MATERIAL AND PROCESS DEVELOPMENTS ON THE BOEING 767

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Abstract

The design goal of the 767 is an economic service life of 20 years with minimum unscheduled maintenance. Materials, material processing, and assembly methods employed on the 767 play a key role in the achievement of this design goal. Materials and processes also are key in maintaining weight within design limits for fuel efficiency. The 767 uses a wealth of new and improved materials, processing methods, and assembly techniques. Some of the innovations are subtle and involve minor changes to previous technology, such as the reduction of certain fastener head diameters. Others are more dramatic, such as the use of new aluminum alloys for wing skins or advanced composites for primary flight-control surfaces. Corrosion resistance is achieved through material selection, attention to design details, and proper finishing and sealing methods. For the most part, the materials selected for the passenger cabin interior are new and are selected for their flame resistance and lack of smoke and toxicant emission during combustion. A review of major structural and nonstructural material and process developments on the 767 will be summarized in this paper.

Introduction

The Boeing 767 is the first of a new generation of airliners designed for fuel efficiency. A medium-range, 211-passenger, wide-body transport, the 767 will save 35% or more of the fuel per passenger now used by the older, standard-body aircraft it will replace. The maiden flight of the 767 took place on September 26, 1981, and subsequent cruise performance evaluations have shown 767 fuel efficiency to be even better than the original predictions. The improvements in fuel efficiency are due to several technological advances: a new-technology wing, fuel-efficient power plants, flight management systems, and new materials. The latter are the subject of this paper.

The 767 challenge for the materials and processes engineer was to develop improved materials and processes that would provide the requisite durability at minimum weight or cost penalties. Fortunately, many of the developments for the 767 not only saved weight, but also had significant durability or cost benefits. These improvements are summarized in six general areas: improved aluminum alloys, titanium hydraulic tubing, fastening methods, corrosion protection, advanced composites, and new interior materials.

Improved Aluminum Alloys

Numerous industry and government programs sought to develop improved aluminum alloys in the 1960s. Efforts in this area by the Boeing Commercial Airplane Company focused on the development of improved 7000- and 2000-series aluminum alloys via composition modifications and thermomechanical treatments. The goals were to develop:

- A 7000-series alloy with an 11% improvement in compression yield strength
- A 2000-series alloy with an 8% improvement in tensile ultimate strength
- Improved fracture toughness and decreased fatigue crack growth rates commensurate with these strength improvements
- Corrosion resistance at least equal to that of the baseline materials (7075-T6 and 2024-T3)

The baseline alloys, 7075 and 2024, are the primary sheet, plate, and extrusion materials for most U.S. commercial and military jet aircraft. The improved, higher performance alloys were to use conventional ingot metallurgy and fabrication technology. Consequently, the extensive substitution of the improved alloys would lead to significant airframe weight reductions at minimum engineering or manufacturing risk.

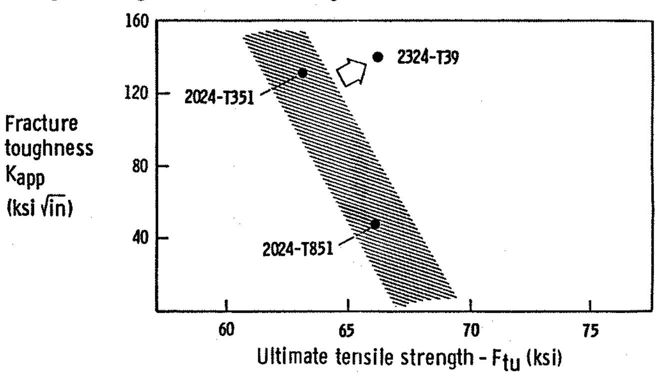


Figure 1. Strength Versus Fracture Toughness

The challenge in developing such new alloys is shown in Figure 1. Generally, increasing strength in an aluminum alloy occurs at a loss of fracture toughness and also fatigue resistance and/or corrosion resistance. The goal of this program was to increase strength, fracture toughness, and fatigue resistance at no loss in corrosion resistance (Figure 2). The developments required a several-year study and a major scale-up program. At the time the improved aluminum alloys were committed to the 767, over one million pounds of metal had been melted and several thousand coupons tested. In fact, a 200-inch-long panel representing a wing lower surface, complete with access holes and panel splices, was built and fatigue tested. The results demonstrated conclusively that the improved alloy was stronger and more fatigue resistant than the baseline alloy and possessed the required fracture properties. Other testing included compression panels (which represent the wing upper surface) and over 5000 corrosion tests performed at 5 different laboratories. Manufacturing verification testing demonstrated that the alloys could be processed by conventional practices.

- Strength
  - Upper surface materials - 11% improvement over 7075-T6
  - Lower surface materials - 8% improvement over 2024-T3
- Fatigue
- Fracture

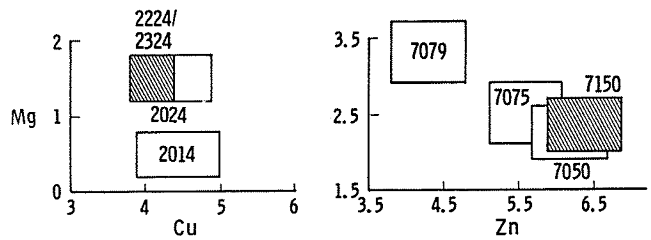
  Commensurate improvement with strength
- Corrosion
- Stress corrosion
- Fabrication

  Equivalent to baseline materials

Figure 2. Improved Aluminum Alloy Goals

7000-Series Alloys

Early Boeing studies discovered that much of the fracture toughness variation of certain 7000-series alloys is due to composition. Particularly significant are the amounts of the tramp elements, iron and silicon. Later studies with experimental alloys found that fatigue and fatigue crack growth properties could be improved by increasing the copper content. Finally, the zinc-to-magnesium ratio was found to influence both fracture toughness and ultimate strength. These studies culminated in the development of 7150 alloy for plate and extrusion applications.



- 70-80% reduction in impurities (Fe/Si)

Figure 3. Improved Aluminum Alloy Compositions

The chemistry of 7150 is compared with that of some other aircraft structural 7000-series alloys in Figure 3. The property improvements are detailed in Figure 4. The strength goals were met or exceeded. Fracture toughness and fatigue testing demonstrated that 7150-T6 possesses fracture characteristics and fatigue performance better than that of 7075-T6, even when 7150 is loaded to an 11% higher stress level. Alloy 7150 is the same as 7075 in stress-corrosion resistance, while both 7075 and 7150 are significantly superior to 7079, an alloy with a relatively poor and unacceptable stress-corrosion resistance, as shown in Figure 5.

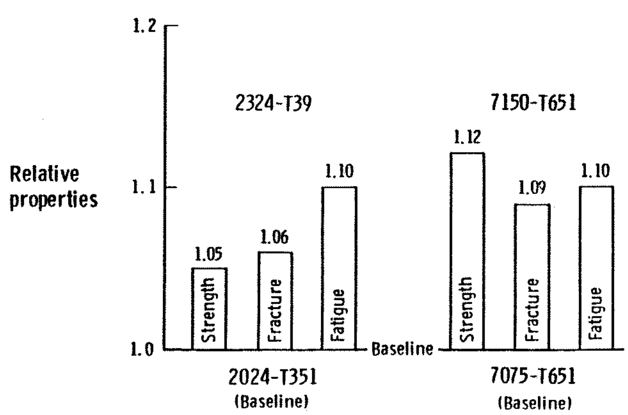


Figure 4. Property Improvements

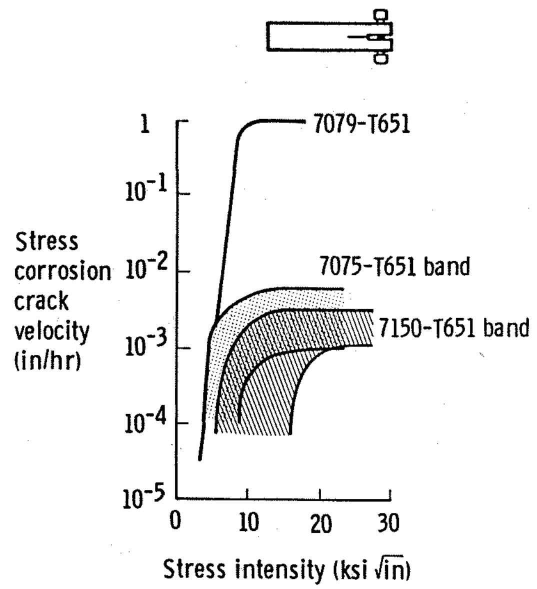


Figure 5. Stress-Corrosion Resistance

2000-Series Alloy

The 2000-series alloy required an entirely different approach. Early work showed that controlling the chemistry to the low copper side of 2024 improved fracture and fatigue properties. Alloy purity was also a factor, and stringent iron and silicon controls were imposed. To increase the alloy strength, a significant degree of cold working was needed. As is well known, cold working, while increasing strength, decreases fracture toughness, and a balance between alloy chemistry and cold working was required to achieve the program goal.

The final chemistry is shown in Figure 3. As can be seen, the alloy has essentially the same composition as 2024, but with tighter control of the alloying and residual constituents. The extrusion alloy 2224 has slightly less stringent impurity controls than the plate alloy 2324, but the alloys are chemically identical in all other respects. Alloy 2224 relies on processing to control recrystallization rather than cold working for added strength.

Final property values are shown in Figure 4. The program goal of an 8% improvement in tensile ultimate strength could be met easily through large degrees of cold working. However, to balance the alloy with the proper level of fracture toughness, less cold working and a slightly lower tensile strength were accepted.

The applications of the improved aluminum alloys to the 767 are shown in Figure 6. The improved aluminum alloys saved 650 pounds of structural weight on the 767.

Titanium Hydraulic Tubing

Titanium hydraulic tubing has been used in military aircraft such as the F-14 for many years. Boeing originally qualified this tubing for the SST program, and the tubing has been verified and made ready for subsonic commercial aircraft application. The use of cold-worked, stress-relieved (CWSR) Ti-3Al-2.5V in the high-pressure hydraulic lines of the 767, along with the associated fittings, will save 250 pounds and provide the airline customer with hydraulic tubing that is inherently corrosion resistant.

Fasteners

Several new concepts in fasteners were developed specifically for, or have been incorporated into, the design and manufacture of the 767. Chief among the new assembly processes is the Automatic Spar Assembly Tool (ASAT), while the chief material development is the 7050-T73 rivet alloy. New rivet geometries are employed also.

ASAT

Boeing has used automatic riveting machines for wing assembly since the beginning of the 727 program. Automatic riveting is very economical and provides an installation with reliable fatigue quality. With this in mind, Manufacturing Research developed a semiautomatic spar assembly tool for the 767 (Figure 7). The new computer-controlled machine takes just 8 seconds to drill a hole, insert and drive the fastener, and move to the next position. The fasteners are usually the slug type, typical of those used on the Drivmatic machines for assembly of wing skin-stiffener assemblies. Slug rivets of 7050 alloy are installed by the ASAT.

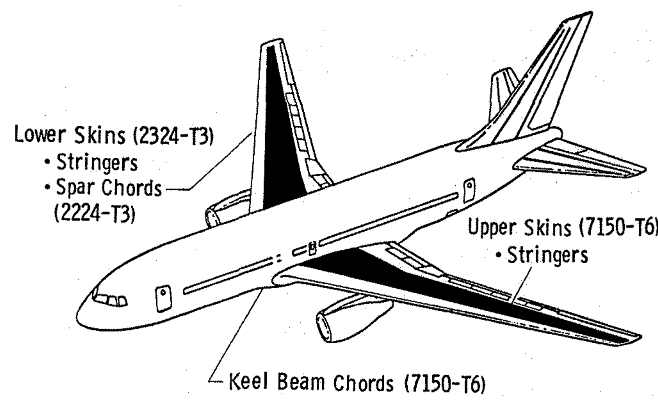


Figure 6. New Aluminum Alloy Applications

7050-T73 Rivets

Alloy 7050 is an aluminum alloy similar in composition to 7150, the improved aluminum alloy used on the 767 upper wing surface. Alloy 7050-T73 is resistant to stress corrosion and exfoliation corrosion. As a rivet alloy, it is stronger than either 2017 or 2117 and does not require the cold storage facilities of 2024 "ice-box" rivets. Superseding 2024 and 2017, 7050 rivets are very malleable and cracks in rivet buttons are rare. As a result, rejections and rework are greatly reduced. The 7050 rivets are used throughout the 767, in wing, fuselage, and empennage applications.

Briles Rivet

The Briles rivet is used extensively in the 767 fuselage. A new design, the rivet provides a unique interference fit that enhances fatigue properties in thin metal sheet structure. With conventional flush-head aluminum rivets, metal sheet gages are limited by the "knife-edge" effect that occurs when the countersink penetrates one of the metal skins. Thus, for a given shank diameter, a minimum skin gage is maintained to avoid "knife-edging" and its consequent fatigue reduction. The Briles rivet uses a 120-degree countersink (as opposed to the conventional 100-degree countersink) and a different head geometry, thus preventing "knife-edging" until thinner gages are encountered. The Briles rivets have been used on the F-18, but this is the first time they have been used in the production of a commercial aircraft or

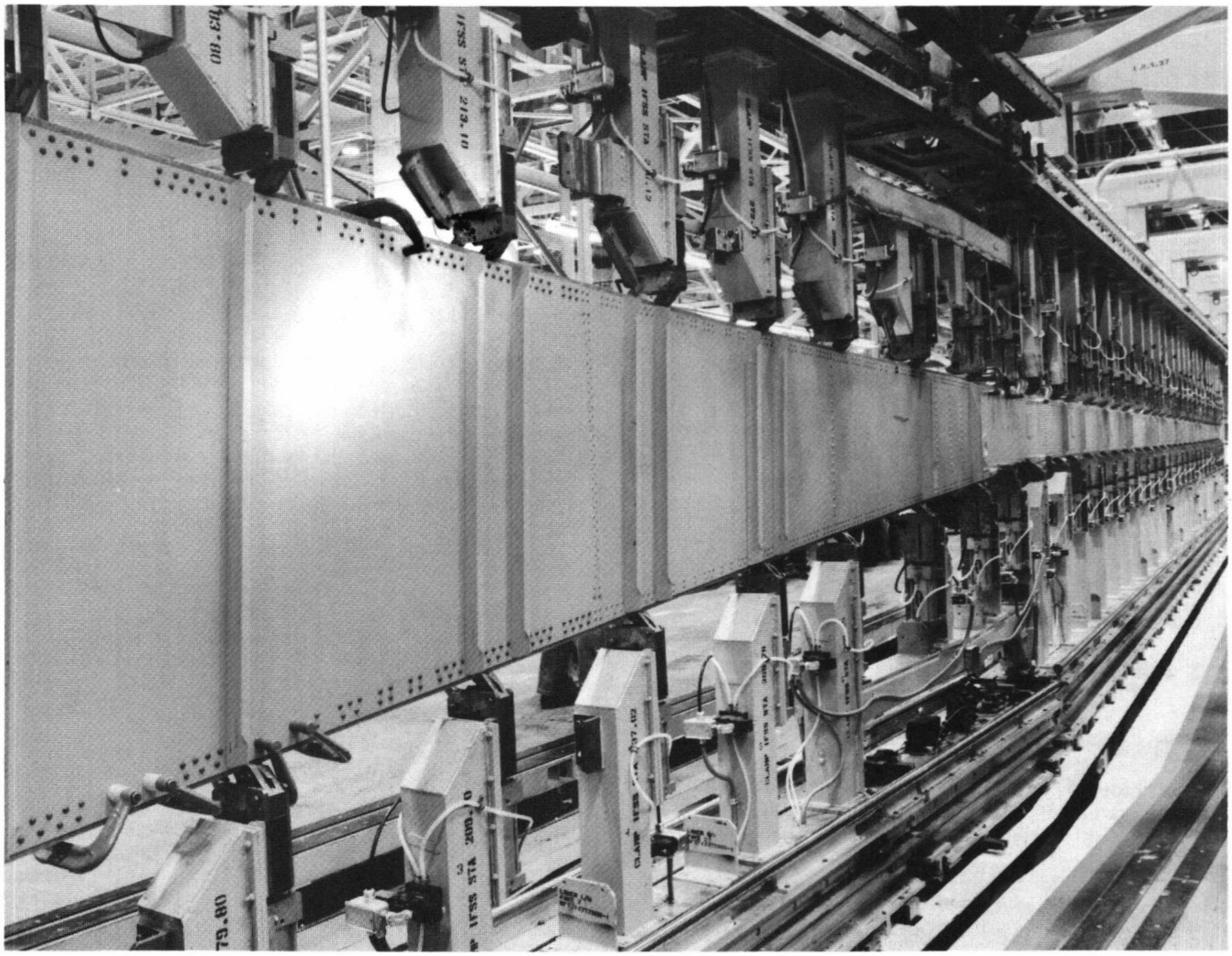


Figure 7. Automatic Spar Assembly Tool

been fabricated of 7050 alloy. The benefit of using thinner gage metal at the fastening attachments means about 250 pounds of weight savings on the 767.

The Briles rivets possess an added advantage directly attributable to their interference fit. The rivets are essentially leak tight. In fact, after fatigue cycling a fuselage panel for 50,000 flights, the Briles rivets easily met the stringent leakage criteria applied to fuel-tank rivets. The Briles rivet configuration is shown in Figure 8.

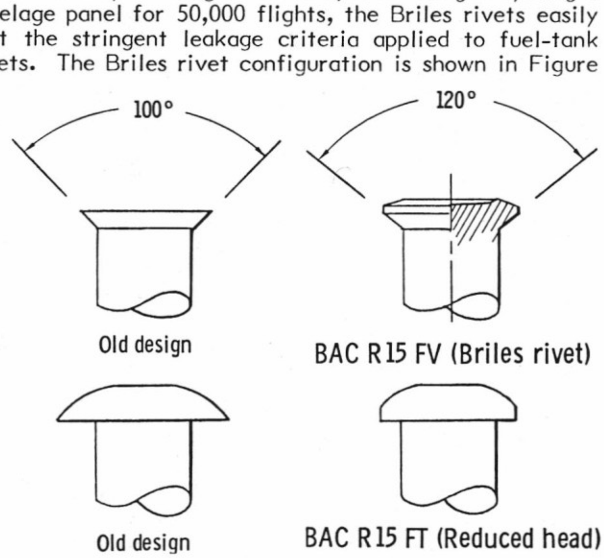


Figure 8. New Rivet Configurations

Reduced-Head Rivets

The standard universal-head rivet has been used in aircraft construction for approximately 50 years. An early compromise in design between the button-head rivet, commonly used in the construction industry, and aerodynamic requirements, the universal-head rivet has a large-diameter head. A reduced-head-diameter rivet (Figure 8) offers several benefits, including:

- Closer fastener spacing
- Decreased geometric interference on contoured parts
- Easier manufacture, especially for automatic equipment
- Weight savings

The reduced-head rivet has been successfully incorporated into the 767 and is used extensively in the fuselage. The weight savings are estimated to be approximately 50 pounds.

Corrosion Protection

The International Air Transport Association (IATA) estimated that corrosion cost its member airlines approximately \$100 million in 1976. Clearly, corrosion control must be one of the major objectives of any new airplane program. Corrosion protection of the 767 structure began very early in the design phase. Significant improvements in the state-of-the-art were realized. The lessons learned from a 3000-aircraft fleet were examined in detail (Figure 9), and service-proven corrosion-control methods were established and documented. New techniques were developed and implemented only after careful review and thorough testing. Structural design for corrosion protection was reduced to practice through the use of color-coded corrosion-control design handbooks. These set the rules for finishing and assembly of aircraft parts being designed in Europe, North America, and Japan. Some selected highlights are discussed below.

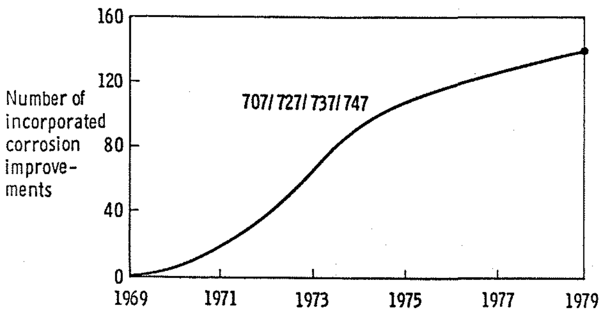


Figure 9. Corrosion Control Improvements

Materials

Corrosion control begins with proper material selection. Corrosion-resistant aluminum alloys with proven service performance were selected for the 767. For example, the baseline forging alloy is 7075-T73. Corrosion-prone materials, such as 7079 or cold bonding, were prohibited. Corrosion-free materials or constructions, such as fiberglass floor panels, were incorporated into the basic design. A key contributor to improved corrosion control is the use of the service-proven phosphoric acid anodizing system for high-durability adhesive bonds. This improvement is described in detail in paper ICAS-82-2.2.3, "Aluminum Bonding for Durable Structures."

Finishes

All aluminum details are anodized if bare and alodined or anodized if clad. Additionally, all aluminum details, except leading edges and fuselage exterior skins, are primed in detail. Wing details are given a slight bake after priming. All details, including fasteners, are touched-up after assembly. The wing tank bottoms, the vertical fin, and the horizontal tail are given a second coat of primer after assembly. All details below the passenger cabin floor are enameled before and touched-up after assembly. Exposed wing, fin, stabilizer, and wheel-well areas are enameled and sealed.

High-strength, low-alloy (HSLA) steel parts are cadmium or cadmium-titanium coated, depending on their heat treatment. HSLA steel parts are primed and exterior parts are enameled.

Sealing

Extensive sealing is accomplished during assembly. All permanent, nonaluminum fasteners penetrating the fuselage or wing are sealed, as are many others in corrosion-critical areas such as the wheel wells. All details contacting the wing or lower fuselage exterior skin are sealed, as are mating surfaces of dissimilar metals. An organic corrosion inhibitor is applied after assembly to the fuselage lower zones; wing and empennage exposed cavities; wheel-well areas; and around and under galleys, lavatories, and battery compartments.

Design

Design improvments to minimize corrosion include stringer drainage, an improved leveling compound, a redesigned bilge drain valve less prone to plugging, the use of titanium and fiberglass for selected structure under galleys and lavatories, sealed floors in the galley area with gutters and overboard drains, an all-new lavatory design that will be virtually leak-proof in service, and a scupper system designed to remove water from the low point of the wing tanks.

Drainage

Lastly, the 767 is designed for drainage and the design was verified by a full-scale test on an airframe. Each hat-section stringer in the fuselage is vented to permit passage of fluids. Gutters are placed around galleys to carry away spilled fluids. Air spaces are designed under the lavatory and galley so that fluids will not "wick" between the faying surfaces. New drain valves have been designed and are located along BBL 0. The vacuum-operated lavatory will not leak even with a large hole in the drain pipe. These and other concepts are aimed at preventing fluids from accumulating.

Advanced Composites

The use of fiber-reinforced plastics has increased gradually with the introduction of each successive Boeing aircraft model (Figure 10). The 767 continues this general trend, with the added feature that advanced fibers--Kevlar and graphite--are employed for the first time in initial design. These advanced composites are being used in place of aluminum in several secondary structures of the 767 and in place of fiberglass in over 100 fairing panels. The use of composites has saved over 1250 pounds of structural weight on the 767 and significantly contributes to fuel efficiency.

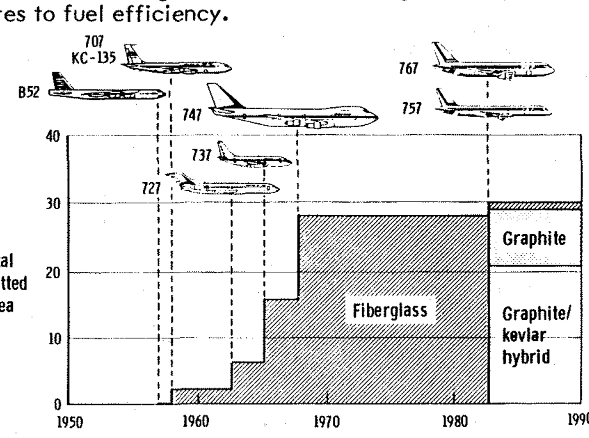


Figure 10. Composite Material Usage Trends

Graphite-fiber-reinforced epoxy resins are used for most of the 767 control surfaces, including the spoilers, ailerons, elevator, and rudder. In fact, the 767 rudder (Figure 11) is one of the largest graphite/epoxy structures ever fabricated, being over 400 inches long at the front spar. These structures not only save weight, but promise improved durability, freedom from corrosion, and trouble-free service as well. Several other graphite applications have been incorporated into the aircraft interior, including several ceiling support channels, torque tubes, and filament-wound bottles for lavatory waste-holding tanks.

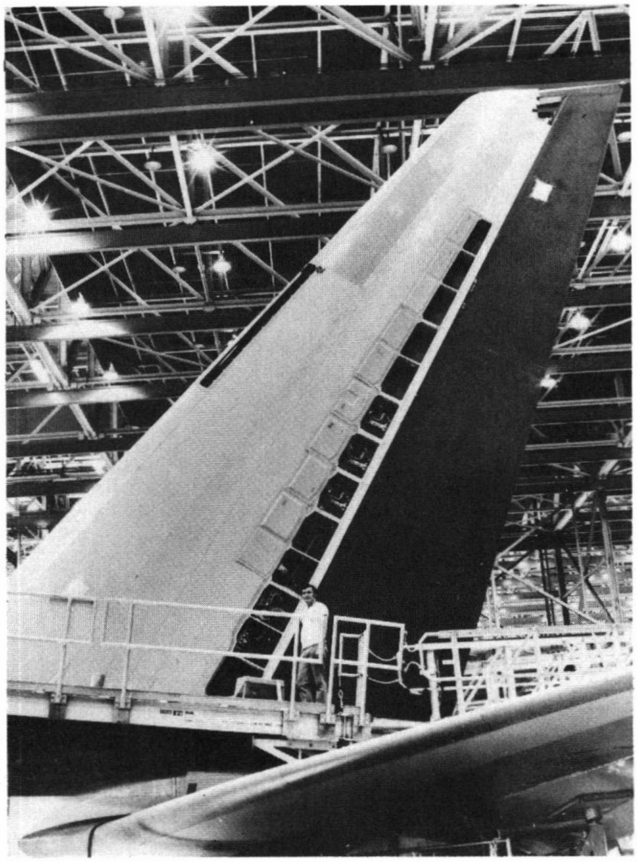


Figure 11. 767 Rudder

Kevlar/graphite assemblies are employed for the cowl panels of the 767 nacelle. The six panels save one-third the weight of traditional all-metal cowlings. Other Kevlar/graphite or "hybrid" applications include the wing-body fairings, wing and empennage fixed trailing-edge fairings, and main landing gear doors. The nose landing gear doors are hybrids of glass and graphite, manufactured using a process originally developed for similarly designed all-glass components on the 737. Composite applications on the 767 are shown in Figure 12.

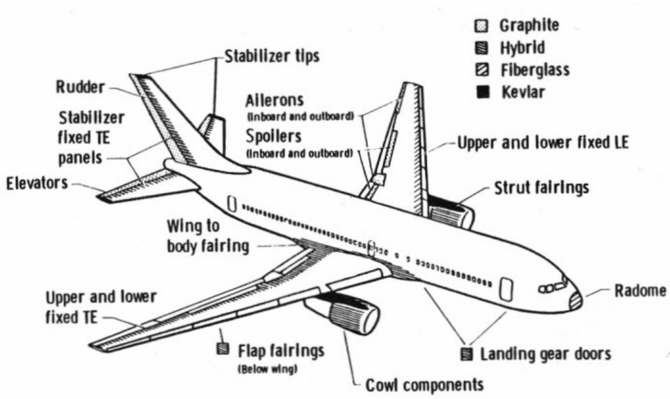


Figure 12. 767 Composite Applications

Interior Materials

Significant advances have been made in the development of improved materials used in the cabin and cargo compartments of the 767. These improvements were made without sacrificing key customer requirements such as durability and maintainability. Most of the visible components of the cabin interior (Figure 13), as well as many "behind the scene" parts, are fabricated from materials that are lighter than those used in commercial aircraft today. In addition, the fire safety of the 767 cabin and cargo compartments has been enhanced through the use of materials that produce substantially decreased amounts of smoke and noxious gases. The technical challenge was to decrease flammability and smoke and toxic gas emissions (Figure 14).

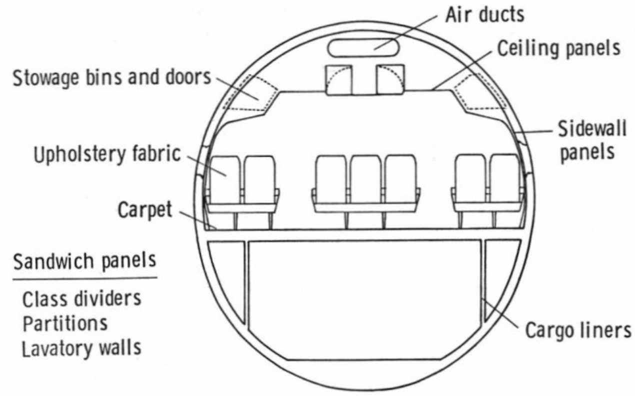


Figure 13. New Interior Materials

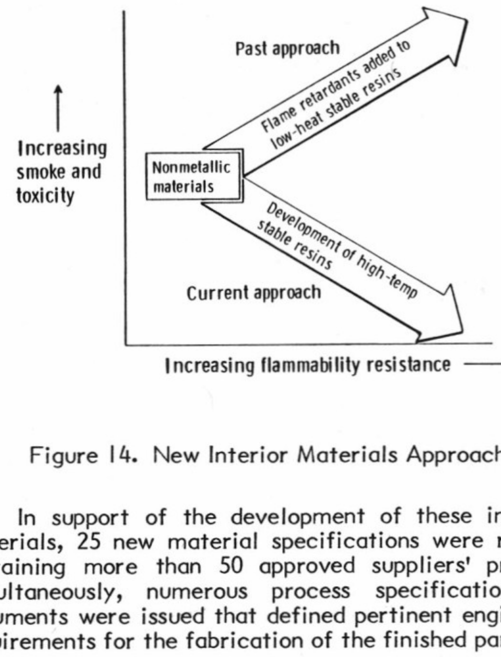


Figure 14. New Interior Materials Approach

In support of the development of these improved materials, 25 new material specifications were released containing more than 50 approved suppliers' products. Simultaneously, numerous process specifications and documents were issued that defined pertinent engineering requirements for the fabrication of the finished parts.

All of the sidewall and ceiling panels are fabricated from low-smoke phenolic/fiberglass prepregs using the crushed-core process. These decorative panels produce significantly less smoke than their counterparts using epoxy-based prepregs. In addition, the crushed-core panels are lightweight and offer some unique design features.

Substantial weight has been saved through the use of Kevlar reinforcement in the production of decorative sandwich panels having little or no contour (partitions, stowage bins, closets, etc.). In addition, Kevlar is used in reinforced cargo liners in the cargo compartment and for low-temperature air ducting, potable water tanks, and flight-deck drip shields.

Improved textiles for drapery, upholstery, and carpet applications have been developed that have reduced weight and upgraded flammability properties. A fire-retardant treatment for wool that also suppresses smoke production, developed by the International Wool Secretariat, has been adopted. Redesign of carpet construction has allowed a weight reduction of almost 1 pound per square yard, and refined upholstery construction has allowed a weight reduction of approximately 4 ounces per square yard; together, these represent a weight reduction of over 200 pounds per airplane.

Summary

The primary reason for developing improved aircraft structural materials is increased structural efficiency, which equates to reduced structural weight. In a given design, weight is directly related to fuel burn and cost of operation. Figure 15 shows an example of direct operating cost elements for a 747-type airplane. The 1973 chart shows the distribution of these cost elements before the first fuel crisis in 1973. Fuel costs at that time were around \$0.12 per gallon, and fuel as an operating cost element contributed only 21%. In 1980, following a dramatic rise in fuel prices, fuel cost was approximately \$1.00 per gallon and contributed about 55% of the direct operating costs. The prediction for the future is that fuel prices will continue to rise. Increased usage of lighter, stronger materials also can be predicted as efforts to control direct operating costs continue. Lighter, more efficient airplanes that require significantly less fuel will help the airline operator maintain profitability. Use of improved materials saved over 3000 pounds in the 767 aircraft (Figure 16) and helped make it the most fuel-efficient jet aircraft in its class.

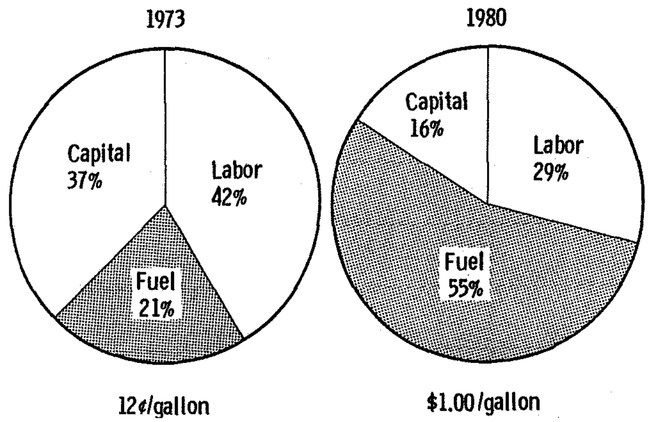


Figure 15. Direct Operating Cost Elements

ACCOMPLISHMENTS	BENEFITS: WEIGHT SAVING (lb)	BENEFITS: OTHER
IMPROVED ALUMINUM ALLOYS	650	---
IMPROVED TITANIUM ALLOYS	250	---
NEW RIVET CONCEPTS	300	---
ADVANCED COMPOSITES	1250	---
IMPROVED INTERIORS	~ 600	IMPROVED SAFETY
	3050	

Figure 16. Materials Technology Advantages for the 767