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THE NEXT GENERATION OF COMMERCIAL AIRCRAFT— THE TECHNOLOGICAL IMPERATIVE

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The Next Generation of Commercial Aircraft
The Technological Imperative

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ABSTRACT

Past, present, and prospective future technological advancements that particularly affect aircraft manufacturers are discussed, focusing particularly on that technology which will improve fuel efficiency and aerodynamic efficiency of current and future aircraft. An overview of the fuel situation and aircraft productivity is presented, and, then, implications of each potential advancement—such as new composite materials, active controls, laminar flow, and propulsion—are explored to reveal their relative contributions, drawbacks, or applicability. The significant improvements in fuel burn resulting from the new advanced-technology aircraft, the 757 and 767, will subsequently provide airlines with substantial savings in a dwindling resource—oil and jet fuel—as well as operating costs.

INTRODUCTION

During the 1970s, a new series of airplanes emerged into the world's commercial fleets to meet the demands of a growing air transportation system and the constraints of its operating environment. Their evolution is still taking place. The purpose of this paper is to examine the commercial airplanes that will be available over the next two decades, the new imperatives that are influencing their design, and the aid they will offer to the air transportation system.

"The Technological Imperative" begins with an overview of the air transportation system and then examines the economic factors influencing transport aircraft return on investment and productivity from a user's point of view as well as that of the manufacturer's.

Next, the airlines' ongoing procedures and practices that help reduce fuel consumption and control fleet operating costs are discussed. As we will note, these conservation measures are key to the survival of the airlines in their current economic environment.

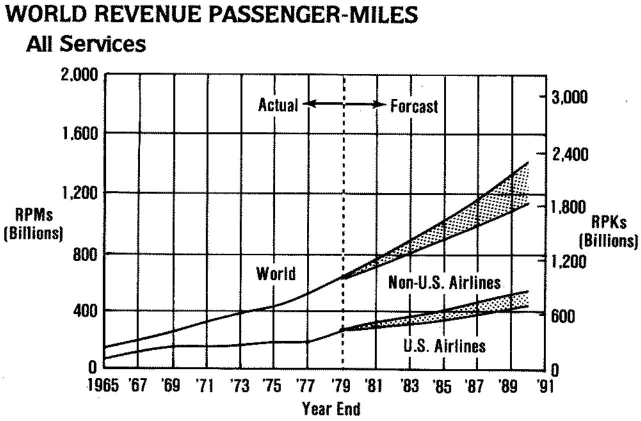
The aircraft industry's contributions to the current environment are also addressed, in terms of current product growth and improvement.

Next, the significant technological advancements that culminated during the 1970s are highlighted. How these advancements have been specifically incorporated into the design of two new-generation transport aircraft—the Boeing 757 and 767—is discussed.

Finally, future technical advances are considered, with each area—avionics, aerodynamics, structural materials, propulsion, and alternate fuels—explored. The relative merits of each advancement are discussed individually, and potential concepts are applied to an integrated design with an estimate of fuel savings.

AIR TRANSPORTATION SYSTEM OUTLOOK

A fundamental measure of passenger growth in the air transportation system is revenue passenger-miles; Figure 1 shows both historical and estimated RPMs for the world. It is notable that there hasn't been a negative-growth year since 1965 and none predicted through 1990—a span of 25 years. The system will double in size during the decade of the 1980s and, although the U.S. is still almost one-half the market, the U.S. rate of increase is smaller, while the rest of the world increases faster year by year.

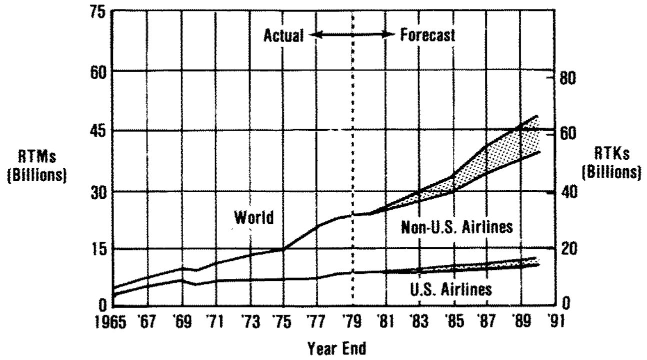

WORLD REVENUE PASSENGER-MILES
All Services

Note: Excludes U.S.S.R., People's Republic of China, and non-ICAO nations, but includes Taiwan and all-charter carriers

Fig. 1

The air freight system is also growing rapidly, particularly the international market. The last 5 years recorded a revenue ton-mile growth of 9% per year (figure 2). The next 10 years are predicted to grow at an annual rate of approximately 7%. Stimulative marketing actions by the airlines—such as wider use of shipper-loaded containers, intermodal system growth, and greater emphasis on creative air freight selling—could increase the growth rate over that predicted. However, it must be pointed out that predictions made for the past 10 years of an imminent explosion in the cargo market have yet to come true.

WORLD REVENUE FREIGHT TON-MILES
All Services



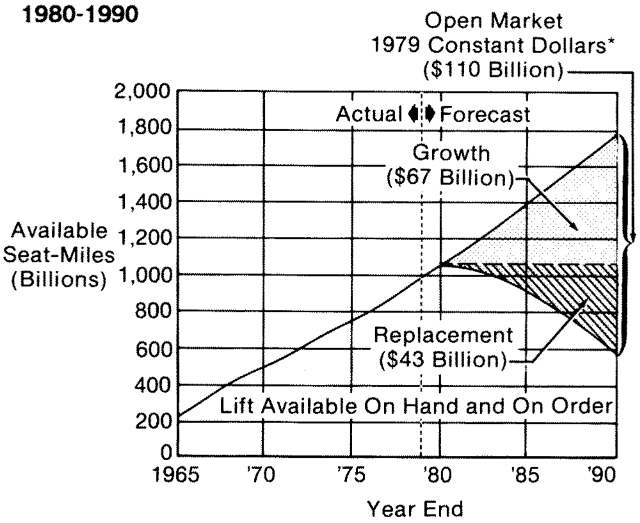
Note: Excludes U.S.S.R., People's Republic of China, and non-ICAO nations, but include Taiwan and all-charter carriers.

Fig. 2

This growth in traffic plus the necessary replacement of older, smaller airplanes represents a very substantial market for aircraft for the airframe and engine manufacturers in the next 10 years.

The total open market in terms of 1979 dollars is shown in figure 3 to be $110 billion by 1990. The replacement market represents about 40% of the total.

WORLD OPEN-LIFT REQUIREMENTS
1980-1990



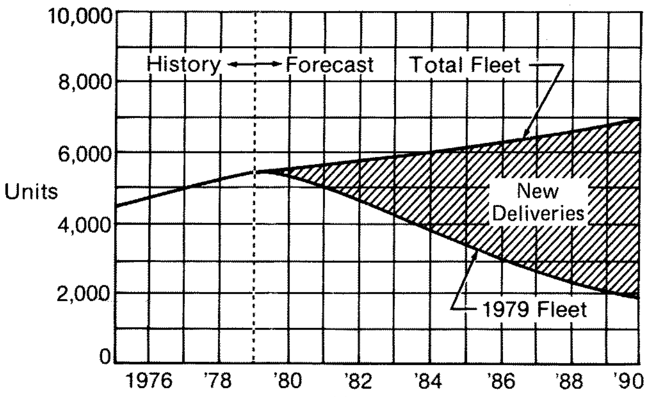
Note: Does not include U.S.S.R.-built jets
*Includes $4 billion freight market.

Fig. 3

Assuming the current operational trends and retirement schedules continue, it is possible to predict the composition of the world airline fleet in future years. The two- and three-engine standard-body category includes the 727, DC-9, 737, BAC-111, Caravelle, Trident, F-28, Mercure, and 757; the four-engine standard bodies are the 707, VC-10, and DC-8 ; the two-engine wide bodies are the A300, A310, and 767; and three- and four-engine wide bodies are the DC-10, L-1011, and 747.

The December 31, 1979 world fleet consisted of 3,436 two- and three-engine standard bodies, 1,136 four-engine standard bodies, 80 two-engine wide bodies, and 849 three- and four-engine wide bodies, for a total of 5,501 airplanes. Figure 4 forecasts the total world commercial fleet (excluding U.S.S.R.) to 1990. The current 1979 fleet, which is composed of better than 80% standard-body aircraft, is predicted to drop to about 55% standard bodies by 1990. Replacing these older aircraft with new fuel-efficient transports as expeditiously as possible will have great impact on long-term overall fuel conservation.

WORLD* COMMERCIAL JET AIRLINE REQUIREMENTS
Includes Freighters



*Excludes U.S.S.R.-built jets

Fig. 4

THE NEW IMPERATIVES

FUEL EFFICIENCY, RETURN ON INVESTMENT, AND AIRCRAFT PRODUCTIVITY

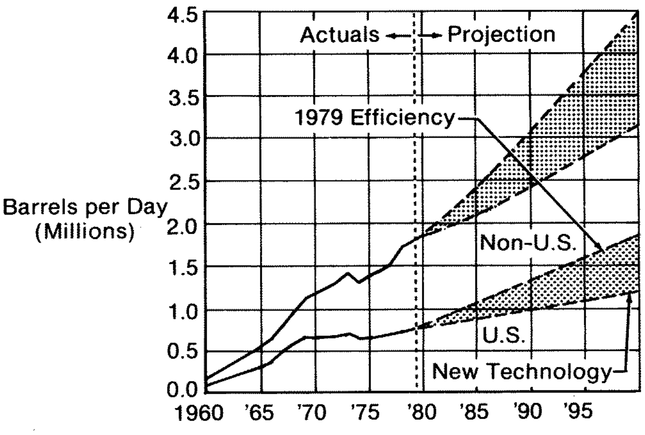
With proper maintenance, most of the commercial airplanes manufactured over the last two decades could fly indefinitely into the future. In a few cases, the smallness of a particular model's fleet has resulted in its disappearance; "wear out" has generally not been the cause. Why, therefore, contemplate new aircraft?

The reason is that a new set of imperatives emerged which caused a rethinking of technology and the serious consideration of developing a new generation of aircraft for service in the 1980s and beyond.

FUEL EFFICIENCY

Recent OPEC announcements to the world concerning the supply and price of their petroleum have served to reinforce fuel conservation policies for oil-importing nations. Ultimately, the United States' objective is to substantially reduce or eliminate its dependence on imported oil. Jet fuel consumption—without a conservation program—is projected to nearly double by 1990 (figure 5). But if the methods for improving fuel efficiency to be discussed here are put into effect, about one-half million barrels of jet fuel per day (or 15% of total jet fuel consumption) can be saved by 1990.

WORLD* AIR CARRIER JET FUEL CONSUMPTION

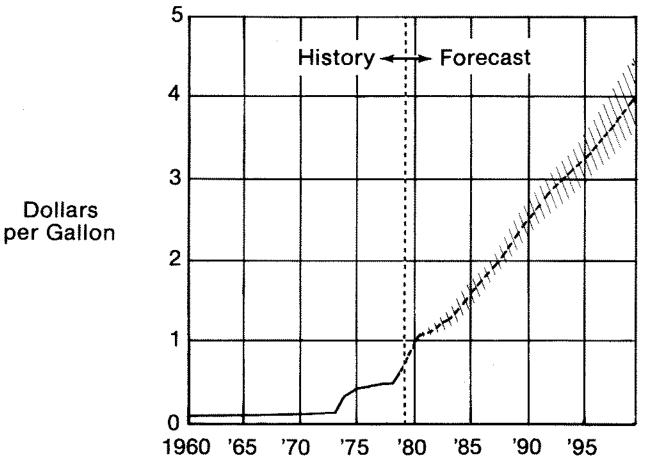


*Excludes U.S.S.R. and PRC

Fig. 5

At this time, only 4% of crude oil consumed by the U.S. is refined into commercial jet fuel. But airlines must increasingly compete for their portion of middle distillates with other important consumers, especially domestic heating oil and diesel fuel (trucks, buses, farm tractors). Furthermore, this competition and other factors will generate upward price trends at an inordinate rate as supply is constrained (figure 6).

WORLD JET FUEL PRICE



Sources: U.S. CAB; BCAC.

Fig. 6

As we know, fuel costs have doubled their portion of the airlines' direct operating costs over the past 5 years. Projecting to 1990 (figure 7), fuel could account for over 60% of the direct operating costs of an airline using current state-of-the-art aircraft. Ten years ago, fuel was less than 25% of operating costs. Therefore, the current focus on world petroleum demand and supply is accelerating the development of technology that will improve fuel efficiency in transport airplanes—much as World War II accelerated the improvement in military aircraft performance.

DIRECT OPERATING COSTS
U.S. Domestic Trunks

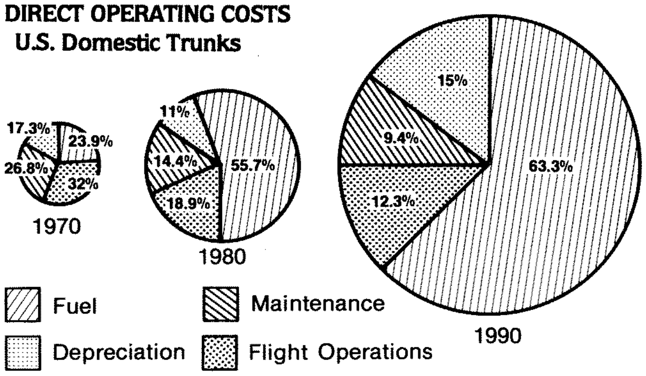


Fig. 7

AIRLINE AND MANUFACTURER RETURN ON INVESTMENT (ROI)

Rising fuel prices have caused both the manufacturer and his customer to take a new look at the imperative for a return on investment.

Industry advancements in aircraft technology are premised on economic returns and the availability of investment capital. ROI becomes particularly important when manufacturer and customer must decide to commit to a new aircraft because of the large requirement for capital and the risks of return. It is not unexpected for the manufacturer to produce an airplane for 10 to 15 years before breaking even on initial investment.

The opportunity for profit lies in maintaining a competitive edge throughout a long production program. Competition stimulates the incorporation of continuous product advances and the initiation of major derivatives, both of which require sizable reinvestments throughout the program life. The reinvestments for a successful commercial program may in fact approximate the initial nonrecurring cost for development. The commercial aircraft manufacturers' profit challenge is illustrated in figure 8.

INVESTMENT, RECOVERY, PROFIT
Typical Commercial Program

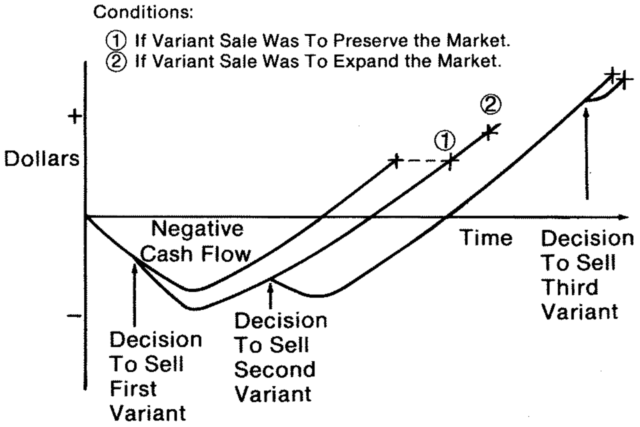
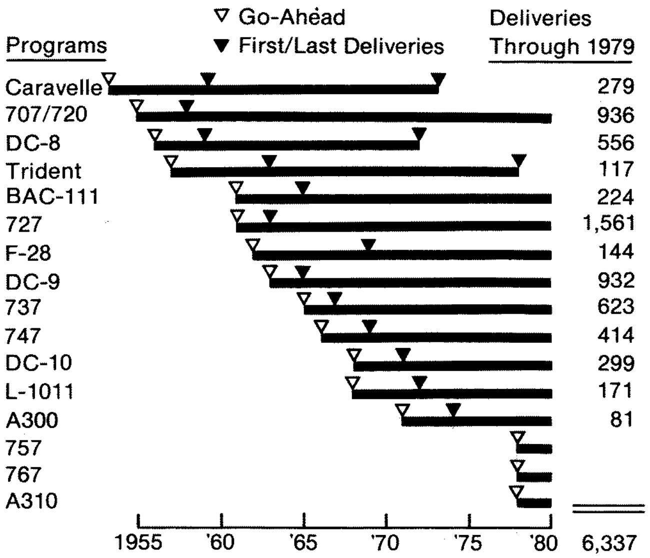


Fig. 8

Market timing is frequently a critical factor in aircraft competitions. The manufacturer needs to maintain a continuous offering of product options and very large internal expenditures for advanced research and development on new items. Existing products must be able to incorporate additional or new technology to successfully compete against an entirely new airplane or production will terminate.

The ability of the manufacturer to insert selected product improvements and options into his production line while maintaining the basic line's efficiency is vital to achieving either breakeven or profit on a commercial program. Figure 9 illustrates the major commercial programs launched over the past two and a half decades. The average is about one new airplane program introduced every 18 months, except for the new programs, a pace indicative of the market demand and airline growth. The gap between the A300 and the new programs start-up is considered a reflection of the economic uncertainties that prevailed in the mid-1970s. The inherent business risk is underscored by the fact that only a few of the past and mature programs have actually returned a profit on their enormous investments.

MAJOR COMMERCIAL JET TRANSPORT PROGRAMS



Excludes Comet and Concorde

Fig. 9

PRODUCTIVITY

Historically, the escalating costs of developing a new generation of airliners have been justified by the higher productivity of the new equipment. For instance, after World War II, commercial aircraft design and development accelerated when the major competition came from trains and buses. The airlines had to overcome the public's fear of flight (less than 1/2% had ever been in an airplane) by offering attractive ticket prices, more frequencies to more places, and greater comfort (pressurization, higher altitudes, smoother flights). Each new aircraft led to an improvement in flight efficiency and capacity, which resulted in greater productivity (figure 10). Contrary to popular opinion of the time, the introduction of the jet aircraft produced lower seat-mile costs than turboprops because of speed, lower maintenance costs per seat, lower costs, and a large increase in seats.

RELATIVE DIRECT OPERATING COSTS (1977 Dollars)

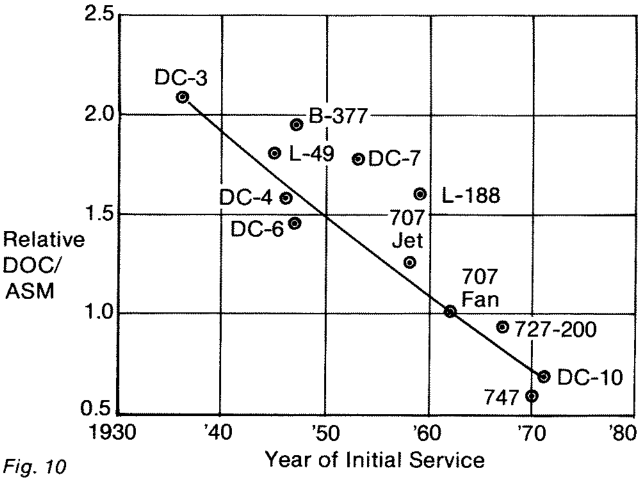


Fig. 10

If the average number of seats per aircraft is computed as the ratio of available seat-miles to revenue airplane-miles flown, then the average is 150 for the U.S. domestic fleet (figure 11). The growth in average seats has been markedly linear for over 30 years at a rate of 4.3 seats per year. With the advent of the jets, this growth rate increased due to increased productivity and their initial use on longer transcontinental routes where they produced a disproportionate amount of ASMs. As smaller jets were introduced, the growth rate returned to its long-term value. Even the introduction of wide-body transports did not impact the growth pattern nor will the introduction of the A310, Boeing 767, or 757, according to Boeing studies. Thus, the average number of seats will grow to above 200 per aircraft by 1990, will further improve productivity, and tend to reduce fuel burn per seat.

GROWTH IN AVERAGE NUMBER OF SEATS U.S. Trunk Carriers, Domestic Operations

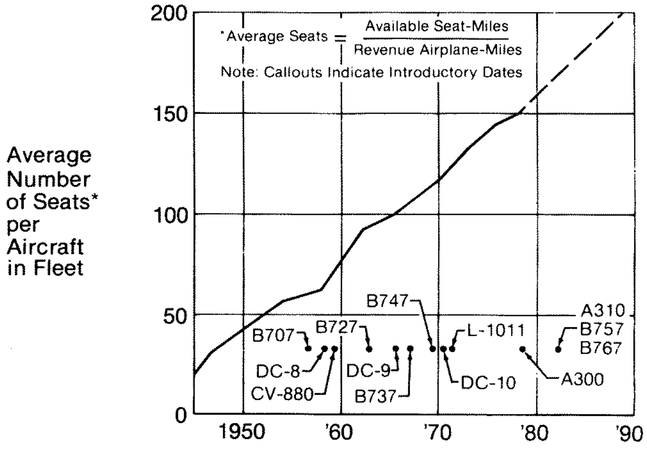


Fig. 11

AIRLINE OPERATIONS EFFICIENCY MEASURES

According to the Air Transport Association of America, soaring fuel costs in 1979 were a major contribution in offseting a 12% traffic gain and leading to an $800 million decline in airline earnings—in spite of an increased fuel efficiency of 43% since 1973. Since fuel efficiency measures of 43% cannot match fuel price increases of 667%, the airlines must take aggressive action to combat profit erosion.

An example of potential items for airline fuel conservation appear in Table 1 with trip fuel savings for a Boeing 727-200. This summary of Boeing-recommended procedures has been published in Boeing's "Airliner" magazine for all Boeing airplanes since 1974.

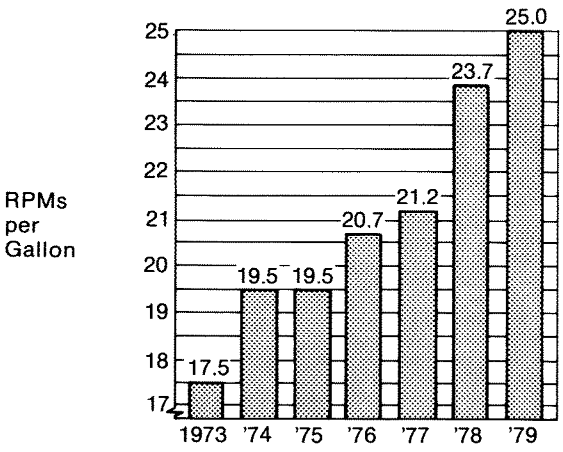
SUMMARY OF FUEL CONSERVATION ITEMS FOR A 727-200

Items Affecting Minimum Fuel Burn	Impact on Trip Fuel
Cruise Speed Reduction	
From Minimum Cost Cruise	1% to 2%
From High-Speed Schedule	2% to 8%
Optimum Altitude	0% to 4% Within 4,000 Ft of Optimum 2% to 12% for 4,000 to 8,000 Ft Below Optimum
Optimum Climb Schedule (Lb)	0 to 300
Optimum Descent Schedule (Lb)	200
Landing Weight Reduction (per 1,000 Lb)	0.47%
One Stop vs. Nonstop	—
Engine Idle Fuel Flow (Lb/Min)	60
APU Fuel Flow (Lb/Min)	5
Reduced Climb Thrust Penalty	—
Cruise Control	1% to 2% per Mach 0.1 Fast
Early Descent (Lb per Minute Early)	60
Early Flap and Gear Extension (Lb per Minute Early)	20
Air Conditioning Bleed Reduction	—
Aft cg Shift (per 4% MAC Shift)	0.5%
Aerodynamic Cleanness	0% to 6%
Engine TSFC Recovery	0% to 6%
Instrument Calibration	1% to 2% per Mach 0.1 Slow Indication

Table 1

The best measure for jet fuel efficiency is revenue passenger-miles flown per gallon. Since 1973, airlines have improved RPMs per gallon from 17.5 to about 25 RPMs per gallon, or 43% (figure 12). This saving has been accomplished by use of larger aircraft, increased load factors, better scheduling, and operational procedures.

REVENUE PASSENGER-MILES PER GALLON
U.S. Trunk Airlines

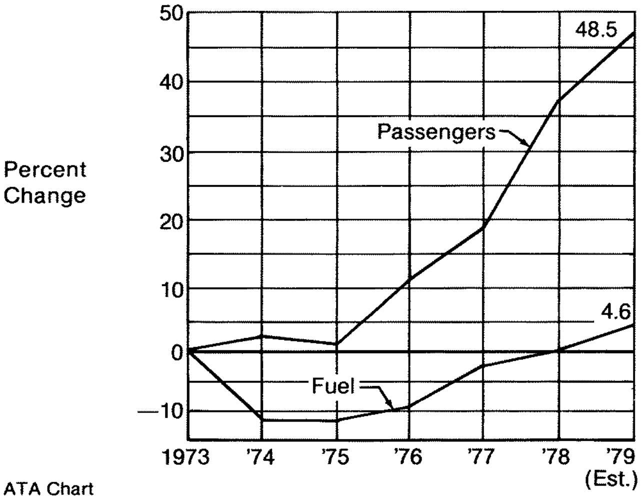


ATA Chart

Fig. 12

Further, passenger count from 1973 to 1979 increased 48.5% while fuel usage increased only 4.6% (figure 13). Also, the industrywide load factor of 63% in 1979 was over 20% higher than it was in 1973. Greater load factors conserve millions of gallons of fuel, particularly by taking advantage of new, more efficient jets that carry more people per aircraft (such as the 747, DC-10, L-1011, and A300).

PASSENGERS vs. FUEL USED
U.S. Trunk Airlines



ATA Chart

Fig. 13

Reducing cruise speed also conserved fuel for the airlines. While a reduction of a few miles per hour will extend a flight only a few minutes, it can substantially reduce fuel consumption—a jet traveling at 500 instead of 520 miles per hour on a 500-mile flight will reduce fuel consumption by 7% and extends the flight only 3 minutes.

Even after an airliner lands, fuel-saving measures are used. Often one or more engines are shut down as the aircraft taxis to the arrival gate. When takeoff is delayed, aircraft are held at departure gates with their engines shut down. Towing aircraft into position rather than taxiing has the potential for impressive fuel-saving benefits. While a taxiing 747 burns 1,075 gallons per hour, a towed 747 with APU running consumes 134 gallons per hour while the tow truck burns approximately 9 gallons per hour.

Expanding the use of sophisticated flight simulators has also conserved fuel. The FAA has adopted a proposal that allows airline pilots to substitute simulator training in lieu of training flights. The three-stage program allows pilots in the final stage to perform nearly all transition and qualification work in simulators. The agency estimated that if simulator training eliminates the approximately 39,000 training hours flown annually in large turbojet airplanes, up to 73 million gallons of aviation fuel might be saved.

MANUFACTURERS' INCORPORATION OF NEW TECHNOLOGY AND GROWTH IN EXISTING PRODUCTS

Continuous improvement or growth of a product line is essential if the commercial aircraft designer/manufacturer wishes to stay competitive and keep pace with the demands of the world airlines. For instance, the 737-100 was designed with a maximum weight of 82,500 pounds (37,422 kilograms), but by first flight it had already increased to 97,800 pounds (44,360 kilograms) to meet customer requirements. Subsequent developments provided the 737-200 with a maximum weight of 128,600 pounds (58,330 kilograms) and the ability to fly an all-tourist payload from Stockholm to Las Palmas. Similar growth in maximum landing and maximum zero-fuel weights paralleled the increase in maximum weight. This growth was made possible by structural analysis, the introduction of structural and aerodynamic modifications, and a growth in engine thrust from 14,000 pounds static thrust (6,350 kgp) of the original JT8D-7 to the 17,400 pounds static thrust (7,900 kgp) of the JT8D-17R with automatic performance reserves. Fuel capacity also increased with an optional 810 U.S. gallons to total 5,970 gallons (figure 14). From the early 737-100 to the Advanced 737-200, fuel burn per seat improved 2.5%. Future derivations with even more dramatic fuel savings are under study.

PAYLOAD RANGE
737 Development

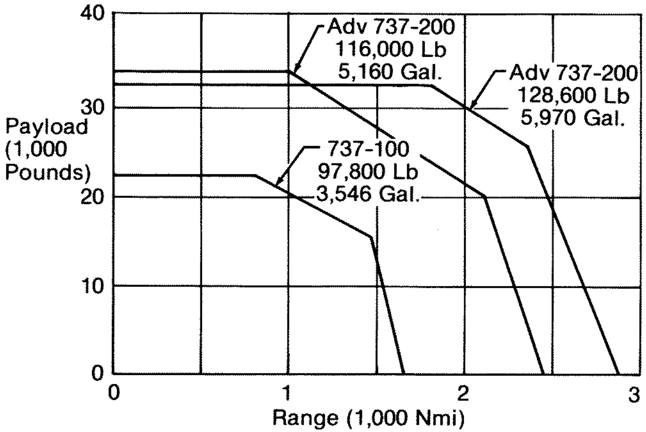


Fig. 14

The 727 has accumulated 6,000 specific items of improvements in its lifetime to date. The majority of these items are oriented to airplane operating economics. Further modifications in areas of engine SFC improvements, drag reduction, and flight deck avionics promise up to 10% fuel savings on future 727s.

Since its introduction in 1970, the 747 has increased its range by 1,000 nautical miles and increased its passenger count by 78 (figure 15). This has resulted in over 20% fuel saved per seat-mile achieved through moderate structural design changes and improved engines. These engines include the Pratt & Whitney JT9D series (-7A, -7F, -7Q, -7J, and -70A), the GE CF6-50 A to E, and the Rolls-Royce RB211-524 A to D.

747 PAYLOAD-RANGE IMPROVEMENT
1970-1980

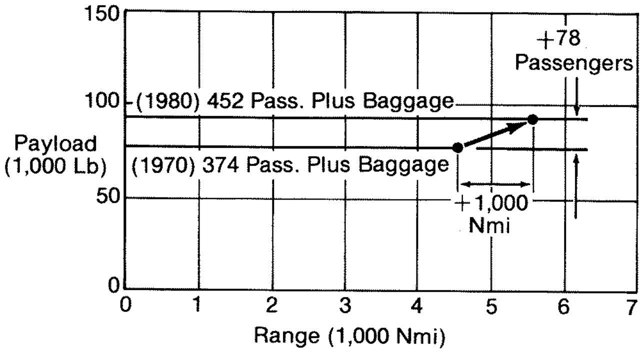


Fig. 15

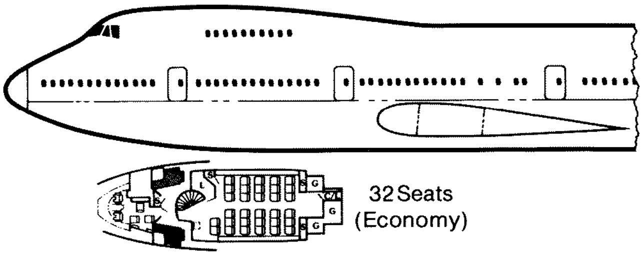
When the 747 started passenger service, it was a large step up in capacity from the standard-body airplanes it replaced, even in its lower density configurations. The nine-abreast main-deck seating had lower seat-mile costs compared to standard-body airplanes; therefore, airlines were inclined to use the upper deck for a lounge or other nonrevenue uses.

As market and economic conditions changed, the airlines were forced to use higher density main-deck seating on the 747. They were able to reduce fares, meet the problems of cost inflation and critical fuel supplies, and at the same time provide greater capacity for the higher travel demand. Half of the 747s delivered from 1977 through 1980 had revenue seats installed on the upper deck instead of a lounge. By the end of 1980, some 28 airlines will have installed or converted their upper deck lounges to revenue seating.

Now a new option is offered that can further expand the 747's upper deck seating to include 37 more seats on the upper deck, for a total of 69 (figure 16). An additional seven seats are added on the main deck due to the rearranging of the galleys, the staircase, etc. To accomplish this, some major structural changes are needed to extend the upper deck 280 inches, to change the fuselage contour, and to add 15 new windows on each side. SwissAir has announced orders for five of these new 747s to be delivered in 1983. This new "stretched" 747 is another example of how improvements (or variants) will keep a product viable, increase market share, reduce seat-mile costs, and prepare for future derivations.

747 UPPER DECK

Standard



280-Inch Stretched

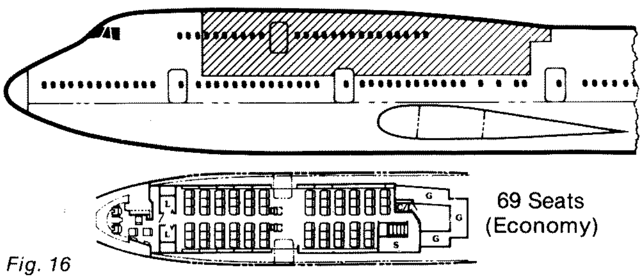


Fig. 16

Extra capacity directly affects the fuel efficiency of an airplane (figure 17).The 496-seat 747 with an extended upper deck, when compared to the 1970 base, saves over 25% in fuel burn per seat at 100% load factor. Obviously, as fuel becomes more expensive or supply is limited, these options can benefit an airline to a great extent.

EFFECT OF 747 IMPROVEMENT/GROWTH ON FUEL BURN PER SEAT

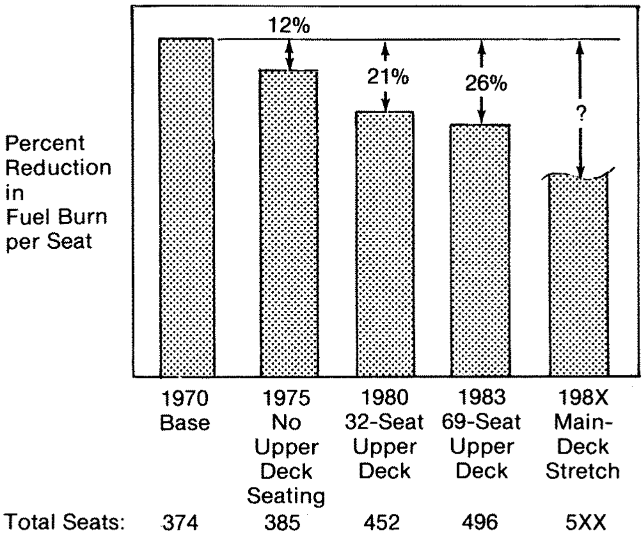


Fig. 17

Advanced on-board avionics have been developed and are available on all Boeing models that can determine and execute flight profiles which minimize total fuel costs. These avionics will also improve flight progress monitoring and aircraft/ATC communication as well as reduce the flight crew's workload.

The heart of the fuel-saving function is the Performance Data Computer (PDC) which matches airplane performance and engine performance to provide a minimum fuel flow flight from takeoff through landing by analysis of air data, weights, and a coupled autothrottle. The addition of the Performance Navigation Computer System, which can further improve fuel flow, provides area navigation capability for altitudes above 1,000 feet. This is coupled to push-of-the-button access to such in-flight performance data as limit EPR (thrust) setting for takeoff and go-around, time/fuel remaining computations, best economy speeds and altitudes, and autothrottle with speed and thrust signals. The PDC system provides operational fuel savings of 3% to 5%, with additional savings expected due to tighter track guidance and direct-routing capabilities. These new avionics are also a step toward providing automatic time-based navigation for the future.

NEW GENERATION AIRPLANES AND ADVANCED TECHNOLOGY

Eight years ago, Boeing design teams began work on the preliminary design of a 200-passenger, fuel-efficient, medium-range transport. It was perceived that the marketplace would need an airplane of this size and range sometime in the early 1980s.

Prior to the 1973 oil embargo and the resultant fuel shortage, technical advancement was focused on noise reduction. The effort to reduce community noise was vigorously pursued by developing quieter engines and airframe configurations. At that time, an "engine over wing" configuration was favored (figure 18). As the energy crisis became a reality, design emphasis shifted to fuel efficiency.

Fig. 18

As the airplane design and the market became clearer, a family of airplanes was determined to be essential for fulfilling the various needs of the world airlines. The basic family which evolved into the Boeing 757 and 767 models had several advanced-technology fuel-saving concepts incorporated into their design.

The four basic technologies are propulsion, aerodynamics, structures and materials, and avionics. Each of these technologies will be discussed and both present and future trends identified.

PROPULSION DEVELOPMENTS

Traditionally, the engine and airplane design/manufacturers work as separate industrial entities, responding to a myriad of demands from a broad spectrum of customers. Modern turbofans (in contrast to surface-transportation internal combustion technology) improve specific fuel consumption while increasing thrust (horsepower). A given amount of fuel has consistently allowed greater ranges and payloads so that today's commercial aircraft engines are 35% to 40% more fuel efficient than the jet engines of the 1950s (figure 19). A successful commercial transport is the union of the powerplant and airframe—a unique design feat.

Ongoing development of the basic high-bypass-ratio engine increased thrust levels while reducing specific fuel consumption. Fuel savings of approximately 6% have been accomplished since wide-body jets were introduced. Recent advances have made possible additional component refinements that, when incorporated, could provide an additional fuel saving of up to 6%.

ENGINE FUEL EFFICIENCY TRENDS

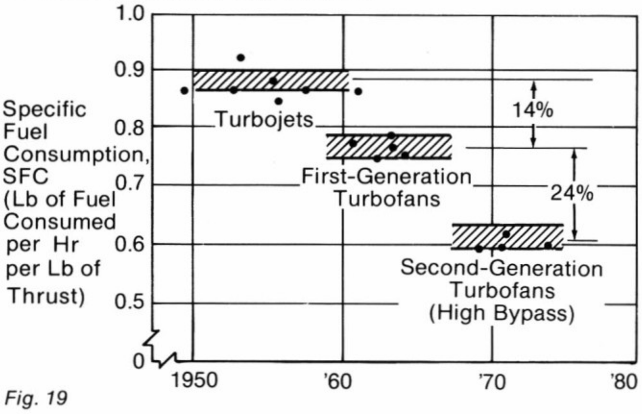


Fig. 19

The 757 and 767 engines are derivatives of the basic wide-body engines introduced in early 1970. These derivative engines take advantage of the low-risk technology advancements of proven basic core engines that have provided specific fuel savings with proven reliability and lower maintenance costs. These engines will be 6% better in fuel consumption than their parent engines. 757 and 767 operating economics are expected to improve as the engine/design manufacturers further refine and develop their products.

Because jet engine technology development has been synchronized with airframe development, the 757 and 767 will offer several engine choices for substantial flexibility. The airline will be able to select the best combination of aircraft and engine to standardize its fleet or to satisfy specific market requirements (table 2).

AVAILABLE ENGINE CHARACTERISTICS

Manufacturer	Designation	Thrust Class (1,000 Lb)	Year of Certification	Boeing Airplane Model
Pratt & Whitney	JT9D	39-56	1971	747-767
	JT10D	25-36	1985	757
General Electric	CF6-32	30-36	1981	757
	CF6-50	49-53	1972	747
	CF6-80	44-54	1981	747-767
Rolls-Royce	RB-211-524	50-55	1975	747-767
	RB-211-535	32-39	1981	757

Table 2

The engine manufacturer is continually challenged to reduce thrust-specific fuel consumption (TSFC) while balancing TSFC, weight, and engine reliability. General Electric and Pratt & Whitney are working with NASA's Aircraft Energy Efficiency (ACEE) program to develop the technology for a new generation of turbofans beyond those to be installed in the 757 and 767 airplanes. These engines promise to be considerably more fuel efficient, less susceptible to performance loss, and more economical to operate and maintain than today's most advanced engines. These manufacturers are currently putting advanced components together into test-bed engines and are working on such items as very-high-pressure-ratio turbines and more efficient combustion (figure 20).

FUEL CONSUMPTION IMPROVEMENTS

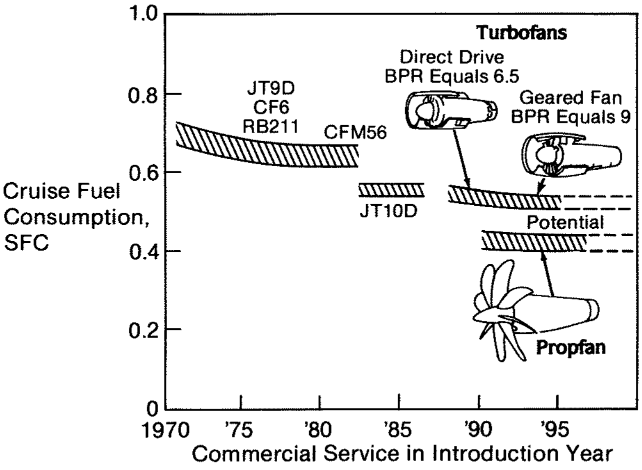


Fig. 20

Engine/airframe structural integration studies are underway with the objective of reducing engine core deterioration and wear. Modern commercial and military high-bypass-ratio turbofan engines can suffer performance deterioration due to engine case distortion resulting from engine bending and local deflection. Engine bending is due to induced moments from aerodynamic, thrust, g-force, gyro, and thermal loads. Local deflections are usually caused by point load attachments such as engine and accessory mounts. Such distortion causes blade tip rub wear and seal damage with consequent increased fuel burn, increased maintenance, and early overhaul. Deterioration in the range of 1% to 3% TSFC can be experienced in the first few hours of operation, and can progressively increase to 4% or 5% within 5,000 hours.

The objective for 1980 will be to design, fabricate, and test hardware to prove the effectiveness of the load-carrying core cowl concept for propulsion system stiffening. This concept is directly applicable to high-bypass-ratio engines mounted in short-fan-duct nacelles and, with minor modification, also applicable to similar engines mounted in nacelles with longer length fan ducts.

A large potential fuel saver in the propulsion system is the new-technology high-speed propeller, or propfan. The objective of the propfan is to retain the high Mach numbers fan jets require for good economics while at the same time maintaining the high fuel economy of the low-speed propeller. Performance tests of propfan models indicate this high efficiency can be maintained; propfan-airplane integration studies indicate a 7% to 10% saving in fuel, depending on the penalties assessed to overcome yet unresolved developmental problems. Supersonic propeller tips have forced the propeller into a swept back design to minimize tip Mach numbers. NASA's advanced turboprop program is studying these and other matters to develop a reasonable solution which can fully realize all potential fuel savings. A thorough study of the maintenance costs will also be required before serious airline studies can be performed.

AERODYNAMICS

Wing Design

Aerodynamic efficiency (lift divided by drag) is directly proportional to miles per pound of fuel burned. Airfoil technology improvements balance wing thickness, sweep, span, and weight to produce higher aerodynamic efficiency. The 767's advanced airfoil is 22% thicker than a 747 airfoil (figure 21) for the same critical Mach number—a thickness chosen specifically to obtain a higher cruise efficiency. The wing span was increased because the span squared divided by the skin friction area of the airplane is a good measure of aerodynamic efficiency.

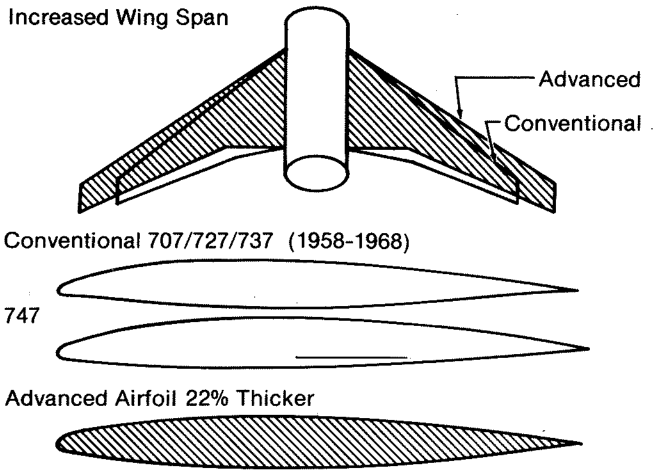


Fig. 21

The wing sweep has been decreased compared to the earlier models to improve the low-speed performance, especially the approach lift-to-drag ratio, and to reduce noise around the airport. Adding thickness to the wing increases fuel volume, which allows for an increase in range. The benefits of additional fuel cells inside the wing have already been recognized and adopted for longer range, higher payload routes.

A comparison (figure 22) of the aerodynamic efficiency (Mach number times lift-to-drag ratio) versus lift coefficient for the 767 and 727 shows the M(L/D) of the 767 is substantially greater than that of the 727 and further potential is available. Further detailed tailoring of the wing-body combination results in additional improvements in M(L/D) over the original wing-body design as shown in the fairings in figure 22.

AERODYNAMIC IMPROVEMENT

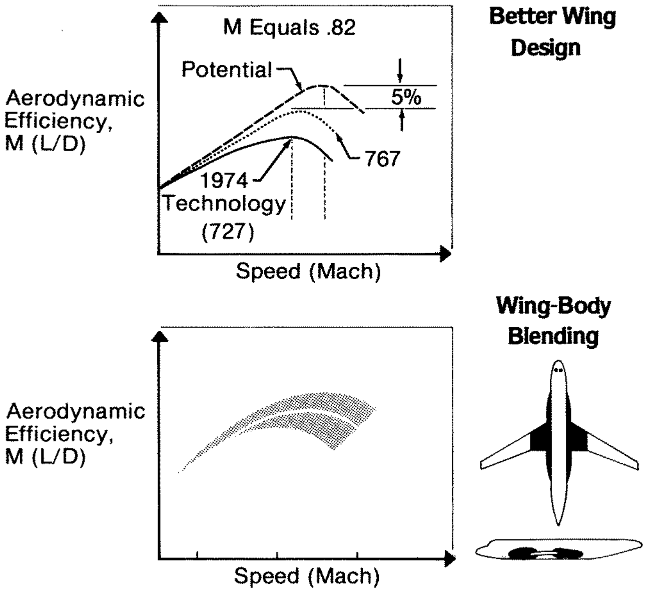
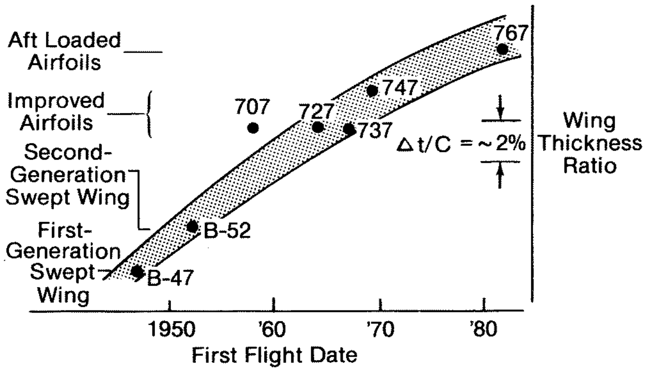


Fig. 22

Successive Boeing designs have included advances in wing technology produced by aggressive research and wind tunnel programs and proven by flight performance. Figures 23 and 24 show wing technology progress and status relative to wing thickness ratios. The 767 configuration has undergone extensive wind tunnel testing; more than 25,000 hours has been accumulated to date in the process of evaluating more than 70 potential wings.

BOEING AERODYNAMIC TECHNOLOGY



Note: Data adjusted to common wing sweep and cruise speed

Fig. 23

Many detailed problems such as depth of rear spar, negative pitching moments due to cusp airfoils, wing flutter, and integration of nacelles, pylon, wing, and wing-body have been solved during these very extensive development programs.

WING TECHNOLOGY STATUS

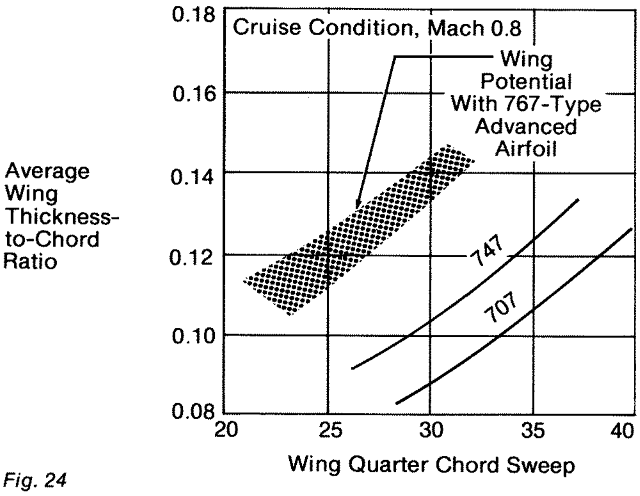


Fig. 24

Typical aircraft design relationships are schematically presented in figure 25. The pertinent aircraft parameters of operating empty weight (OEW), takeoff weight (TOW), and aerodynamic cruise efficiency (L/D) are plotted as a function of wing span. Increases in wing span decrease fuel burn at a faster rate than the increase in OEW up to the point where stiffness or strength must be added (more weight) to meet gust and flutter load requirements.

TYPICAL DESIGN RELATIONSHIPS

- Fixed Payload Range
- Fixed Engine Size
- Constant Cruise Speed

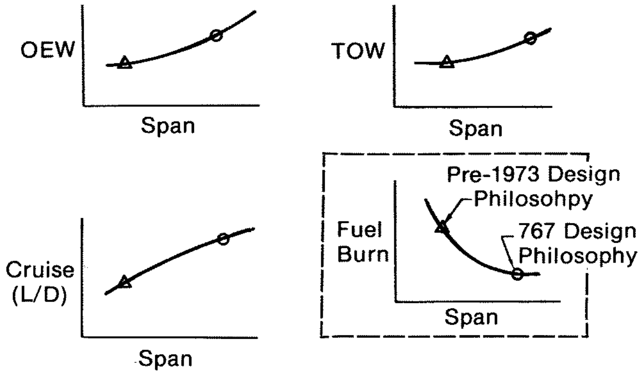


Fig. 25

The 767's increased wing span naturally resulted in an increase in structural weight. The decision to invest greater weight in order to produce greater aerodynamic efficiency was necessary to lower fuel burn. To obtain a more efficient wing structure, a 3,050-square-foot wing area, combined with the 767's 155-foot span, allowed a larger chord wing box and permitted the use of simpler single-slot trailing-edge flaps. This larger structural box increases torsional stiffness to prevent flutter and provides several other important features such as easier incorporation of the main landing gear and flap structure.

Active Controls

Active controls offer potential improvement in aerodynamics through drag reduction and in structure by load control or alleviation (figure 26). The aerodynamics will be improved by increasing the wing span and reducing trim drag. Load-distributing active controls will reduce the structure weight penalty normally required to accommodate gust and flutter loads for high-aspect-ratio wing planform.

IMPACT OF ACTIVE CONTROLS TECHNOLOGY

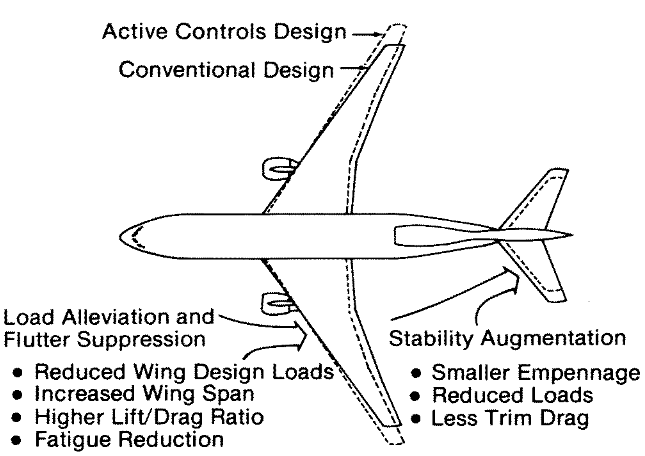


Fig. 26

When related to fuel efficiency, active controls technology offers promise for weight reduction by controlling or reducing aerodynamic and inertial loads imposed on airframe structure and/or allowing improved aerodynamic performance without incurring structural weight increases that would otherwise negate the aerodynamic improvement. The aerodynamic improvements can take the form of improved L/D offered by increased wing aspect ratio with little or no weight penalty, and the desirable effect on profile drag of comparatively small empennage size needed when reduced stability margin design criteria are followed. Weight reduction results through alleviating maneuver, gust, and fatigue loads on the wing, suppression of wing flutter, and reduction of empennage surface size. Active controls technology functions can be applied to existing or new transport designs. Resultant weight reduction and increased aerodynamic efficiency could bring about fuel savings of 5% to 10%.

Under NASA contract and in parallel with investigation of the wing tip extensions and winglet concepts, Boeing conducted analytical and wind tunnel research to apply wing load alleviation to the 747 (figure 27). Evaluation reveals that such a system could reduce weight by approximately 1,500 pounds. Further tests showed that the wing load alleviation system also significantly reduced weight penalties associated with wing tip extension.

WING LOAD ALLEVIATION SYSTEM COMPONENTS

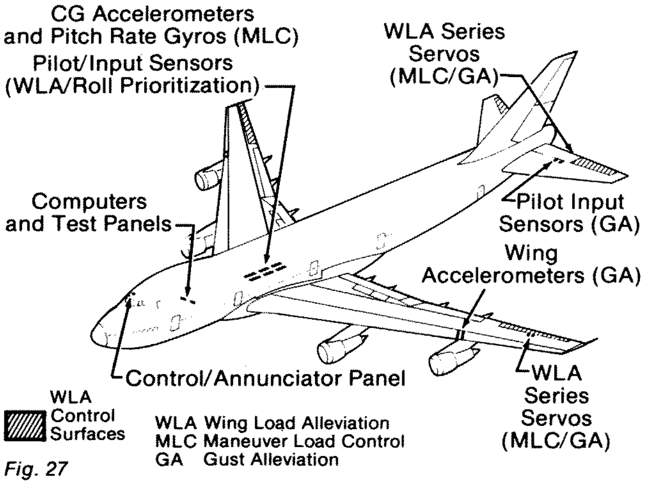


Fig. 27

The advent of samarium-colbalt magnets and advanced digital electronic data buses has made possible the concept of an "all electric" airplane. This highly interesting innovation will eliminate all hydraulic system components and control cable systems and replace them with a unified digital fly-by-wire, powered-by-wire system. Figure 28 shows a proposed configuration for such a system. The application of low-weight, low-cost, low-energy solid-state technology to aircraft systems would be a major state-of-the-art advancement and appears to have the potential to reduce fuel consumption considerably.

NEW TECHNOLOGY TRANSPORT WITH ELECTRICAL CONTROL ACTUATION

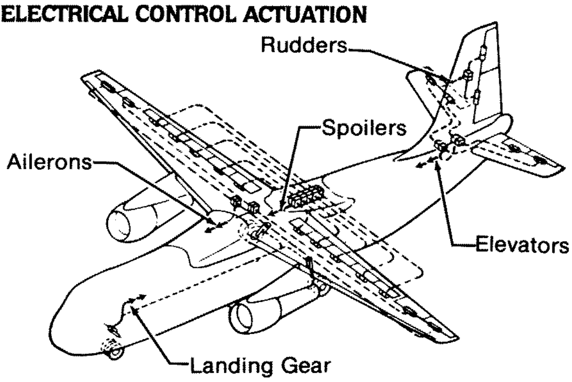


Fig. 28

The elimination of multiple actuator tubes and a myriad of holes, brackets, and fittings required to accommodate the hydraulics and conventional control systems will not only reduce weight but will impact manufacturing and maintenance costs resulting in improved operating costs. Although commercial application may be near the year 2000, operating costs savings of 5% to 8% appear likely.

Laminar Flow

Airfoil turbulence—instability or shear in the boundary layer—produces drag. Natural or controlled laminar airflow has great potential for reducing drag and improving airplane efficiency. Natural laminar flow studies (NLF) under a NASA contract used recent advancements in aerodynamic design technology to successfully define an airfoil with favorable pressure gradients to 35% chord on the upper surface and to 50% chord on the lower surface. Other studies identified several areas where further research on NLF airplanes could improve design, such as a thicker wing section at side-of-body; however, the biggest benefit appears to be related to the degree of wing sweep.

Laminar flow control (LFC), or the removal of the boundary layer by suction, offers the largest potential for improving airplane efficiency. On a long-range flight, LFC could result in a 40% reduction in fuel burned (figure 29).

LAMINAR FLOW CONTROL (LFC) TRANSPORT

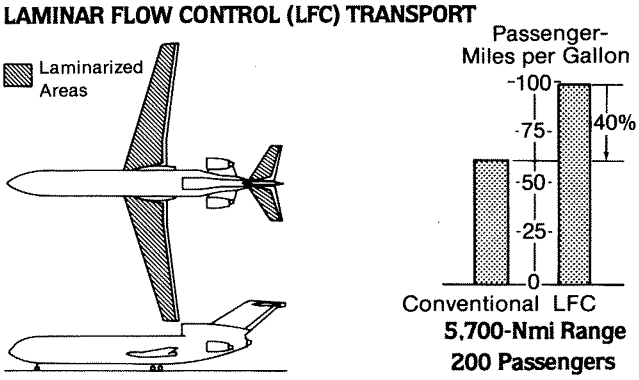


Fig. 29

The challenge for LFC is in discovering or inventing a practical structural concept; several distinctly different types of structural concepts are presently being explored (figure 30). Present suction requirements call for approximately 3 miles of spanwise slots, and the weight penalty for the suction surface must be minimized.

LFC WING STRUCTURE CONCEPTS

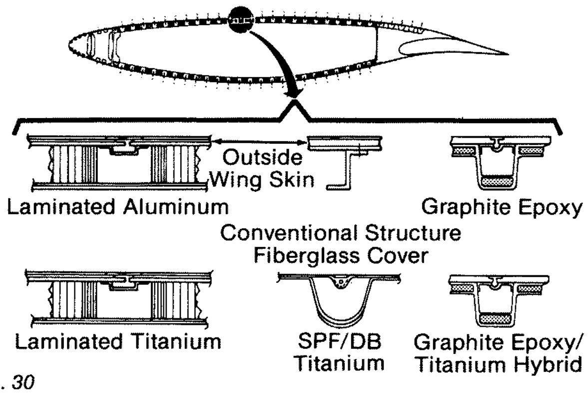


Fig. 30

Engineering studies continue to search for a commercial transport which can feasibly use controlled laminar flow. Many studies are conducted in conjunction with NASA's Aircraft Energy Efficiency (ACEE) program. Available options for aerodynamic design, structural concepts, and subsystems selection are evaluated in the search for an LFC aircraft for the late 1990s.

NASA will flight test two leading-edge configurations to try to overcome one of the vexing problems of LFC—leading-edge contamination by insects in conjunction with their LFC flight test program (figure 31).

LFC LEADING-EDGE FLIGHT TEST

Objective

Demonstrate effectiveness of leading-edge systems to maintain laminar flow under representative flight conditions

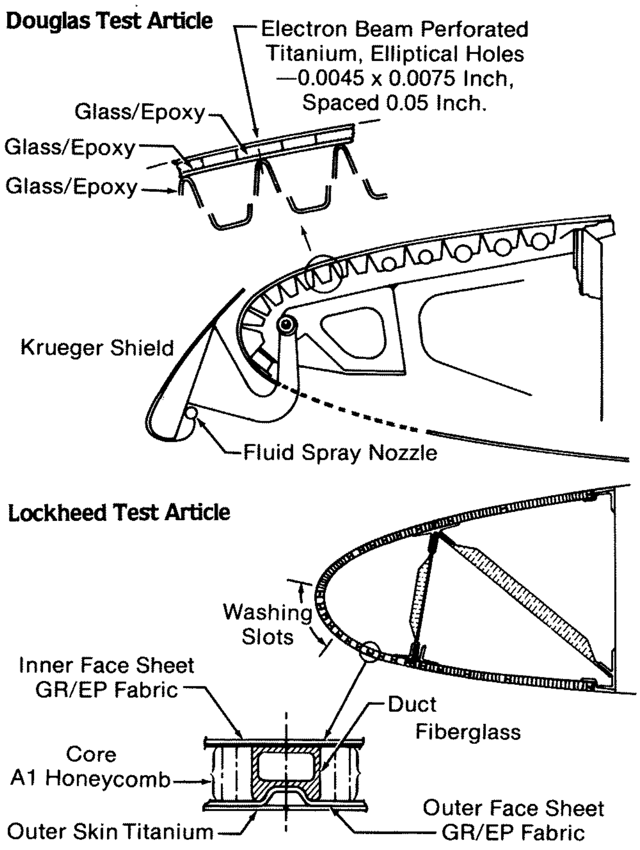


Fig. 31

NEW STRUCTURE MATERIALS

The potential savings in weight and fuel burn resulting from the use of new materials in aircraft structures are significant. Interest in hybrid graphite composites has grown due to their huge potential for reducing weight. The extensive use of these composites raises such related issues as their cost effectiveness, availability, producibility, and long-term durability.

In 1973, 112 graphite composite spoilers were installed in the 737 fleet; one Frontier 737 has accumulated approximately 19,000 flight hours. Graphite epoxy elevators were installed on five 727s delivered to United Airlines in March 1980 and a 737 graphite/epoxy horizontal stabilizer will begin flight testing in October 1980. So far, results have been highly favorable in terms of durability and producibility. Table 3 summarizes the weight-saving potential on specific applications to current Boeing airplanes.

ADVANCED COMPOSITE BENEFITS

Graphite/Epoxy Design

Component	Reduction		
	Parts	Fasteners	Weight
727 Elevator	41%	60%	26%
737 Stabilizer	55%		26%
747 Aileron	47%		28%

Table 3

Graphite composites represent a saving in weight of approximately 25% over aluminum honeycomb structures. Combined with their excellent stiffness characteristics, these advanced materials (including the new aluminum) when applied to the 767 will represent a saving in empty weight of approximately 1 ton. On the 767, the wing skins, stringers, spare chords, keel beam, and vertical tail spare chords are made of improved aluminum alloys (figure 32).

ADVANCED MATERIALS

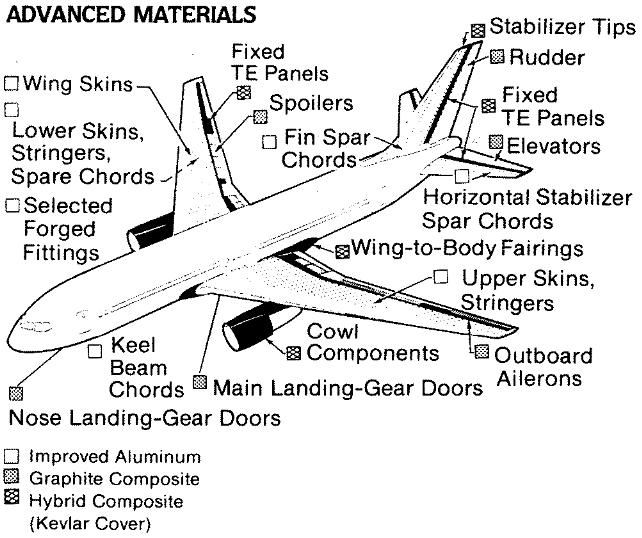


Fig. 32

These aluminum alloys, a slight modification of the present 2000 and 7000 series alloys, are improved 7% to 10% in strength and in toughness with no deterioration in corrosion resistance. For the main landing-gear doors, some of the nacelle cowl components, the wing-to-body fairing, and the fixed torque box structure on the wing and the tail, a hybrid composite is being used, i.e., a graphite composite structure with a Kevlar cover sheet. For ailerons, spoilers, elevator, and rudder, a pure graphite composite is used.

The extensive use of these materials on medium-primary structures could significantly reduce weight as well as improve environmental durability. The flight tests of the 737 graphite/epoxy horizontal stabilizer are expected to provide concrete proof of these theoretical expectations. Figure 33 projects the potential weight savings that may result from use of advanced composite structures as well as improved alloys. If 15% to 25% of weight were saved, the fuel burn savings would be 7% to 12%.

ADVANCED COMPOSITE STRUCTURE

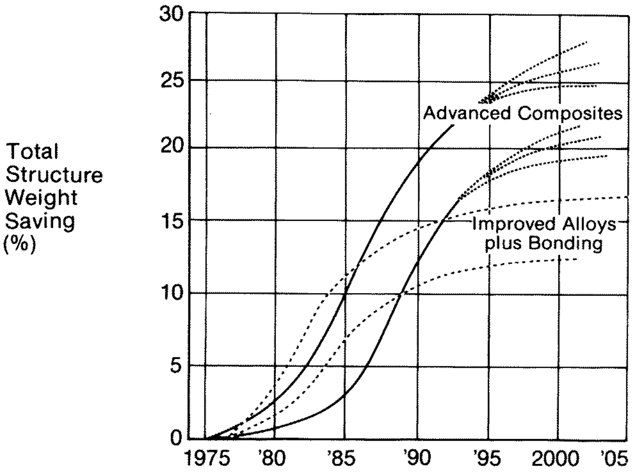


Fig. 33

Composite materials will also impact airplane proportions, because weight savings are much greater when today's wing configurations are used and composite structures replace aluminum. Preliminary indications are that composite wings will weigh between one-third and one-half that of conventional aluminum wings of the same size. Figure 34 shows two design concepts in the utilization of composites in primary structures.

ADVANCED COMPOSITES DESIGN CONCEPTS

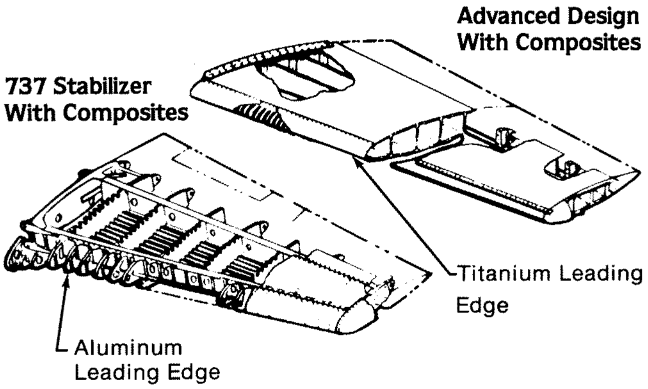


Fig. 34

It is necessary that hardware programs using advanced composite structures be conducted in a production environment to demonstrate the safety, operating life characteristics, and manufacturing cost of these materials. To accelerate the application of advanced composites, Boeing has integrated advanced composite technology developed under NASA contracts with company efforts to obtain reliable production, technical, and cost data bases. One important development from this effort was the application of Kevlar as an insulator between the aluminum honeycomb core and graphite to prevent galvanic action. The direct coupling of these two dissimilar materials would have caused corrosion to aluminum in natural moist environments.

Other structural materials are applied in the New Technology Transport (NTT) studies. One innovative example is the application of advanced bonded materials to the NTT structure areas (figure 35), which combines bonded aluminum honeycomb body, filament-wound tail cone, and graphite and fiberglass fairings and control surfaces. The bonded structure promises lower weight, smoother exterior surface, lower aerodynamic drag, and better noise attenuation.

Although studies are far from complete, early estimates consider weight savings of 25% to 30% over conventional structures possible, producing fuel savings in the order of 10% to 15%.

ADVANCED BONDED MATERIALS APPLIED TO STRUCTURES

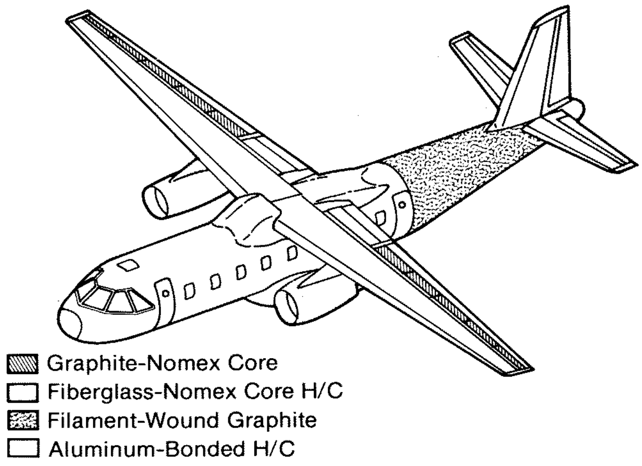


Fig. 35

ADVANCED FLIGHT DECK DEVELOPMENTS

The flight deck on the Boeing 757 and 767 new generation aircraft will be the most advanced system offered for commercial flight. All known human factors were thoroughly evaluated before being incorporated, ranging from crew ventilation and noise levels to seat comfort and instrument panel visibility. The all-digital automatic flight management system not only reduces crew workload but also contributes significantly to lower fuel consumption (figure 36).

FLIGHT MANAGEMENT SYSTEMS

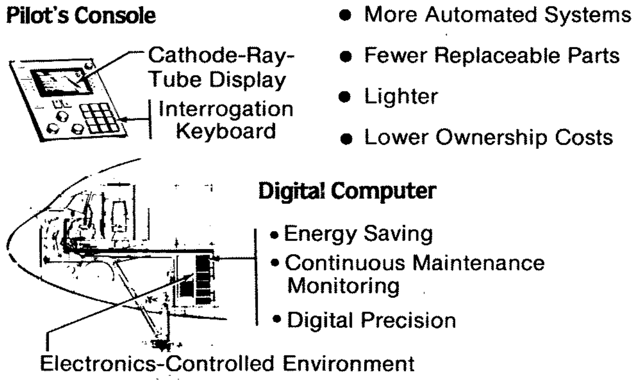


Fig. 36

The 757 and 767 flight deck utilizes an Electronic Altitude Director Indicator (EADI) and an Electronic Horizontal Situation Indicator (EHSI). These multicolor cathode-ray TV tube displays resulted from extensive testing by Boeing starting in 1964 on the SST and continued with NASA. The displays allow the pilot to obtain necessary flight information and to remove unneeded information. The EADI displays normal attitude and directional indicators, autopilot and autothrottle modes, fast-slow indications, ground speed, ILS, and radar altitude.

The EHSI indicates the normal heading situation, ground track, a map display (with radar overlap, wind direction, and speed), navigation routes, VOR's with bearings, trend vectors, and so on.

This flight management system will allow the pilot to select optimum navigation routes and speed profiles in order to minimize fuel burn. The pilot can also choose to fly the airplane manually from the map display with the flight director or place the flight in the hands of the autopilot and autothrottle. This new flight management system has already undergone thousands of hours of fully automatic testing on a flight test 737.

To minimize the workload for the two-crewmember flight deck, an Engine Indicating and Crew Alerting System (EICAS) has been incorporated. This system, using a cathode-ray-tube display, monitors all engine operating parameters, provides caution and warning functions for crew alert, displays preflight airplane system status information for dispatch, and displays airplane system maintenance information for ground use by the maintenance crew. The Boeing 757 and 767 will be certified for a two-person flight crew—an important cost-saving and safety consideration for the airlines.

TOTAL AIRPLANE PERFORMANCE—FUEL BURN

The individual elements contributing to aircraft efficiency have been discussed independently. Here the sum of all this fuel-efficient technology on total airplane performance is examined. The Boeing 737 is an example of a manufacturer's effort to offer product variants to maintain its viability in the marketplace.

Figure 37 plots the 737's fuel burn using a typical U.S. domestic mission of 500 nmi. Tracking the 737-100 at 93 passengers in mixed-class seating to the current model 737-200 at 100 passengers to a potential derivative at 115 passengers reveals substantial improvement in efficiency. Further technological advances indicated for a new model 737 could incorporate individually or collectively new technology in propulsion, aerodynamics, structure, and avionics. A 25% reduction in fuel burned per trip and a 37.5% reduction in fuel burned per seat could result from the technology incorporated in a new small airplane for the next generation.

737 FUEL BURN EVOLUTION

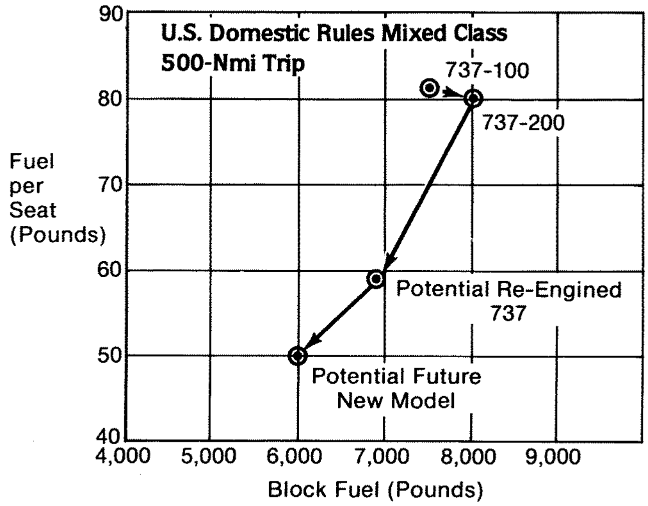


Fig. 37

ALTERNATE FUELS

A discourse on advanced technology would not be complete without a word about the potential use of alternate fuels. The problems associated with liquid hydrogen and liquid methane are not so much technical as they are economic (figure 38).

COST OF ALTERNATIVE FUELS

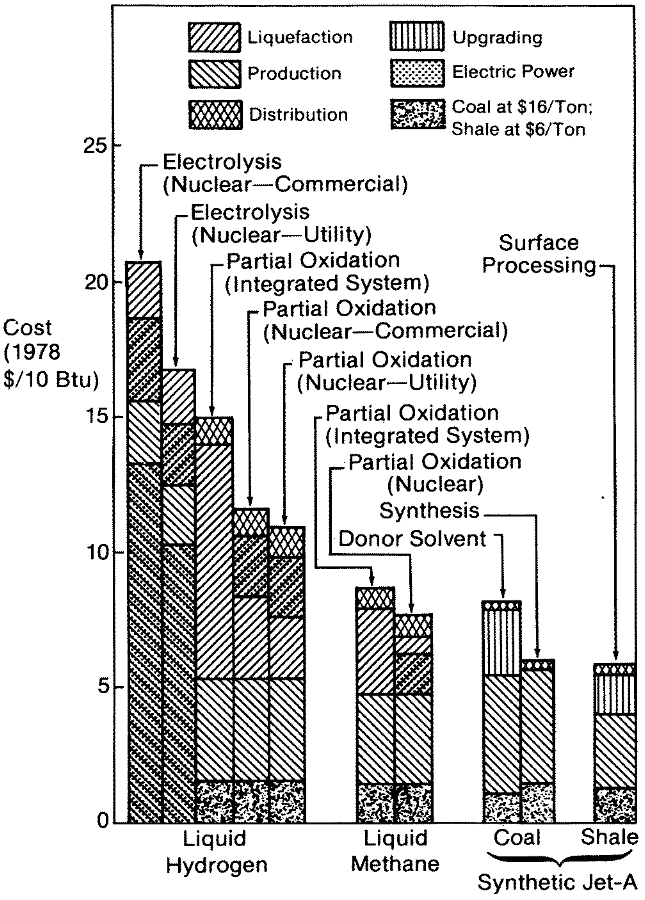


Fig. 38

Barring an unforeseen major breakthrough, the costs involved with modifying or redesigning airplanes, processing cryogen fuels, and handling the logistics problem are deemed prohibitive. Synthetic sources of jet fuel, such as extracting oil from coal and oil shale, could supply JP fuel well into the next century. Until the end of fossil fuels is clearly at hand, alternate fuels—especially the cryogenics—will remain of only academic interest.

SUMMARY

The prospect of a finite petroleum supply has imposed a sense of urgency on the development of fuel-saving technologies. It is absolutely necessary that the U.S. reduce its dependence on petroleum-based fuels in order to lessen our vulnerability to supply interruptions and excessive price hikes.

The commercial aircraft manufacturers and users have responded admirably to the crisis. The manufacturers have incorporated fuel-saving devices into current products and the airlines have developed operational techniques that save fuel. By working together, airline fuel savings have gone up 40% since 1973.

But what of the next generation of commercial aircraft? Can the 757 and 767 meet the challenge of the 1980s? The answer is yes, for three reasons. First, they will be using 25% to 30% less fuel per passenger than the airplanes they are replacing. Second, their fuel efficiency has been achieved with minimal technical risk. Third, further growth of these airplanes promises even greater operating economics.

As the world's older aircraft are phased out or replaced with the fuel-efficient airplanes of the 1980s, projected jet fuel demand will be affected significantly. But current products can also offer fuel savings as they are modified to incorporate new-technology improvements. The 737 and 747 can be stretched and advanced engines added to improve seat-mile costs.

The long-range technology view is exciting. Since the advent of the jet engine and swept wing, airplane performance has improved primarily through better engine performance. Future generations will probably incorporate composite structures, active controls, better electronics, as well as improved propulsion systems. It is doubtful that laminar flow control can be practically applied in the near term. If just three areas are successful, fuel burn can be reduced another 25% to 30% relative to the 757 and 767. It is expected that this technology will be applied to new or derivative airplanes intented for service in the 1990s and beyond (figure 39). Airline operations will also be more efficient as on-board aircraft instrumentation and calculation as well as ATC procedures improve in the long term.

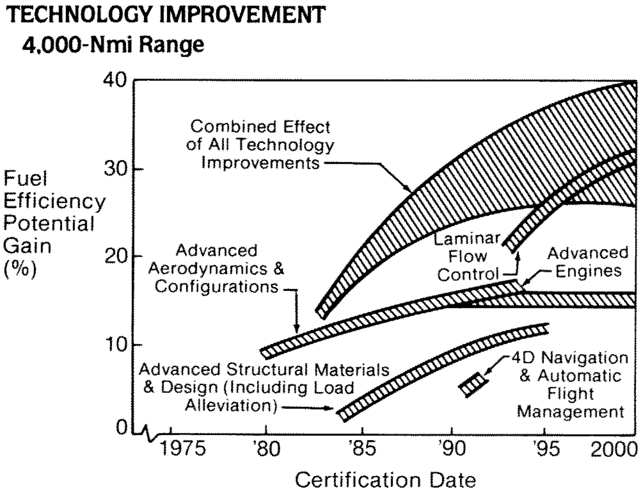


Fig. 39

Air transportation will continue to be more efficient. Research and development funded by both industry and government will advance technology in all fields of engineering. Applying these advancements will produce better aircraft that use less fuel and have lower relative operating costs. But exploiting all of these opportunities effectively must be a responsibility shared equally among aircraft and engine manufacturers, airline operators, and regulatory agencies.

In today's commercial world, the technological imperatives are founded on cost considerations, and both product improvements and cost reductions are therefore vital to the success of future commercial aircraft programs. Our experience has shown that both can be accomplished and that they are not necessarily in conflict. The rewards of a successful program will not necessarily go to the one who gets there first. In all probability, they will go to the one who is still there last, and it takes an intensive dedication to the new imperatives to make that happen.

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