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Technological Development of Transport Aircraft—Past and Future

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Richard S. Shevell
Stanford University, Stanford, Calif.

Past and Present

IT is common to study the history of a technology with a growth curve showing the annual production vs time. Growth usually starts slowly, as only the bold and/or the rich can afford, psychologically and financially, to explore the new invention. Then if the product is useful, acceptance grows exponentially. Increased production lowers costs, further accelerating the demand. Eventually, the market is saturated and demand slows to the replacement market. The technology is said to have matured. A major improvement, such as the development of color capability in television, may start the cycle over again.

In addition to charting production and popular acceptance in this manner, technical progress can be similarly displayed. Figure 1 shows the speed history of transport aircraft. From 1928 to 1958, speed increased fivefold; the beginning of the jet age in 1958, however, established speed levels that have shown little change in the past 20 years. We have known how to increase speed above the typical airline cruise Mach numbers of 0.80–0.84 for decades, but we have not known how to substantially increase these speeds while simultaneously complying with the other major aircraft trend characteristic, namely, ever decreasing cost.

Figure 2 shows the relative direct operating cost per seat mile from the DC-3 in 1936 to the Boeing 747 and DC-10 of the present. The standard 707/DC-8 aircraft have a relative cost value of 1.0. This chart has been constructed on an approximate constant dollar basis by using the cost ratios between one aircraft and the one proceeding it, as determined at the time of the aircraft's development. The smaller aircraft, such as the DC-9-30, show costs for their own shorter ranges which are similar to the larger aircraft with the same technology at the same short range, but only because they are designed for these much shorter ranges. Normally, increasing size decreases seat-mile cost up to 350-400 passenger capacities, after which this trend flattens out. The trend toward improved operating cost is strong and steady with only the Boeing Stratocruiser, the DC-7, and the Comet rising above the curve. The message to be learned from 50 years of aircraft history is clear. Successful aircraft have almost always had equal or lower operating cost compared to their predecessor, while offering service improvement in either speed, range, comfort, or combinations of them. In some cases, they have offered a significantly different size suitable to certain markets. The exceptions have offered a unique service at a moderately higher (10-15%) direct operating cost—and their success was generally limited.

The rapid improvement in speed, the main commodity offered by aircraft, together with comparable gains in range and comfort, and the cost decrease led to the huge growth in air travel shown in Fig. 3 from Ref. 2 and in aircraft capacity shown in Fig. 4 from Ref. 1. As an industry, we became accustomed to rapid technical progress, imposing technological functional obsolescence on each succeeding type within two to seven years. Table 1 shows the chief technological developments that enabled each generation to reign supreme—although usually only for a brief period.

Not listed specifically but continuing throughout the entire period have been significant improvements in airfoil design, flap systems, structural materials, and increasingly sophisticated methods of detail design and manufacture. The enormous contributions of avionics to aerial navigation, both en route and in the terminal area, were essential to the growth and safety of the air transport system. Great strides have been made in the electrical, hydraulic, pneumatic, and mechanical systems, which have permitted greater capability with reduced weight and exceedingly high reliability. But from the overall airplane design point of view, the items listed in Table 1 were most significant in making each succeeding design possible. Except for the World War II period, a first-line aircraft held that position for no more than six to seven years. Technological functional obsolescence was the way of life

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Richard S. Shevell was educated at Columbia College (B.A., 1940) and the California Institute of Technology (M.S., 1941 and A.E., 1942). He then joined the Douglas Aircraft Company, Santa Monica, Aerodynamics Group working successively on stability and control, wind tunnel testing and performance. He then became the project aerodynamicist on the Nike Ajax missile. In 1947 he was appointed supervisor of aircraft aerodynamic performance working on the DC-6, DC-7, and DC-8. In 1959 Mr. Shevell became Director, Aerodynamics during the development of the DC-9 and stretched DC-8. In 1967 he was appointed Director, Commercial Advanced Design and was involved with the DC-10. In 1970 Professor Shevell joined Stanford University where he now teaches aircraft system design and a course on introduction to aeronautics. He has authored and co-authored numerous papers on aerodynamic design, aircraft performance, and transportation systems analysis. He serves on the NASA Aeronautics Advisory Committee, the AGARD Flight Mechanics Panel, and has participated in several National Academy of Engineers Ad Hoc study committees. He is an Associate Fellow of the AIAA.

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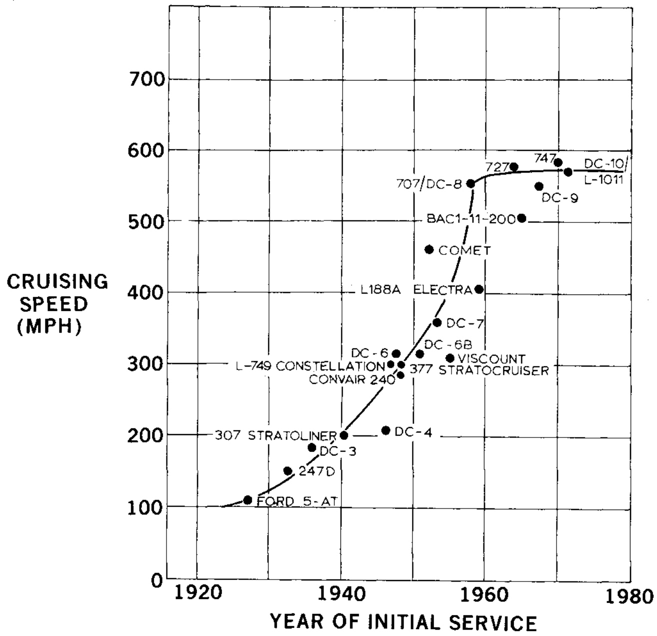

Fig. 1 Speed history of transport aircraft.

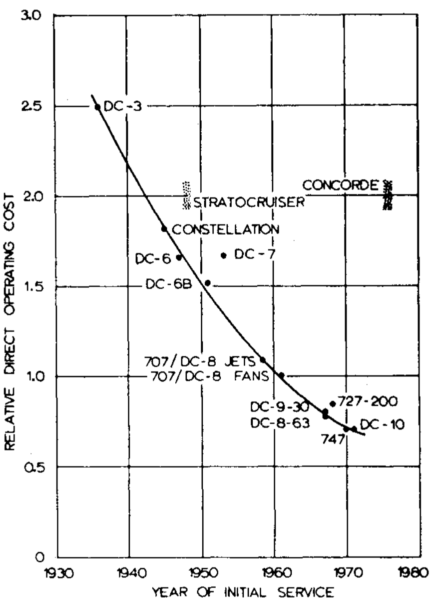

Fig. 2 Direct operating cost from the DC-3 to the DC-10.

Growth rate percent	1960-1965	1965-1970	1970-1975	1975-1977	1977-1987 (Conservative)	1977-1987 (Potential)
World	13.0	16.2	8.0	9.2	6.0	7.1
Total non U.S.	14.0	16.4	13.2	9.5	6.6	7.8
Total U.S.	12.2	16.0	2.9	8.9	5.2	6.1

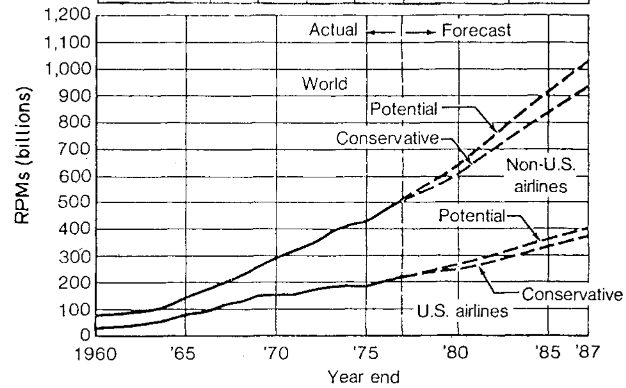

Fig. 3 World revenue passenger-miles, all services.

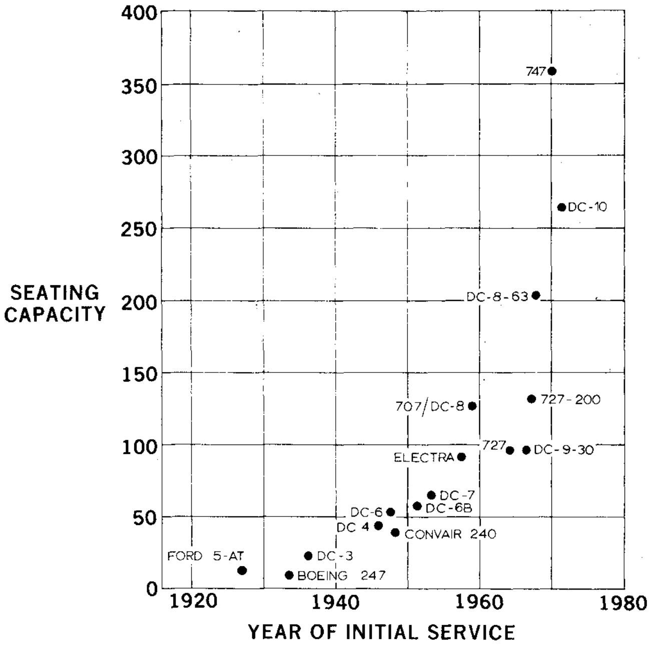

Fig. 4 Growth of passenger capacity.

along with economic gains in the majority of steps.

In 1958 that changed. The jet transports of the 707/DC-8 class boosted speed to the threshold of the transonic region, greatly reduced operating cost, practically eliminated vibration, reduced internal noise almost as much as one could want, and essentially eliminated ride roughness as a significant problem by high-altitude flight, high-wing loading, and the speed and climb performance to go around or above most bad weather. One knew that these aircraft would be a hard act to follow!

Twenty years later, these aircraft are still in service on major routes. Although the current "wide-body" generation of aircraft bring together much improved high bypass ratio turbofan propulsion, many modest improvements in aerodynamic components such as airfoils, flaps and slats, and structural gains in construction and material properties, their functional benefits are primarily associated with large size. From the coach passengers' standpoint, the advantages were 2 in. in seat width and a high ceiling. Speed, cabin environment, and even range are essentially unchanged. Of course, high bypass ratio turbofans and acoustically treated nacelles have achieved large reductions in community noise. In the late sixties, the conventional wisdom in the airline and aircraft industry believed that no passenger would fly in the "long narrow tubes" after experiencing the wide body. One engine manufacturer's marketing study predicted "passenger preference for these [wide-body] aircraft will have nearly as dramatic an effect on the industry as the introduction of jets in the early 1960's." In truth, the wide-body preference is rather marginal, certainly not enough to generate many new trips. And, with the trend toward higher density seating, i.e., from nine to ten across in the 747 coach and from eight to nine across in DC-10/1011, the seat width advantage over the 707/DC-8 will drop to 1 in. One cause of the aircraft production decrease in the early and mid-seventies was that the expected phasing out of 707's and DC-8's due to functional obsolescence did not occur. These aircraft, some of which are twenty years old, will be forced out by 1985 only by community noise requirements, even though the unanticipated fuel cost increases of the seventies favor replacement by more efficiently powered aircraft. In fact, some of the DC-8 stretched aircraft will be re-engined with high bypass ratio

Table 1 Technological Advances in Transport Aircraft

Approximate year	Aircraft	Multi-engine	Engine cowl	Flaps	Cantilever wing	Load carrying skin	Retractable landing gear	Engine superchargers	Cabin superchargers	Compound engine	Turbine Engines: Turboprop	Turbine Engines: Turbojet	Swept-back wings	Rip-stop structure	Turbofan engines	Leading edge slats	High bypass ratio turbofan
1927	Ford Trimotor	√	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1933	Boeing 247	√	½	-	√	½	√	-	-	-	-	-	-	-	-	-	-
1936	DC-3	√	√	√	√	√	√	-	-	-	-	-	-	-	-	-	-
1939	Stratoliner	√	√	√	√	√	√	√	√	-	-	-	-	-	-	-	-
1946	DC-4	√	√	√	√	√	√	√	-	-	-	-	-	-	-	-	-
1947	Constellation/ DC-6/240/202/ Stratocruiser	√	√	√	√	√	√	√	√	-	-	-	-	-	-	-	-
1952	DC-7/1049	√	√	√	√	√	√	√	√	√	-	-	-	-	-	-	-
1955	Viscount/ Electra	√	-	√	√	√	√	-	√	-	√		-	-	-	-	-
1953	Comet	√	-	√	√	√	√	-	√	-	-	√	½	-	-	-	-
1958	707/DC-8 Turbojet	√	-	√	√	√	√	-	√	-	-	√	√	√	-	-	-
1961	707/DC-8 Turbofan	√	-	√	√	√	√	-	√	-	-	√	√	√	√	-	-
1965	727/DC-9-30/ 737	√	-	√	√	√	√	-	√	-	-	√	√	√	√	√	-
1970	747/DC-10/1011	√	-	√	√	√	√	-	√	-	-	√	√	√	√	√	√

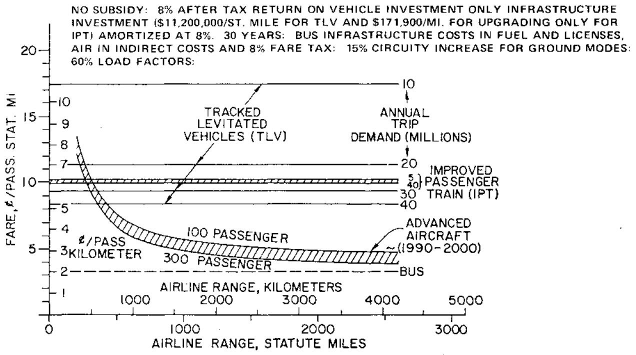

Fig. 5 Comparative fares ($ 1974) for various transportation modes.

power plants that will extend their lives through the 1990's.

So eleven years after the introduction of jets, the industry brought forth new airplanes that did not fly significantly faster or more comfortably. And nine years after that, we still cannot go faster without a large cost penalty. On this basis, pending the development of a cost-competitive, environmentally acceptable supersonic transport, the design of transport aircraft may be deemed to have reached technical maturity. Some seers have compared the airplane design field to the railroads or naval architecture—examples of fields that reached maturity and withered. It can be shown, however, that this analogy is a poor one.

The growth of air travel was associated with improvements in speed, comfort, safety, and cost. Although we have reached a plateau in speed and comfort, the 747/DC-10/1011 aircraft have continued the progress in cost, an equally important characteristic. Even with a performance plateau, improving cost leads to market growth, as the large 1978 traffic increases stimulated by reduced fares have shown.

Air Transportation—the Dominant Public Mode

The fundamental reason for the importance of aeronautical technology is shown in Fig. 5,[27] in which the economics of the competitive public intercity transportation modes are compared in 1974 dollars. The fares shown cover total costs and return on investment and do not necessarily equal fares charged. The lowest cost mode is the intercity bus. The bus also has the lowest speed. At ranges beyond 300 statute miles (500 km), the airplane is the next most economical mode, coming surprisingly close to the bus, with great performance advantages. At lower ranges, the improved passenger train (IPT), such as the Metroliner, is less expensive than the airplane. Comparative total trip times are heavily dependent upon the access/egress characteristics of specific city pairs. The economics of the exotic track-levitated vehicles (TLV) is a function of demand because of the very large fixed investment. At high annual demands, up to 40 million riders per year, this 300 mph mode can compete with aircraft economically out to 400 statute miles (645 km), with very competitive performance. As demand decreases to 20 million annual riders, the cost rises significantly, matching air only at ranges below 250 statute miles (400 km) while, at 10 million annual rides, TLV could compete only up to 100 miles (160 km). Such ranges are ill-suited to aircraft, except in special cases, and auto, bus, or IPT seem most effective. There are only a few corridors in the United States that can approach 10,000,000 annual rides.

It is clear that at moderate and long ranges air transportation has little effective competition from other public modes. Air transportation produces over 80% of all public carrier passenger miles in the U.S.[3]

Technological Development of the Future

What are the criteria by which successful aircraft of the future will be chosen? I would like to suggest a simple

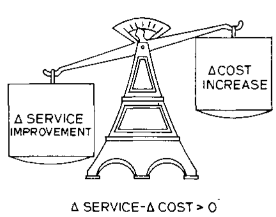

Fig. 6 Service-cost index.

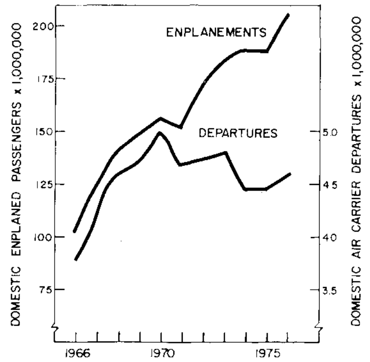

Fig. 7 Enplanements vs departures of domestic air traffic.

semiquantitative figure of merit—specifically, the improvement in service offered by a new design reduced by the increase in cost or the service-cost index. Each succeeding airplane type must provide an increase in service that has a sufficiently greater value than the associated increase in cost or, correspondingly, a decrease in cost that is substantially greater than any possible decrease in service (Fig. 6). In the past, the service has usually improved while accompanied by a cost decrease (Figs. 1 and 2). In the "wide-body" era, the service improvement was small, but the cost decreased significantly. Also, the large capacity was very significant in reducing the number of aircraft operations even while passenger traffic continued to grow (Fig. 7).[4] Airport/airway congestion was thereby reduced. Furthermore, improved fuel efficiency is important in itself, provided the service-cost criterion is satisfactory.

With this view of the present status of airline aircraft, what are the likely developments in the foreseeable future? Some potential technical directions have been pursued for decades without achieving significant acceptance in the marketplace. Others are beginning to be introduced into service. Among the possible new technologies are laminar flow control, nuclear propulsion, V/STOL propulsive lift, and supersonic transports. The latter is included, although the Mach 2.0 Concorde is already in service because, with direct operating costs three times that of the wide-bodied aircraft, the Concorde is a magnificent technical achievement but a technological failure. Technology is defined as "the application of scientific knowledge to practical purposes."[5] Practical purposes involve the economic ability to use the product—a severely limiting aspect of the Concorde. Other developing or possible technologies include hypersonic transports, hydrogen-fueled transports, propfan powered aircraft, improved transonic airfoils, active controls, advanced filamentary composite materials, and improved turbofans.

Laminar Flow Control

Laminar boundary layers can be obtained in flight by proper airfoil design and continuous removal of part of the boundary layer by applying suction over the surface of the wing or body.

Laminar boundary layers offer very large reductions in skin-friction drag. Figure 8[6] shows the comparison between the skin friction of the turbulent boundary layer, normally experienced in flight, and the laminar boundary layer as a function of Reynolds number. At the Reynolds numbers

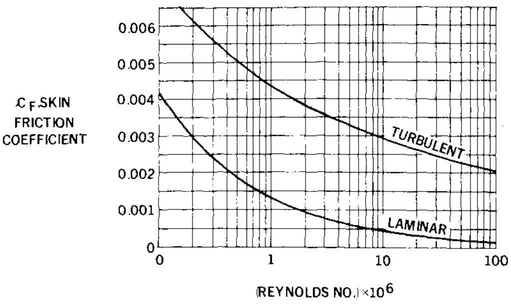

Fig. 8 Laminar and turbulent (Karman) skin-friction curves.

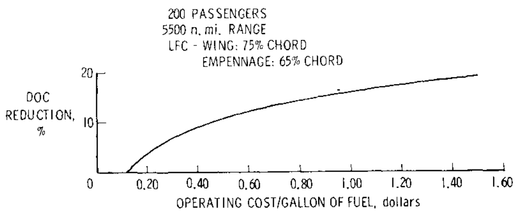

Fig. 9 Effect of fuel price on economic advantage of laminar flow control.

typical of transport aircraft in cruise flight, between 20 and 70 million, the potential reduction in skin friction approaches 90%. In addition, reducing skin friction diminishes the associated pressure drag. There is no other way to achieve such a large drag savings. The pure turbulent skin friction of a typical airplane accounts for three-quarters of the total parasite drag and about 45% of the total cruise drag. Elimination of, say, 70% of this skin-friction drag, after allowing for the equivalent drag of the suction system power, can lead to overall drag reductions of 31% and an increase in the ratio of lift to drag of 45%. For a given mission, the large savings of fuel reduces the weight of the airplane, further reducing drag, and allows corresponding reductions in the size of the wing and tail because of the lower weight. Furthermore, with very low skin friction, the optimum airplane design is significantly changed. It becomes profitable to use lower wing loading because of the reduced wing parasite drag and achieve significant reductions in induced drag that result from the large span. Theoretically, the idealized design offers total improvements in the lift/drag ratio of the order of 50%. This is partly counteracted by the weight of the additional wing area associated with lower wing loading, by the higher construction weight of porous or slotted surfaces, and by the weight of the pumping system required to draw away the boundary layer. Of course, in a practical design, it would never be possible to achieve laminar flow over the entire aircraft; perhaps 75% of the wing and tail areas is a reasonable goal, but even this represents a reduction approaching 30% in parasite drag and a lift/drag ratio increase of 30%, including span effects associated with the resized wing. The exact values are dependent on the particular design since they are functions of the relative surface areas of the wing and fuselage. Corresponding reductions in direct operating cost have been estimated at over 10% by Goodmanson and Gratzer.[7] The potential gains are a strong function of fuel cost (Fig. 9).[8]

Since laminar flow control strives for significant reductions in drag, fuel consumption, and direct operating cost, it certainly offers a potential improvement in the service-cost index. The problem with laminar flow control has been the cost and difficulty of making wings with continuous suction capability, either through large numbers of holes or spanwise slots every few inches along the chord that were of sufficiently smooth quality so that the laminar flow could be maintained. Even in cases where this has been successfully achieved in occasional flight tests, there is the continual concern about dirt or insects, the presence of which creates sufficient roughness to change the laminar flow boundary layer to a turbulent one and destroy the possibility of achieving the expected drag gain.[9] There are associated maintenance problems with the suction system. Because of these difficulties, efforts toward laminar flow control had almost ceased in the 1960's.

The realization in recent years that the fossil fuel supply is limited and the sharp increase in fuel prices have stimulated reconsideration of laminar flow control. The National Aeronautics and Space Administration is sponsoring extensive research of laminar flow control (LFC) techniques as part of its Aircraft Energy Efficiency (ACEE) program. The work, both within NASA and through contracts with industry, covers every aspect of the problem.

Technology developed since the pioneering work with the X-21A aircraft by Northrop and the Air Force[9,10] in the early 1960s promise a more practical system. Computational aerodynamics permits the development of airfoils with favorable supercritical characteristics, while retaining a pressure distribution conducive to laminar flow. Boundary-layer stability calculations have been programmed to optimize the suction distribution required to control the amplification of disturbance waves in the laminar boundary layer to avoid transition to a high-drag turbulent layer. Many material and structural design alternatives for suction wing construction are being investigated. The most common basic concept is still the slotted wing. Advanced graphite/epoxy composite materials hold the hope for smoother surfaces, although structural concepts also include aluminum-riveted skin-stringer construction, bonded aluminum, titanium, titanium honeycomb, and fiberglass.[11] Porous surfaces that would permit uniform suction and minimize the disturbances from the slots in the boundary layer are being analyzed.

Since insects occur only at low altitude, a possible solution to the LFC insect problem has been shown to be a continuous flow of water through orifices on the wing leading edge during takeoff and low-altitude climb. This approach may produce an icing problem further back on the wing. A deicing fluid may have to be used. The fluid weight has been estimated to be about 1% of the takeoff weight.

Acoustic disturbances from turbine engines can cause laminar boundary-layer flow to become turbulent. It, therefore, appears that an LFC airplane will have aft-mounted engines.

The likelihood of the introduction of LFC into airline service depends upon the construction and maintenance cost of the slotted, or porous, suction surfaces, system reliability under all weather conditions, and upon the solution of the insect and dirt problem. Since the NASA LFC program contemplates completing flight tests at the end of 1986, the earliest possible timing of LFC introduction is in the mid-1990s. The concept is unusually risky because the optimum LFC wing area is much larger than a conventional design. If an LFC airplane were to be operated without suction, it would not just regress to a representative turbulent boundary-layer airplane, it would be a badly misdesigned turbulent boundary-layer aircraft—an economic disaster. On the other hand, the potential fuel savings are very large. We conclude that LFC has great energy efficiency and moderate economic potential, but remains rather speculative.

Nuclear-Powered Aircraft

Nuclear-powered aircraft were explored in considerable detail starting in the 1950s. Studies indicated that feasible nuclear aircraft would be possible with gross weights of the order of a million pounds. Certainly most of those who worked on these studies, although aware of the handicaps of high-shielding weight and certain radiation risks, felt that by 1970 nuclear aircraft would be flying. A major problem was

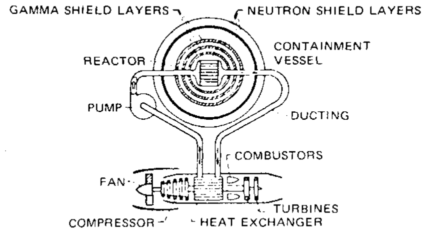

Fig. 10 Schematic drawing of a nuclear aircraft power plant.

the required weight of the reactor shielding to protect the crew and passengers (Fig. 10).[12]

Today, over twenty years later, it appears that nuclear-powered aircraft would require a takeoff weight of perhaps 1.5 million lb to carry a practical payload.[12] This may not seem to be an insurmountable obstacle since the 747 is already approaching 800,000 lb gross weight. However, the technological advances that would lead to greatly reduced nuclear shielding weights have not occurred and the development of flight weight reactors and heat-transfer equipment has made only slow progress. Because of the total power plant weight, it seems that the payload carrying ability would be comparatively small, even though the large fuel weight requirement of conventional turbine engines has been eliminated. The increased price of fossil fuels is certainly a favorable factor for the relative economics of the nuclear airplane. On the other hand, the costs of nuclear power plants and fuel, and the cost of the airframe to carry the heavy power plant, are such that even with high fossil fuel costs it is not at all clear that there would be an economic gain, or even a close equivalence. The high investment costs appear to outweigh the fuel savings, at least in the author's opinion, until the gross weight approaches 2.5-3 million lb.

In addition, environmentalists are deeply worried about even stationary nuclear power plants located in relatively isolated areas and protected by enclosures in which weight is no problem. Obtaining the equivalent security with lighter weight shielding and encasement, and soothing the concerns over carrying the nuclear plant in an airplane which might crash in populated areas, seems to be an almost insurmountable task. The experts' words about feasibility sound very much like they did twenty years ago, but the goals that would have to be met to overcome environmentalists' concerns are much greater. Nuclear aircraft for commercial transport purposes are very definitely not on the near horizon and will not be seen in this century.

Short Takeoff and Landing (STOL) Aircraft

Let us now turn to the use of short takeoff and landing (STOL) aircraft in short haul transportation. This development is of a different nature than laminar flow control and nuclear aircraft in that the technology has been sufficiently developed to establish feasibility. The uncertainties are matters of design optimization and the impacts on cost and reliability of complex control systems rather than fundamental questions of feasibility.

A STOL aircraft is generally understood to require a runway length of 2000–2500 ft or less and utilize propulsive lift. The fundamental problem with STOL arises from the fact that direct operating costs increase as design runway length is reduced. While true for any airplane, this trend is especially marked below 3000 ft. A 1973/1974 detailed study of a short haul air transportation system in the California Corridor,[13,14] showed that any runway length below about 4000 ft serves primarily to increase system costs. The normalized direct operating costs used in this study are plotted against field length in Fig. 11, along with more recent (1978) data from Ref. 15 which show the same trend. Furthermore, on a high-density 300 n.mi. route, the required increase in fare, Fig. 12, is large compared to the prorated amortization cost of

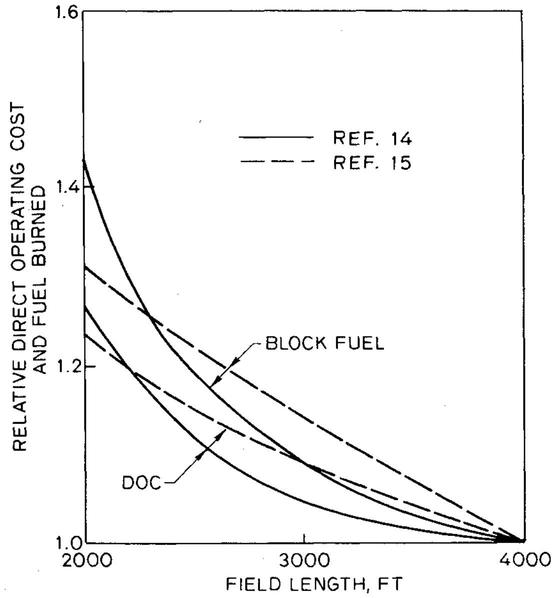

Fig. 11 Normalized direct operating cost and fuel consumption for STOL aircraft.

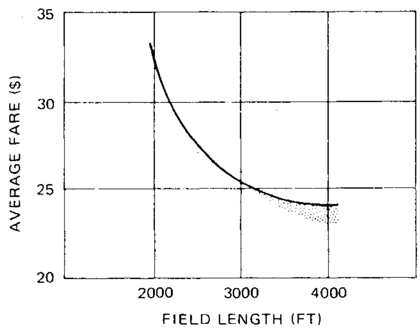

Fig. 12 Fare vs design field length in the California Corridor for quiet propulsive lift aircraft.

another 1000 or 2000 ft of runway length.[14] The fare is calculated to cover direct and indirect costs and provide a 12% return on investment after U.S. corporate taxes. It has been argued often that only a 2000-ft runway or less can be located close to city centers. There are few places, however, that can accommodate a 2000-ft runway but not a 3000- or 3500-ft runway. Equally important is the fact that environmental considerations such as noise, safety, and congestion will prevent any significant number of city-center STOL-ports anyway.

Another potential use of short haul STOL aircraft is to utilize short, nonconflicting runways on existing large congested airports to increase airport capacity. In most cases, such runways could be 3500-4000 ft in length. Both Fig. 13 from Ref. 15, and Ref. 14 indicate that above approximately 3500 ft, mechanical (conventional) flaps become more efficient than propulsive lift. In Fig. 13, USB and MF designate upper surface blowing and mechanical flap, respectively, while QCSEE designates NASA's quite clean short-haul experimental engine. Thus, propulsive lift is not required for this application.

The final nail in the coffin of high-density commercial STOL is fuel consumption. The relative fuel requirement for a 150 passenger aircraft at 300 n.mi. range is shown in Fig. 11 as a function of required field length.[14] The 2000 ft runway case uses 33% more fuel than the 3000 ft design and 44% more than the 4000 ft design. This trend is confirmed by the relative fuel-burned characteristics of a 150 passenger aircraft at a design range of 500 n.mi. from Ref. 15, also shown in

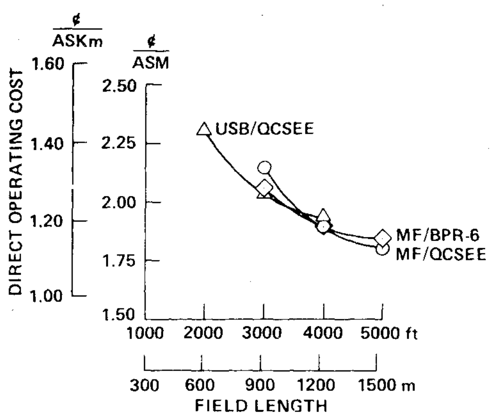

Fig. 13 Direct operating cost for minimum DOC STOL aircraft as a function of field length.

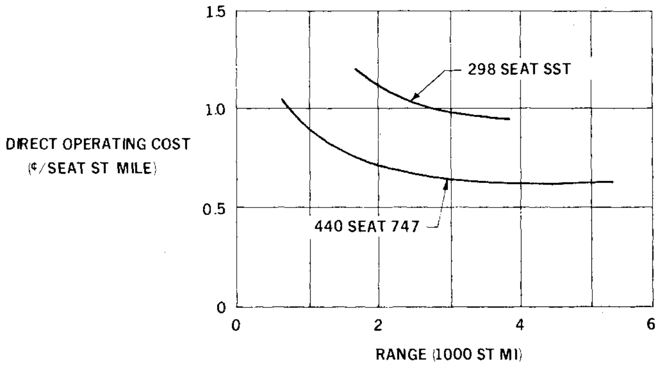

Fig. 14 Comparison of direct operating costs for the Boeing SST and 747 airplanes.

Fig. 11. The increasing value of fuel conservation as a virtue in itself will further negate the development of STOL aircraft.

Vertical takeoff and landing (VTOL) aircraft are the limiting cases of STOL with high costs and fuel consumption. For those special situations where no runway is available, VTOL is invaluable. Thus, production of helicopters has soared, but the economics of VTOL, as with STOL, will limit applications to possible military purposes and to small aircraft responsive to very specialized needs. VTOL aircraft cannot be expected to make a significant impact on air transportation.

Supersonic Transports

The most controversial subject in aircraft technology for the last decade has been the supersonic aircraft. In the United States, supersonic transports were first predicted to have a viable future in the late 1950's. About the same time, several aircraft companies and NASA began intensive configuration studies and development efforts. The project was buffeted by alternating waves of optimism and pessimism with respect to obtainable ratios of payload to gross weight and lift to drag and the anticipated economics.

The development process of the supersonic transport represented a fundamental departure from previous commercial aircraft. The capital investment required for development, flight test, and production tooling was so large that no single aircraft company, or even a consortium of them, could afford to undertake the project. In the United States, therefore, the government undertook a program whereby 90% of the development funding was to come from the government and the remaining 10% from private industry. The government's investment was to be returned eventually from the proceeds of the sale of the aircraft. Very large markets, projected as high as 500 aircraft, were anticipated. In Europe, the British and French governments had joined earlier to develop the Concorde with the same expectation of recovering the investment from the sale of the aircraft.

In 1979, we find the United States supersonic transport program nonexistent, having been cancelled in 1971, and the Concorde successfully operating on a small scale. The U.S. supersonic transport candidate, the Boeing 2707, died from such a complex illness that even today the primary cause is not clear. Some people remember the environmental problem as the prime objection, including both noise and the concern over reduction in the ambient ozone concentration at high altitudes; others think the SST was the victim of a dramatic reordering of national priorities that coincidentally occurred about that time; while still others feel that its economic disadvantages were the major cause.

A strong case can be made for the point of view that the dubious economics of the project was a prime reason for its demise. In 1969, the Boeing 2707 had an estimated direct operating cost almost 50% higher per seat mile than that of the 747, as shown in Fig. 14.[16] The 2707 had a cruise speed slightly over three times as high as current subsonic aircraft, a small decrease in comfort resulting from the supersonic drag requirement for a narrow body, and an increase in direct operating cost much higher than any transport aircraft had ever been able to tolerate. We were faced with the very difficult problem of trying to determine whether or not our basic figure of merit, Δ service − Δ cost, is improved. Neglecting the small decrease in comfort, since the shorter flight times would more than compensate for this, it is simply a question of how much more the passenger will pay to save a given amount of time. Also affecting SST economics was the sonic boom. Since the sonic boom was and is a serious environmental problem, eliminating flight over populated land areas, the market for the aircraft was substantially decreased.

As a result of the enormous increase in fuel price in recent years, the original 50% higher direct operating cost the SST suffered with respect to the 747 would have increased to about 85% higher cost with the triple fuel prices typical of international fuel costs of the mid-1970s and even higher with 1979 fuel costs.

Consideration of indirect costs and the necessary return on the very high investment per seat would have led to 2707 fares about 31% higher than the wide-body subsonics in the framework of 1972 dollars and fuel costs. The tripling of fuel prices would have raised this value to more than a 45% increase in fare.

The Concorde, a fantastic technical achievement, has a considerably higher direct operating cost per seat mile than the once-planned 2707, a higher investment cost per seat, and a lesser block time advantage. Concorde direct operating costs are three times the current subsonic costs based on 1976 fuel prices, Fig. 2, and total operating costs are about twice the subsonic level. Although there are certain people who will pay well over $100 to save an hour of time, it would appear that this is a very small part of the market. Such fares cannot attract a sufficient number of passengers to make a significant impact on air transportation.

Since the demise of the Boeing 2707, a small but vital and productive supersonic cruise aircraft research (SCAR) program has been pursued by NASA. Working both in-house and through contracts with industry, important advances have been made in aerodynamics, structures, and propulsion. Supersonic drag has been reduced by developing blended wing-body configurations (Fig. 15) which significantly reduce frontal area, assuming claustrophobia is not a problem. Optimum wing planform, twist, and camber analysis has shown significant improvements in lift/drag ratio (Fig. 16). Major advances in the concept of variable cycle engines have been attained which would permit engines that can operate as turbofans in subsonic flight, reducing takeoff and landing noise and raising subsonic cruise efficiency, and as jets for efficient supersonic cruise. Coannular nozzles, with the faster

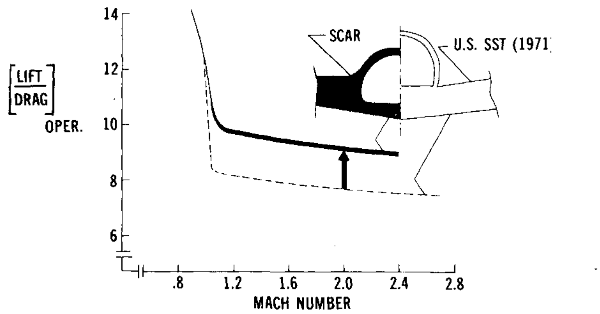

Fig. 15 Improvement in supersonic lift/drag ratio due to blended wing-body configuration (courtesy National Aeronautics and Space Administration).

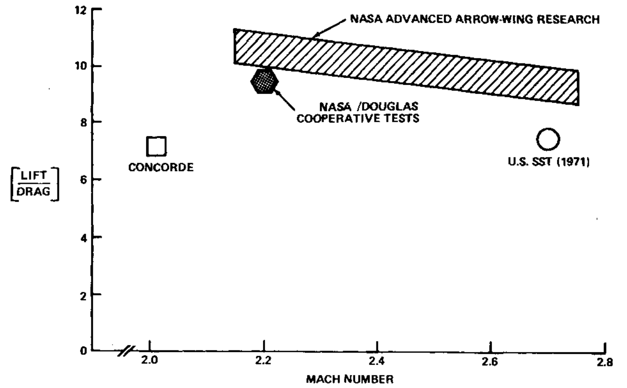

Fig. 16 Comparison of improved supersonic lift/drag ratios with Concorde and the U.S. SST (1971) (courtesy National Aeronautics and Space Administration).

higher temperature exhaust stream on the outside, have demonstrated significant noise reductions. Improved titanium manufacturing methods, such as superplastic forming, composite materials where applicable, and new structural concepts offer significant cost and weight savings.

The supersonic transport, whose development could be started in 1979, is much improved over the cancelled 1971 vehicle. In fact, if 1971 fuel costs still prevailed, direct operating costs would probably be no more than 20-25% above the wide body with required fares of the order of 12-15% higher. With prevailing international fuel prices of about 90 cents/gal vs 11 cents/gal in 1972, it is reasonable to expect a second-generation SST direct operating cost of 50-55% above the wide bodies. Of course, the subsonics in the mid-1990's when the second-generation SST may enter service will also have reduced costs due to fuselage extensions and advanced technology. Fare differences of 35-45% may then exist—an enormous improvement compared to the roughly 100% now in effect on Concorde.

The major question is how much of the market this huge supersonic performance advance (Δ service) will gain with a significantly higher fare (Δ cost). Although this is very subjective, it is doubtful that even the lower end of the fare possibilities would gain a very large market share. Although the market elasticity is not well-established, economic viability would be difficult—even if the goals were met and the product brought to the market.

Other impediments to a second-generation SST are environmental, financial, and political. The community noise problem must be solved probably to the same standards as any other airplane at the time of introduction. Minimizing nitrogen oxide emissions in the engine exhaust at cruise will probably be a requirement, although the high-altitude ozone problem associated with this seems to have become much less well defined than it appeared a few years ago. It may not even be a problem. The difficulty is that without convincing proof

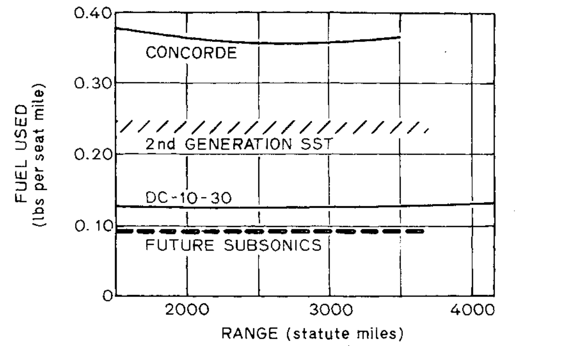

Fig. 17 Comparison of subsonic and supersonic transport fuel consumption.

that it is not a problem, the known ecological degradations of recent decades has led to a conservative approach. The burden of proof lies with the new technology.

The financial problem is enormous. The research, development, and tooling costs have been estimated at five to seven billion 1977 dollars,[18] far beyond the capability of the aircraft industry. A nationalized program and consortium of manufacturers, and possibly of governments, would be required to provide capital of this magnitude. This kind of financing requiring governmental participation makes program approval especially sensitive to environmental lobbies questioning the adequacy of the studies which must necessarily clear the upper atmosphere and noise problems. The much greater fuel consumption compared to the subsonics (Fig. 17) remains a potential political problem even if the economic criterion of total cost per seat mile is shown to be acceptable.

In conclusion, even with a large, well-financed research program, it is questionable whether an environmentally acceptable, economically viable supersonic transport will evolve. Difficult technical problems still remain, particularly the mechanical reliabilty and efficiency of the variable cycle engine. Whether the United States will adequately fund this research and, later, the full program, remains the decisive question. But there is no doubt that the supersonic transport is the one technology that potentially offers a large step forward in functional capability and a large increase in service.

Hydrogen-Fueled Aircraft

A fertile field of study for future transport aircraft is the use of alternative fuels. Liquid hydrogen is the most spectacular of these possibilities. Liquid hydrogen benefits first from its high-energy content per pound. As shown in Table 2, hydrogen has 51,560 Btu/lb compared to 18,600 Btu/lb of jet A fuel, a ratio of 2.8. Since weight is so important in aircraft design, there is an enormous advantage in reducing the weight of fuel required. The disadvantage of hydrogen is its low density. Since a pound of liquid hydrogen fills 11.0 times as much volume as a pound of kerosene, the overall result is that, for a given amount of energy, hydrogen requires a volume that is 3.9 times as large as jet A.

Table 2 Comparative characteristics of liquid hydrogen and synthetic jet A fuel (1976 dollars)

	Synthetic jet A	Liquid hydrogen, LH2	LH2 / Jet A
Heat of combustion, Btu/lb	18,600	51,560	2.8
Liquid density, (lb/ft^3)	48.6	4.43	0.091
Price (120,940 Btu, the energy in 1 gal jet A, based on $20/ton coal)	67¢	82¢	1.22
Thermal efficiency, coal-to-fuel	54%	49%	0.907

The result of these characteristics is that a hydrogen powered aircraft looks quite different from a conventional jet fuel-powered aircraft. The differences are in the use of a very large fuselage to carry the additional fuel or, alternatively, in the presence of very large bodies placed on the wings to provide the extra tankage. This increased volume increases structural weight and drag. On the other hand, the much lighter quantity of fuel required greatly reduces the takeoff weight and permits smaller wings and engines.

Studies by Lockheed[19] and Douglas[20] have indicated that subsonic hydrogen-powered aircraft, designed for ranges of 3400 to 5000 miles, respectively, would have takeoff weight reductions of 26-34% and engine size reductions of 0-30%, but a weight empty reduction of only 7-10%. The reason for the small reduction in weight empty is that the reductions in structural weight due to the lighter takeoff weight and smaller engines are largely balanced by the larger structural weight required to house the high volume of fuel. Because of the large reduction in average flight weight, even though there is somewhat more drag due to the large fuel storage requirements, the fuel energy requirement is down approximately 5-20% and the fuel weight by a very large 65-70%. More recent Lockheed studies[21] are in general agreement with these results.

The economics of hydrogen aircraft is a different story. Hydrogen is expensive to produce and expensive to liquify. In Ref. 22, the cost of a gallon of synthetic jet A fuel produced from $20/ton coal is estimated at 67 cents, while the cost of liquid hydrogen with the same energy, 120,940 Btu (127,600 kJ), is estimated at 82 cents in 1976 dollars (Table 2). Since the comparable cost of petroleum-based jet fuel is about 30 cents (1976 dollars), both alternate fuels are much more expensive than the natural product. Although hydrogen costs are 22% higher than synthetic jet A per unit of energy, the lower fuel energy required by a hydrogen-fueled airplane at long range may make the total fuel costs about equal. A recent Lockheed study[21] shows the operating costs of a long range 5500 n.mi. (10,200 km) aircraft using hydrogen to be the same as a synthetic jet fuel aircraft with $10/ton coal and about 7% less with $30/ton coal. The study assumed significant savings in engine maintenance and efficiency with hydrogen. The cryogenic fuel system, on the other hand, penalizes the hydrogen aircraft.

Table 2 also shows the relative thermal efficiency[22] of the processes converting coal to jet A or liquid hydrogen. The latter loses 10% more energy in the process but, since the long-range hydrogen aircraft uses up to 20% less onboard energy, the hydrogen aircraft uses less effective fossil energy. At medium and short ranges, hydrogen is less advantageous (Fig. 18).[23]

A serious problem with hydrogen is that an entirely new logistic system for the transportation, storage, and handling of fuel would be required at airports throughout the world. The investment would be extremely high. Results in Ref. 24 lead to a 1978 estimate of about $400,000,000 capital cost for hydrogen liquification, storage, and distribution facilities for San Francisco Airport. Nationwide, this investment would be $5-10 billion, an enormous capital requirement. Of course, the capital investment in coal gasification or liquefaction facilities would also be substantial.

It has been said that we have a limitless supply of hydrogen in the oceans. Unfortunately, the electrolysis of water to produce hydrogen results in costs about four times as high as conventional jet fuel. Another important problem with production of hydrogen from water is that the electrolysis process plus liquefaction requires 4.2-4.9 Btu of heat energy to produce 1 Btu of liquid hydrogen. Unless the 4.2 Btu can come from some unlimited source of power, such as fusion or solar sources, this does not appear to be the way to conserve energy resources. One advantage that would accrue from hydrogen is that it is a nonpolluting fuel. However, the pollution effects of present aircraft are limited to the immediate vicinity of the airport and, with improved engine design and operational methods, the objectionable kerosene smell from ground operations should be substantially reduced. Thus, the advantage of hydrogen in air pollution is small.

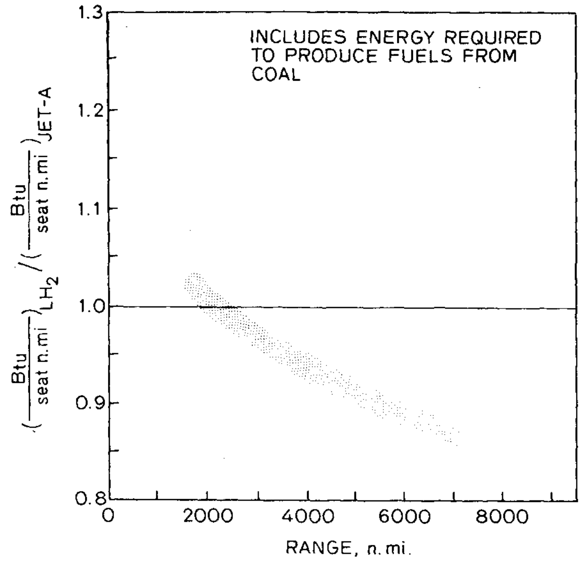

Fig. 18 Effect of range on the relative energy efficiency of liquid hydrogen, LH_2.

Because of the high cost and major revision of the supply and logistic system required for the use of hydrogen, it is not believed that hydrogen aircraft will play any role in commercial aviation through the year 2000. Based on the ability to produce synthetic jet fuel at about the same cost from coal as hydrogen, after considering the impacts on the aircraft, it seems likely that the greater risk and investment of the hydrogen system will stall its implementation—until cheap, unlimited energy becomes available from fusion and/or solar sources. Then, hydrogen produced from water by electrolysis or some thermochemical system could provide the portable form of this fusion and/or solar energy. But, until all ground electric power is provided by fission, fusion, or solar, it is inefficient to use electricity to produce hydrogen.

Propfan-Powered Aircraft

New developments in an old technology plus the rise in fuel costs and the energy conservation ethic have revived interest in turboprop aircraft. The turboprop airframe itself is not necessarily technologically different at a given design Mach number from that of a turbofan. The turboprop propulsive system offers lower fuel consumption at the expense of the maintenance cost, noise, and vibration of propellers and, in the past, lower cruise speeds. Application of improved transonic airfoils, swept blade tips, high solidity ratios obtained by using up to eight blades, and improved materials now offer propeller efficiencies approaching 0.8 at airline cruise speeds of $M=0.8$. Lower tip speeds help to reduce noise. This new form of propeller is being called a propfan due to its resemblance to a fan.

The integration of the propfan into an airplane involves many tradeoffs and the full realization of the improved propeller performance depends upon the evaluation of these tradeoffs (Fig. 19). The potential gain appears to be as high as 20% in fuel and perhaps 5-8% in direct operating cost with respect to aircraft powered by turbofans of equivalent technology. The actual gain after the design problems are fully explored may be less. Among the design problems are interior noise due to the propellers, requiring additional fuselage weight, propeller structural and mechanical problems, the disturbance to the supercritical wing flow due

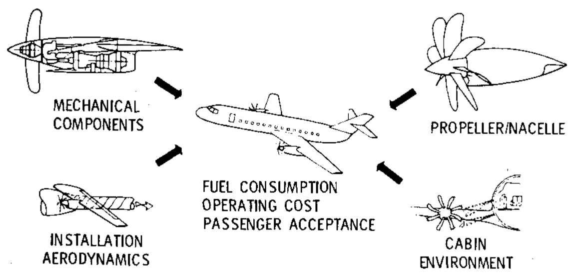

Fig. 19 Advanced turboprop tradeoffs.

to the slipstream, and the scrubbing losses of the slipstream on the surfaces behind them. Preliminary studies on propfan/wing interference show surprisingly little adverse interference. If the cost gains are retained at current speeds after these matters are thoroughly explored, and if the interior noise can approach that of the jets, a problem far from solution even with propeller tip-fuselage clearances of 5-10 ft, the turboprop may return to the airways. Although a step backward to the mechanical problems of propellers and possible increased cabin noise and vibration will be difficult to take, the potential fuel and cost benefits demand full study of this concept.

The main nontechnical obstacle to propfan implementation is probably development cost. Unless the military develops a requirement for such an airplane (the Navy reconnaissance mission may be suitable), the cost of developing and proving a new turboshaft engine and a propfan will be hard to justify. The aircraft manufacturers and the airlines will certainly hesitate to commit huge sums until a service-proven propfan and engine exist. On the other hand, compared to a laminar flow aircraft, the propfan risk seems modest and the potential gains almost as great. If the goal is a 20% fuel gain, the propfan seems to be the clear choice over laminar flow control.

Hypersonic Transport (HST)

The hypersonic transport (HST) represents an even larger technological step forward from SST technology than the SST requires with respect to current subsonic jet technology. The most optimistic analysis would not predict the advent of a commercially feasible HST before the end of the century.

Technologically, an HST requires significant advances in propulsion, structures, and aerodynamics. A dual-mode propulsion system is required: turbojets for subsonic and low-supersonic speeds and ramjets or scramjets (supersonic combustion ramjets) for hypersonic cruise. Such a dual system introduces the need for complex separate controls, as well as variable inlet and nozzle geometry and doors to close the inoperative engines. Because of the extreme engine temperatures, an engine cooling system would be required, with cryogenic liquid hydrogen appearing to be the best heat sink available. The hydrogen coolant would then flow to the engine combustion chamber and serve as the fuel. The logistics of hydrogen fuel is a complicated problem in itself.

The structural design problems of an HST are as formidable, if not more so, than those of the propulsion system. Most notable is the fact that the stagnation temperature of a Mach 6 HST at 100,000 ft would be almost 3000°F. Such temperatures would require either the use of high-temperature materials or normal aircraft materials coupled with a thermal protection system. Three candidate thermal protection schemes are active cooling, insulation, and radiation shields, or combinations of the three.[25] Large temperature gradients through the aircraft represent additional complications, not to mention containment and insulation of the cryogenic hydrogen fuel. Any solution to these problems must be economically reasonable, demanding low manufacturing cost, long life, and low maintenance.

Aerodynamic considerations, though less severe than propulsive and structural problems, demand significant state-of-the-art improvements. For example, static longitudinal stability variations with increasing Mach number would require a sophisticated fuel-management system to avoid excessive trim drag.[25] Directional stability is also a problem that is aggravated at higher Mach numbers.

In summary, the technological advances required before an HST is technically feasible, let alone economically plausible, are significant.

Economic performance of an HST is highly speculative, although one study[25] indicates marginal economic viability. Development and production of an HST would require an extremely large capital investment exceeding $10 billion.[25] Such an investment is beyond the means of most national governments, let alone private enterprise. The development of HST, then, would probably require an international cooperative effort.

The environmental problems associated with an HST are probably more severe than those of an SST. One of the more important problems is the projection that a fleet of HSTs would produce water vapor in the atmosphere at a rate comparable to what occurs naturally. The resulting climatic impacts could be significant. Likewise, the effect of nitrogen oxide emissions may be serious and more difficult to control in hypersonic ramjets than in turbojets.

Like SST, HST would present a sonic boom problem. This would be most acute during climb and acceleration; during cruise at very high altitude, the overpressure is predicted to be less than 1 psf and, thus, less serious than the SST.

Near-Term Technological Advances

Although the exotic major potential advances are beset by difficulties in obtaining an acceptable service-cost index, by large financial obstacles to implementation, by environmental objections, or by combinations of these, significant technology gains will be introduced to improve the efficiency of subsonic transports in the near term, i.e., 5-15 years. These near-term technologies include active controls, improved transonic airfoils, composite materials, winglets, and improved turbine engine efficiency. For most of these, implementation will be gradual rather than a quantum jump such as the introduction of wing sweep and gas turbine power plants in jet transports.

Active Control Technology

A major technological effort has been concerned with the use of rapid response automatic control systems to provide static and dynamic stability for an aerodynamically neutrally stable or even unstable airplane, thereby permitting reductions in tail surface areas, to reduce loads generated by gusts and maneuvers and even to control flutter. For example, positive maneuver loads can be reduced by negative outboard aileron deflections which act to shift the load inboard (maneuver load alleviation—MLA), while gust loads can be reduced by dumping lift with both outboard and inboard ailerons and using elevator controls to reduce lift by pitching the airplane (gust load alleviation—GLA). Reducing gust loads would extend fatigue life and may even permit designing the structure to lower maximum loads. If maneuver loads are critical, maneuver load control will lower critical design loads. Using control action to prevent flutter would eliminate weight increases sometimes required to increase wing stiffness above that provided by a structure designed for strength. Cost and fuel savings would result from less tail drag and weight with smaller tail surfaces and less structural weight because of reliance on load and fatigue limiting by control systems.

Fundamentally, the concept replaces some tail area and structural materials with sensors, "chips," and actuators. Multiple fail-operative redundancy would be required. The higher acquisition and maintenance cost of the equipment will have to be balanced against weight and drag savings.

Nevertheless, automatic control, when properly developed and backed up by sufficient redundancy, has been demonstrating high reliability. A first conservative use of active controls in a new design would be to permit reduced static stability, but only to a level that is not unsafe but merely uncomfortable to the crew. Then the rare chance of failure will require increased pilot attention without introducing a hazard. Reduced static stability will permit smaller tail areas and a further aft center of gravity, thereby reducing tail surface weight and drag and trim drag. The associated reduction in direct operating cost has been estimated at 2-4% with an associated fuel savings of 4%. It now appears, however, that the rapidly growing experience in active controls will permit their use for gust and maneuver load alleviation not only in new aircraft but even in derivative versions of existing transport aircraft. Both Douglas DC-10 stretched fuselage versions and long-range Lockheed 1011 configurations are being designed with load alleviation to minimize weight penalties of span extensions. Weight empty savings up to 2-3% of total weight empty can be anticipated. Corresponding fuel savings would be about 1.5-2.5%. Thus, active controls have a fuel reduction potential, when fully implemented, of about 6%, with an operating cost reduction of 4-6%.

Improved Transonic Airfoils

Development of improved transonic or supercritical wing (SCW) airfoils, spearheaded by R. T. Whitcomb of the NASA Langley Research Center, is being pursued in many countries in universities, industry, and national laboratories. These airfoils offer a substantially higher Mach number for initial drag divergence, M_{DIV}, for a given airfoil thickness ratio (Fig. 20),[1] an excellent structural shape, and high maximum lift coefficient. Their only disadvantage is the large negative C_{Mo}, the pitching moment coefficient about the center of lift.

The main characteristics of the new airfoils are an increase in the loading toward the rear of the airfoil due to aft camber, the small curvature of the upper surface, and the tangency of the upper and lower surfaces at the trailing edge.

The large negative (nose down) C_{Mo} requires an increased download on the tail for trim. This increases the wing lift, and, since M_{DIV} characteristically decreases as lift increases, a part of the M_{DIV} gain is negated. In addition, a larger trim drag must be considered in evaluating airplane performance. To avoid excessive trim drag, less than maximum aft camber may be selected. This also serves to reduce the M_{DIV} gain. The supercritical airfoil M_{DIV} potential gain is shown in Fig. 20 to be 0.06-0.07. In practice, the trim requirement may lower this to an effective M_{DIV} gain of about 0.05.

There are various ways that one can use the transonic airfoil. First, the cruise Mach number can be increased by about 0.05 Mach number for a given wing sweep and thickness. This increased speed without structural weight penalty actually improves direct operating cost since direct operating cost varies almost inversely as block speed. Furthermore, the fuel burned is nearly the same.

Another way to utilize the improved transonic airfoils is to maintain current cruise speeds and either use less wing sweep, which increases the maximum lift coefficient and, for a given aerodynamic aspect ratio, decreases the wing weight or increase wing thickness ratio, which significantly reduces wing weight. The latter, however, increases airfoil profile drag. In practice combinations of thickness increase and wing-sweep reduction are studied to find the optimum configuration for any design speed. Significant benefits can be obtained if the design cruise speed is high enough to require thin wings, below about 12%, and/or sweepback angles above 20 deg with current airfoils. A typical current aircraft cruising at $M=0.82$ could benefit by about 3% in direct operating cost and 5% in fuel requirements. In addition, the reductions in wing weight and increases in thickness permit the use of higher aspect ratios with less weight penalty than heretofore. The higher aspect ratio raises the lift-drag ratio and further reduces fuel consumption. The further reduction in fuel may be about 8%.

Advanced Filamentary Composite Materials

Another major technological development is advanced composite materials for structure. These materials, composed of graphite or boron fibers in an epoxy binder or matrix, offer very superior ratios of strength and stiffness to density. Figure 21 shows a comparison of aluminum, steel, titanium, and graphite-epoxy composite materials in terms of specific tensile strength and specific tensile modulus.[26] The improvement over the conventional aluminum alloys is about 50%, offering very large reductions in structural weight. Composite materials do have difficulties, however. Since composites are not isotropic or homogeneous and lack the ductility of metals, the usual fittings and bolt and rivet fasteners cannot be used. A long development period has been necessary to learn to use the material with fibers running in various directions in order to optimize the strength and stiffness for specific applications. Many of these problems have now been overcome. Another difficulty has been the high cost of material and fabrication. With increasing use of composites, however, material costs, particularly for the graphite-epoxy composite, have dropped sharply. Furthermore, fabricators are learning how to handle the material efficiently. Many people working with composites now feel that the fabrication costs will eventually be lower than the fabrication costs of aluminum. As a result, there is reason to hope that use of composite materials will yield both weight and cost savings.

A third disadvantage of composite materials has been lack of experience. Aluminum structures have been used since the early 1930's. A great volume of knowledge, both in service and laboratory tests, has been accumulated about the strength, fatigue life, corrosion, and failure mode characteristics of various types of built-up aluminum panels and shells. Now, similar knowledge of composites is being accumulated. The NASA Aircraft Energy Efficiency (ACEE)

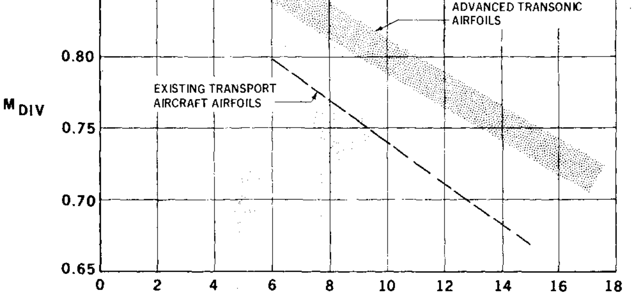

Fig. 20 Advanced transonic (supercritical) airfoil performance.

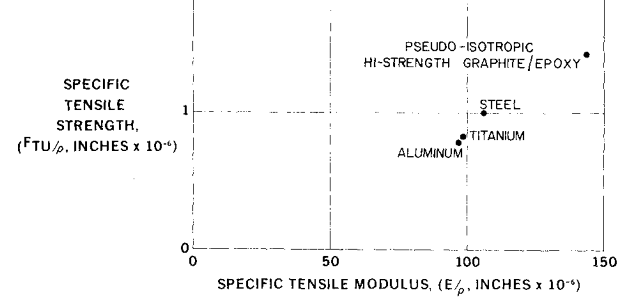

Fig. 21 Composite material specific strength and modulus comparison.

program is sponsoring the development of many secondary structural components along with extensive service testing. Rudders, ailerons, flaps, spoilers, slats, wheel well doors, vertical stabilizers, and in-military service, horizontal stabilizers are being flown. In general, the experience has been excellent. The materials are resisting water, sun, heat, and cold and show excellent fatigue characteristics.

Figure 21 would indicate potential weight savings of over 30% for pseudo-isotropic graphite-epoxy. In actual use, however, compromises have to be made at fittings and joints in order to maintain the integrity of the material. Some parts will have to be made of metal both at fittings and to provide current flowpaths in the event of lightning strikes. Because of poor fracture toughness (a result of low ductility), composites may not be usable in a pressurized fuselage shell—or if they are, a composite/metal mix may be necessary. It has been estimated in the past that up to 25% structural weight savings would someday be possible with composites. At this time, it seems that 15-20% is a better estimate. The corresponding fuel savings, after resizing the airplane due to the structural weight savings, will be about 7-10%.

In the next generation of aircraft, composites will be limited to secondary structure. The benefits will be 1/4–1/3 of the full potential, i.e., 4–6% in structural weight and 2–3% in fuel consumption.

Induced Drag Improvements

Another class of potential gain is the reduction of aerodynamic-induced drag. Significant progress in this direction has been achieved by R. Whitcomb of NASA's Langley Research Center using well-designed, endplatelike devices called winglets. A 4–8% decrease in drag appears possible with less wing structural bending moment increase than when obtaining the same induced drag reduction from simple span extensions. The drag gain due to winglets is dependent upon the original span loading of the wing. The net gain due to winglets applied to a well-designed, high-aspect ratio wing is not yet clear and may, in some cases, prove to be marginal compared to the technical risks of flutter and possible adverse effects at high-lift coefficients.

Propulsion

The history of aircraft has been closely identified with the development of aircraft propulsion. In fact, improvements in specific fuel consumption and in power to weight ratios of power plants, plus the invention of new types of propulsion such as the gas turbine, are probably the most important influences in airplane development. Therefore, one must anticipate significant propulsion improvements in the future. Nevertheless, at this time, only modest advances appear likely.

The logical extension for the present high bypass ratio turbofans is to still higher bypass and compression ratios. This development trend would lead to lower specific fuel consumption. The problem with the higher bypass ratios is, however, that as bypass ratio increases, the engine weight and the diameter of the engines for a given thrust increase. The result is that the drag and weight increases counterbalance the improvement in specific fuel consumption. Results of studies of the total effect of bypass ratio on transport aircraft have indicated the optimum bypass ratio to be between six and eight for both fuel and cost criteria with only small gains, about 2%, at bypass ratios above the present values of 5.0–6.0. Increasing compression ratios from current values around 25 to about 38 would improve efficiency about 4%. But these changes are associated with higher turbine temperatures, whereas an important requirement is to reduce engine maintenance costs, a goal usually obtained by lowering turbine temperatures. Thus, considerable technology in terms of blade cooling and materials is required. When the potential gains of mixer nozzles, component efficiency improvements, improved blade tip sealing (reduced leakage) are added to the cycle improvements, the potential gain in specific fuel consumption (sfc) is 12–15%. It is unlikely that all the gains will be realized, however, so a reasonable projection might be 10%. It is noteworthy that sfc was reduced from the original jets, 1958, to the first-generation turbofans, 1961, by 15%. By 1970, the high bypass ratio fans had reduced sfc by another 20%. The engines proposed for the next generation of transport aircraft, about 1983, are little different in sfc from the larger engines of 1970. A 10% further improvement by perhaps 1990 will be significant progress, but at a much slower rate than in the past.

The Next Generations of Transport Aircraft

The next generations of transport aircraft will be based on today's aircraft in general form, gradually improved by aerodynamic, materials, control, and propulsion developments and with design influenced by energy costs and availability. Based on the new Boeing 767 design, from the passengers' viewpoint, the main change is likely to be +1 in. in seat width if he is comparing with the original jet transports or −1 in. if he is comparing with the original wide-body coach configuration of the 747/DC-10/1011.

The large increase in fuel costs will change the shape of future aircraft. Aircraft configurations are usually optimized for minimum cost. One of the parameters affected is aspect ratio, the selection of which is a compromise between minimum fuel weight and cost obtained with high aspect ratio and lower structural weight and cost obtained with low aspect ratio. With higher fuel costs, optimum operating costs obviously occur at higher aspect ratios. The minimum fuel consumption aircraft would tend to have very high aspect ratio, excessive structural weight, and a rather high cost. If stability comes to fuel prices, aircraft design criteria are not likely to be based on minimum fuel usage, but rather on minimum operating cost with the expected fuel price. In any case, composite materials, when applied to primary structure, are particularly well-suited to higher aspect ratio designs, both because of the lower structural weight and because the high-elastic modulus will reduce weight penalties that might have to be applied for aeroelastic reasons as the span increases.

The improved transonic airfoils complement this scenario very well. For any design speed in the transonic region, the lower permissible sweepback angle and/or higher wing thickness ratio increase effective wing stiffness, favorable for the aeroelastic problems of high aspect ratio, and reduce the basic wing weight level. The fuel savings that can result from the supercritical wing (SCW), when used at today's cruise speeds and aspect ratios, is about 5%. The additional savings

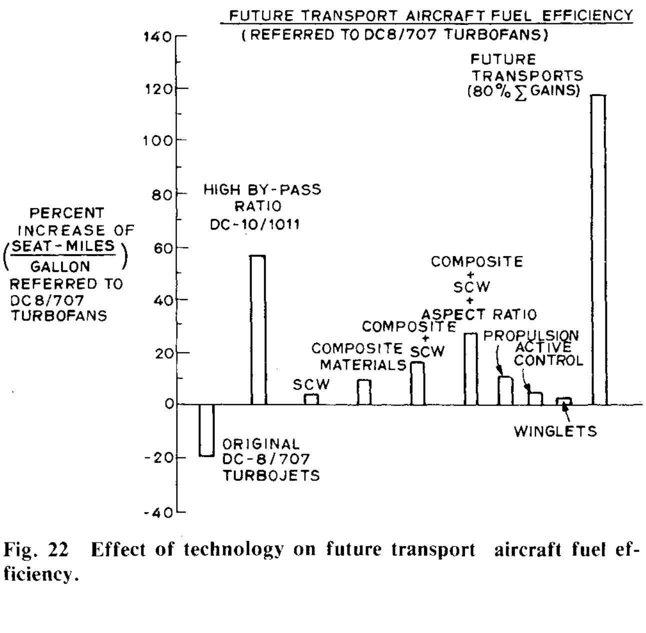

Fig. 22 Effect of technology on future transport aircraft fuel efficiency.

in fuel from full use of composite materials, perhaps in the 1990's, will be about 10%. The total fuel advantage is of the order of 15%. If, at the present cruise speeds, the aspect ratio is now increased to an optimum cost value with the thicker airfoils and lighter materials, a further fuel reduction of up to perhaps 8% will be obtained. These decreases in fuel usage can be translated into increases in seat-miles provided per gallon of fuel as shown in Fig. 22. Also shown in Fig. 22 are the increments in seat-miles/gal of the DC-10/1011 aircraft and the original 707/DC-8 jets with respect to the fan-powered 707/DC-8 aircraft which were typical of the transport fleet through the early 1970's.

Combining all of the preceding potential with control, propulsion, and winglet advances may then lead to fuel consumption reduction ratios of

$$\underset{\text{airfoils}}{0.95} \times \underset{\text{composites}}{0.90} \times \underset{\text{aspect ratio increases}}{0.92} \times \underset{\text{active controls}}{0.94}$$

$$\times \underset{\text{winglets}}{0.98} \times \underset{\text{propulsion}}{0.90} = 0.65$$

or a reduction of about 35.0%. It is unlikely that all of these will be achieved, however, without reducing the effects of other elements. For example, design for Mach numbers that favor fuel consumption will reduce the trim drag, the further reduction of which is a portion of the active control gain. A combined gain of about 80% of the potential gain seems reasonable. The total reduction in fuel used is then 28.0% and the increase in seat-miles/gal is 39%, i.e., 1/0.72 = 1.39.

Figure 23 shows the fuel efficiency of existing and future aircraft in terms of seat-miles/gal of fuel. The B-747, DC-10,

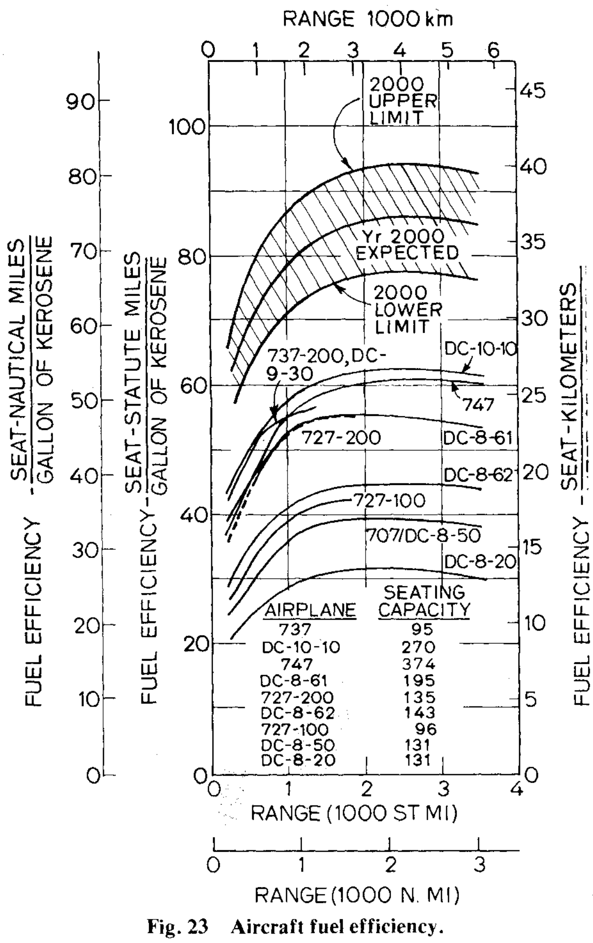

Fig. 23 Aircraft fuel efficiency.

L-1011 type aircraft with high bypass ratio engines offer improvements in passenger miles/gal of 50-60% over the 707/DC-8 turbofan airplanes and almost 100% over the 707/DC-8 original jet airplanes. The additional improvement of the order of 40% possible with full implementation of the new rear-loaded transonic airfoils, composites, active controls, propulsion improvements, and correspondingly increased aspect ratio can bring the combined improvement in passenger miles/gal of future aircraft, as compared to the original 707/DC-8 turbojets, to as high as 170%. Inversely, the fuel consumption per seat mile is lower for today's wide-body airplanes by 34-36%, compared to standard 707/DC-8 turbofan airplanes and about 48% compared to the original jets and will in the long-term future be 54% below the requirements of today's 707/DC-8 turbofan airplanes and 63% below the original jets.

The "expected" curve of fuel efficiency in Fig. 23 is shown as the center of a band indicating a $\pm 10\%$ tolerance. The tolerance is related to the degree of success in applying the various technologies.

If propfans are implemented, an additional 20% in fuel efficiency is possible. And if propfans and laminar flow could be combined—but perhaps we should not dream too far.

The effects of some technological advances on the direct operating costs of aircraft are very difficult to analyze. Those advances that simply reduce fuel consumption can, of course, be appraised. But one of the major potential impacts is the use of new materials and here the future cost of both material and fabrication is quite speculative. A summary of cost increment estimates by various aircraft companies with respect to various technological improvements has been reviewed.[27] Based on these values, plus the author's judgment, a range of reasonable estimates of direct operating cost improvement to turbofan aircraft due to technology has been estimated from 6-18% with a mean value of 12% for full implementation. These gains are with respect to the current wide-body aircraft.

Unfortunately, relatively small impacts of these potential technological advances will be present in the next new aircraft, the Boeing 767. The 767 airfoil is only a modest step toward the SCW, composites are limited to secondary structure, active controls are not used, and the propulsion is only slightly improved from the latest existing aircraft. The degree of implementation of new technology is limited by an overall evaluation of the economic value, including consideration of technological risk at this time.

Conclusions

The near future will continue the evaluation of new transport aircraft on a service-cost basis. The major developments that promise to play an important part in this ongoing process are rear-loaded transonic airfoils, composite material structures, active controls, and propulsion advances. The propfan is a promising possibility.

While it is believed that one or more of the economic, environmental, financial, and technological difficulties make difficult a substantial near-term impact on air transportation from laminar flow control or the SST, research in these areas should be vigorously pursued. Propulsion advances have usually paced aeronautical progress and may again, particularly for the SST.

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