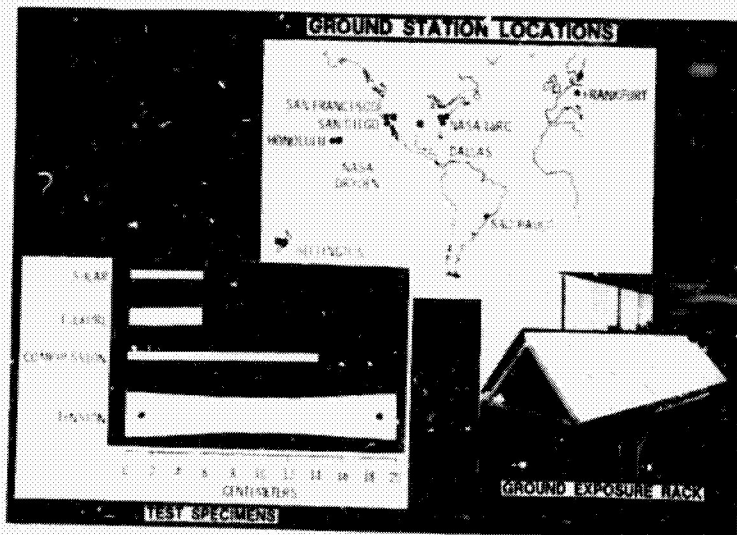


Figure 34. Worldwide environmental exposure of composite materials for commercial aircraft.

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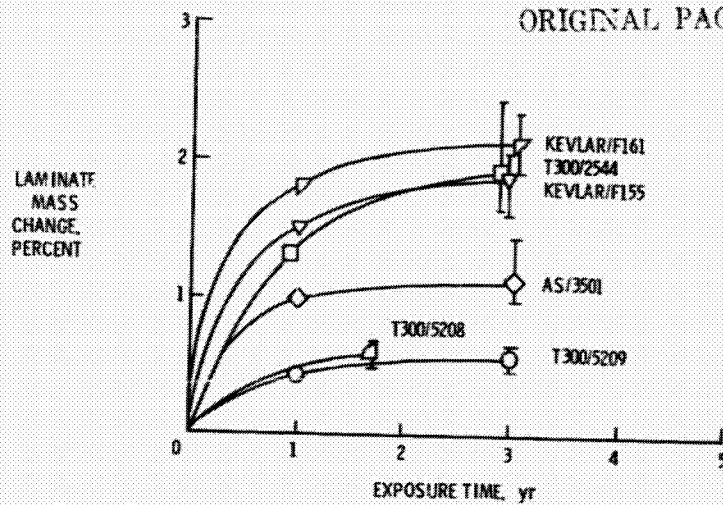


Figure 35. Moisture pickup after worldwide exposures.

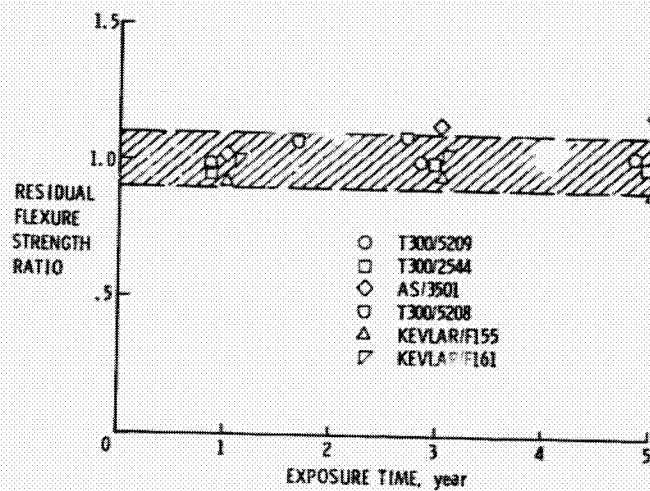


Figure 36. Residual flexure strength after worldwide exposure.

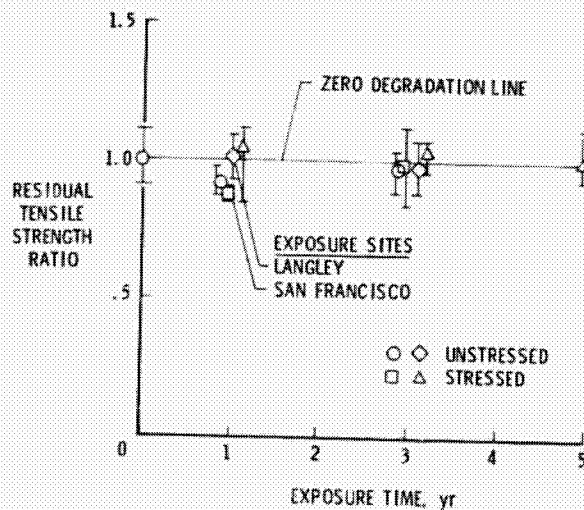


Figure 37. Residual tensile strength after sustained stress outdoor exposures; T300/5208, [0°:45°:90°] laminate stressed at 40 percent ultimate.

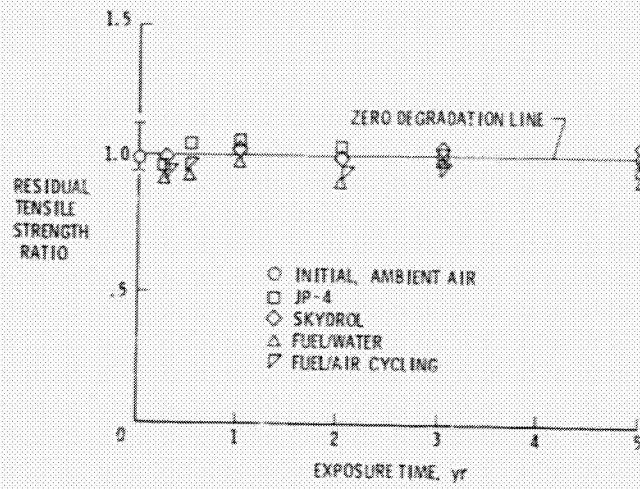


Figure 38. Effect of fuels and fluids on strength; T300/S209, ±45° tensile specimens.

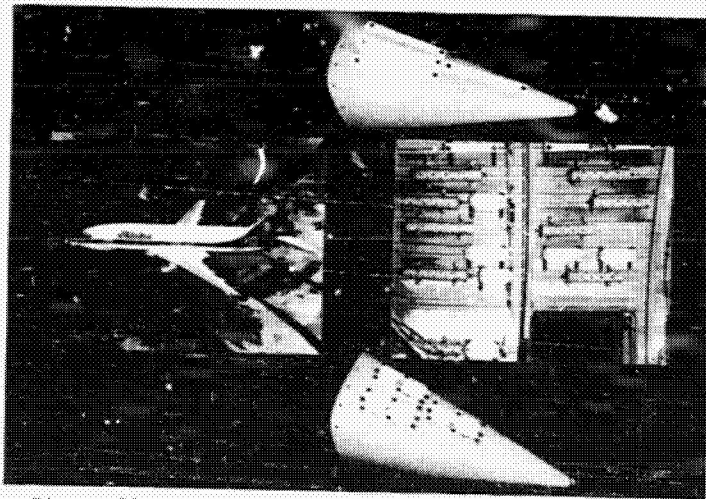


Figure 39. Boeing 737 flight environmental exposure.

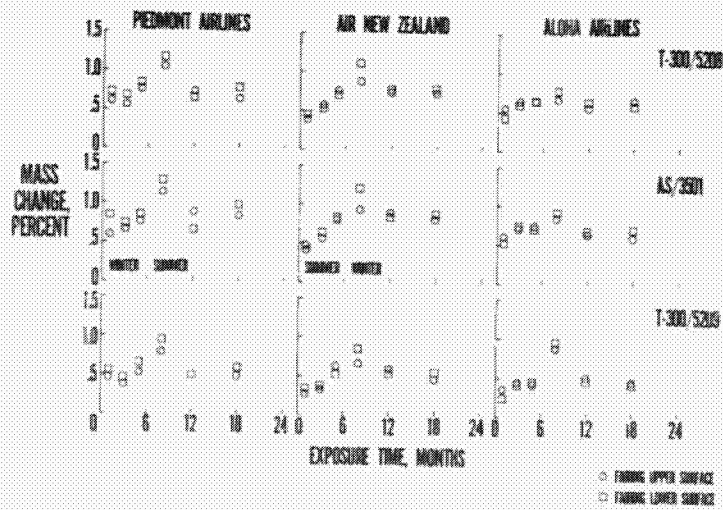


Figure 40. Composite mass change during flight exposure on Boeing 737.

1. Report No. NASA TM 80231	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle Composite Components on Commercial Aircraft		5. Report Date March 1980	
		6. Performing Organization Code	
7. Author(s) H. Benson Dexter		8. Performing Organization Report No.	
9. Performing Organization Name and Address NASA Langley Research Center Hampton, VA 23665		10. Work Unit No. 505-33-43	
		11. Contract or Grant No.	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546		13. Type of Report and Period Covered Technical Memorandum	
		14. Sponsoring Agency Code	
15. Supplementary Notes This paper will be presented at the AGARD Specialist Meeting on Effect of Service Environment on Composite Materials in Athens, Greece on April 13-18, 1980.			
16. Abstract <p>The technology development of advanced composite structures has progressed to the point where commercial aircraft manufacturers are making production commitments to composite structure for future aircraft and modifications to current production aircraft. NASA has been active in sponsoring flight service programs with advanced composites during the past 10 years. Approximately 2.5 million total composite component flight hours have been accumulated since 1970 on both commercial transports and helicopters. Design concepts with significant mass savings were developed, appropriate inspection and maintenance procedures were established, and satisfactory service was achieved for the various composite components. Also, a major NASA/U.S. industry technology program to reduce fuel consumption of commercial transport aircraft through the use of advanced composites has been undertaken. Ground and flight environmental effects on the composite materials used in the flight service programs supplement the flight service evaluation.</p> <p>Identification of commercial products in this report is to adequately describe the materials and does not constitute official endorsement, expressed or implied, of such products or manufacturers by the National Aeronautics and Space Administration.</p>			
17. Key Words (Suggested by Author(s)) Composite Materials Flight Service ACEE Program Environmental Effects		18. Distribution Statement Unclassified - Unlimited Subject Category 24	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 22	22. Price* \$4.00