NASA TECHNICAL MEMORANDUM **NASA TM X-72659**

NASA TM X-72659

(NASA-TM-X-72659) FUTURE LONG-RANGE TRANSPORTS: PROSPECTS FOR IMPROVED FUEL EFFICIENCY (NASA) 19 p HC $3.25 CSCL 01C
N75-17339
Unclas
G3/05 11065

FUTURE LONG-RANGE TRANSPORTS - PROSPECTS FOR IMPROVED FUEL EFFICIENCY

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February 1975

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LANGLEY RESEARCH CENTER, HAMPTON, VIRGINIA 23665

1. Report No. TM X 72659	2. Government Accession No.	3. Recipient's Catalog No. N75-17339
4. Title and Subtitle FUTURE LONG-RANGE TRANSPORTS - PROSPECTS FOR IMPROVED FUEL EFFICIENCY		5. Report Date
		6. Performing Organization Code 31.000
7. Author(s) A. L. Nagel and W. J. Alford, Jr., Langley, and J. F. Dugan, Jr., Lewis		8. Performing Organization Report No.
9. Performing Organization Name and Address NASA Langley Research Center Hampton, Virginia 23665		10. Work Unit No.
		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics & Space Administration Washington, DC 20546		14. Sponsoring Agency Code

15. Supplementary Notes

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PRICES SUBJECT TO CHANGE

17. Key Words (Suggested by Author(s)) (STAR category underlined) Long-range transport airplanes Fuel conservation Air cargo Advanced technology Advanced composite materials Advanced engine cycles	18. Distribution Statement Unclassified - Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	18	$3.25

*Available from The National Technical Information Service, Springfield, Virginia 22151
STIF/NASA Scientific and Technical Information Facility, P.O. Box 33, College Park, MD 20740

FUTURE LONG-RANGE TRANSPORTS — PROSPECTS FOR IMPROVED FUEL EFFICIENCY

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Abstract

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Symbols

AR	Aspect ratio
BPR	Bypass ratio
b	Wing span
C_D	Total drag coefficient
C_F	Skin-friction coefficient
C_L	Total lift coefficient
C_ℓ	Section lift coefficient
C_s	Section side-force coefficient
c	Section chord
$\bar{c}$	Mean aerodynamic chord
DOC	Direct operating cost
F	Engine thrust
FPR	Fan pressure ratio
f	Frequency
M	Mach number
OPR	Overall pressure ratio
P/L	Payload
R	Range
SFC	Specific fuel consumption
S_W	Wing area
T	Temperature, °F
TF	Turbofan
TOGW	Take-off gross weight
TP	Turboprop
t	Thickness
V_∞	Free-stream velocity
W_E	Engine weight
y	Spanwise location
δ	Boundary-layer thickness
Λ	Wing sweep angle

Introduction

Since 1970 NASA Research Centers have conducted a series of advanced transport technology (ATT) studies focused primarily on long-range subsonic and near-sonic transport aircraft.[1-14] The objectives of this activity, conducted in cooperation with the Department of Transportation; the airframe, engine, and avionics industries; and the airlines, are to:

> Identify and expedite the development of promising advanced technologies to ensure that the next generation aircraft, when needed, will be competitively superior and environmentally acceptable in the World's market.

Major systems analyses, research and technology investigations, and proof-of-concept flight demonstrations have been responsive to an increasing number of concerns and constraints including: safety, comfort, economics, noise, chemical pollution, and terminal-area compatibility. More recently, the compelling consequences associated with the "energy crisis" have dictated that the activity be focused on fuel conservation and alternate fuels.

One assessment of the future natural petroleum situation is presented in Figure 1. This figure, based on data presented in Reference 15, indicates that by the year 2000, the U.S. supply will be virtually exhausted and that less than half of the world supply will remain. Essentially total exhaustion is predicted to occur within 100 years. Although these estimates are alarming, they are generally more optimistic than the "Survey of Past Forecasts,"[16] shown in Figure 2.

As a result of the limited petroleum supply and its increased usage, it must be expected that severe fuel shortages and high prices will result. Since members of airplane families whose designs begin today will still be in service in the year 2000 (based on past experience), there must be no delay in developing advanced technologies to provide compensating improvements in fuel consumption. Sufficient research must be done to accommodate the use of alterante fuels should the need arise. While it may be hoped that economies in other areas (heating, automobiles) will leave sufficient petroleum for the relatively small requirements of aviation, it is unacceptably risky to rely on such policies — witness the fact that airlines were the first, not the last, to have imposed fuel allocations in the fuel crisis of 1973-1974. A number of studies[17-20] have recently been made in response to the concern of the impact of the energy crisis on commercial aviation. These studies indicate that although current transport aircraft are reasonably energy-efficient, considerable improvements can be made in future aircraft designs through incorporation of advanced technology.

The purpose of this paper is to provide a status report on current thinking about potential improvements in fuel efficiency and possible alternate fuels. In the following sections we will discuss:

- Historical Trends in Airplane Efficiency
- Technological Opportunities for Fuel Conservation
- Unconventional Design Concepts
- Hydrogen-Fueled Airplanes

Acknowledgment

The background material for this paper was developed as part of the NASA Langley Research Center 1974 Inspection entitled, "Technology in the Service of Man," "Stop 2 — Energy Efficient Flight." Contributions were made by a number of individuals throughout the NASA organization and the aviation industry. The authors gratefully acknowledge these contributions.

Historical Trends in Airplane Efficiency

It is pertinent here to examine the historical trends in civil transport airplane efficiency. Such a review is provided in Figure 3, based largely on data presented in Reference 21. The fuel-sensitive indicator utilized is passenger miles per gallon, plotted against initial date of airline service. This indicator inherently includes the airplane size (seats available), aerodynamic efficiency (lift-to-drag ratio), propulsive efficiency, (velocity divided by engine specific fuel consumption), structural efficiency (structural-weight-to-gross-weight ratio), and fuel used.

The data of Figure 3 indicate that the efficiency of both propeller-driven and jet-propelled transports was approximately tripled in 15 years, improvements that were made possible by continuing advances in all of the aeronautical disciplines. The trends reflect a favorable effect of increased size that occurred in spite of the adverse implications of the so-called "square-cube law." The role of technology in overcoming adverse size effects is discussed by F. A. Cleveland in Reference 22.

The French-British Concorde, as a matter of reference, is estimated to begin its service life at nearly the same efficiency level as the first jets, while flying more than twice as fast.

Propulsion improvements have accounted for much of the increase shown in Figure 3, as may be seen from the data of Figure 4. The first jet transports which operated in the U.S. in the late 50's, were powered by turbojet engines with a cruise specific fuel consumption (SFC) of about 1 pound fuel/hour/pound thrust. A few years later, the first-generation turbofans were introduced and improved the cruise SFC about 20%. The higher bypass ratio second-generation turbofans introduced in the late 60's, reduced cruise SFC by another 25%, to a value 40% below that of the first jets.

Technological Opportunities

The following advanced technologies, illustrated on the model shown in the photograph of Figure 5 have potential for providing important improvements in fuel efficiency:

- Supercritical Aerodynamics
- Vortex Diffusers
- Composite Materials
- Propulsion Systems
- Active Controls
- Terminal Area Operations

In the more distant future, boundary-layer control for reducing skin friction offers the hope of large improvements in airplane efficiency, but presents difficult practical problems that must be overcome.

Supercritical Aerodynamics

Supercritical aerodynamic concepts originally developed to attain a high efficiency near-sonic cruise speed can also be utilized to increase airfoil thickness ratios by as much as 50%, relative to conventional sections, without incurring compressibility drag rise.[23,24] Supercritical and conventional airfoils are compared in the upper portion of Figure 6. Thousands of hours of testing in NASA and industry facilities and considerable analytic effort have been devoted to the development of this technology. Three flight demonstration programs (also illustrated in Fig. 6) have verified the predicted benefits: (1) improved speed with a modified F-8, (2) equal performance with a thicker wing of potentially higher structural efficiency with a modified T-2C, and (3) greater maneuverability with a modified F-111. These results demonstrated that supercritical aerodynamics extend the useful limits of airfoil speed and thickness, so as to enable designers to strike a more favorable balance between wing weight and aerodynamic efficiency (Fig. 7). Recent preliminary NASA estimates indicate that supercritical aerodynamics would permit increasing the aspect ratio of airplanes similar to the current wide-body transports, from 7 to 10 by increasing the thickness ratio to about 14% and reducing the sweep by several degrees, with an improvement in lift-to-drag ratio and fuel consumption of 10 to 15% at no weight increase. Data from a recent NASA-funded study by Boeing,[25] (Fig. 8) indicate that for a cruise Mach number of 0.80, a wing sweep of 25°, and aspect ratio of 12, and a thickness ratio as low as 0.08 provides further significant fuel savings relative to lower aspect ratios and higher wing sweeps. The more detailed Boeing analysis indicates that the improved aerodynamic performance associated with the thinner sections and higher aspect ratios is more beneficial for this range of variables than weight reductions that could be obtained with increased thickness and somewhat lower aspect ratios. To place these analytic estimates on a firmer basis, additional wind-tunnel data are required for wings with aspect ratios from 10 to 14, thickness ratios from 0.08 to 0.14, and sweep angles from 20° to 30°, as well as more study of the flutter characteristics of high-aspect-ratio wings.

Vortex Diffusers

The use of end plates to reduce induced drag actually predates the manned airplane, having been involved in a patent obtained by Lanchester in 1897, although the first tests did not take place until 1924. Since that time, they have been suggested on a relatively continuous basis, but tests have always shown that the added skin-friction drag more than offsets the reduction in induced drag, except for very low-aspect-ratio wings. Usually, these devices were designed on the premise of providing a boundary for the lift vortex, rather than as lifting surfaces. Recently the concept of a carefully tailored lifting surface for reducing induced drag has been proposed by Dr. R. T. Whitcomb.[19,24] These winglike devices, called "vortex diffusers" by Dr. Whitcomb, are mounted at the tip of the main wing, as shown in Figure 9, and are designed with the same attention to flow field detail as the main wing, including the use of supercritical airfoil sections. The upper wing surface vortex diffusers are positioned aft on the wing chord and those on the lower surface are positioned forward on the wing chord to place them in the most favorable velocity flow fields. They are canted outward at about 17.5° relative to the wing. The aspect ratio and sweep of the upper vortex diffusers are approximately the same as the main wing, but the lower vortex diffuser must be smaller to provide ground clearance. The area of the vortex diffusers is about 2% of the wing area, and they are estimated to weigh about 1% of the wing weight. Although vortex diffusers are still under development by NASA and industry, preliminary results of analytic and wind-tunnel investigations, extrapolated to full-scale conditions, Figure 10, indicate a reduction in induced drag of about 15%, which corresponds to improvements in cruise lift-drag ratio and fuel consumption of about 5%.

The mechanism by which the vortex diffusers reduce the induced drag is not completely understood at this time, although several hypotheses have been proposed. One explanation is that the vortex diffuser creates several trailing vortices which are weaker in combined strength than the usual single concentrated wing-tip vortex. Another explanation, illustrated in Figure 10, is that since the local flow above the wing is inclined inward and the flow below the wing is inclined outboard, placing the winglets in these flow fields at the correct incidence results in the development of side-force vectors which have components that are inclined forward and thus produce an effective thrust component that exceeds the profile drag of the vortex diffuser. Favorable effects of approximately the magnitude observed have been predicted theoretically (see Refs. 26 and 27, for example).

It has been argued that an increase in wing span, or aspect ratio, might be more effective than vortex diffusers in reducing induced drag. The advantage of the vortex diffuser, indeed the motivation for the original vortex diffuser research, lay in the combined considerations of aerodynamics, wing weight, and the possible application to existing airplanes with minimum difficulty. The essential point is that the vortex diffuser's normal force has a very small moment arm, and so does not produce a large increase in wing root bending moment as would a span extension. An increase in wing bending moment would, of course, require strengthening the wing structure, with an attendant weight penalty, and perhaps rule out any possibility of retrofitting vortex diffusers to existing airplanes.

To verify that the reduced drag is not accompanied with a significant increase in bending moment, both bending moment and spanwise pressure distribution data were obtained from which the spanwise lift distribution can be determined. Some of this information is presented in Figure 10. Curves are shown for a basic reference wing, a wing with vortex diffuser, and an elliptically loaded wing with increased aspect ratio so as to provide the same drag benefit as the wing with the vortex diffuser. As shown, the vortex diffusers cause only a slight increase in wing root bending moment (one-half of 1%) while that of the increased aspect-ratio wing is much larger (8.5%). Thus, the vortex diffuser should have little impact on wing weight, perhaps none with further tailoring, while span increases are likely to cause appreciable weight penalties.

Another question that must be addressed is the effect of vortex diffusers on flutter. The results of preliminary flutter tests (by R. V. Doggett of LRC) Figure 11, indicate only a slight reduction (about 1% to 2%) in flutter speed with this effect resulting primarily from mass-balance considerations rather than from adverse aerodynamic effect. Thus, it appears that the use of nonplanar wing and vortex diffuser combinations may offer a means of providing an appreciable fuel savings by improved aerodynamic efficiency, both as modifications of current designs and for future airplanes.

Composite Materials and Structures

Since the late 1950's, it has been recognized that the high strength-to-weight and stiffness-to-weight ratios associated with advanced composite materials could significantly reduce aircraft structural weight.[28] The blending of high-strength fibers such as graphite, boron, Kevlar 49, and glass in epoxy, polyimide, or metallic matrices (as illustrated in Fig. 12) to produce a tailored structure offers new possibilities to the creative structural engineer. The potential for structural weight reductions as determined from a number of design studies is presented in Figure 13.[29] These reductions in structural weight can either be used directly for fuel savings or can be traded off to gain improved structural lifetime, or lower cost manufacturing.

In a recent fuel-conservative transport aircraft study made by Boeing,[25] it was estimated that sizable weight savings could be achieved with an all-composite primary structure aircraft. The various types of composite structure and the weight savings of various composites relative to conventional aluminum skin stringer construction are shown in Figure 14. Graphite epoxy honeycomb is used for the wing, fuselage, and empennage primary structure and for all control surfaces. Honeycomb with face sheets of Kevlar-49 is used for the wing leading- and trailing-edge structure, fairings, and other secondary panels. Graphite epoxy is used for the nontemperature critical area of the nacelles with the acoustic treatment integrated into the structure. In the wing primary structure, the high panel end loads and areas that are stiffness critical due to flutter requirements make the epoxy construction very attractive and result in an estimated structural weight saving of 25%. Weight savings of this order translate into fuel savings of from 10% to 15%.

Despite their advantages, composites have not yet been widely used in commercial airplanes. High cost has been one deterrent. Fortunately, price is becoming less of a deterrent as increased use of composites in other applications is causing prices to drop. Perhaps the largest deterrent at the present time is the lack of experience with composites under actual service conditions and the resulting uncertainty as to their durability and what maintenance they will require. A relatively small amount of out-of-service time on the airplane could more than offset the weight advantage. In order to obtain the necessary experience and data under actual service conditions the U.S. Air Force Materials Laboratory has a considerable flight service program underway. NASA Langley is sponsoring a program involving both military and civil airplanes, beginning with secondary structural components and progressing to primary load-carrying structure. The program also includes an investigation of the possible use of composite reinforcements in primary structure to extend the service life of military airplanes. C-130 and CH-54B airplanes will be used in these latter programs. Examples of some of the secondary structure components involved are shown in Figure 15 and include spoilers, fairings, and rudder segments. Initial procurement actions are underway to support the design and construction, and to make a flight service evaluation of composite primary wing and tail structures for commercial transports.

The current and projected status of the flight service programs is presented in Figure 16.[28] Boron/epoxy, Kevlar 49/epoxy, graphite/poly-sulfone, and boron/aluminum composite materials are being evaluated in the programs, the first of which began flight service in March 1972, and the most recent of which will begin flying about June 1975. Nine airlines and two military services are presently involved, and three more airlines are expected to become involved in the future. As the curve shows, a quarter of a million component flight hours were accumulated by July 1974 and approximately 500,000 hours should be accomplished by June 1975. This rapid accumulation of flight service time spread over five types of composite materials with 14 different user organizations will provide a data base to establish the confidence in long-term structural performance.

In addition to the advanced composite flight service program, NASA is in the early stages of another program, the Advanced Acoustic Composite Nacelle Program, Figure 17, which will provide data for the application of composite materials to nacelles and inlets. The firm go-ahead of a flight test of the nacelle depends on the final results from feasibility studies now in progress, but the early results from those studies have so far shown significant benefits. Not only is there the potential for weight savings in the nacelle, there are also potential benefits in improved aerodynamics, noise reduction, and perhaps better endurance in the severe acoustic environment generated by the engine.

Propulsion

The objectives of the NASA propulsion research are to improve the efficiency of existing engines and to provide technology for improved future engines. For existing engines, the following have been identified as some of the promising ways to improve the efficiency.

1. Reduce compressor and turbine tip clearance by about 10%. SFC reductions of about 4% are possible.

2. Replace conventional seals with labyrinth seals to provide up to 2% reduction in SFC.

3. Install low pollution combustors which have high efficiency at idle and low thrust conditions to provide about 1% reduction in SFC.

4. Reduce compressor and turbine end wall pressure losses at hub and tip for 1% reduction in SFC.

5. Improved cooled turbines to provide about 1% reduction in SFC.

When all such items are evaluated as to their economic practicality, it is anticipated that fuel usage of current engines can be improved 5% to 10%.

For advanced turbofan engines, NASA/industry efforts currently underway include consideration of (Fig. 18): improved fan efficiency, composite blades, advanced compressor design, reduced emissions combustors, improved seals and bearings, and composite nacelles.

Figures 19 through 21 summarize results of recent NASA-Lewis in-house studies of advanced engines. Figure 19 compares an advanced 1985 turbofan with a current turbofan. Relative to a current turbofan, the 1985 engine has considerably higher F/W_E ratio; its cruise turbine temperature is 500° F higher; overall pressure ratio has increased from 28 to 40; fan pressure ratio is somewhat lower; and bypass ratio increased from 6 to 10.4.

These engines were evaluated with a simplified analysis of a 200-passenger, 3000-nm range airplane, assuming constant structural weight fraction. The 1985 engine had an 8% cruise SFC lower than the current engine. Also, the engine weight was 20% less. These factors compounded to give a take-off gross weight reduction of 18%. Figure 20 indicates how this large improvement came about. With advanced full-coverage film cooling in the turbine, cruise turbine temperature was raised to 2500° F, a 500° F increase over the current level. At this higher temperature level, overall pressure ratio reoptimized at 40 and bypass ratio at 10.4. The resultant reduction in fuel consumption was 9.75%. The combined result of these cycle, efficiency, pressure loss, and engine weight improvements is an impressive 22.3% reduction in fuel consumption. The level of technology required to achieve this large reduction in fuel usage will not be easy to attain. The more difficult parameters will make it harder to maintain component efficiency, avoid increased amounts of cooling air and air leakage, and achieve high levels of durability and performance retention.

Figure 21 shows that there are other new engines which offer even greater gains in SFC than an advanced turbofan such as the one just discussed. Relative to the JT9D, the high bypass-ratio turbofan has a cruise SFC reduction of about 8%. The shaded part of the bar indicates that the improvement in SFC was 6% when current component efficiencies were assumed, as was done for the other engines listed in the figure. The 6% improvement jumps to 15% for a regenerative turbofan. An advanced turboprop has a cruise SFC 30% below that of the JT9D and with a regenerator, SFC improves 34%. With regard to the turboprops, there is considerable uncertainty as to whether or not a high propeller efficiency can be achieved at the desired cruise Mach number of about 0.8. Also, much work is needed to minimize installation losses.

In addition, Lewis-funded studies of fuel conservative engines are being conducted by General Electric and by Pratt and Whitney. The objectives are: (1) to study modifications of existing turbofan engines for reduced fuel usage, and (2) study new engine designs for low fuel usage. The first task will be completed by June 1975. The second study will consider regeneration, intercooling, and interburning. This effort will be completed by December of 1975.

The total improvement in specific fuel consumption that is envisioned is shown in Figure 22, which indicates that an improvement of as much as 40% may be possible, as compared with current turbofan engines.

Active Controls

Active controls, that is, control systems wherein aerodynamic surfaces may be actuated automatically without command from the pilot, can improve the performance of airplanes by stabilizing the flight path and reducing loads and accelerations. Active control concepts, now under investigation by NASA and the Air Force (summarized in Fig. 23), include relaxed static stability, gust and maneuver load alleviation, flutter suppression, and ride quality improvement. The Air Force has recently completed the B-52 CCV Program,[30] in which several active controls were flight tested, and NASA has an Active Controls Aircraft Program[31] which has the objectives of identifying, developing, and validating technology required for the use of active controls in future civil airplanes.

Before the advent of the fuel crisis, the major benefits attributed to ACT were expressed in terms of reduced drag, reduced weight, increased range or payload, and improved economics.[32-34] With increasing emphasis on reducing fuel consumption, it seems that another look at active controls would yield somewhat different answers as to their best application. To date, this has only been done in a preliminary fashion.

Relaxing the static stability requirements would allow the configuration to be designed for minimum trim drag and would result in smaller, lighter horizontal and vertical tail surfaces. An illustration of such a reduction is presented in Figure 24.[6,34] Both the reduction in drag and weight would contribute to reduced fuel consumption. Even further savings may be achieved if provision is made for a center-of-gravity (c.g.) control system. However, a full-time stability augmentation system would be required.

Gust and maneuver load alleviation systems may be used to shape the wing loading during flight through turbulence and in maneuvers with a resulting reduction in wing-root bending moment. Previous studies have indicated that, for a given aspect ratio, use of load alleviation systems would lead to a savings in gross weight. This, in turn, would reduce fuel consumption. However, preliminary work indicates active load alleviation devices may best be used to permit increased aspect ratio rather than saving weight. Lockheed recently completed a study[35] of redesigning the Jetstar (Fig. 25) using active controls (gust load alleviation) and a supercritical wing to achieve reduced fuel consumption. After performing various trade studies, the final configuration had an aspect ratio of 9, compared to the original 5, and the wing sweep had been reduced from 30° to 5.5°. The redesigned configuration would meet all of the original mission requirements with a 26% reduction in fuel consumption.

In another study,[36] Douglas examined the application of active controls to transport aircraft and indicated various ways in which ACT could be utilized. Although fuel consumption was not identified directly as a benefit, they did show that using ACT on the DC-9 and DC-10 could result in an increase in aspect ratio of 2.3 and 3.0, respectively, with no increase in operating empty weight.

Other active control concepts have not been investigated in detail to determine their impact on fuel consumption. However, it is certain that the introduction of ACT in the initial design cycle of a new configuration will yield significant benefits. What form these benefits take will be up to the designers who make the trades. The technology and tools required to integrate these concepts early in the design cycle must be developed and verified so the designers will have the knowledge and the confidence to take advantage of them.

Although there is currently insufficient data to accurately quantize the direct benefits of ACT concepts in fuel consumption, it appears possible that savings of 5% to 10% may be attainable.

Terminal Area Operations

Improved operations (Fig. 26) in future high capacity terminal areas depends on improvements in a number of areas including: reduced delays due to congestion and weather, noise and pollution, and fuel consumption.[14, 37-38] The NASA, in cooperation with the FAA, has underway a Terminal Configured Vehicle Program[37] whose objectives address most of these problems. It should be recognized that the potential methods available for providing the required improvements can lead to both conflicting and complementary results. For example, engine acoustic treatment to reduce noise can lead to increased fuel consumption whereas reduced delays, possible by advanced operational procedures, can provide fuel reductions.

Operational procedures, to reduce delays and noise, are possible through utilization of advanced aircraft electronic and airframe design concepts and are illustrated in Figure 26 (from Refs. 37 and 38). Flying in the Microware Landing System environment, being developed by the FAA, which can, with proper airborne automatic controls and pilot displays, allow operators to take advantage of steep, curved, decelerating approaches with close-in capture. Onboard precision navigation and guidance systems are required for 3D/4D navigation for sequencing and closer lateral runway spacing, and displays are under development with the intent of achieving zero visibility operations with sufficient confidence that they become routine. Programed turnoffs at relatively high speed should clear the runway to allow operations to proceed with perhaps 35 to 45 seconds between aircraft, should the vortex wake problems be solved.

Recent Boeing studies[25] have indicated that a fleet of fuel-conservative aircraft (Fig. 27), designed to provide terminal area compatibility, could reduce the 36-minute airborne delay, expected to occur with 40 to 50 movements per hour of present technology aircraft, by 30 minutes. The terminal compatible features envisioned would consist of: programed flaps for wing tip vortex dissipation; powered wheels; advanced automatic guidance, control, and navigation avionics; brakes and thrust reversal for rapid runway deceleration; and landing gear designed for high-speed runway turnoff. These features, which are estimated to be about 5.3% of the operating empty weight, allow the delay reduction of 30 minutes which corresponds to fuel reduction of approximately 4% relative to the aircraft without these features. In the near term, where ground delays before take-off and after landing are still significant, the use of powered wheels to minimize engine operation on the ground could also reduce fuel consumption by 1% to 2%.

Skin-Friction Reduction

The largest single component of drag of current subsonic transport airplanes is skin friction. Skin friction originates in the boundary layer, a thin region near the surface of the airplane wherein viscosity effects are large. Boundary layers may be either laminar, transitional, or turbulent. On current airplanes the boundary layer is virtually always turbulent, with friction forces several times larger than would be the case if turbulence could be prevented. There are therefore two avenues of possible skin-friction reduction: (1) preventing turbulence, and (2) reducing turbulent skin friction. Both approaches are being investigated in the current NASA program.

Laminar Flow Control. Of the various possible techniques for maintaining laminar flow on large powered airplanes, only the method of suction boundary-layer control has so far been successful in actual flight. In this approach, a small amount of air is sucked through the skin, thinning and stabilizing the boundary layer, as illustrated in Figure 28. Ideally, the skin should be porous, but in actual practive it has been found possible to obtain extensive laminar flow with suction through narrow spanwise slots with spacings of a few inches. On the X-21 Laminar Flow Control Airplane (Fig. 29), laminar flow was repeatedly maintained over virtually the entire wing with this technique[39-41] in the 1960's. While the X-21 showed that laminar flow could be obtained in flight, the program was terminated before much information could be obtained about maintenance and operational aspects. Thus, although early design studies[42,43] indicate fuel savings on the order of 30%, little is known of the total economics of an LFC airplane. It should be regarded as very encouraging that this early flight program was so successful.

In the many years since the X-21 program was initiated, a great amount of progress has been made in material and fabrication technology and in reducing engine noise that should ease the development of an LFC airplane. NASA has recently awarded a contract to the Lockheed-Georgia Company to assess prospects for LFC airplanes in the light of the current and foreseeable environment. This study is now scheduled for completion in the fall of 1975.

Turbulent Skin-Friction Reduction. Several researchers[44-47] have reported reduced skin friction over compliant walls; that is, flexible skin coatings that respond somewhat to the turbulent pressure fluctuations. A summary of such data, taken from Reference 47, is shown in Figure 30. It is seen that reductions of more than 50% have been reported. These data obviously have very important implications, not only for airplanes, but for other forms of transportation as well. In order to develop a better understanding of the compliant wall phenomenon and how it can be applied to airplanes, Langley has initiated a program of both analytic and experimental research. Early results that have been obtained in the Langley low turbulence pressure tunnel show a promising 16% reduction in wall shear stress as compared to a rigid plate. The test surface was a 0.0025-cm-thick mylar membrane bonded with silicone rubber to a 0.64-cm-thick Scottfelt polyurethane foam substrate. Preparations are being made to publish these data.

Another way in which turbulent skin friction can be reduced is by mass injection into the boundary layer, either through a porous skin or through aft-facing slots.[48] In order for mass injection to provide an overall gain in efficiency, it is necessary to obtain the air without paying a large drag penalty, such as would be associated with decelerating an equivalent amount of free-stream air. One possibility is to use air collected from LFC suction on the wings to reduce turbulent skin friction on the fuselage.

Unconventional Configurations

Distributed Loading

Distributed loading, wherein all or most of the payload and fuel are carried in the wing to achieve a better balance between the gravity loads and the external aerodynamic loads, has the potential for substantially reducing structural weight. The concept is illustrated in Figure 31. In conventional configurations (upper figure) with the major weights in the body, the wing structure must be designed to withstand large bending moments that the aerodynamic lift produces at the wing root. Placing the cargo in the wing (lower figure) reduces the unbalanced load and so reduces the bending moments, and hence the structural weight. The concept is best applied to very large airplanes; Figure 31 also shows how a typical wing section might be loaded.

The magnitude of the potential bending-moment reductions, associated with various payload distributions, is presented in Figure 32.[49] Calculations indicate that payload fractions can be doubled as compared to conventional airplanes.

To realize the performance benefits offered by balanced aerodynamic and payload distributions, all loading conditions must be similarly approached. Landing loads, for example, will have to be distributed over the span as well, perhaps through use of air-cushion landing systems.

The estimated improvement in fuel efficiency of span-distributed loading aircraft, as compared to fuselage cargo-carrying wide-body aircraft is presented in Figure 33 (from several industry sources). Not only is the efficiency greatly improved at moderate ranges, but the ultimate range is also much greater, an important factor in military applications. A typical span-distributed loading configuration is shown in Figure 34. A wind-tunnel model of this particular "flying-wing" concept is currently under construction. Tests in several NASA wind tunnels will determine performance and stability and control characteristics. Also, tests will be made of a family of 2D thick airfoils ranging from 19% to 25% thickness ratio.

Liquid Hydrogen-Fueled Aircraft

Since conservation measures alone can only delay, not prevent, the exhaustion of fossil fuels, it is clear that at some point in the future man-made fuels will be required. The question is "when," not "if." If it could be shown with certainty that U.S. petroleum reserves would last until the very remote future, the study of alternate-fueled aircraft would not be necessary at this time. However, the evidence is all to the contrary. U.S. oil production is declining, and we are all feeling the unpleasant consequences of our dependence on foreign petroleum.

Present trends, extrapolated for a decade or so, offer a grim outlook for fuel costs and availability. It is only prudent that we examine now the options that are before us, and take whatever steps are necessary to assure that commercial aviation is not stifled by lack of fuel. Therefore, NASA has been examining options for alternatives to natural petroleum fuels. On the basis of a preliminary screening, it has been concluded that the first two possibilities that should be examined are: (1) synthetic jet fuel, and (2) liquid hydrogen. Synthetic jet fuel is attractive because it involves the least change from present designs and operations and is therefore within the state of art and will not be discussed further. Hydrogen is attractive because of its high energy content, its freedom from hydrocarbon pollutants, and the possibility of complete independence from fossil resources that it offers. In any application, hydrogen serves only as an energy carrier, not an energy source, so that the question of hydrogen-fueled aircraft really involves the much larger questions of national energy policies.

NASA experience with hydrogen fuel in aircraft goes back almost two decades, to 1957, when flight experiments were conducted with a B-57 airplane[50] modified so as to permit fueling one of the engines with hydrogen in flight. The landing and take-off were accomplished with conventional fuel. The results of that early experiment were entirely favorable, verifying the very low SFC's that had been expected, and the easy ignition characteristics. This very early experiment indicated that the real questions as to the use of hydrogen fuel are in the larger issues of hydrogen production and handling, and system operation rather than in the airplane or engine design. The safety and economics of the entire system are the ultimate questions.

In the same time period, Lockheed made a rather extensive study of a hydrogen-fueled supersonic aircraft under Air Force contracts. While none were ever built, significant progress was made in the areas of safety, fuel handling, tank construction, propulsion, and other design problems. These studies concluded that hydrogen-fueled airplanes were feasible, even at that time.

While there have been no further experiments with liquid hydrogen-fueled airplanes since the B-57, a great deal has been learned about practical aspects as a result of the massive use of liquid hydrogen in the space program and from the hypersonic research engine (HRE) project. The space program has made NASA the world's largest user of liquid hydrogen. Over 600,000,000 gallons of liquid hydrogen were obtained, transported, loaded, and consumed without a significant accident attributable to the use of that fuel. Complete liquid hydrogen fuel systems were developed including pumps, valves, conduits, fuel injectors, and leak detectors. In the HRE project,[51] an experimental convertible ramjet engine was built and tested. This engine featured regenerative cooling of all of its internal surfaces and addressed many of the problems of producing flight-weight aircraft type hardware that tended to be different from those of the space program. Both structural and performance tests were made of the HRE with excellent results. The regeneratively cooled structure survived the severe thermal environment representative of Mach 7 flight, and the specific impulse agreed with the predictions.

As a result of this previous work, the outlook for liquid hydrogen as of about 2 years ago may be summarized as follows:

1. Liquid hydrogen-fueled airplanes are technically feasible.

2. With proper procedures, liquid hydrogen is at least as safe as jet fuel.

3. Considerable experience with fuel systems indicated that the hardware problems could be overcome.

With this background, NASA undertook a series of studies of liquid-hydrogen-fueled airplanes in 1971. These involved parametric calculations to establish broad trends and more detailed examinations of particular aircraft, most of the latter being done under contract. The most recent results applicable to subsonic airplanes were obtained under contract by Lockheed Aircraft Corporation.[52] The passenger aircraft designs selected in the Lockheed study are shown in Figure 35. The nearer of the two configurations shown represents the most efficient design, which, however, has the disadvantage that the fuel is carried within the fuselage. The close proximity of the fuel to the passengers may be undesirable from a safety point of view. The vehicle in the background was found to be the most attractive of several configurations considered to eliminate this feature. It is, however, appreciably heavier and consumes 15% to 25% more fuel than the conventional configuration in the foreground. The major characteristics of these two airplanes are compared with a jet-fueled airplane sized for the same mission in Table 1.

The conclusions of the subsonic airplane studies to date may be summarized as follows:

1. The gross weight and fuel weight of hydrogen-fueled airplanes are much less than for conventional airplanes, with the differences increasing with range.

2. The size and cost of LH_2 airplanes are greater than for JP airplanes, although the parametric studies indicate that this may not be true for very long ranges.

3. Hydrogen-fueled airplanes use slightly less mission energy per seat mile, but the total energy consumed, considering the energy required for producing the hydrogen is greater. Again, for extremely long ranges (for which no detailed conceptual designs have been made) the parametric studies show the probability of overall energy savings.

4. In general, the technology for hydrogen-fueled airplanes is available. The major deficiency identified so far is the lack of a suitable fuel tank insulation. The insulations that now exist would not be serviceable for the long life expected of commercial airplanes. Engine manufacturers have reported little need for research on hydrogen-burning engines, and that the development of hydrogen-fuel engines could proceed.

Thus, it is considered that the major questions related to the introduction of hydrogen-burning airplanes are not in the airplane and its design, but related to such factors as the availability of hydrogen and the cost of producing and handling. The airplane studies conducted to date have been very consistent and it is felt that most of the conceptual design questions have been answered, so that barring the discovery of some new and promising configuration that offers a unique advantage (such as the separation of the fuel from the passengers without the performance penalties of the configurations so far proposed), there is little to be gained from further conceptual design studies. The next major area that will be studied are the ground facility and logistic problems.

Studies have also been made of supersonic and hypersonic hydrogen-fueled airplanes that also show significant performance improvements. Langley has been studying hydrogen-fueled hypersonic airplanes for several years, motivated solely by the performance advantages.

Concluding Remarks

In this paper, we have reviewed prospects for improved efficiency in transport airplanes. Figure 36 summarizes the fuel savings relative to current transports for near-term and far-term advanced technologies and those possible in the further future by unconventional concepts. Supercritical aerodynamics, advanced composite materials in secondary structures, improved engines, and active controls and operating procedures should combine to yield reductions in fuel consumption per seat mile on the order of one-third. The aircraft designed to obtain this result will tend to higher aspect ratios and lower sweep angles than current airplanes, but will be superficially similar to today's transports and probably operate at about the same speed.

For the more distant future large further gains are possible, but will require the development of new technologies. Since so much of the drag of a well-designed subsonic airplane is due to skin friction, it is here that the fundamental gains must be made. It is fortunate that so much research has been done that confirms the theoretically predicted stabilizing effect of boundary-layer suction in actual flight, since laminar flow control offers the largest gain in flight efficiency of any of the currently known technologies. LFC also requires much greater sophistication in airplane manufacturing than is current practice, and may also require special ground servicing. The challenge of LFC, therefore, is to develop the techniques to meet these requirements without exorbitant cost. Similar challenges have been met in the past; we are surrounded with devices that could not have been economically produced only a few years ago.

Early results from renewed investigations of compliant surfaces have shown promising results in reducing turbulent skin friction. It may be that such coating will be preferable, on balance, to the potentially more beneficial LFC, since the problems of manufacturing and maintenance may be less difficult. There is also a possibility that such coatings could be added to existing airplanes. However, the compliant wall studies are still in an early stage, and much basic work remains to be done before its potential can be accurately assessed.

As time goes on, it is expected that increasing use will be made of advanced composite materials, including application to much of the primary structure. Together with additional improvements in avionics and the foreseen advances in propulsion, a further reduction in fuel consumption of one-third to one-half is possible. For very large airplanes the use of distributed loading offers significant further benefits.

Although the combined effect of the foreseen fuel conserving developments is very large, it cannot be concluded with confidence that they will be adequate. If necessary, hydrogen can be used as an airplane fuel, totally eliminating any dependence on fossil fuels. If the so-called "hydrogen economy" actually materializes, the airplane could be an efficient part of the total energy system. Although the performance of airplanes is improved by the high energy content of hydrogen, the performance advantages do not seem sufficient in themselves to justify the development of hydrogen production and distribution facilities that would be required. It is, however, important that sufficient research be done to provide the nation with the option of developing such airplanes if they are needed. The required research is mainly for tankage and insulations suitable for the long lifetimes expected of commercial airplanes, and operational aspects.

The "energy crisis" poses a severe challenge to aviation. Not only is there the direct economic impact of drastic increases in fuel cost, there are also social and political questions: "Is it right to consume so much energy merely to save a little time for the favored few?" The proponents of aviation must make the point that while aviation is not grossly consumptive of energy, as often assumed, and that future airplanes will compete very favorably with other forms of transportation on an energy basis, the proper criterion is not energy consumption alone, but maximizing the benefit derived from the energy consumed. In this regard the airplane provides vital services and capabilities achievable in no other way.

From the economic viewpoint, aviation is vital to the nation. Our total resources consist of the natural resources of the land plus the skills of our people. The ideal product is one which uses none of our finite natural resources and whose entire value is composed of the skilled work that made the product possible. The airplane comes very close to this ideal, with only a tiny fraction of its cash value due to material costs. We must continue the research that will make our aviation industry as successful in the future as in the past. Fuel economy is one area that must be pursued.

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TABLE 1. LH_2 CONFIGURATION COMPARISON

Range = 5500 NM Mach = 0.85 400 PAX

Cruise Mach number		External fuel	Internal fuel	Jet A fuel
Gross weight	lb	436,800	391,700	523,100
Fuel weight	lb	81,000	61,600	190,700
Operating empty weight	lb	267,800	242,100	244,400
Wing area	ft^2	3,640	3,360	4,190
Sweep	degrees	30	30	30
Span	ft	171	174	194
Fuselage length	ft	197	219	197
F.A.R.T.O. field length	ft	5,290	6,240	7,990
F.A.R. landing field length	ft	5,810	5,810	5,210
L/D (cruise)		13.4	16.1	17.9
SFC (cruise)	$(\frac{lb}{hr})/lb$	.199	.199	.582
Thrust/engine	lb	38,760	28,690	32,690
Energy/seat mi.	Btu/AS NM	1.634	1.239	1.384
Airplane price	$\$10^6$	30.2	26.9	26.5
DOC	¢/ASn mi	1.277	1.079	1.01

(LH_2 fuel cost = $\$3/10^6$ Btu = 15.48 ¢/lb)

(Jet A fuel cost = $\$2/10^6$ Btu = 3.68 ¢/lb = 24.8 ¢/gal)

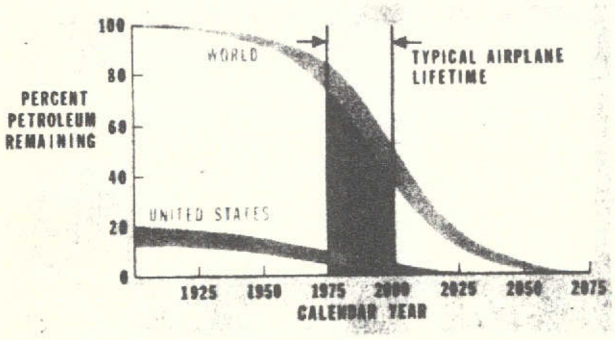


Figure 1. Natural petroleum supply and decline.

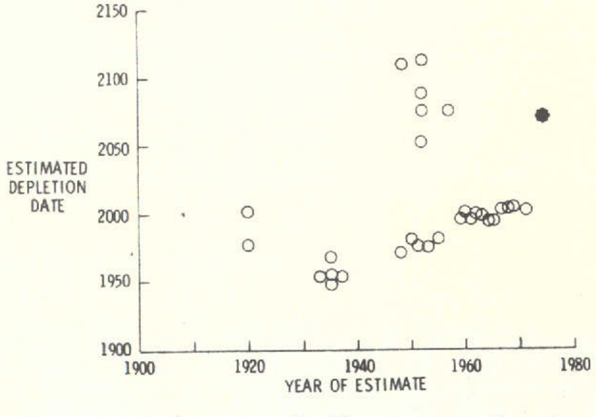


Figure 2. Depletion of oil — survey of past forecasts.

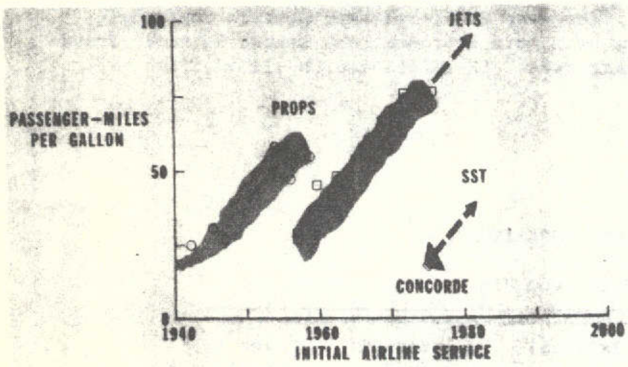


Figure 3. Efficiency trend.

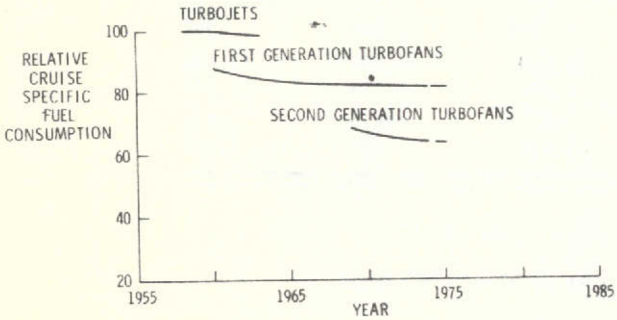


Figure 4. Trends in aircraft engine fuel consumption.

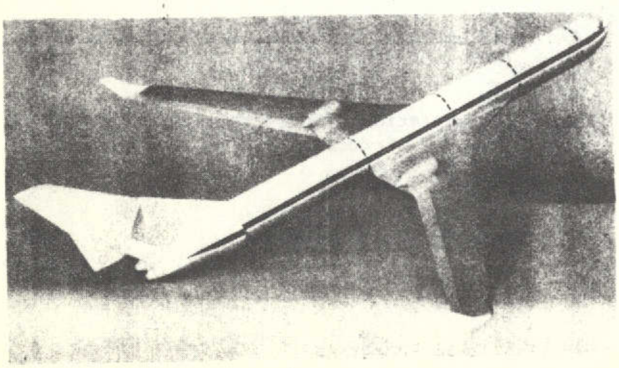


Figure 5. Fuel conservative aircraft concept.

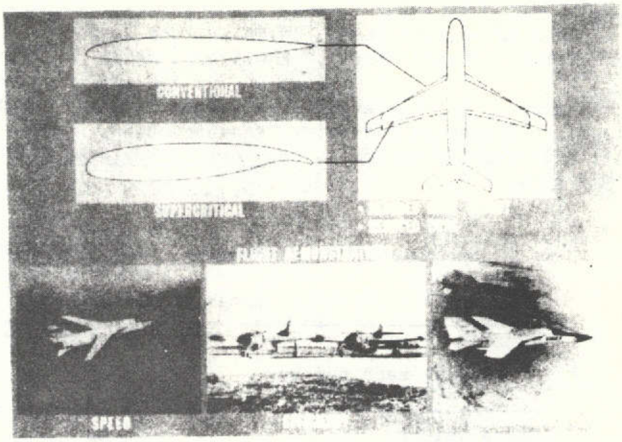


Figure 6. Supercritical aerodynamics.

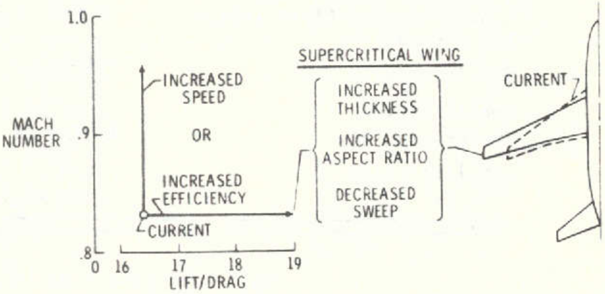


Figure 7. Use of supercritical airfoils to reduce induced drag.

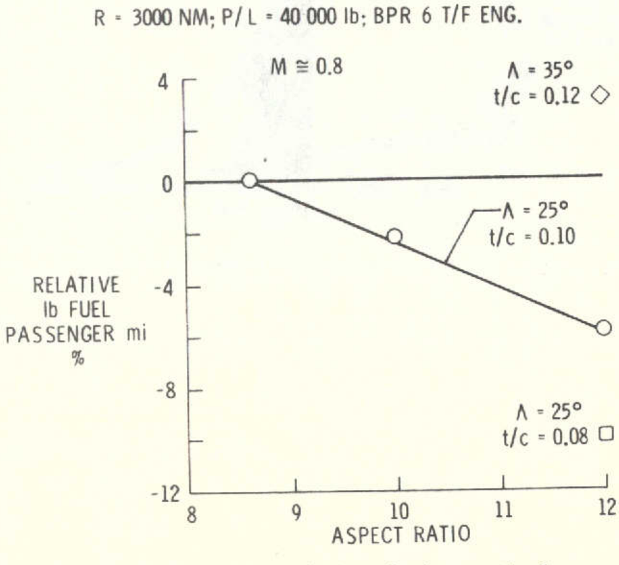


Figure 8. Effect of wing design on fuel consumption.

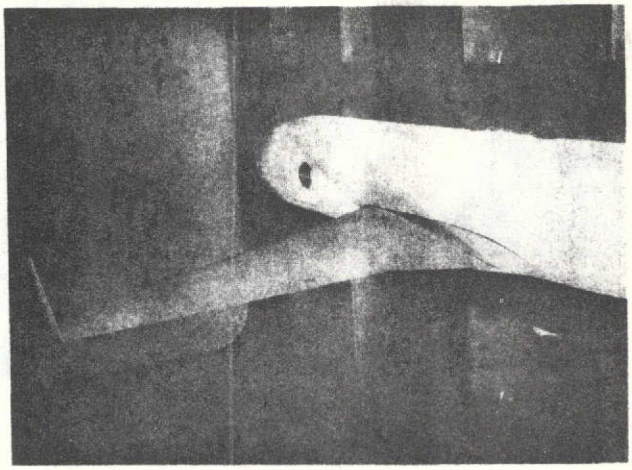


Figure 9. Vortex diffusers installed on wind-tunnel model.

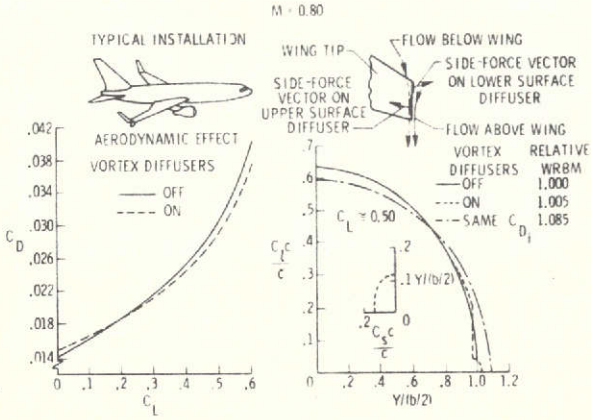


Figure 10. Wing-tip vortex diffusers.

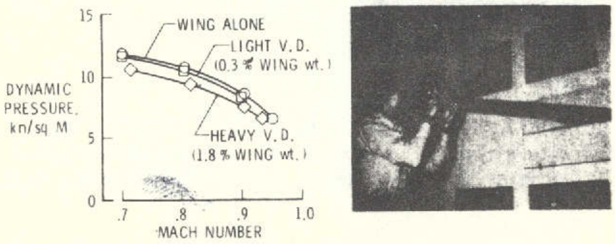


Figure 11. Effects of vortex diffusers on flutter.

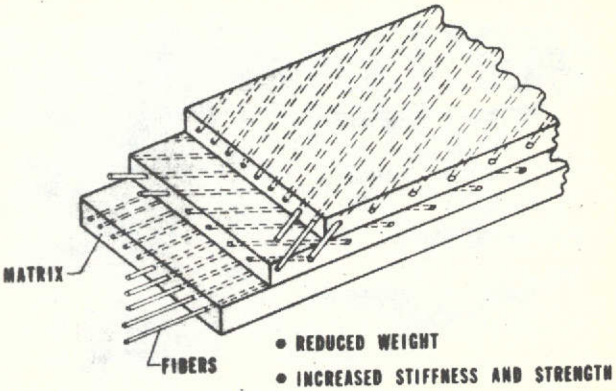


Figure 12. Composite material.

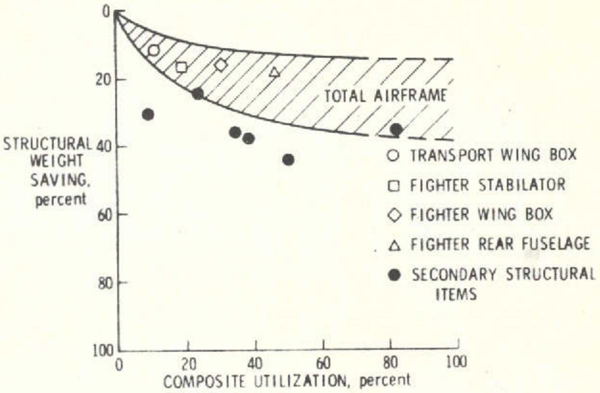


Figure 13. Potential weight saving from use of composites.

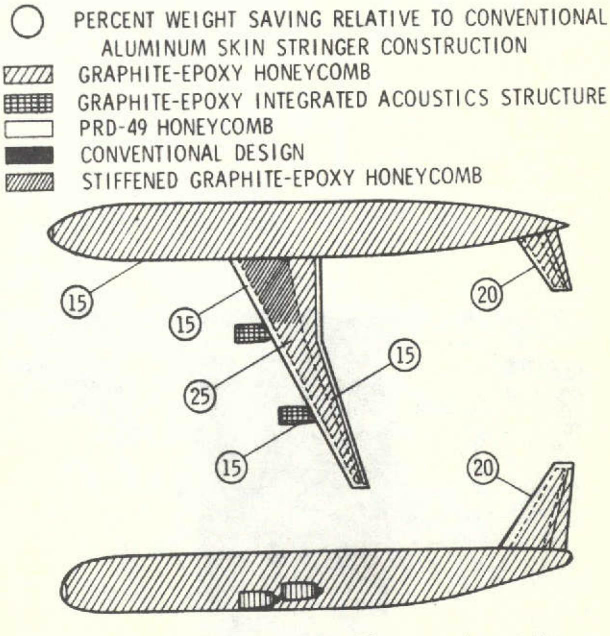


Figure 14. Airplane with all composite primary structure.

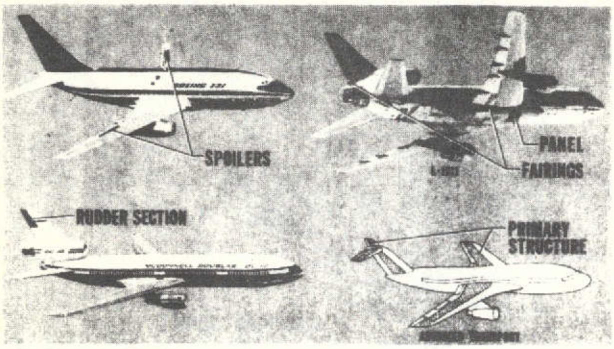


Figure 15. Advanced composites for aircraft.

COMPONENT	FIRST FLIGHT	USER
1 CH-54B HELICOPTER TAIL CONE	MARCH 1972	US ARMY
2 L-1011 FUSELAGE PANEL	JAN 1973	EASTERN, TWA, AIR CANADA
3 737 SPOILER	JULY 1973	ALOHA, LUFTHANSA, NEW ZEALAND
4 737 ADVANCED SPOILER	OCT 1974	PIEDMONT, PSA, VASP (BRAZIL)
5 C-130 CENTER WING BOX	NOV 1974	US AIR FORCE
6 DC-10 RUDDER	MAY 1975	
7 DC-10 AFT PYLON PANEL	JUNE 1975	

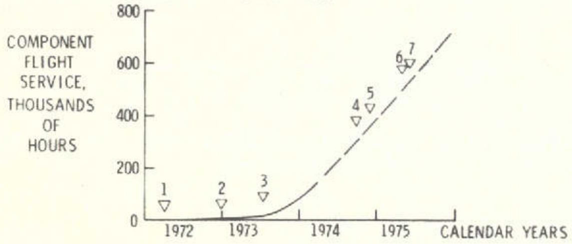


Figure 16. Current program for flight service evaluation of composite structural components.

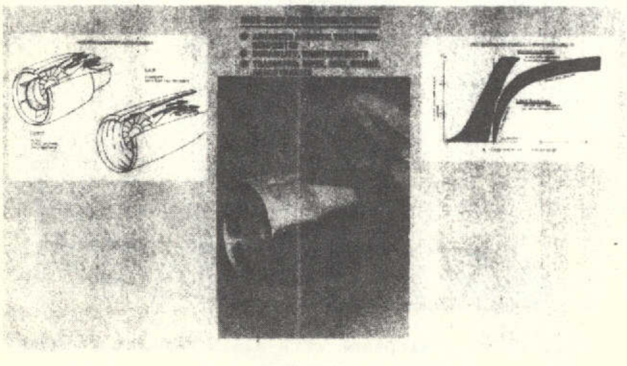


Figure 17. Advanced acoustic composite nacelle program.

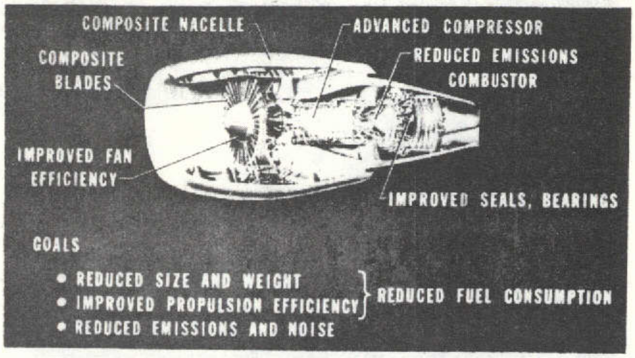
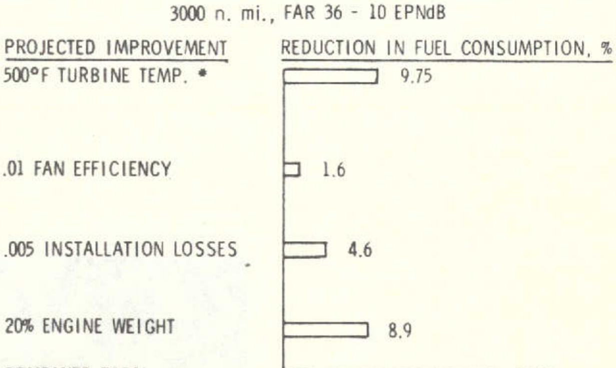


Figure 18. Advanced turbofan engine.

TURBOFAN	CURRENT	1985
F/W_E	3.65	4.96
T_{CR}, °F	2000	2500
OPR	28	40
FPR	1.69	1.60
BPR	6	10.4
PERCENT REDUCTION		
SFC_{CR}	0	8
TOGW	0	18
DOC	0	15
FUEL USAGE	0	22

Figure 19. Potential of advanced turbofan.



* ADVANCED FULL-COVERAGE FILM COOLING ALLOWS THIS 500°F INCREASE. OPTIMUM BYPASS RATIO INCREASES FROM 6 TO 10.4 AND OVERALL PRESSURE RATIO FROM 28 TO 40.

Figure 20. Sensitivity of fuel consumption to turbofan improvements. 1985 engine technology, Mach 0.85, 200 passengers.

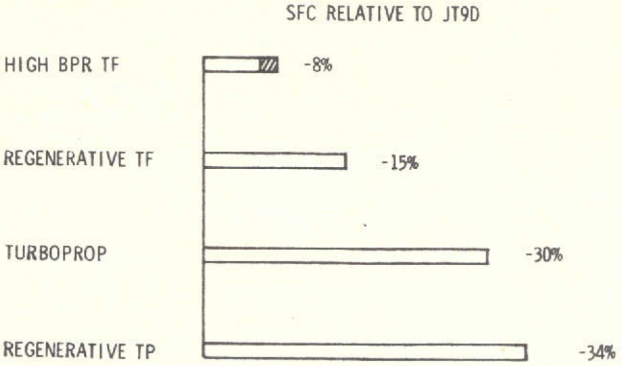


Figure 21. New engines offer lower SFC.

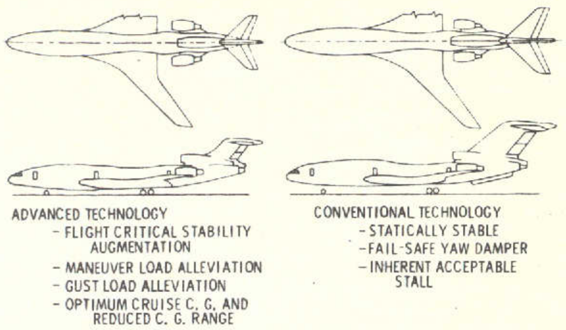


Figure 24. Active controls technology application.

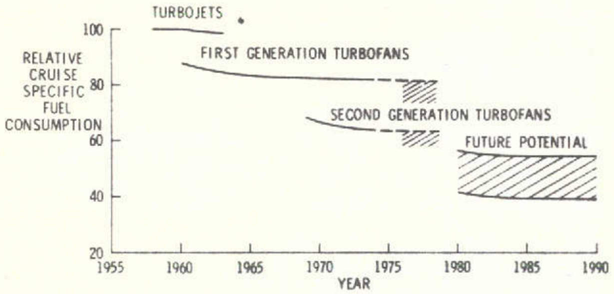


Figure 22. Trends in aircraft engine fuel consumption.

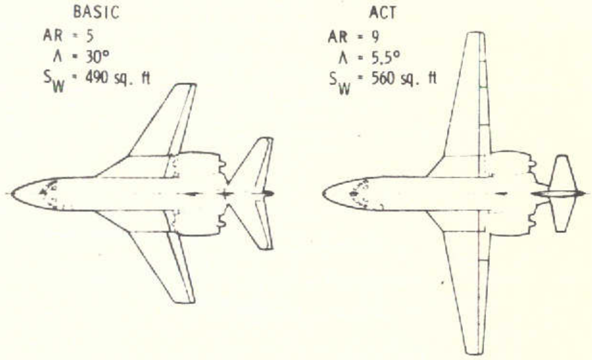


Figure 25. Comparison of basic and ACT airplane.

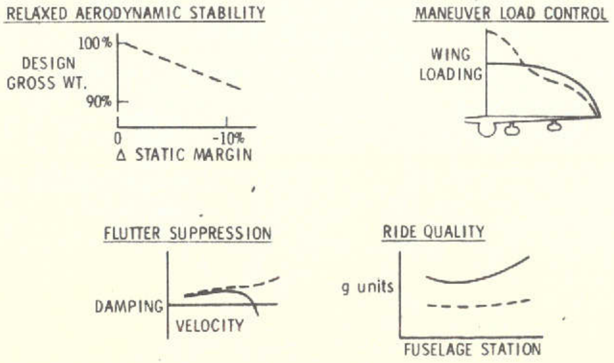


Figure 23. Advanced control concepts.

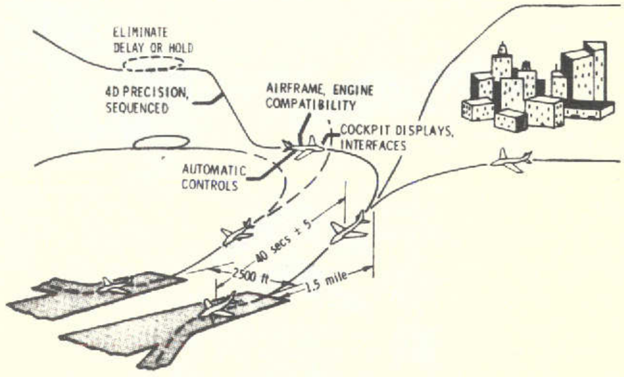


Figure 26. High capacity terminal area operations.

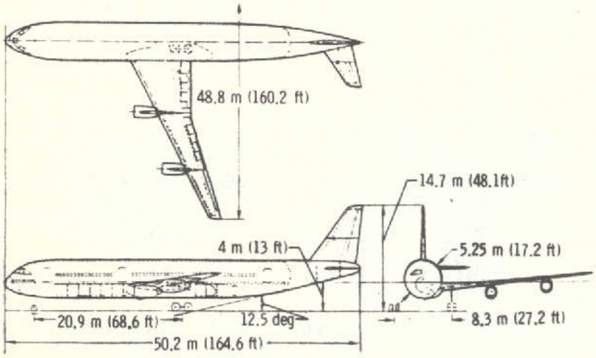


Figure 27. General arrangement, TAC/energy airplane.

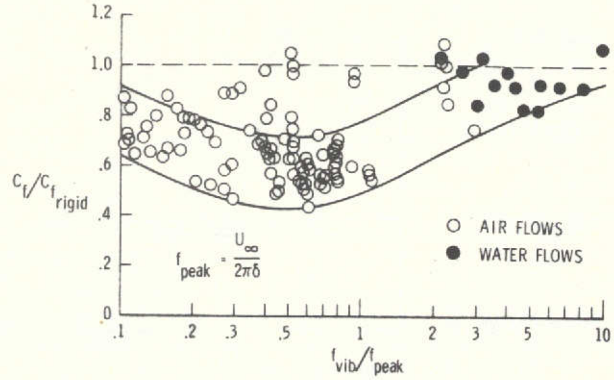


Figure 30. Compilation of experimental data on compliant walls.

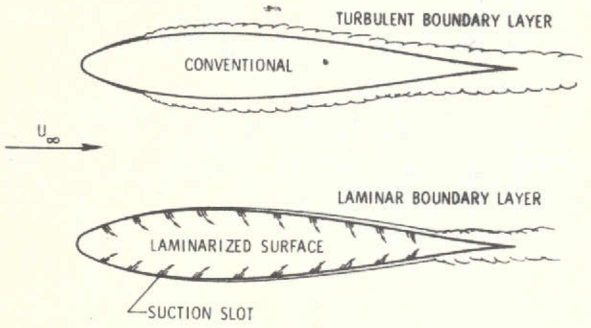


Figure 28. Comparison of conventional and laminar flow airfoils.

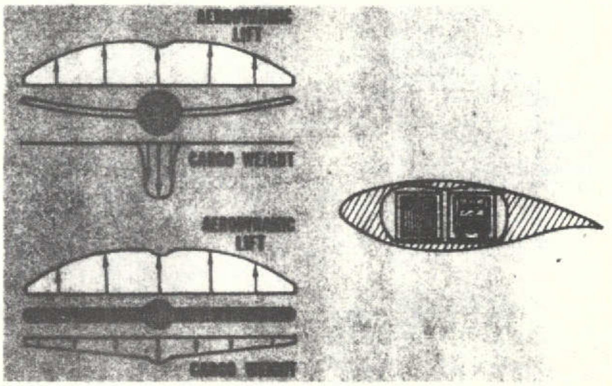


Figure 31. Wing-span distributed load concept.

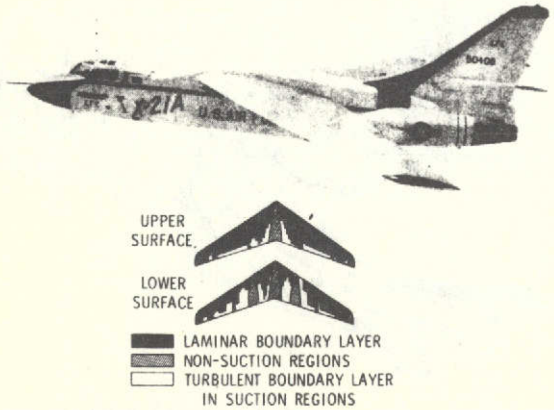


Figure 29. X-21A aircraft in flight.

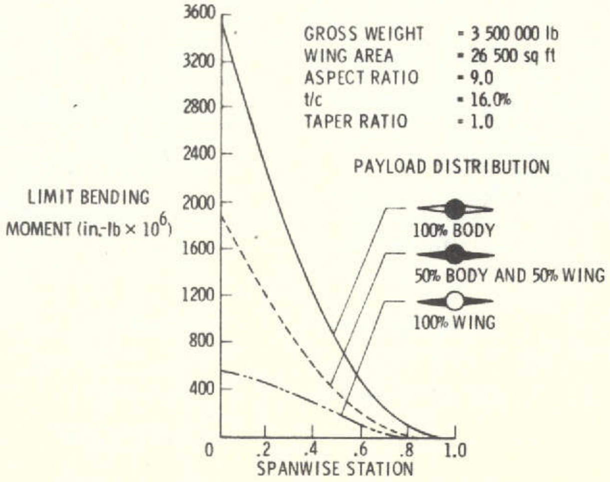


Figure 32. Payload distribution effects.

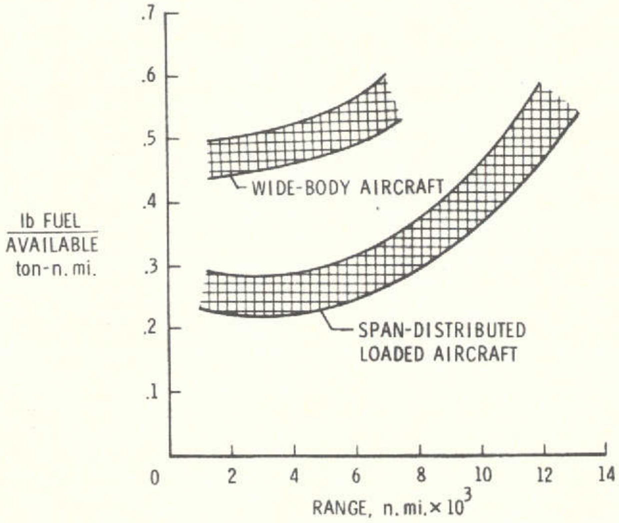


Figure 33. Fuel efficiency comparison.

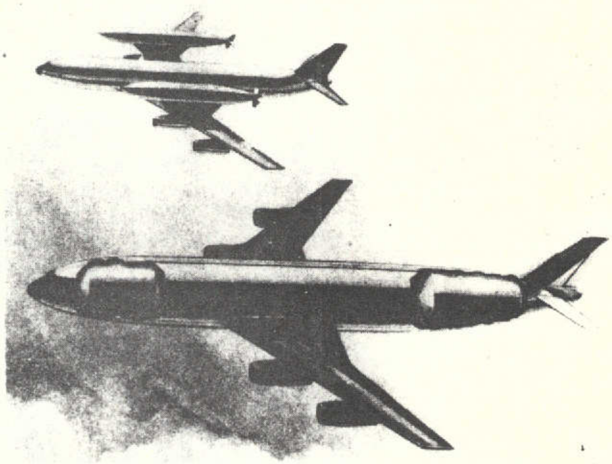


Figure 35. Liquid hydrogen airplane concepts.

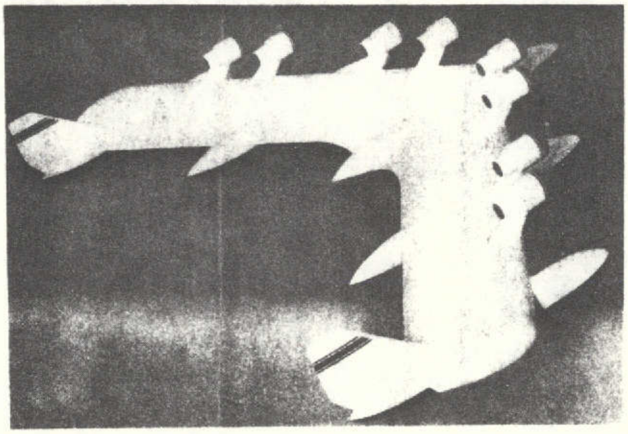


Figure 34. Span distributed load airplane concept.

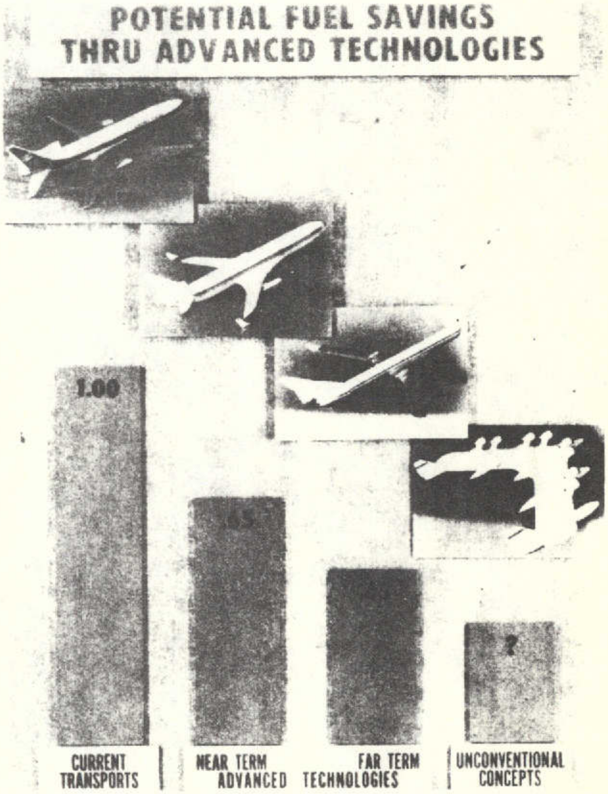


Figure 36. Potential fuel savings through advanced technologies.