Conceptual Design of Reduced Energy Transports

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The recent "energy crisis" and subsequent increases in fuel prices have provided increased incentive to reduce the fuel consumption of transport aircraft. Operators of current aircraft have responded to this situation by changing operational procedures to decrease fuel consumption. In the future, however, it may become desirable or even necessary to introduce new fuel-conservative aircraft designs. This paper reports the results of a conceptual design study of new, near-term fuel-conservative aircraft. A parametric study was made to determine the effects of cruise Mach number and fuel cost on the "optimum" configuration characteristics and relative economic performance. Supercritical wing technology and advanced engine cycles were assumed. For each design, the wing geometry was selected to maximize an economic figure of merit which reflects the potential rate of return on investment. Based on the results of the parametric study, a reduced energy configuration was selected. Compared with existing transport designs, the reduced energy design has a higher aspect ratio wing with lower sweep, and cruises at a slightly lower Mach number. It yields about 30% more seat-miles/gal than current wide-body aircraft. At the higher fuel costs anticipated in the future, the reduced energy design has about the same economic performance as existing designs with the same technology level. As an example of a far-term technology application, a design with a composite material wing was also investigated.

I. Introduction

THE "energy crisis" of 1973-74 highlighted a serious problem that has been developing for years. The use of petroleum-based fuels has been increasing at an alarming rate in the face of dwindling world supplies. The energy crisis imposed severe restrictions on the use of this fuel. Because of its heavy dependence on petroleum-based fuels, transportation, (particularly aircraft transportation), was affected most severely by these restrictions.[1]

Although the severe restrictions on the use of fuel have been lifted to a great degree, it is clear that the limited availability and higher cost of petroleum-based fuel will be a very significant factor in the future course of air transportation. Even if fuel is not restricted or allocated, continually higher prices will undoubtedly prevail. This situation may well have a profound effect on the design and operation of future air transports.

There are several ways in which the fuel consumption of the civil air transportation fleet can be reduced, and most of these are under study at the present time. These range from changes in the cruise altitude and speed of current aircraft, to the development of new, far-term aircraft designs employing advanced, currently undeveloped technology by which minimum fuel consumption can be achieved.[2,3] In the study reported herein, primary consideration was given to decreasing fuel consumption by the design of a new, near-term aircraft; i.e. a design which employs existing technology and which could be introduced into the fleet by 1980. To represent a far-term aircraft, the effect of using a composite material wing was also investigated.

The primary tool used to generate the data for this study was a transport synthesis (TRANSYN) computer program. This program is basically a computerized, integrated form of an aircraft preliminary design process. The program consists of a control module and discipline-area modules to perform the required geometry, aerodynamics, propulsion, structure, weight, volume, and economics computations. In the present study, a parameter optimization module[4,5] was also used to optimally shape the wing planforms of the vehicles. Currently, flutter and aeroelastic computations are not an integral part of the TRANSYN program; these computations are performed externally for selected vehicles. TRANSYN has been used extensively in the past for similar studies.[6,7]

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II. Study Ground Rules and Constraints

The study ground rules are presented in Table 1. The aircraft selected for study has a passenger capacity of 200 and a range of 3000 n.mi. This aircraft would be a possible replacement for the older, first-generation jet transports. The selected capacity and range results in favorable economics and fuel economy in the medium-to high-density intra-continental market. For high-density routes, it offers increased scheduling flexibility that can be used to increase frequencies and/or load factors over those of larger aircraft. The baseline study assumption of fixed utilization means that faster aircraft will have greater productivity (i.e., greater seat-miles/day). The values of utilization and load factor are typical average values for large commercial aircraft fleets. The baseline fuel cost of 30¢/gal (in 1975 dollars) is representative of expected prices in the 1980's, assuming development of alternative petroleum fuel sources (i.e., coal gasification or oil shale.)[1]

The ground rules assume the use of existing technology. While everything from lighter-than-air systems to the use of liquid hydrogen fuel has been suggested for relieving the aircraft fuel-consumption problem, it seems likely that the next generation of transport aircraft will evolve by improving conventional configurations. The JT-10D engine cycle and weights were adopted as representative of an advanced near-term engine design. In this study, the engine thrust and weight were scaled as required to match the mission requirements. In an actual aircraft design, the aircraft capacity and number of engines would be matched to the size of a specific engine. The latest supercritical wing data were used for aerodynamic analyses. These data indicate that Mach numbers up to 0.8,

Table 1 Study ground rules

- MISSION AND ECONOMIC
  - 200 PASSENGER, 3000 n. mi.
  - 1975 DOLLARS
  - 250 FLEET SIZE
  - 3290 HOURS/YEAR UTILIZATION
  - 0.5 LOAD FACTOR
  - BASELINE 30¢/gallon FUEL COST
- TECHNOLOGY
  - CONVENTIONAL FOUR ENGINE CONFIGURATION
  - JT10D ENGINE CYCLE WITH SCALED THRUST AND WEIGHT
  - FAR 36-10 NOISE LEVEL
  - SUPERCRITICAL AIRFOILS
  - CONVENTIONAL ALUMINUM STRUCTURE

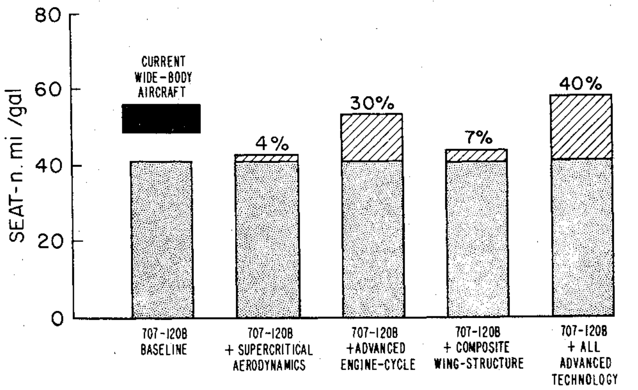

Fig. 1 Impact of advanced technologies on fuel efficiency for fixed configuration (wing sweep, aspect ratio, passenger capacity) with the exception of reduced wing sweep for configurations with supercritical aerodynamics.

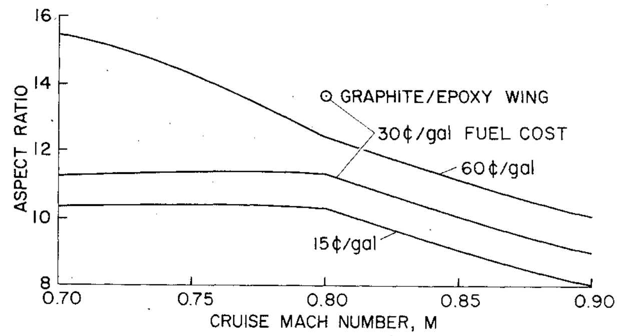

Fig. 2 Effect of cruise Mach number on aspect ratio.

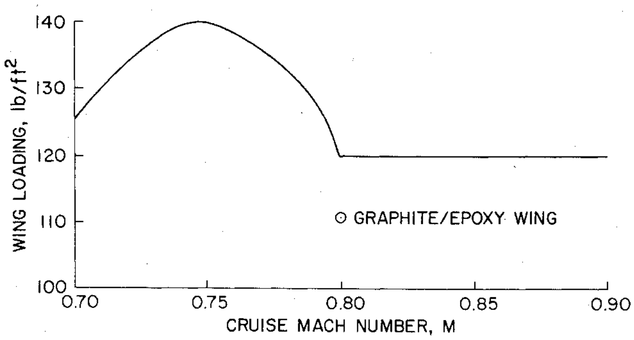

Fig. 3 Effect of cruise Mach number on wing loading.

measured perpendicular to the wing semichord, are possible without incurring excessive drag rise. Generally, conventional state-of-the-art aluminum structure was assumed. However, a design employing a graphite/epoxy wing was also assessed.

Cruise Mach number is one of the most important parameters influencing aircraft economics and fuel consumption. Therefore, one of the principal aims of the current study was to examine aircraft designed for a range of Mach numbers from 0.7 to 0.9. The constraints used to size these aircraft are shown in Table 2. The restrictions on Mach number perpendicular to the semichord and the thickness-to-chord ratio are consistent with current supercritical airfoil technology. The Mach number restriction determines the wing sweep for speeds greater than Mach 0.80; aircraft with speeds less than 0.80 Mach number have straight wings. The wing thickness-to-chord ratio was constrained at the maximum value consistent with good aerodynamic characteristics. A lower limit of 30,000 ft on cruise altitude and an upper limit of 0.60 on section lift coefficient were imposed. The altitude limit is necessary to avoid delays due to adverse weather and the lift coefficient limit is necessary to provide adequate margins for maneuvering. These limits were encountered only by the lower-speed, straight-wing aircraft. The aircraft were subject to a fuel volume constraint because it was assumed that all required fuel is carried in the wing. This constraint was important only for the higher-speed, swept-wing aircraft.

To properly reflect the importance of fuel cost, initial investment, and productivity, the rate of return on investment to the operator of the aircraft is the most desirable design criterion or figure of merit. However, computation of an accurate return on investment involves life cycle costing and requires detailed information regarding route structures, production rates, program lifetime and other factors. Since such a computation is beyond the scope of the present study, a simplified economic figure of merit (EFOM) was used. This EFOM is based on a single aircraft flying a year on routes at its design range. Although the absolute value of the EFOM has little meaning, it is felt to be accurate on a relative basis to select superior configurations. Since the engine cycle is fixed, the optimization involves only the wing aspect ratio (*AR*) and the wing loading (*W/S*). Therefore, the aircraft were sized by maximizing the EFOM with respect to the *AR* and *W/S*, subject to the constraints previously described. This maximization was done for different specified cruise speeds and fuel prices.

III. Results

Impact of Advanced Technologies

To isolate the effects of advanced technology from those of design changes, the following procedure was used: first, the effect on fuel consumption was assessed by applying, individually, supercritical airfoil aerodynamics, an advanced engine cycle, and a graphite/epoxy wing to an existing aircraft design holding the configuration fixed (except for a sweep reduction when supercritical aerodynamics are applied). The Boeing 707-120B was chosen as the baseline case because it is representative of older, first-generation jet transport aircraft. The designs were all sized to meet the same payload and range requirement. Then the combined effect of applying all three technologies simultaneously was assessed for the fixed configuration. Finally, the configuration was redesigned using these advanced technologies for maximum EFOM at various values of fuel cost. The results for the fixed and redesigned configurations are presented in this and the following sections, respectively.

Figure 1 shows that for the fixed configuration, the largest improvement in fuel efficiency, 30%, comes from improved engine performance. Much of this improvement is already being realized by the current wide-body aircraft, as shown on the left of the figure. The effects of supercritical aerodynamics and advanced composites are relatively small, however, this reflects the limitation that the aircraft have not yet been redesigned to take full advantage of these technologies. Also shown in Fig. 1 is the combined effect of applying all three technologies simultaneously. This results in

Table 2 Sizing

- CONSTRAINTS
  - $M_{\perp C/2} \leq 0.80$
  - $(t/c)_{\perp C/2} = \begin{cases} 0.1, & 0.8 \leq M_{CRUISE} \leq 0.9 \\ 0.9 - M_{CRUISE}, & 0.7 \leq M_{CRUISE} < 0.8 \end{cases}$
  - $h_{CRUISE} \geq 30{,}000$ ft
  - $c_{l_{SECTION}} \leq 0.60$
  - $VOL_{WING} \geq VOL_{FUEL}$
- CRITERIA
  - MAXIMIZE EFOM WITH RESPECT TO AR AND W/S

about a 40% improvement in fuel efficiency (in terms of seat n.mi./gal) over that for the 707-120B baseline.

Effects of Cruise Mach Number and Fuel Cost

Higher fuel costs may well alter the selection of cruise Mach number (M). To determine the effects of M and fuel cost on performance and economics, and to aid in selecting the best value of M, six aircraft with values of M from 0.70 to 0.90 were optimized for fuel costs of 15¢, 30¢, and 60¢/gal., according to the constraints and criteria discussed earlier. The lowest cost of 15¢/gal is only slightly higher than pre-energy crisis fuel costs; the middle cost of 30¢/gal is the baseline value discussed previously, and the high cost of 60¢/gal is representative of values which may occur in extreme cases. To put these fuel cost in perspective, the average fuel cost (as of Jan. 1975) was 25.8¢/gal for scheduled domestic trunk aircraft operations and 36.3¢/gal for international trunklines. All configurations employ supercritical aerodynamics and the advanced engine cycle. In addition, a design employing a graphite/epoxy wing (as well as supercritical aerodynamics and the advanced engine cycle) was optimized for $M=0.80$ and 30¢/gal fuel cost. The results for this special case are discussed subsequently.

The optimum values of aspect ratio (AR) are shown in Fig. 2. As M decreases from 0.90 to 0.80, the AR increases because the decreasing wing sweep causes the difference between the structural and aerodynamic aspect ratios to decrease (the optimum structural aspect ratio at a given fuel cost remains very nearly constant for all values of M). In other words, at lower speeds, a higher aerodynamic aspect ratio is possible for the same wing weight. The optimum AR of the swept-wing designs is higher than for current swept-wing designs primarily because of the higher fuel costs. Below $M=0.80$, the wing sweep remains the same and there is little or no incentive to increase AR as M is decreased. The aspect ratio of the straight-wing designs optimized for 30¢/gal fuel cost is about 11.5. In all cases, the constraints have little effect on the selection of the optimum value of AR.

Figure 2 also shows how the optimum wing aspect ratio changes as the fuel cost is varied. The AR tends to increase as fuel cost increases. This is so because, at the higher fuel costs, relatively more emphasis is placed on aerodynamic efficiency than on structural weight. It should be remembered that, for this study, the wing is assumed to be designed for static strength and stability. A preliminary flutter analysis indicates that all the configurations designed for 15¢ and 30¢/gal fuel cost are flutter-free, although some may be only marginally so. Flutter has not been analyzed for the 60¢/gal fuel cost designs, and these may well require additional weight to compensate for aeroelastic effects. This would tend to lower the values of optimum aspect ratios for those wings above AR 14. Since the sensitivity to changes in aspect ratio about the optimum values is small, this would have only a small effect on performance. There may also be problems other than flutter associated with the high aspect ratio, straight-wing designs. Particular areas of concern are flexibility, gust load response, and ride quality. These are discussed later.

The value of the optimum wing loading (Fig. 3) at each cruise Mach number is nearly the same for all three fuel costs. This is because wing loading is determined primarily by the constraints. The wing loading would tend to be higher (smaller wing) if the constraints were relaxed. The optimum wing loading remains nearly constant at a value of 120 lb/ft^2 for the swept-wing designs due to the fuel volume constraint. Below $M=0.80$, the increased wing thickness allows a smaller wing platform. At values of M below 0.75, the altitude constraint forces the wing loading to decrease. The corresponding values of aspect ratio for Fig. 3 are the optimum ones as shown on Fig. 2.

The optimum configuration with the graphite/epoxy wing, designed for $M=0.80$ and a fuel cost of 30¢/gal, has an AR of 13.5 (Fig. 2) and a W/S of 110 lb/ft^2 (Fig. 3). Thus, advantage has been taken of the lighter weight material to further increase the aerodynamic efficiency.

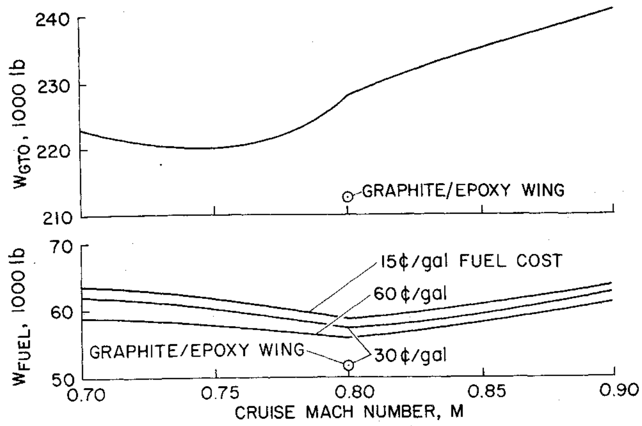

Fig. 4 Effect of cruise Mach number on weights.

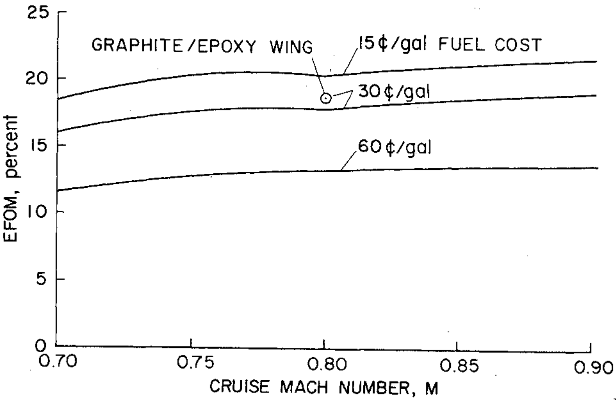

Fig. 5 Effect of cruise Mach number on the economic figure of merit.

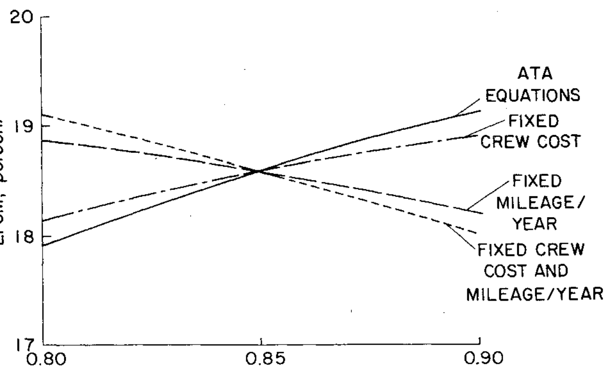

Fig. 6 Effect of cost assumptions. Notes: fixed crew cost-crew cost/trip held constant at $M=0.85$ value. Fixed mileage/year-number of trips held constant, not utilization.

The effect of M on the aircraft gross takeoff weight (W_{GTO}) and mission fuel weight (W_{FUEL}) for the design range of 3000 n.mi. at full payload is shown in Fig. 4 for the optimum configurations. As M decreases from 0.90, W_{GTO} and W_{FUEL} decrease because of decreasing wing sweep and increasing thickness. W_{GTO} decreases faster than W_{FUEL} because the structural weight is also decreasing due to resizing. The weights of the straight-wing aircraft designs increase slightly as M is decreased below 0.75. This is due to use of an engine cycle designed for 0.85 M and to the minimum altitude constraint. The optimum 0.80 M configuration consumes about 8.0% less fuel than does the optimum 0.90 M configuration when designed for the same fuel cost. It should be noted that the designs on Fig. 4 have low values of W_{GTO} compared with existing designs for the same mission. This difference is due to the use of supercritical wing aerodynamic data and an advanced engine cycle. The cruise lift-to-drag ratio of the 0.80 M design for 30¢/gal fuel cost is 18.5. Figure 4 also shows that the graphite/epoxy wing design has 6.6% less W_{GTO} and uses 9.8% less fuel than the corresponding all-aluminum design.

Figure 5 shows the values of the EFOM for the various values of M and fuel cost. As before, each of the designs is optimized for its cruise Mach number and fuel cost. At the lowest fuel cost, the swept-wing configurations (0.80 M to 0.90 M) have EFOMs which are superior to those of the straight wings. At pre-energy crisis values of fuel cost (10¢-12¢/gal), the 0.90 M design would have the best EFOM. This is not surprising in view of the fact that the most recent of the current generation of jet transports, designed for pre-energy crisis fuel costs, have cruise Mach numbers around 0.85. As fuel cost increases, the EFOM of the swept-wing designs decreases more rapidly than does that of the straight-wing designs because of their higher fuel fractions. At the highest fuel cost, EFOM is very nearly the same at all values of M. The slower straight-wing designs (0.70 M to 0.75 M) suffer from lower productivity, an engine cycle that is better suited for the higher speeds, and the minimum altitude constraint. The figure also shows that the graphite/epoxy wing gives an incremental improvement in EFOM of about 1%.

The selection of the best cruise Mach number is highly influenced by assumptions on productivity and utilization and by ground rules for computing operating cost. In this study, the standard Air Transport Association method of computing direct operating costs,[8] with the assumption of constant utilization, was used. Thus faster aircraft fly more mileage per year (thereby generating more revenue) and have lower crew costs per mile than slower aircraft. The resulting effect on EFOM is shown by the solid line on Fig. 6, which indicates that the faster aircraft are superior. If, however, the assumption of fixed mileage per year is adopted, the trend is reversed and the slower aircraft are superior. The effect of assuming a fixed crew cost per mile is also shown on the figure. In practice, EFOM is a discontinuous function of M and selection of the optimum cruise speed can only be based on a detailed study of airline route structures and operating procedures.

To show explicitly the effects on fuel weight and EFOM of changes in fuel cost, the 0.80-M data of Figs. 4 and 5 are cross-plotted in Fig. 7. The solid lines show the sensitivities if the wing geometry is optimized at each value of fuel cost; the dashed lines are for the wing designed for the nominal 30¢/gal fuel cost. W_{FUEL} decreases with increasing fuel costs for the optimized designs. At about 60¢/gal, a minimum fuel design is approached and further reductions in fuel consumption are small. It was found that W_{GTO} remains nearly constant as fuel cost is increased, indicating a nearly even trade-off between increasing structural weight and increasing lift-to-drag ratio. Thus, empty weight (and therefore also acquisition cost) increases as fuel cost increases.

The bottom of Fig. 7 shows that use of configurations optimized at each fuel cost does not give significantly better economic performance than that of the design optimized for the nominal fuel cost. It may be concluded that a 0.80-M straight-wing design would give relatively good economic performance at any fuel cost. However, the fuel consumptions of the designs represented by the solid and dashed lines are significantly different, as shown by the top half of the figure. The figure indicates that there may be very little economic incentive to operate fuel-conservative aircraft.

To place the effect of fuel cost in perspective with the effects of other important economic parameters, Fig. 8 compares the effects of fuel cost and load factor on EFOM. As shown on this figure, an increase in load factor from 50% to 60% can completely compensate for anticipated increases in fuel cost. Thus, even though sharply increased fuel costs will have a significant impact on the economics of transport aircraft, there are other powerful economic factors which may be used to counteract this impact.

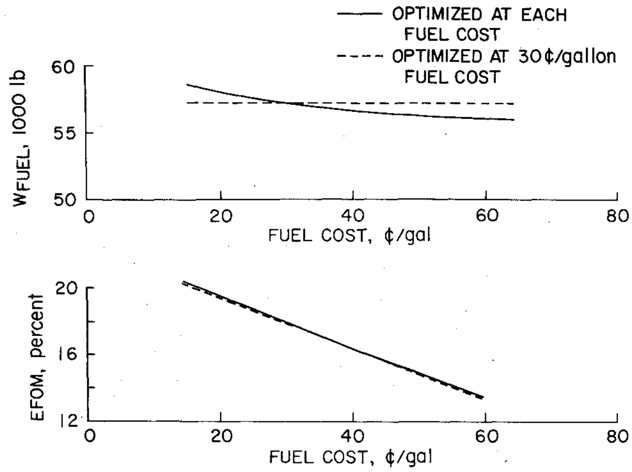

Fig. 7 Effect of fuel cost on fuel weight and the economic figure of merit, $M = 0.80$.

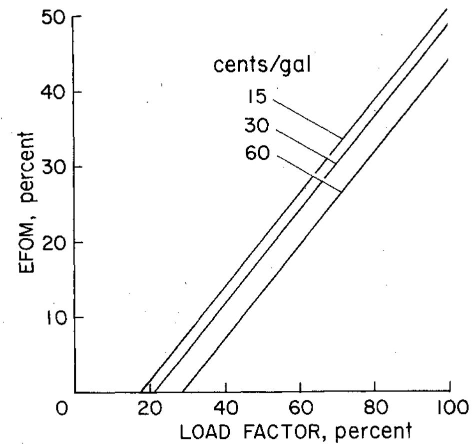

Fig. 8 Effect of fuel cost and load factor on the economic figure of merit, $M = 0.80$.

Reduced Energy Transport Configuration

Based on the discussions of the previous section, the most promising near-term low fuel consumption configuration identified in this study has a cruise Mach number of 0.80 and a straight wing of aspect ratio 11-½. Such a design would have significantly better fuel economy than existing transport designs and would have about the same economics at the higher anticipated future fuel costs. In addition to improved fuel economy, such a low fuel consumption design has some other attractive features. Aircraft noise reduction is inherent in the design and the goal of FAR 36-10 can be met by the basic engine with minimum wall treatment only. Also, due to the high aspect ratio straight wing, field length is not a constraint. In fact, because of the superior high lift characteristics of the straight wing, it may be possible to eliminate some of the complex high lift devices found on current transport designs.

On the other hand, a high aspect ratio straight wing may introduce some new problems and constraints. Many of these may turn out to be relatively unimportant, but all must be investigated. For example, as mentioned earlier, this design tends to be limited by cruise altitude and lift coefficient constraints. The low fuel consumption design also has lower cruise and approach speeds than existing designs which may cause some problems in enroute and terminal area air traffic control. Straight wings with high aspect ratios result in large

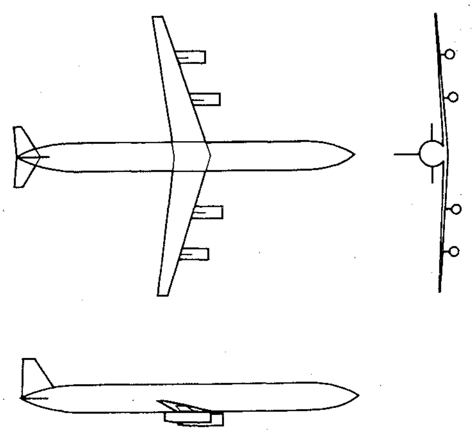

Fig. 9 Reduced energy transport (RET) configuration.

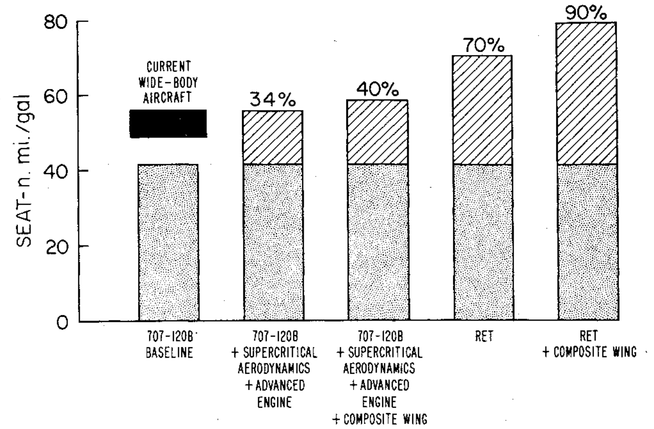

Fig. 12 Relative fuel efficiency.

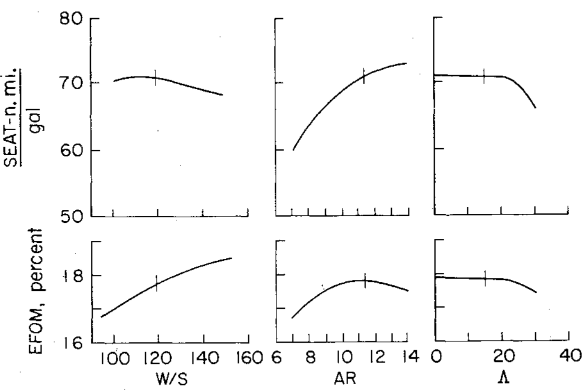

Fig. 10 Sensitivity to wing geometry, RET.

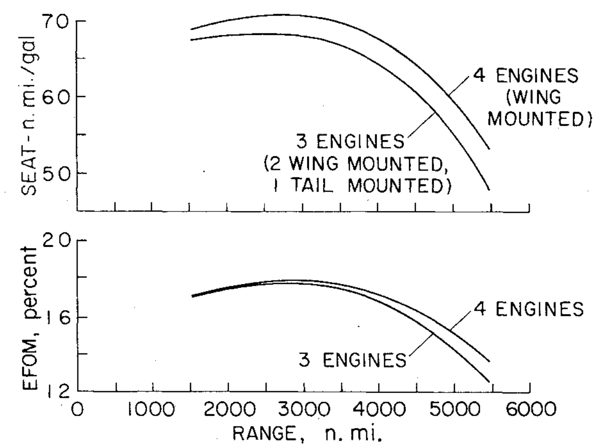

Fig. 13 Effect of range and number of engines, 200 passengers, $M = 0.80$.

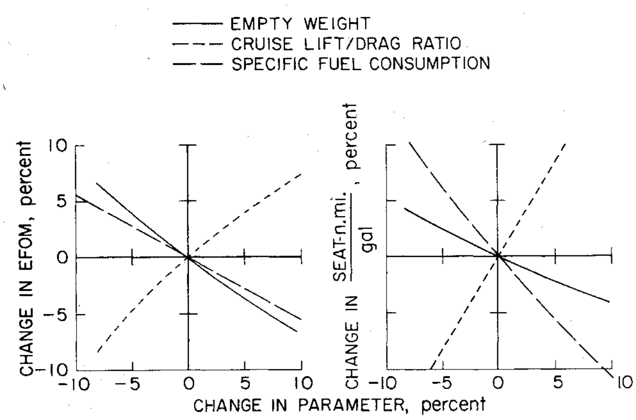

Fig. 11 Sensitivity to empty weight, cruise lift-to-drag ratio, and specific fuel consumption, RET. $M = 0.80$; $W_{GTO} = 228{,}000$ lb; $AR = 11.50$; $W/S = 120.0$ lb/ft^2; $\Lambda = 15°$.

wing spans. This could lead to gate spacing incompatibility with existing swept-wing aircraft. Passenger appeal is another area that may be affected by the slightly higher block times or by the identification of straight wings with old-fashioned aircraft designs. An undesirable feature of a configuration with four engines mounted on a straight wing is that the rotating machinery is all in approximately the same lateral plane. Thus, a catastrophic failure of one engine could also cause the failure of its neighbor.

Perhaps the most serious questions concerning the low fuel design are those concerned with the flexibility and loading characteristics of high aspect ratio straight wings. It has already been mentioned that a preliminary flutter analysis shows the configuration to be marginally flutter free. However, the wing may still be too flexible to be acceptable because of other aeroelastic constraints. Further, the high lift curve slope of the straight wing makes the configuration more susceptible to gust loads and could result in a high fatigue environment. Also, the ride quality may be slightly degraded. (Such an airplane may be a good candidate for load alleviation by active controls.) Because of these factors, a practical design would probably have a nominal amount (about 15°) of quarter-chord sweep. Such a configuration, called the reduced energy transport (RET) configuration, is shown in Fig. 9. This design has slightly greater fuel consumption and about the same economic performances as the straight-wing design discussed previously. In addition to having a wing less prone to flexibility effects and gust loading, such a configuration would also benefit from a staggered engine placement to avoid engine failure coupling.

The sensitivity of the fuel efficiency and the EFOM of the RET to changes in wing geometry is shown in Fig. 10. For these variations, the wing volume and minimum altitude constraints were relaxed. Increasing wing loading improves the EFOM but such designs would violate the constraints. The aspect ratio which minimizes the fuel consumption is higher than that which maximizes the EFOM, but the benefits are small above AR 12. The penalty for adding 15° of wing sweep is very small.

The sensitivities to changes in structural efficiency (as measured by empty weight), aerodynamic efficiency (lift-to-drag ratio), and propulsive efficiency (specific fuel consumption) are shown in Fig. 11. EFOM is most sensitive to empty weight and lift-to-drag ratio and slightly less sensitive to specific fuel consumption. On the other hand, fuel efficiency is most sensitive to lift-to-drag ratio and specific fuel consumption since these have a direct effect on fuel con-

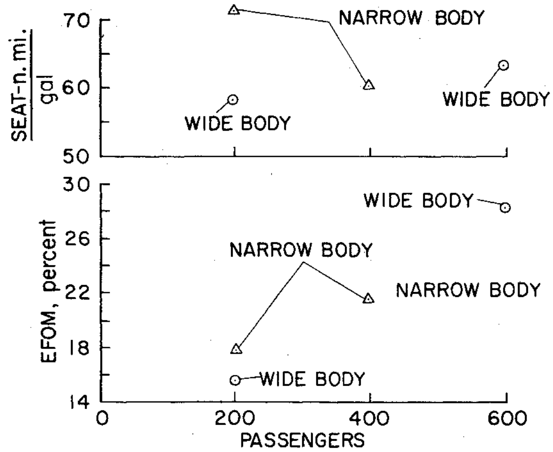

Fig. 14 Effect of passenger capacity and body width, 3000 n.mi., M =0.80.

sumption. Empty weight is more important for EFOM because of its effect on aircraft cost.

Figure 12 compares the fuel efficiency of the reduced energy transport configuration to that of existing transports. The fuel efficiencies are shown in terms of seat-n.mi./gal for full payloads and design ranges and would be lower for shorter stage lengths. The first bar on the figure shows the 707-120B baseline, and the next two bars show the result of applying advanced technology to this aircraft with no change in cruise speed or wing geometry (see Fig. 1). The fourth bar shows that adopting the RET configuration gives an additional significant gain in fuel efficiency. As discussed earlier, this configuration has a lower cruise speed, less wing sweep, and a higher aspect ratio than existing designs. Finally, the figure also shows that redesigning the wing for composite materials (the major change is an increase in the aspect ratio from 11-½ to 13-½) increases the benefit of such materials. It appears that use of advanced technology (including a composite material wing) and an aircraft designed for low fuel consumption will give about a 90% improvement in seat-n.mi./gal compared to the first generation narrow-body jet transports. Compared with the current wide-body transports, the improvement is about 43%.

Effect of Range, Number of Engines, Number of Passengers, and Body Width

The effect of design range and number of engines is shown in Fig. 13. The fuel efficiency and economic performance are again computed at design range. At short ranges, the aircraft become less efficient due to the large portion of the flight spent in climb and descent while at the longer ranges the efficiency falls off due to the increasing amount of fuel which must be carried. At about 3000 n.mi. there is a maximum for both fuel efficiency and EFOM for these designs. Under the ground rules of the present study, four wing-mounted engines are always superior to the three-engine design due to the extra wing inertia relief, although the difference is small.

Figure 14 shows that EFOM increases with passenger capacity (assuming constant load factors). The narrow-body designs have better fuel efficiency and EFOM at small passenger capacities but the wide bodies are superior for high passenger capacities. The cross-over point is around 400 passengers.

IV. Conclusions

New transport aircraft designs appropriate for an environment of high fuel costs have been investigated. Emphasis in this study was on designs which are "near-term" in that they employ technology which is either existing or in an advanced state of development. Some "far-term" designs using graphite/epoxy wings were also analyzed. The principal results are summarized in Fig. 12. The following conclusions may be made:

1) Application of advanced technology (supercritical aerodynamics, an advanced engine cycle, and a composite material wing) to a typical first generation jet transport (707-120B) gives a 40% improvement in fuel efficiency. Without changing the aircraft geometry, the advanced engine cycle has the most substantial impact, and much of this improvement is already being achieved by the current wide-body aircraft.

2) The most promising reduced energy transport configuration (aluminum) has a high aspect ratio (11-½), nearly straight, supercritical wing and a cruise Mach number of about 0.80. Such a configuration would have reasonably good economic performance across a wide range of fuel prices.

3) The reduced energy transport configuration (aluminum wing) results in approximately a 70% improvement in fuel efficiency when compared with the 707-120B and a 30% improvement when compared with the current wide-body transports. Use of a composite material wing increases these relative improvements to 90% and 43%, respectively.

4) For pre-energy crisis fuel costs, there would be a slight economic penalty associated with the reduced energy transport configuration. At anticipated higher future fuel costs, there may be little or no economic penalty. On the other hand, there appears to be no strong economic incentive for commercial transport operators to operate reduced energy designs.

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