NASA TECHNICAL MEMORANDUM

NASA TM X-62,156

NASA TM X-62,156

TRANSONIC TRANSPORT STUDY – SUMMARY

Louis J. Williams

Office of Aeronautics & Space Technology
Advanced Concepts & Mission Division
Moffett Field, Ca. 94035

(NASA-TM-X-62156) TRANSONIC TRANSPORT STUDY, SUMMARY L.J. Williams (NASA) May 1972 46 p CSCL 01B

N72-26009

Unclas
G3/02 31392

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

WASHINGTON, D. C. MAY 1972

SUMMARY

This paper summarizes a study of transonic transport aircraft designed for introduction in 1980. The study considered transcontinental aircraft that would not produce a sonic boom on the ground. The aircraft studied are conventional swept wing configurations designed for a range of 2700 n. mi. with a payload of 200 passengers and no cargo. The results are reported in this summary paper and in specialty papers in the areas of aerodynamics and structures, propulsion, and economics.

The effects of possible increases in cruise speed over present-day transports were investigated. Increased cruise speed is desirable not only because of a possible competitive market advantage, but also because of the resulting increase in aircraft productivity. Aircraft designed to cruise at Mach numbers greater than those of present-day transports but less than those which produce a sonic boom on the ground were studied.

The purpose of the study was three-fold: first, to compare, on an equal basis, the performance and economics of advanced commercial transport aircraft designed to cruise at Mach numbers 0.90, 0.98, and 1.15; second, to determine the sensitive technical areas affecting the performance and economics of the aircraft; and third, to assess the impact of advanced technology, particularly the supercritical wing and advanced composite materials on the performance and economics of the aircraft.

To perform this study, an aircraft synthesis program called TRANSYN-TST was developed. This computer program allows comparison of aircraft on an equal basis, since the same computing methods and ground rules (range and payload requirements) can be applied to all aircraft. TRANSYN-TST consists of a control program and numerous subroutines to do the various tasks required to synthesize an aircraft design.

The conclusions of the study may be summarized as follows. First, the optimum engine cycles of all the study aircraft are within the current state-of-the-art, but fan noise suppression will be required to meet the noise requirements of FAR Part 36. Second, fuselage area ruling causes wing and fuselage weight interactions. Third, it was found that full use of advanced composite materials in the wing and fuselage structure is neutrally cost effective when compared with aluminum for aircraft designed to cruise in the low transonic regime (Mach 0.90 to Mach 1.0) but that such materials are very cost effective for aircraft designed to cruise in the high transonic regime (Mach 1.0 to Mach 1.15). Finally, increasing speed results in reduced trip times with very slight increases in cost in the low transonic regime, but cruise speeds in the high transonic regime result in a significant economic penalty for the conventional configurations considered in this study.

INTRODUCTION

In order to maintain the superiority of U.S. commercial transport aircraft in the world economic arena, the U.S. must remain a leader in developing and applying advanced aeronautical technology. Since the U.S. is not in a position to compete with foreign countries on the basis of labor rates, we must produce a product that is more cost effective by incorporating technological advances that are not available elsewhere. Toward that end, this study examines commercial transport aircraft, designed for introduction in the early 1980's, to determine the advanced technology areas that give the largest improvements in performance and economics.

The study is limited to transcontinental aircraft that would not produce a sonic boom on the ground. The aircraft studied are conventional swept wing configurations designed for a range of 2700 n.mi. with a payload of 200 passengers and no cargo. The effects of possible increases in cruise speed were investigated. Increased cruise speed is desirable not only because it gives a competitive market advantage, but also because of the resulting increase in aircraft productivity. Aircraft were designed to cruise at Mach numbers of 0.90, 0.98, and 1.15. For the purposes of this study the aircraft are denoted respectively as CVT (conventional transport), ATT (advanced technology transport), and TST (transonic transport). Mach number 0.90 represents, approximately, the highest cruise speed achievable with no significant wave drag for an aircraft using the supercritical wing and no fuselage area ruling. Mach number 0.98 represents, approximately, the highest cruise speed achievable without wave drag by using the supercritical wing and fuselage area ruling. Mach number 1.15 represents, approximately, the upper limit for cruise with no sonic boom reaching the ground. This limit occurs due to the atmospheric temperature gradient. Because of the lower temperature at altitude, the speed of sound there is lower than at ground level. As a result an aircraft flying at Mach 1.15 at 40,000 feet is actually flying at a velocity that corresponds to Mach 1 at sea level, and its sonic boom does not reach the ground. Recent results suggest that Mach 1.15 may be too high, and that perhaps Mach 1.08 would be more reasonable to allow for terrain and weather fluctuations. For the purposes of this study, it is felt that the results pertaining to the aircraft designed to cruise at Mach 1.15 would be very close to those for an aircraft designed to cruise at Mach 1.08.

It is interesting to examine the historical trend in cruise speed shown in figure 1. Beginning with the introduction of the Ford Tri-Motor in 1929 with a cruise speed of 104 knots, the speed of propeller-driven, piston engine aircraft steadily increased with the DC-3, the DC-6, and up to the DC-7 in 1956 with a cruise speed of 300 knots. The development of the turboprop Lockheed Electra in 1957 resulted in a step increase to 350 knots. A large jump in cruise speed came with the introduction of the turbojet engine on commercial transports. The cruise speed of the 707-120, introduced in 1957, was 456 knots, an increase of 156 knots or approximately 50% over the DC-7. Since the introduction of the turbojet and, subsequently, turbofan engines, aircraft cruise speed has increased gradually up to the present-day Boeing 747 with a speed of 492 knots. Projecting the current trend to 1985 results in aircraft cruising at 514 knots or a Mach number of 0.90. A step improvement would occur with an increase to Mach 0.98, or 560 knots, and a large step increase would be obtained at a cruise speed of Mach 1.15, or 660 knots.

The purpose of this study was three-fold: first, to compare on an equal basis the performance and economics of advanced commercial transport aircraft designed to cruise at Mach numbers 0.90, 0.98, and 1.15; second, to determine the sensitive technical areas affecting the performance and economics of the aircraft and point out areas where more precise estimation methods or experimental data is needed to more accurately determine aircraft performance; and third, to assess the impact of advanced technology, particularly the supercritical wing and advanced composite materials, on the performance and economics of the aircraft.

METHODS

To analyze the aircraft of this study, a long haul transport aircraft synthesis program, TRANSYN, was adapted for transonic speeds. The resulting computer program is designated TRANSYN-TST and is shown schematically in figure 2. This program consists of a control program and several subroutines to do the various tasks in designing an aircraft. The program is controlled by input data which dictates the subroutine to be employed at each stage of the calculation. As an example of a typical aircraft analysis, figure 2 shows a flow through the subroutines of the program, involving both the design and performance phases of analysis.

In the design phase, the control program calls the geometry subroutine to calculate the wing and tail geometry, to size the fuselage for the required passenger capacity, and to area-rule the fuselage if required.

After the geometry calculations are completed, an aerodynamics subroutine is entered and lift and drag characteristics of the configurations are estimated. The methods used in this subroutine are discussed in detail in reference 1. Once the aerodynamics of the configuration have been calculated, particularly the cruise drag, the propulsion subroutine is entered to match the engine size to the thrust required for cruise and for takeoff. The engine is sized on the basis of the largest required thrust. The engine weights, dimensions, specific fuel consumption, and noise characteristics are then estimated. The methods used in this subroutine and some of the detailed propulsion system results are given in reference 2.

Based on the aircraft design developed in the first part of the synthesis program, a trajectory subroutine is entered and the mission fuel required is calculated. The structures subroutine is then entered and the loads resulting from a maneuver condition are calculated. These loads are then used to size the structural elements in the wing and fuselage, and the weights of these structures are determined by summation. The methods used in this subroutine and particular results are discussed in reference 1. A weight and volume subroutine is used to estimate other component weights and volumes for the aircraft, including such items as passenger accommodations, electrical system, flight controls, crew, avionics, and landing gear. In conjunction with the structures subroutine, this results in a total aircraft weight and volume breakdown. With this information, the economics subroutines are entered to estimate aircraft initial costs. Next the aircraft operating costs and return-on-investment are computed. The methods used and specific results in the economics area are given in reference 3.

The TRANSYN-TST aircraft synthesis program may be coupled to a parameter optimizer, AESOP, which is described in references 4 and 5. AESOP determines the optimum combination of values of a given set of parameters to minimize a specified performance function. In this study, AESOP has been used extensively to determine the combination of wing-loading, aspect ratio, and engine bypass ratio which will minimize configuration gross takeoff weight for the given mission.

Figure 3 shows a comparison of TRANSYN-TST results for two existing aircraft with actual aircraft values. On the left is a 707-120B comparison and on the right is a comparison for the 747B. In each case, the actual aircraft is shown on the left, and the TRANSYN-TST mathematical model is shown on the right. For the 707-120B, the operating weight empty was underpredicted by TRANSYN-TST, and hence, the range capability of the aircraft for the given takeoff gross weight is overestimated. The higher direct operating costs from the synthesis program occur because the calculation is based on 1970 unit costs, giving higher depreciation costs than those of the currently operated 707's.

In the case of the 747B, the operating weight empty is overpredicted, and the range capability of the 747B for the given takeoff gross weight is underpredicted. The higher operating weight empty prediction is probably due to advanced technology in the 747B (in the fuselage structure in particular) that was not accounted for in the basic synthesis program which was calibrated using 707-era aircraft. The decreased range leads to a slightly higher direct operating cost than that for the actual aircraft.

Overall, the agreement between the TRANSYN-TST results and actual aircraft values is quite satisfactory. The main value of the synthesis program is to give reasonable performance estimates and allow consistent comparison between study configurations on the basis of the same ground rules and estimation methods.

The major differences between the study configurations are delineated in figure 4. All study configurations are conventional wing/body configurations designed for a range of 2700 n. mi. with a payload of 200 passengers and no cargo. In the following discussion, the configurations will be denoted by CVT (conventional transport), designed for a cruise Mach number of 0.90; ATT (advanced technology transport), designed for a cruise Mach number of 0.98; and TST (transonic transport), designed for a cruise Mach number of 1.15. To maintain satisfactory aerodynamic characteristics the wing sweep of each configuration was adjusted to maintain the same Mach number perpendicular to the wing quarter-chord. The wing sweep of the CVT was 35^{o}, that of the ATT was 41^{o}, and that of the TST was 50^{o}. For the CVT configuration the fuselage was not area ruled and no wave drag penalty was included in the aerodynamic estimates. For the ATT configuration the fuselage was area ruled and no wave drag penalty was included. For the TST configuration the fuselage was area ruled, and a wave drag equivalent to the theoretical minimum wave drag for a body of the given length and volume was included.

RESULTS

Optimum Aluminum Configurations

The three "optimum" configurations which result from using the AESOP parameter optimizer with the TRANSYN-TST aircraft synthesis program are shown in figure 5. These are labeled optimum configurations because they have minimum gross takeoff weight for the mission with respect to wing aspect ratio, wing loading, and engine bypass ratio.

As shown in figure 5, the operating weight empty percentage is greater for the ATT than the CVT. This is primarily due to the fuselage area ruling and the higher wing sweep of the ATT. Since the ATT optimized at an aspect ratio of 8.1, compared to an aspect ratio of 6.8 for the CVT, the ATT has a slightly higher cruise L/D than the CVT. This higher L/D is predicated on the assumption that there is no wave drag for either the ATT or the CVT. In order to compare the landing quality for all configurations, their approach speeds were estimated based on the use of double slotted flaps and leading edge slats. With these high lift devices the approach speed of the CVT is 160 knots, while the approach speed of the higher sweep ATT configuration is 170 knots. Compared on the basis of direct operating cost, the ATT is slightly more costly to operate than the CVT. The optimum engine bypass ratio for the CVT was 4.9; for the ATT it was 5.6. The optimum wing loading for both the CVT and ATT was 123 pounds per square foot.

For the TST configuration, the operating weight empty is higher than for the CVT and ATT due primarily to the greater wing sweep. The cruise L/D is significantly lower than for either the CVT or the ATT configurations, because of the inclusion of transonic wave drag for the TST. The optimum aspect ratio for this configuration was 6.4, and the wing loading was 127 pounds per square foot. The optimum engine bypass ratio was 2.5. The approach speed of 198 knots for this configuration is significantly higher than for either the CVT or ATT. Because of the decrease in the cruise L/D and the increase in the operating weight empty percentage, the gross weight of the configuration for the same mission is considerably higher. The direct operating cost reflects this increase in gross weight, and is considerably higher than either the CVT or the ATT configuration.

Sensitivity to Aspect Ratio

To illustrate the design interactions characteristic of these aircraft, the sensitivity to aspect ratio will be considered. Other sensitivities are discussed in references 1, 2, and 3. Figure 6 shows the effect of wing aspect ratio variation on aircraft performance for the ATT configuration. During the variation, all other configuration parameters were held fixed, and the gross takeoff weight was determined to satisfy a design range of 2700 n. mi. and a payload of 200 passengers with no cargo. Increasing the aspect ratio resulted in increased aerodynamic efficiency for the wing (due to decreasing induced drag) and increased L/D_{MAX}. However, increasing the aspect ratio had a detrimental effect on the operating weight empty percentage because increased aspect ratio resulted in a higher structural span (for the same wing area) and increased wing weight. When these opposing aerodynamic and structural effects were combined, the aircraft gross takeoff weight required for the mission varied as shown on the bottom right of the figure. Aircraft gross takeoff weight decreased slightly with increasing aspect ratio up to an aspect ratio of about 8. This trend in gross takeoff weight also was reflected in aircraft direct operating cost. Direct operating cost in cents per seat-mile decreases very slightly with increasing aspect ratio. From this figure it is evident that optimizing the configuration with respect to aspect ratio on the basis of minimum gross takeoff weight for the mission is essentially equivalent to optimizing it on the basis of minimum direct operating cost.

Aerodynamic Sensitivities

Figure 7 shows the sensitivity to zero-lift drag for both the ATT and the TST configurations. The change in L/D_{MAX} resulting from a change in the nominal zero-lift drag (C_{D_0}) estimated by TRANSYN-TST is shown at the bottom left of the figure. The nominal parameter values are denoted by a triangle for the TST configuration and a square for the ATT configuration.

For the ATT configuration a reduction in C_{D_0} would result in an increase in L/D_{MAX} and a decrease in gross takeoff weight required for the mission. This also would result in a decrease in direct operating cost. However, the C_{D_0} for the ATT configuration is based on friction drag only and values below the nominal value are probably unlikely. If the nominal value underestimates the actual C_{D_0}, the ATT gross takeoff weight and direct operating cost would be increased.

The TST configuration is much more sensitive to configuration changes because the design requirement of 2700 n. mi. is near its ultimate range capability. For the TST a decrease in C_{D_0} would result in a slight increase in L/D_{MAX}. However, because of the extreme sensitivity, this slight increase in L/D_{MAX} would produce a large decrease in gross takeoff weight required for the mission and a significantly lower direct operating cost. This indicates the large performance gains that can be achieved by reducing the C_{D_0} on the TST configuration. However, the estimated TST wave drag value corresponds to the theoretical minimum Sears-Haack wave drag for the configuration, and therefore, it may be very difficult to reduce drag below the nominal value.

The sensitivity to induced drag is shown in figure 8. As with the previous figure, when the induced drag is changed the gross takeoff weight is adjusted to maintain the same mission performance (2700 n. mi. with 200 passengers). The induced drag value is represented by a parameter called $K_{C_{D_i}}$. As shown in the figure, this parameter is defined as the coefficient which would be multiplied times the minimum theoretical subsonic induced drag to obtain the induced drag coefficient of the configuration. The shaded bar on the figure indicates the range of uncertainty in the estimated value of $K_{C_{D_i}}$, the darker shaded part of the bar showing the more probable value for $K_{C_{D_i}}$ and the lighter part of the bar showing less probable values for $K_{C_{D_i}}$. A value of $K_{C_{D_i}}$ equal to 1.0 corresponds to an Oswald's efficiency factor of 1.0 and is the minimum subsonic value for induced drag (also referred to as full leading edge suction). A value of $K_{C_{D_i}}$ above 4 is in the region of supersonic induced drag (no leading edge suction).

For the ATT configuration, the nominal value for $K_{C_{D_i}}$ is denoted by the square. This estimate includes a separation drag component and is equivalent to subsonic induced drag with an Oswald's efficiency factor of .6. Recent flight experience with the F-8 supercritical wing airplane suggests that this value for $K_{C_{D_i}}$ may be conservative and the actual induced drag may be closer to an Oswald's efficiency factor of .9, corresponding to a $K_{C_{D_i}}$ of around 1.1. The potential gain in performance for such a reduction in induced drag is indicated in this figure and is reflected in the decrease in aircraft gross weight and direct operating cost for the mission. With the nominal value for induced drag on the ATT, the direct operating cost is 1.05 cents per seat-mile. Without any separation drag, the direct operating cost would decrease to about .99 cents per seat-mile.

For the TST configuration the range of uncertainty in the estimate of $K_{C_{D_i}}$ is considerably larger. The minimum value for $K_{C_{D_i}}$ is indicated at the left end of the light part of the shaded bar and corresponds to an induced drag computed with vortex drag corresponding to an Oswald's efficiency factor of .85, the theoretical minimum lift induced wave drag, and no separation drag. The far right light part of the shaded bar corresponds to the supersonic value of induced drag. The potential gain that would be achieved with a reduction in induced drag for the TST is evident in this figure. Reducing $K_{C_{D_i}}$ results in increased L/D_{MAX} which allows large decreases in aircraft gross takeoff weight and direct operating cost for the mission. With the nominal value for induced drag, the TST direct operating cost is 1.78 cents per seat-mile. Without any separation drag the direct operating cost would drop to 1.27 cents per seat-mile. The accurate estimation of induced drag for the ATT and especially for the TST configuration offers an area for research and experimental study to develop improved analytical estimation techniques.

Propulsion Sensitivities

The effect of engine bypass ratio and noise suppression on aircraft performance is examined in figure 9. Aircraft noise has become an extremely important design consideration and as such must be considered early in the design process. In this figure the effect on performance is measured by the range decrement at a fixed aircraft gross takeoff weight, relative to the nominal value of 2700 n. mi.

Results for the ATT configuration at 250,000 lbs gross takeoff weight are shown on the left of figure 9. For the ATT the optimum engine bypass ratio is about 4.5 and would result in a 200 n. mi. increase in range over the nominal aircraft with engines of bypass ratio 2. With increasing engine bypass ratio, the fan approach noise remains relatively constant while the sideline takeoff jet noise decreases rapidly. At the nominal bypass ratio of 2 the value for the ATT sideline takeoff jet noise is above the FAR Part 36 requirement. However, at the optimum bypass ratio value of 4.5, the ATT jet noise drops below the FAR requirement. At all engine bypass ratios the fan approach noise is above the FAR requirement and requires suppression. With current noise suppression technology, lining the intake and fan exhaust ducts of the engine would reduce the approach fan noise by about 15 PNdB. (Long fan ducts are assumed for both the ATT and TST engines.) At the optimum engine bypass ratio of 4.5 for the ATT this would result in a decrease in the range increment on the order of 150 n. mi. With fan noise suppression at the optimum engine bypass ratio, the ATT configuration is approximately 7 PNdB below the current FAR requirement.

Results for the TST configuration at 550,000 lbs are shown on the right of figure 9. For the TST the optimum turbofan engine bypass ratio occurs at about 2. This is because the increased thrust lapse with speed of the higher bypass ratio turbofan engines is more penalizing to the TST which is designed to cruise at a higher Mach number than the ATT. The TST engines are sized to satisfy the cruise thrust requirement while the size of the optimum ATT engines result in a good match between the takeoff and cruise thrust requirements. The TST engines are throttled to meet the takeoff requirement, and the resulting jet noise is lower than the ATT even though the TST engines are larger. The fan approach noise is still a problem area. At the optimum bypass ratio of 2, the jet noise is slightly below the current FAR requirement, while the fan noise is considerably above that requirement. Applying fan noise suppression to the TST engines would reduce the fan noise by approximately 15 PNdB and would result in a 150 n. mi. range penalty. With fan noise suppression and operating at a slightly higher engine bypass ratio than optimum, the noise of the TST configuration could also be reduced to a level 7 PNdB lower than the current FAR requirement. With more effective fan noise suppression techniques it should be possible to reduce the engine noise to 10 PNdB below the current FAR Part 36 requirements by going to higher than optimum engine bypass ratios.

Structural Material Sensitivities

One of the most promising areas for increasing the performance of aircraft through the application of advanced technology is the use of advanced composite materials. The potential decrease in aircraft structural weight obtained by substituting advanced carbon/epoxy composite material for aluminum is shown in figure 10. For the CVT configuration at 235,000 lbs gross takeoff weight, full use of carbon/epoxy material for the fuselage structure would result in a 37% reduction in structural weight relative to the aluminum fuselage. Replacement of aluminum with carbon/epoxy material in the wing structure would result in a 33% reduction in the wing structural weight. The combined effect of full use of advanced carbon/epoxy material for the fuselage and wing structure would result in a 15.5% decrease in operating weight empty for the same configuration design. The use of carbon/epoxy material in the structure of the fuselage and wing of the ATT and TST configurations shows slightly larger reductions in operating weight empty. The largest reduction is for the TST configuration with a 19.6% reduction in operating weight empty. The weight reduction predicted for the ATT and TST is larger than for the CVT because the structure of these configurations tends to be more heavily loaded and hence more strength critical, and the advantage of carbon/epoxy material is greatest on this type of a design. The weight reductions shown in figure 10 are for fixed configurations and do not include resizing of the aircraft.

Optimized Carbon/Epoxy Configurations

Figure 11 shows the weights of resized, optimized configurations which make full use of advanced carbon/epoxy composite material in the wing and fuselage structure. These configurations are optimized in the same sense as the aluminum ones, that is, the values of wing loading, aspect ratio, and engine bypass ratio are those which give minimum gross takeoff weight for the mission. The figure shows payload, fuel weight, wing weight, fuselage weight, and other (than wing or fuselage) dry weight. On the left of the figure is the weight comparison of the aluminum and carbon/epoxy

CVT configurations. In reoptimizing the aircraft, it was found to be advantageous to trade increased structural efficiency for increased aerodynamic efficiency, as will be discussed subsequently. This resulted in carbon/epoxy wings which were only slightly lighter but had better L/D_{MAX} than their aluminum counterparts. Thus the percentage weight reduction in the fuselage is higher than that in the wing. The comparison between the weights of the aluminum and carbon/epoxy ATT configurations shows approximately the same weight reductions as for the CVT. The largest reduction in the aircraft gross takeoff weight due to the use of advanced carbon/epoxy material occurs for the TST configuration. As mentioned previously, the aluminum TST performance is very sensitive because it is close to ultimate range with the required mission of 2700 n. mi. As a result, the reduction in structural weight possible with advanced carbon/epoxy composite material is enhanced for the TST. The gross takeoff weight of the aluminum TST is 504,000 lbs and that of the carbon/epoxy TST is 323,000 lbs.

The optimized carbon/epoxy configurations are shown in figure 12. The increased structural efficiency obtained by the complete use of carbon/epoxy material in the wing and fuselage structure is also utilized to increase the aerodynamic efficiency of the configurations. As a result, the optimum wing aspect ratio for all three carbon/epoxy configurations is increased relative to the aluminum configurations. The wing aspect ratio of the CVT increased from 6.8 to 9.1, the ATT aspect ratio increased from 8.1 to 12.4, and the TST aspect ratio increased from 6.4 to 9.8. The optimum wing loading of the carbon/epoxy configurations decreased with respect to the aluminum configurations to values of 113 psf for the CVT, 106 psf for the ATT, and 100 psf for the TST. The optimum engine bypass ratios for the carbon/epoxy configurations are 5.7 for the CVT, 4.4 for the ATT, and 2.5 for the TST.

Comparison of the performance of the optimized carbon/epoxy configurations shown in figure 12 with the optimized aluminum configurations of figure 5 indicates that the operating weight empty fraction has decreased by about 2% of gross takeoff weight for all configurations and the cruise L/D has increased by at least 1 unit of L/D. Because of the lower wing loadings and higher aspect ratios of the carbon/epoxy configurations the approach speeds are lower than for the aluminum configurations. This is particularly true in the case of the TST, for which the approach speed has decreased from 190 knots for the aluminum TST to 168 knots for the carbon/epoxy TST.

Comparison of the aircraft costs illustrates a tradeoff between the increased unit cost for building a vehicle out of carbon/epoxy relative to aluminum and the increased operating efficiency of the carbon/epoxy vehicle. In the case of the CVT, the aluminum vehicle has a DOC of .99 cents per seat mile. Despite the increased unit price for the carbon/epoxy CVT the DOC is slightly lower at .97 cents per seat-mile. In the case of the ATT, the use of carbon/epoxy material is more cost effective with a DOC of .94 cents per seat-mile for the carbon/epoxy configuration compared to 1.01 cents per seat-mile for the aluminum ATT. For the TST configuration, the use of carbon/epoxy material is very cost effective in terms of DOC because of the large decrease in gross takeoff weight for the carbon/epoxy configuration. The use of carbon/epoxy material results in a DOC of 1.22 cents per seat-mile relative to the aluminum TST value of 1.58 cents per seat-mile.

Because the increased structural efficiency of carbon/epoxy material results in high aspect ratio wings for the optimized configurations the question of possible aeroelastic problems arises. The present synthesis program does not contain any separate structural penalty for additional material that may be necessary to supply increased stiffness to prevent flutter, and therefore some of the benefits shown here may not be realizable.

Approach Speed Constraints

The increase in wing sweep necessary for increased vehicle cruise speeds results in higher landing approach speeds for the study vehicles. Using the parameter optimizer, AESOP, and including a penalty function for high approach speed results in a change in the optimized configuration as shown in figure 13 for the aluminum ATT. (The approach speeds of all configurations were estimated for double-slotted flaps and leading edge slats.) On the left of the figure is the aluminum ATT with no constraint on landing speed, and on the right is the ATT reoptimized with a penalty function for higher landing speeds. The configuration changes are an increase in wing aspect ratio and a decrease in wing loading. These design changes result in a slightly higher gross takeoff weight for the constrained configuration due to increased wing and fuselage structural weight. The decrease in approach speed for the constrained configuration is substantial, from 170 knots for the unconstrained case to 151 knots for the constrained case. The DOC penalty that results from the increase in gross takeoff weight for the constrained ATT is .04 cents per seat-mile; the DOC is 1.01 cents per seat-mile for the unconstrained vehicle and 1.05 cents per seat-mile for the constrained one.

In figure 14 the effects of a landing approach speed constraint for the optimized carbon/epoxy TST configuration are examined. As with the ATT configuration, the inclusion of a penalty for high approach speed in the optimization results in a higher wing aspect ratio and lower wing loading, and this leads to a higher operating weight empty and gross takeoff weight. The resulting decrease in approach speed is less for the TST than the ATT, having dropped from 168 knots for the unconstrained case to 158 knots for the constrained case. For this reduction in approach speed the penalty in direct operating cost is large, from 1.22 cents per seat-mile to 1.60 cents per seat-mile. Because of this large cost increase other means of obtaining high-lift for this high sweep configuration, such as variable geometry, may be attractive.

Costs and Economics

Because the use of carbon/epoxy advanced composite material is so promising from a performance standpoint for all the vehicles, and particularly for the TST, it is important to consider the effects of reducing carbon/epoxy material cost. Figure 15 shows the effect of carbon filament cost on cash flow return on investment (ROI). This return on investment is based on a fleet of 250 aircraft and is a result of combining the acquisition costs and the operating costs over the lifetime of the aircraft. Reference values of ROI for the optimized aluminum CVT, ATT, and TST aircraft are also shown on the figure. The ROI calculations are based on the assumption of equal load factors of 50% and equal fares for all configurations, but the increased productivity associated with higher speeds is accounted for. The calculation procedure is described in detail in reference 3. It is important to remember that the results presented here are for complete substitution of carbon/epoxy for aluminum in both the wing and fuselage structures. It is possible that a more selective use of composites would be more cost effective than complete substitution.

The current cost for carbon filaments is roughly $75/lb with an estimated cost of $20/lb by 1985. A fixed cost of $17.50/lb was assumed for the epoxy, which typically makes up half of the carbon/epoxy material. Because epoxy is now produced in large quantity, its cost is not expected to decrease significantly.

Consider the cost comparison for using carbon/epoxy on the CVT. The ROI increases with reduced carbon filament cost, but even if this cost is reduced to zero, the ROI is still about the same as the reference value of the aluminum CVT aircraft due to the cost of the epoxy. Engineering costs also affect the ROI, but it is assumed that the engineering cost for designing a given size piece using either carbon/epoxy or aluminum is the same. This results in a higher engineering cost per pound for carbon/epoxy structure relative to aluminum structure. Clearly, full use of carbon/epoxy material in the wing and fuselage does not appear to offer large cost benefits for the CVT.

The ROI of the aluminum ATT is slightly lower than the aluminum CVT. For the ATT full use of carbon/epoxy for the wing and fuselage is slightly cost effective at low values of filament cost. Because the TST is very sensitive to reductions in empty weight, full use of carbon/epoxy material is very cost effective even at high values of raw material cost. The crossover point for equal ROI for the carbon/epoxy TST relative to an aluminum TST occurs at approximately $250/lb of carbon filaments.

In figure 16, the effect of possible changes in load factor due to the market advantages of an aircraft with higher cruise speed is examined.

The fare required for equal ROI is shown relative to the aluminum CVT fare. For the ATT aircraft a very slight fare increase is required to obtain the same ROI as the CVT. On the other hand, if the advantage of the higher cruise speed of the ATT resulted in load factors greater than 52% the ATT would have a higher ROI than the CVT. The block time saved would be 25 minutes for a trip of 2700 n. mi.

At the nominal load factor of 50% the aluminum TST would require a fare surcharge of 45% to obtain the same ROI as the aluminum CVT. The carbon/epoxy TST would require a fare surcharge of 18% for the same ROI. With equal fare, the carbon/epoxy TST would require a load factor of 62% compared to the aluminum CVT at a load factor of 50% to obtain the same ROI. The aluminum TST would require a load factor of 76% to obtain the same ROI as the aluminum CVT at a load factor of 50% and equal fare. The block time saved for the TST would be one hour for the 2700 n. mi. trip.

Market studies of passenger preference would be necessary to determine tolerable surcharges relative to time saved or the load factors that would result for a faster aircraft at equal fares. The only advantage for the faster aircraft in this study results from the assumption of a 9 hour/day utilization for all aircraft. This results in higher productivity for the aircraft with the higher cruise speeds since it makes more trips.

In figure 17 aircraft economics are summarized in terms of aircraft unit price, operating costs, and return on investment for the optimized CVT, ATT, and TST aircraft. The values for the aluminum aircraft are shown by the dotted bars and the nominal values for the carbon/epoxy aircraft are shown by the cross-hatched bars. A comparison of the three aluminum aircraft shows that the unit price increases with increasing cruise speed. A comparison of the carbon/epoxy aircraft with their aluminum counterparts shows an increase in unit price for the CVT, a slight increase in unit price for the ATT, and a decrease in unit price for the TST. The reduction in vehicle gross takeoff weight using carbon/epoxy material on the TST is so large that the resultant price of the carbon/epoxy aircraft is less than the price of the much larger aluminum aircraft.

In the center of figure 17, the operating cost in terms of cents per seat-mile is shown for all aircraft. The operating cost is broken into indirect operating cost (IOC) and direct operating cost (DOC). For the aluminum aircraft, the ATT shows a very small increase in operating cost over the CVT while the TST shows a significantly higher operating cost. A comparison of the carbon/epoxy aircraft shows a decrease in operating cost for the ATT relative to the CVT and an increase in costs for the TST relative to the CVT or ATT. The slight decrease in operating cost for the carbon/epoxy CVT relative to the aluminum CVT occurs despite the increase in aircraft unit price. In the case of the ATT, the slight increase in unit price is more than offset by other items which make up the operating cost. The carbon/epoxy TST benefits both from the reduction in unit price relative to the aluminum TST and the decrease in operating cost because of the lighter aircraft weight.

The right side of figure 17 shows a comparison of the aircraft on the basis of return on investment. A comparison of the aluminum aircraft shows a slight reduction in ROI for the ATT relative to the CVT, and a larger reduction for the TST. In the case of the carbon/epoxy aircraft, the ATT has a higher ROI than the CVT, and the TST has a lower ROI than either. Of the optimized configurations, the carbon/epoxy ATT has the highest return on investment.

The values for the carbon/epoxy aircraft economics shown by the cross-hatched bars are based on the assumption that the engineering and manufacturing costs for designing and fabricating a given size piece out of carbon/epoxy are the same as for designing and fabricating the same size piece out of aluminum. This assumption represents a consensus of what experienced people in composite material development feel to be reasonable for high volume production use of such materials in the 1985 time frame. Use of this assumption results in higher engineering and manufacturing costs for carbon/epoxy aircraft on a per pound basis. Since the equal cost per piece assumption is regarded as conservative in some quarters, the result of using a more optimistic assumption was investigated. The solid bars in figure 17 represent carbon/epoxy aircraft with cost calculation based on the assumption that the engineering and manufacturing costs would be the same as the aluminum aircraft on a per pound basis. This means that designing and fabricating a given size piece from carbon/epoxy would cost less than building the same size piece out of aluminum, because of the associated weight reduction for carbon/epoxy relative to aluminum. In both cases the carbon filament cost is fixed at the same projected 1985 value of $20 per pound.

Examining the effect on aircraft economics of the reduced engineering and manufacturing costs shows that significant reductions in aircraft unit price would be achieved, and that these reductions lead to significant reductions in operating costs and significant increases in ROI. Even with the projected higher material cost of approximately $25 per pound for a finished carbon/epoxy piece relative to $6 per pound for the finished aluminum piece, the reduction in engineering and manufacturing costs results in a significant increase in cost effectiveness for the use of carbon/epoxy material, particularly for the more advanced aircraft. On the basis of this assumption, the carbon/epoxy ATT would have the highest ROI and the carbon/epoxy TST ROI would increase to a level almost as high as the aluminum CVT and ATT aircraft. It is concluded that the application of advanced composite materials to these aircraft can significantly improve the aircraft economics if low engineering and manufacturing costs can be achieved.

CONCLUDING REMARKS

A number of significant conclusions can be drawn from this study. First, the optimum engine cycle for all the study aircraft is within the current state-of-the-art; i.e., for all the engines studied, the optimum engine bypass ratio, fan pressure ratio, and turbine inlet temperature are reasonable values falling within current state-of-the-art capability. The largest performance gains possible in the engine technology area would stem from decreases in engine weight. Examination of the engine noise from the aircraft studied shows that in all cases fan noise suppression is required to meet current FAR Part 36 requirements. Jet noise does not appear to be a problem at the optimum engine bypass ratio for the aircraft studied. Reductions in the engine noise to values 7 to 10 dB below FAR Part 36 appear possible without major advances in engine noise suppression technology. Further decreases would require significant advances in noise suppression technology or serious compromises in engine performance.

Second, an important effect of area ruling a configuration is a significant wing and fuselage weight interaction. For example, in an area ruled configuration, going to a thicker wing section to reduce the wing weight requires more fuselage area ruling and results in a heavier fuselage. This type of wing/fuselage weight interaction is not present for non-area ruled configurations.

Third, the full use of advanced composite materials in the wing and fuselage structure of the study aircraft is neutrally cost effective on the CVT, slightly cost effective on the ATT, and very cost effective on the TST. It must be emphasized that this conclusion is based on full use of advanced composite materials in the wing and fuselage; the use of advanced composite material to increase stiffness in specific areas of the structure may well be cost effective for all configurations. As the cost of designing and fabricating a carbon/epoxy structure decreases, the performance advantages resulting from the lighter structural weight will benefit all aircraft.

Fourth, the ATT offers the potential of reducing trip times relative to the CVT with very slight increases in total operating cost. These increases in cost are considered negligible and within the accuracy of the computations in the study.

Fifth, for the TST the wave drag and structural weight increases result in a significant economic penalty. This conclusion is, of course, confined to the conventional swept-wing/body configurations studied here. There are other relatively unconventional configurations which are under study and offer promise for changing this conclusion (c.f., ref. 6).

There are several promising technology areas that can improve the aircraft performance and economics, particularly for the more advanced ATT and TST aircraft. The first promising technology area has been mentioned previously, and involves the reduction of basic engine weight. Reductions in weight for effective engine noise suppression would also result in increased aircraft performance. This is particularly true if noise levels below the current FAR Part 36 are required. As the requirements for aircraft noise become more stringent, effective noise suppression techniques become increasingly important to the total aircraft performance.

The aircraft sensitivity to aerodynamic drag, particularly induced drag, indicates that large gains in performance are possible through reductions in drag. Because minimum wave drags were assumed in this study, the most likely reductions in drag would result from reductions in the separation drag component of the induced drag. This study is based on realistic estimates of separation drag, but reductions in separation drag would result in large performance gains particularly on the more sensitive TST aircraft.

Airframe structural weight has important implications in the performance of any aircraft. Reduction in airframe structural weight can be achieved in several ways. One possibility is through reductions in the structural non-optimum factor by using more effective joining techniques. The elimination of excess structural material for fasteners and joints can result in a large decrease in structural weight. Another possibility is the use of advanced composite materials. The cost effectiveness of composite materials is dependent upon the cost of the composite material itself, the cost of designing an aircraft using composite material, and the cost of manufacturing an aircraft out of a composite material.

In summary, this study has indicated that use of supercritical wing technology can result in a next generation of conventional wing/fuselage configured long haul transports with increased cruise speed (up to Mach 1) and competitive economics as compared with present generation transports.

However, conventionally configured vehicles designed to cruise at speeds greater than Mach 1 were found to be uncompetitive. The cost effectiveness of advanced composite materials will depend on the eventual high volume raw material and manufacturing costs of such materials in the case of aircraft designed to cruise at less than Mach 1, but these materials will almost certainly be cost effective on faster aircraft.

REFERENCES

1. Ardema, Mark D. and Williams, Louis J.: "Transonic Transport Study - Structures and Aerodynamics," NASA TM X-62,157, May 1972.

2. Waters, Mark H.: "Transonic Transport Study - Propulsion Systems," NASA TM X-62,158, May 1972.

3. Smith, Cynthia L. and Wilcox, Darrell E.: "Transonic Transport Study - Economics," NASA TM X-62,159, May 1972.

4. Hague, Donald S. and Glatt, Curtis R.: "An Introduction to Multivariable Search Techniques for Parameter Optimization," NASA CR-73200, April 1968.

5. Hague, Donald S. and Glatt, Curtis R.: "A Guide to the Automated Engineering and Scientific Optimization Program," NASA CR-73201, June 1968.

6. Jones, Robert T.: "Properties of Oblique-Wing--Body Combinations for Low Supersonic Speeds," NASA SP-292, November 1971.

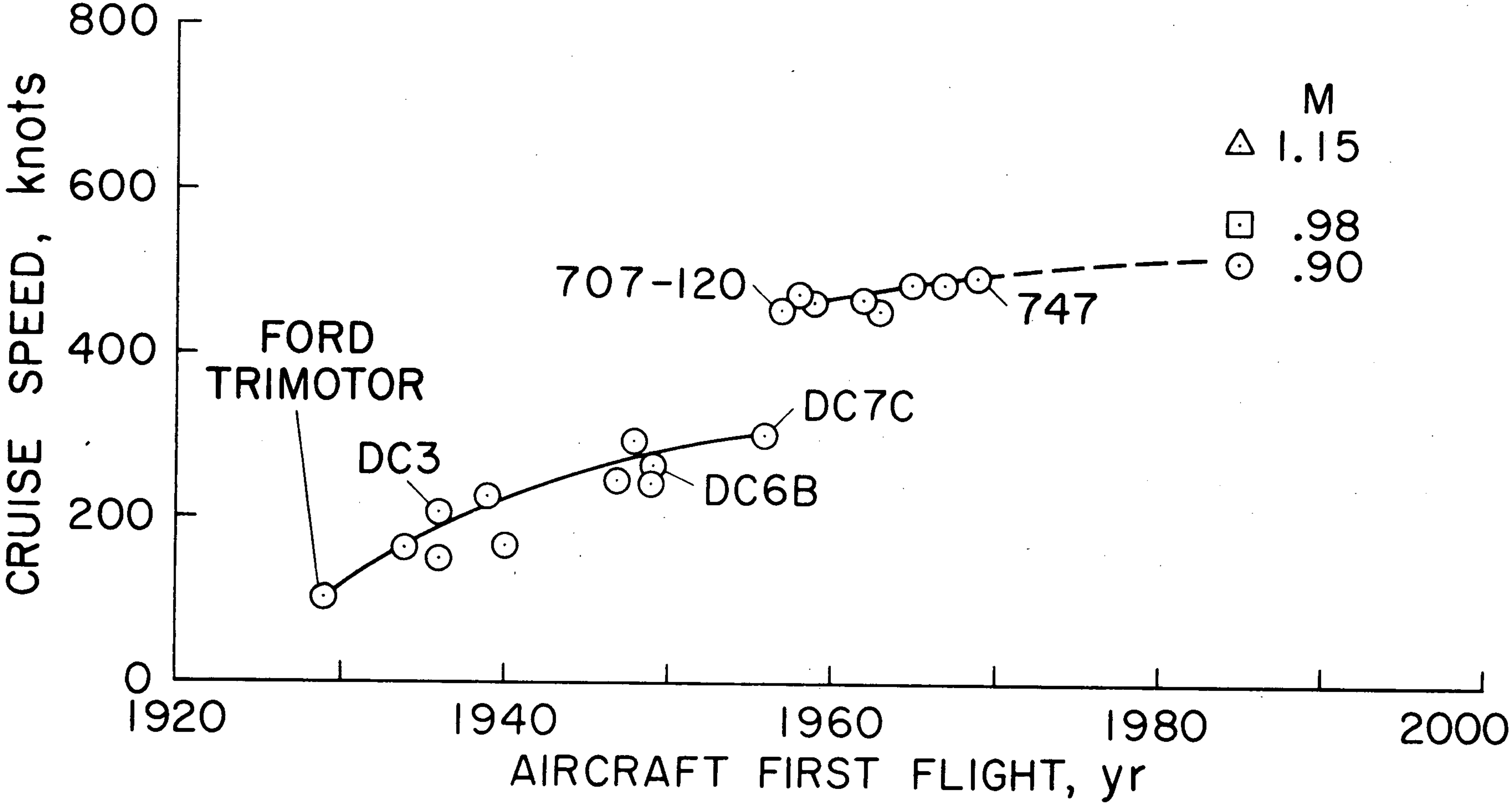


Figure 1.- History of Commercial Aircraft Cruise Speed.

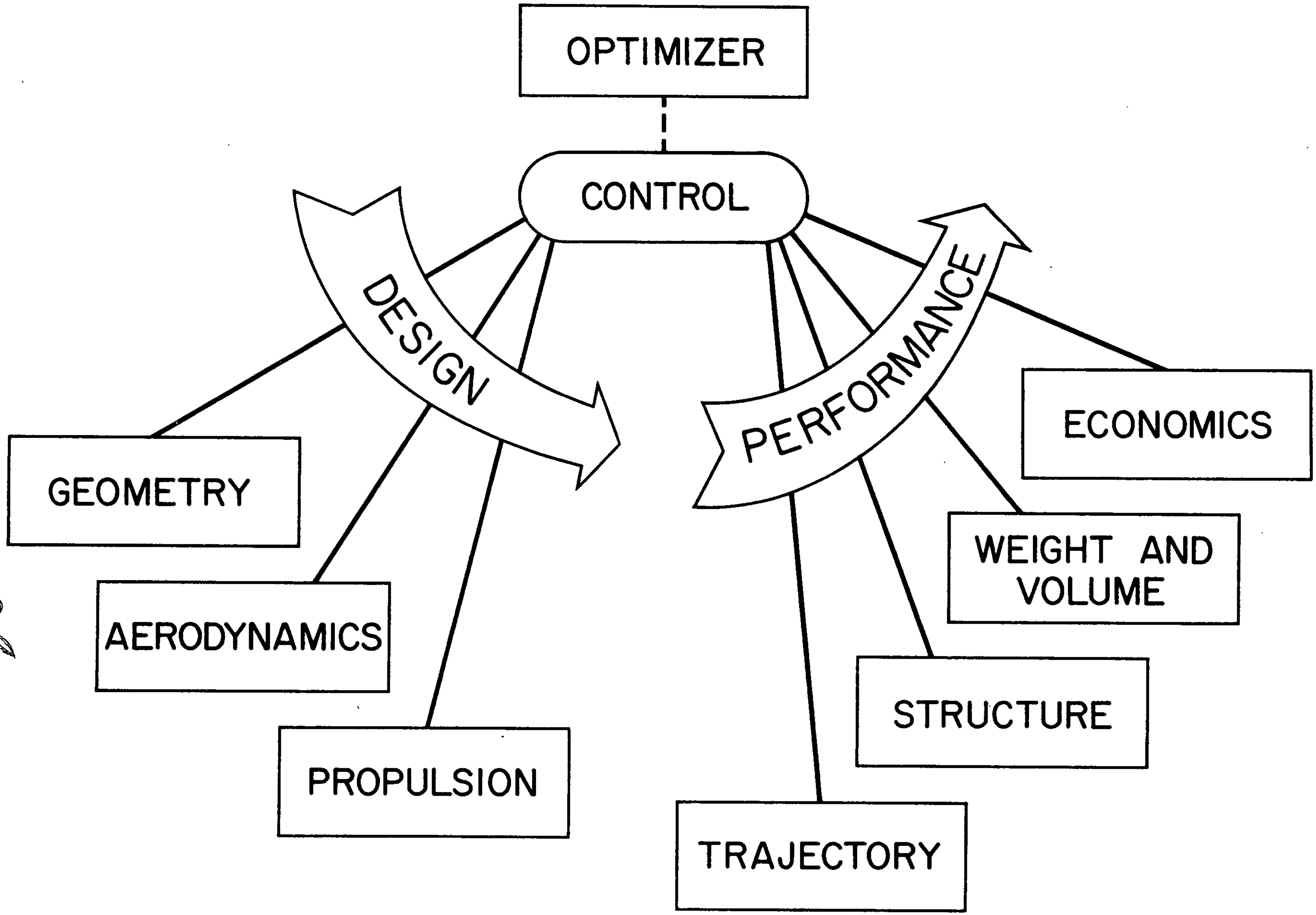
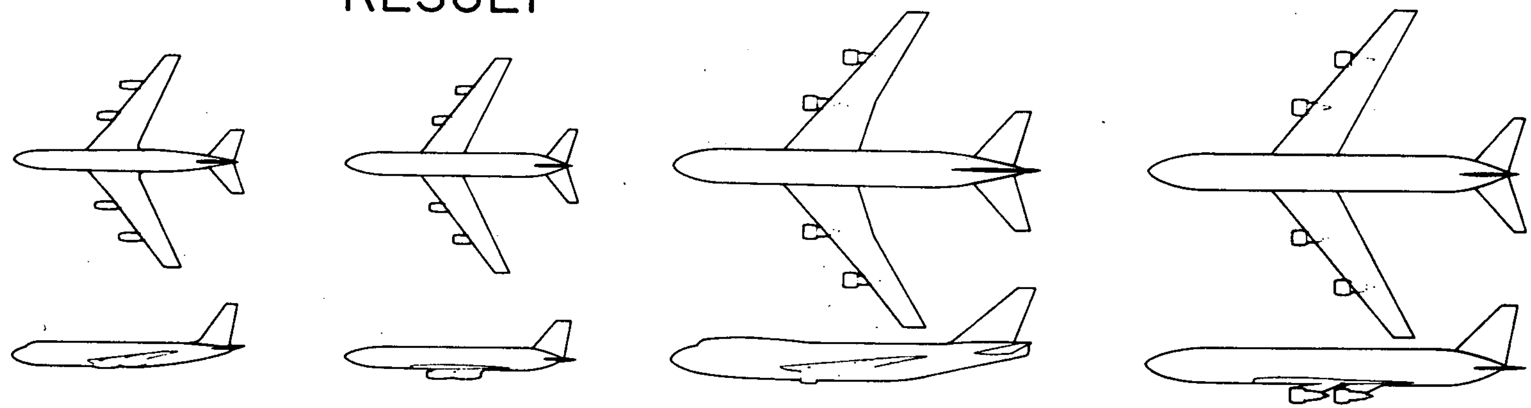


Figure 2.- TRANSYN-TST Aircraft Synthesis Program.

	707-120B		747B	
	EXISTING AIRCRAFT	TRANSYN - TST RESULT	EXISTING AIRCRAFT	TRANSYN - TST RESULT



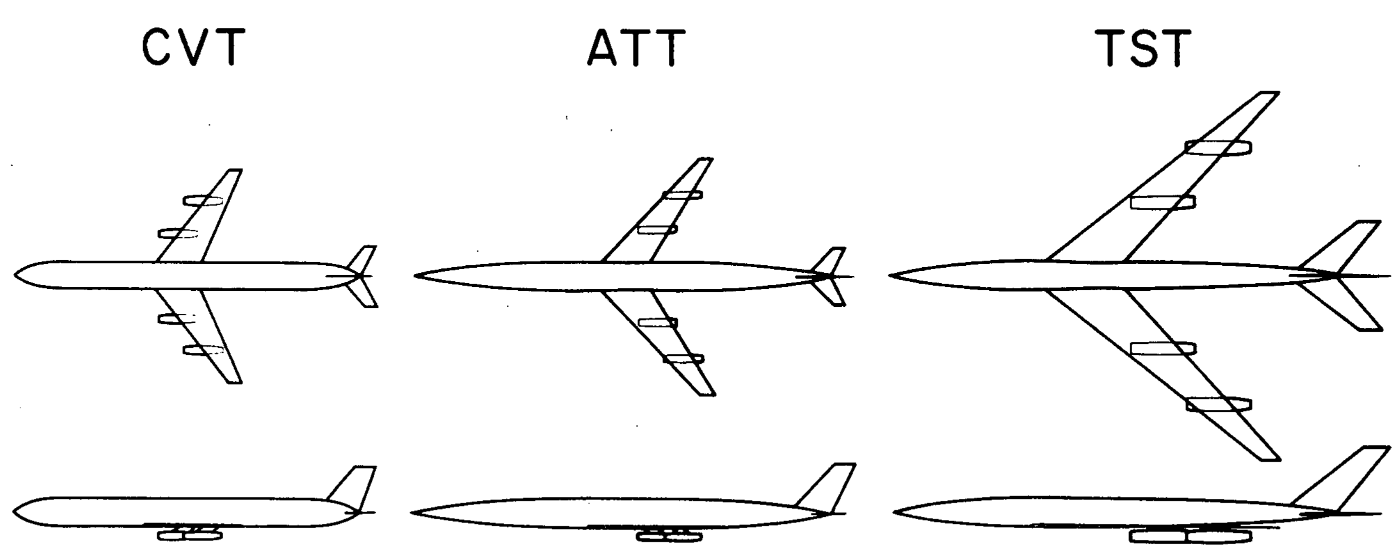
RANGE	3677 n.mi.	3950 n.mi.	5748 n.mi.	5074 n.mi.
O.W.E.	125,060 lb	122,670 lb	361,216 lb	395,000 lb
D.O.C.	1.2¢/seat mi.	1.40¢/seat mi.	0.8¢/seat mi.	0.89¢/seat mi.

Figure 3.- Comparison of TRANSYN-TST Results with Existing Aircraft.

CONFIGURATION	CVT	ATT	TST
CRUISE MACH NUMBER	0.90	0.98	1.15
WING SWEEP	35°	41°	50°
FUSELAGE AREA RULING	NO	YES	YES
WAVE DRAG PENALTY	NO	NO	YES

Figure 4.- Major Differences Between Study Configurations.

RANGE = 2700 n.mi. 200 PASSENGERS



	CVT	ATT	TST
M_{CRUISE}	0.90	0.98	1.15
GROSS WEIGHT	214,500 lb	232,500 lb	504,000 lb
O.W.E. (% W_{GTO})	54.8	57.8	58.2
$(L/D)_{CRUISE}$	15.1	16.3	11.8
$V_{APPROACH}$	160 knots	170 knots	198 knots
D.O.C.	0.99 ¢/seat mi	1.01 ¢/seat mi	1.58 ¢/seat mi

Figure 5.- Optimum Aluminum Configurations.

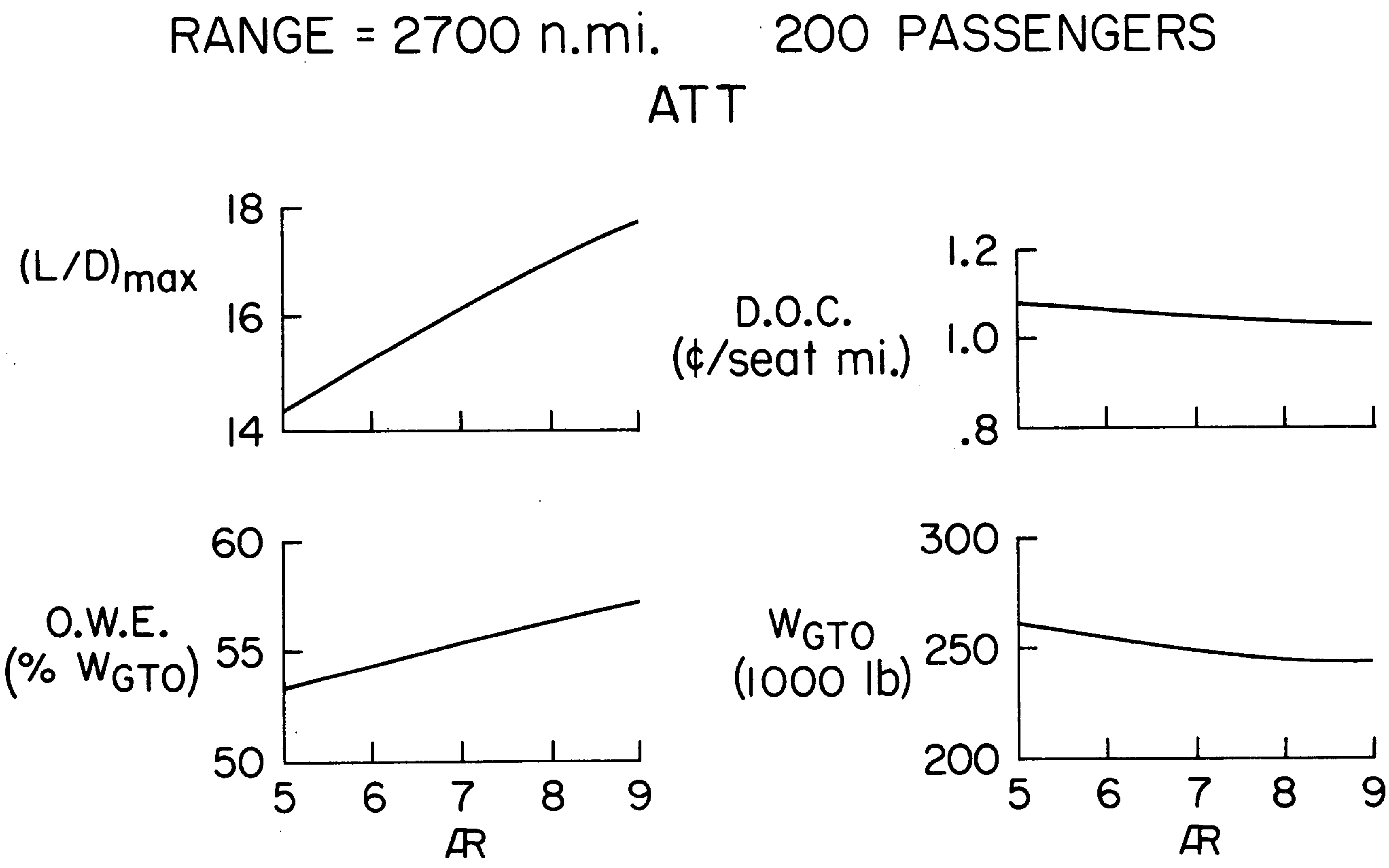


Figure 6.- Effect of Aspect Ratio on Aircraft Performance.

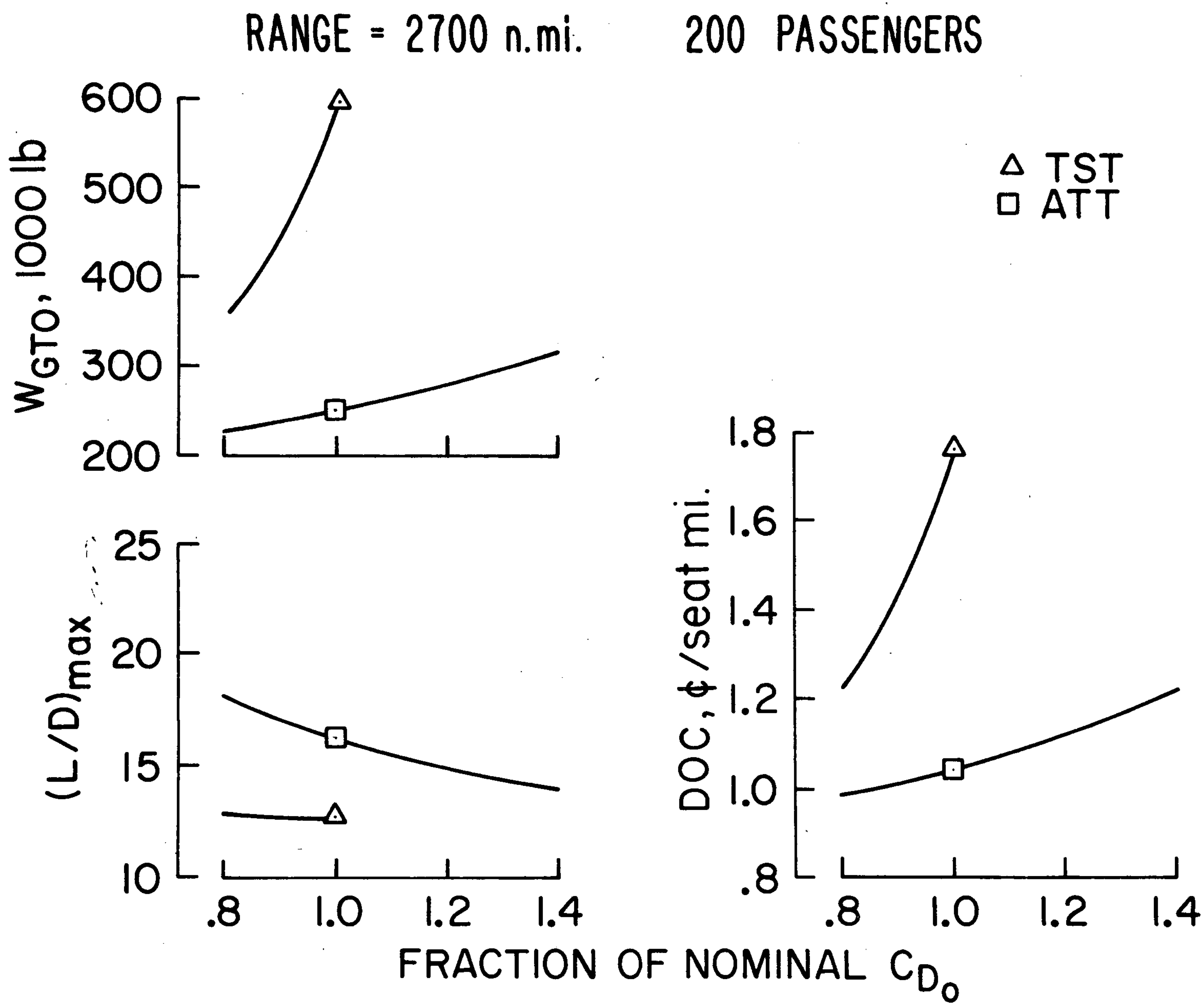


Figure 7.- Sensitivity to Zero-Lift Drag.

33

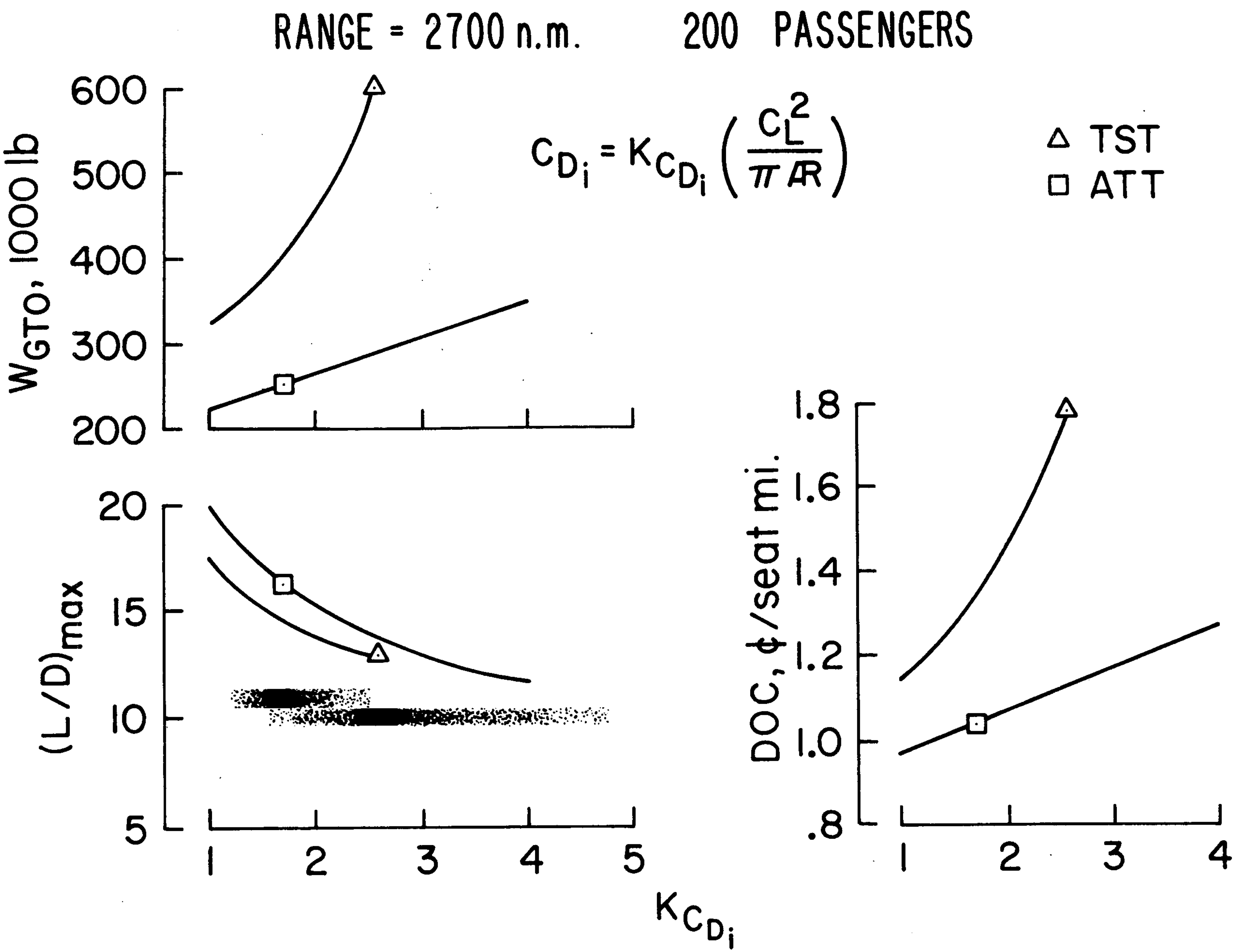


Figure 8.- Sensitivity to Induced Drag.

34

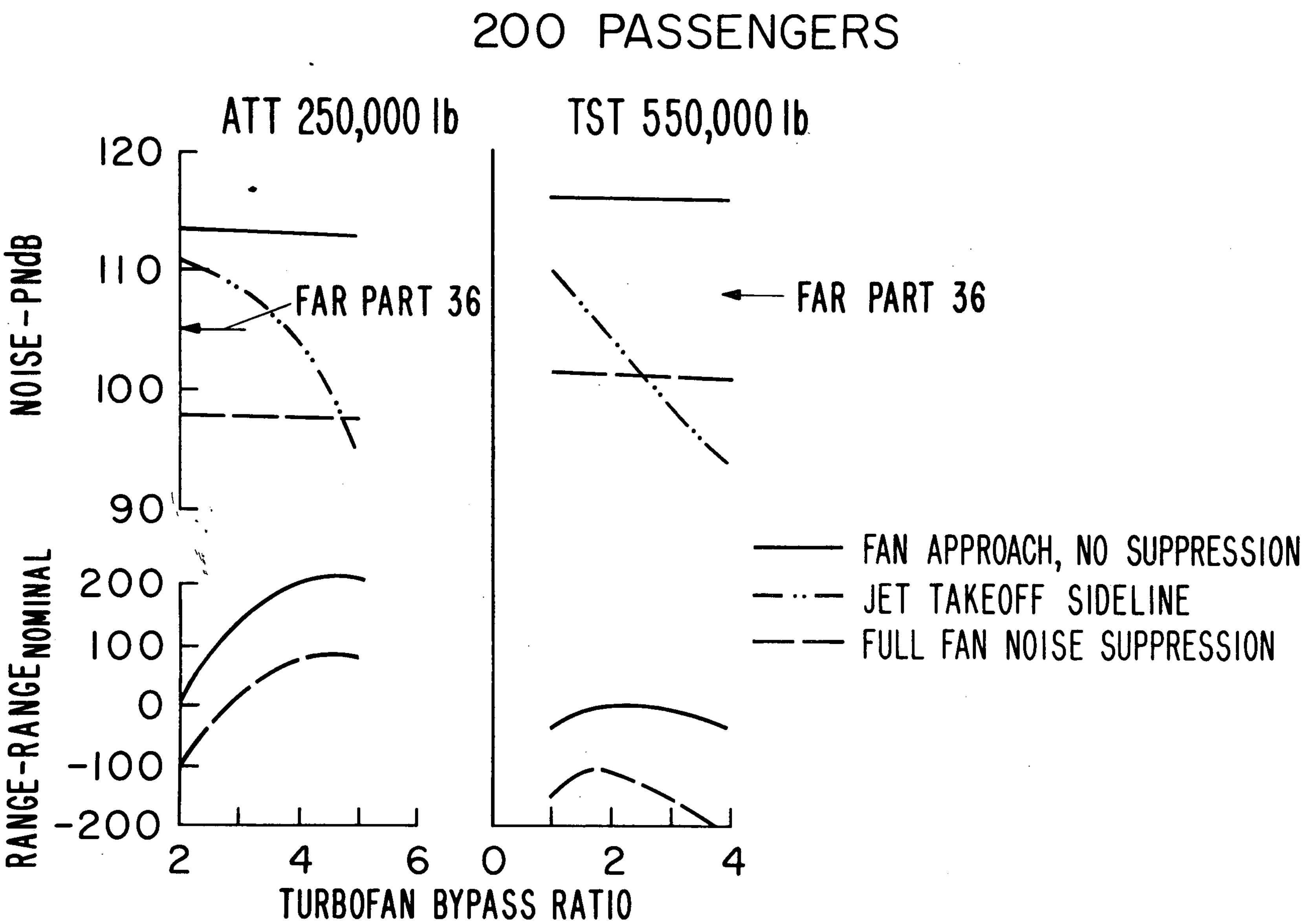


Figure 9.- Effect of Engine Bypass Ratio and Noise Suppression on Aircraft Performance.

	FUSELAGE	WING	O.W.E.
CVT @ 235,000 lb	36.7%	33.0%	15.5%
ATT @ 250,000 lb	35.0%	35.2%	17.1%
TST @ 400,000 lb	42.9%	37.3%	19.6%

Figure 10.- Weight Savings Obtained by Replacing Aluminum with Carbon/Epoxy at Constant Gross Takeoff Weight.

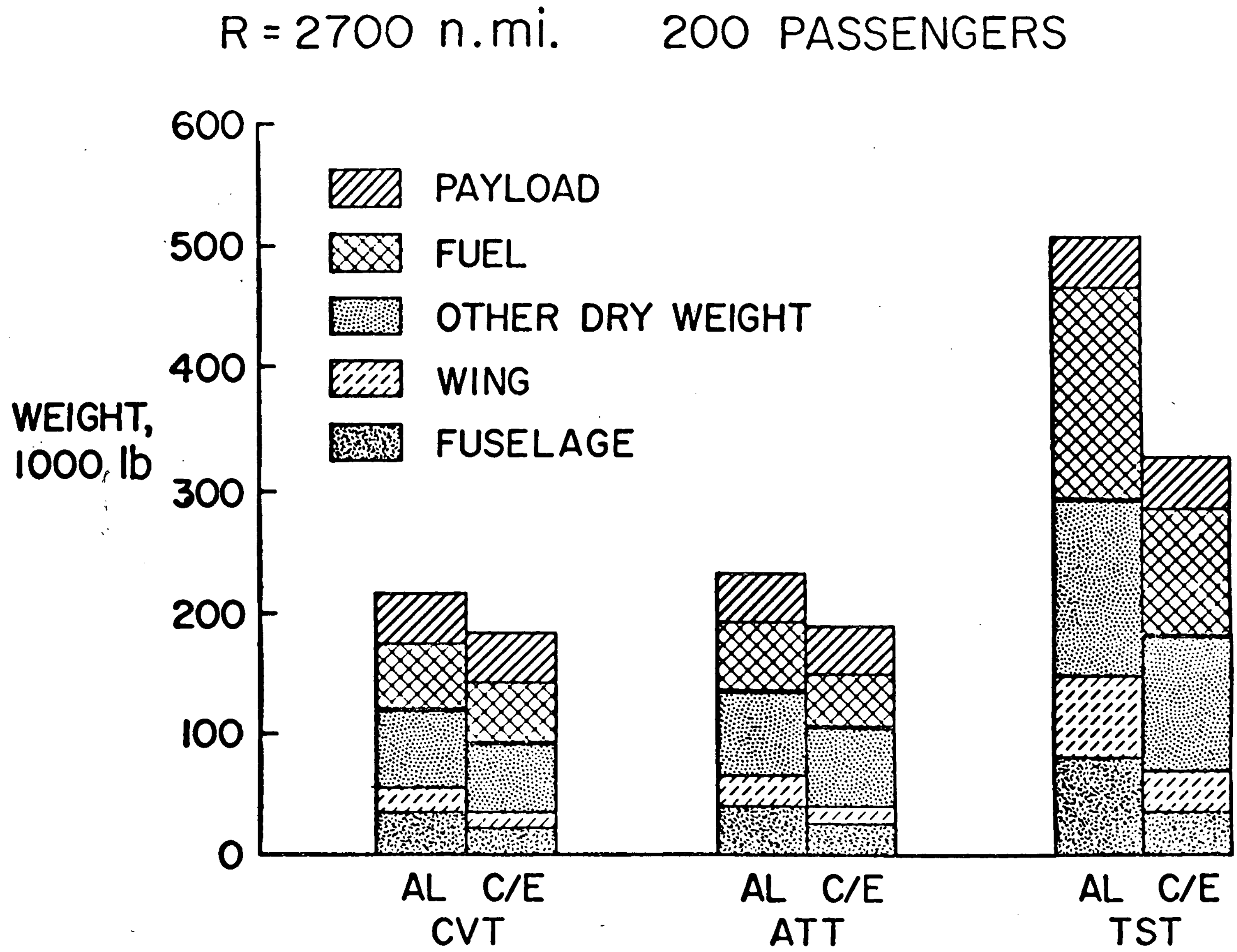
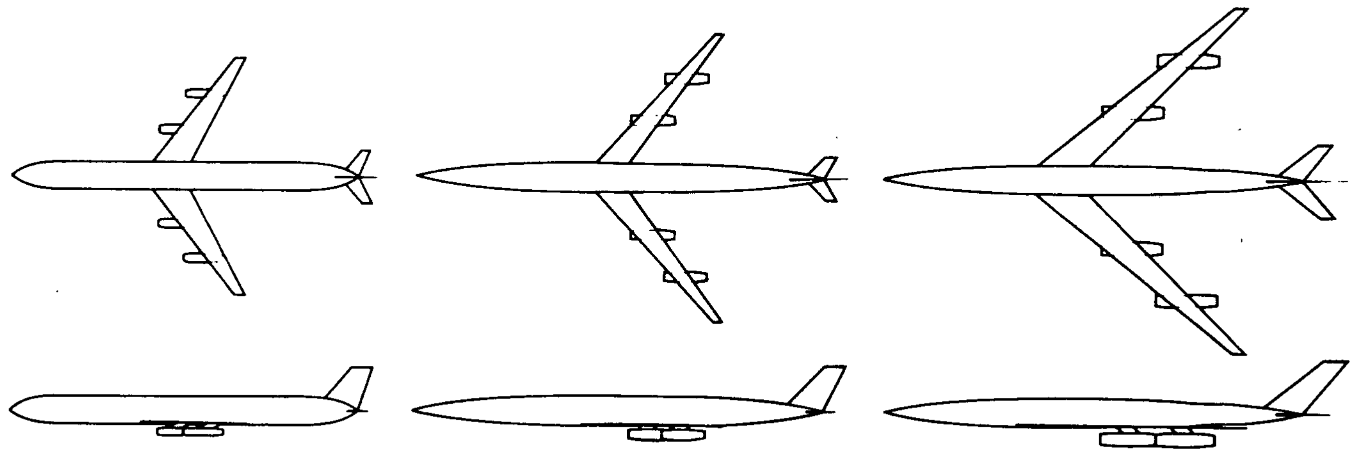


Figure 11.- Weights of Optimized Configurations.

RANGE = 2700 n.mi. 200 PASSENGERS

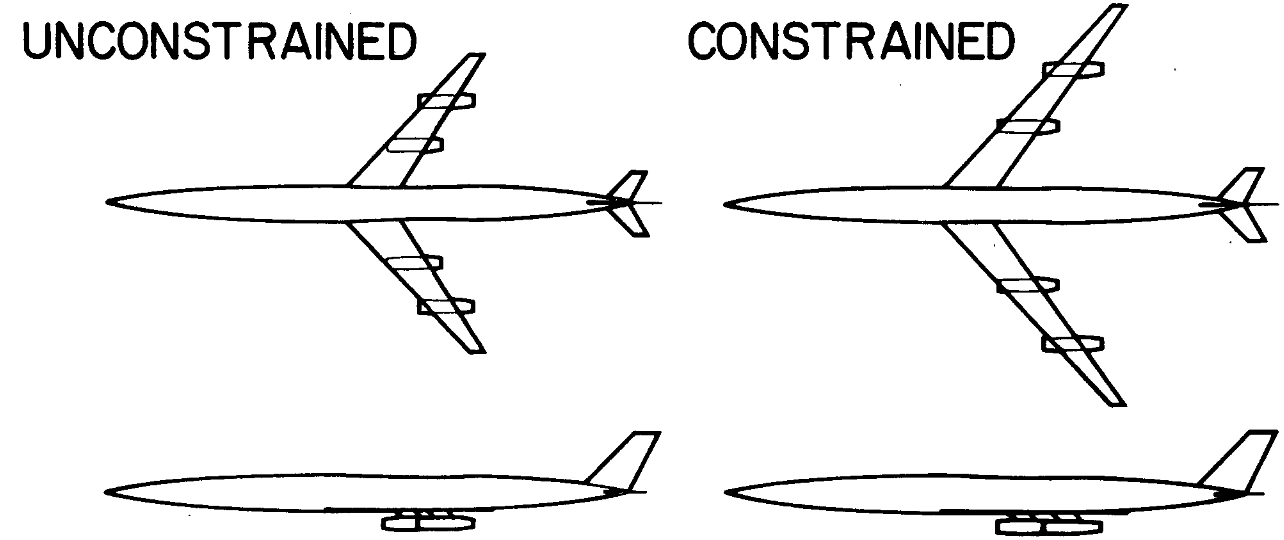
	CVT	ATT	TST



	CVT	ATT	TST
M_{CRUISE}	0.90	0.98	1.15
GROSS WEIGHT	182,500 lb	189,000 lb	323,000 lb
O. W. E. (% W_{GTO})	52.5	55.9	56.0
$(L/D)_{CRUISE}$	16.3	18.6	12.8
$V_{APPROACH}$	148 knots	152 knots	168 knots
D. O. C.	0.97 ¢/seat mi	0.94 ¢/seat mi	1.22 ¢/seat mi

Figure 12.- Optimum Carbon/Epoxy Configurations.

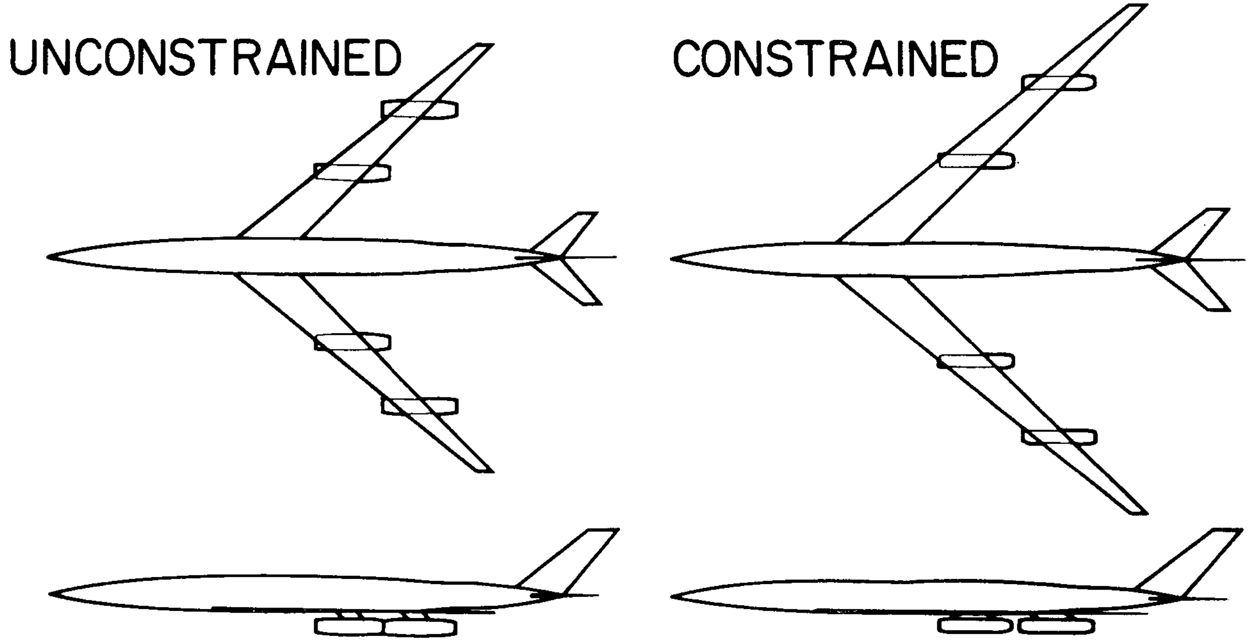
RANGE = 2700 n.mi. 200 PASSENGERS



	UNCONSTRAINED	CONSTRAINED
ASPECT RATIO	8.1	11.8
WING LOADING	123 lb/ft^2	101 lb/ft^2
GROSS WEIGHT	232,500 lb	250,000 lb
O.W.E. (%W_{GTO})	57.8	62.2
$(L/D)_{CRUISE}$	16.3	19.7
$V_{APPROACH}$	170 knots	151 knots
D.O.C.	1.01 ¢/seat mi	1.05 ¢/seat mi

Figure 13.- Effect of Landing Speed Constraint on Optimum ATT Aluminum Configuration.

RANGE = 2700 n.mi. 200 PASSENGERS



	UNCONSTRAINED	CONSTRAINED
ASPECT RATIO	9.8	11.4
WING LOADING	100 lb/ft^2	89 lb/ft^2
GROSS WEIGHT	323,000 lb	347,000 lb
O.W.E. (% W_{GTO})	56.0	58.3
$(L/D)_{CRUISE}$	12.8	14.3
$V_{APPROACH}$	168 knots	158 knots
D.O.C.	1.22 ¢/seat mi	1.60 ¢/seat mi

Figure 14.- Effect of Landing Speed Constraint on Optimum TST Carbon/Epoxy Configuration.

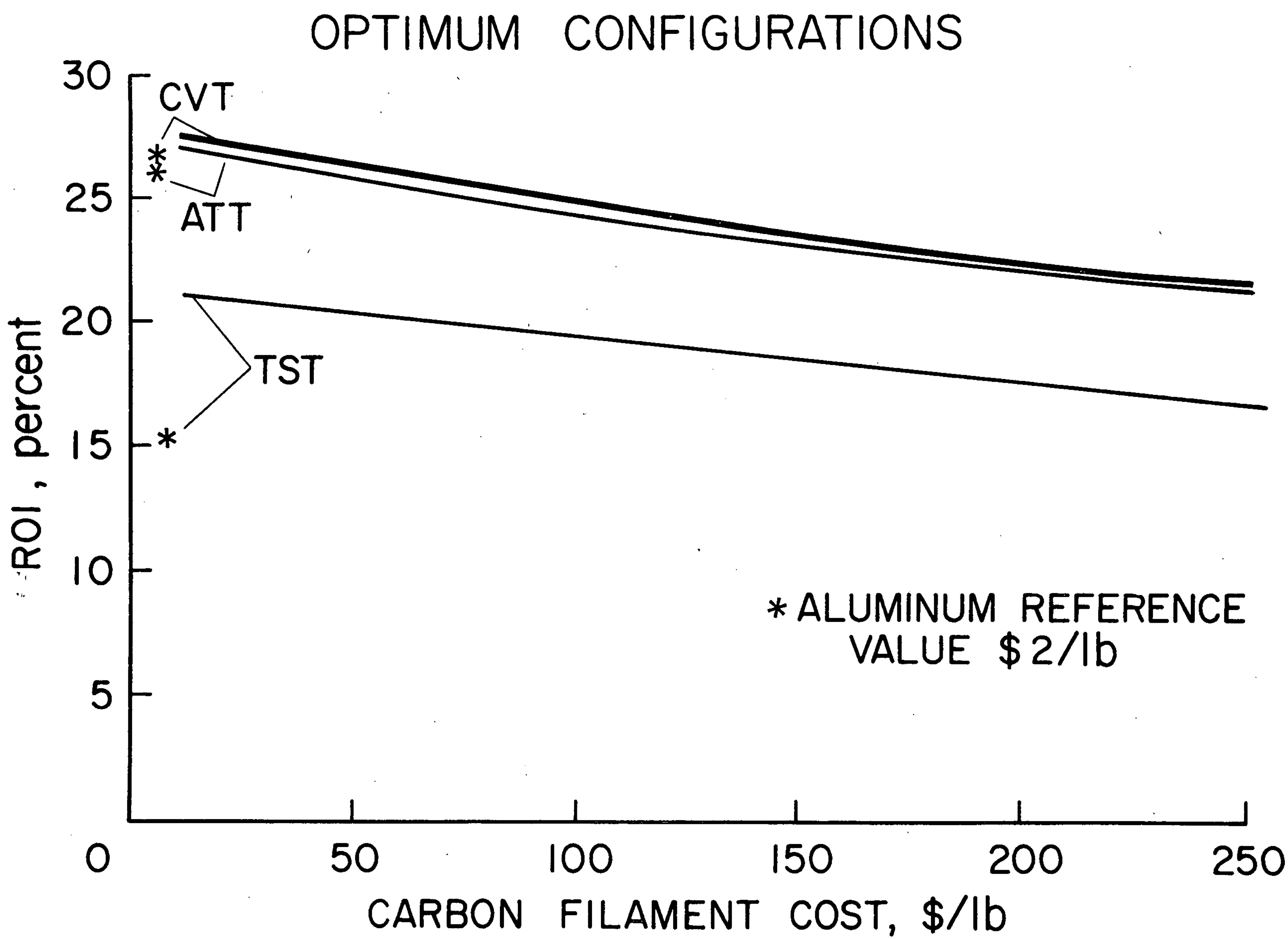


Figure 15.- Effect of Carbon Filament Cost on Return on Investment.

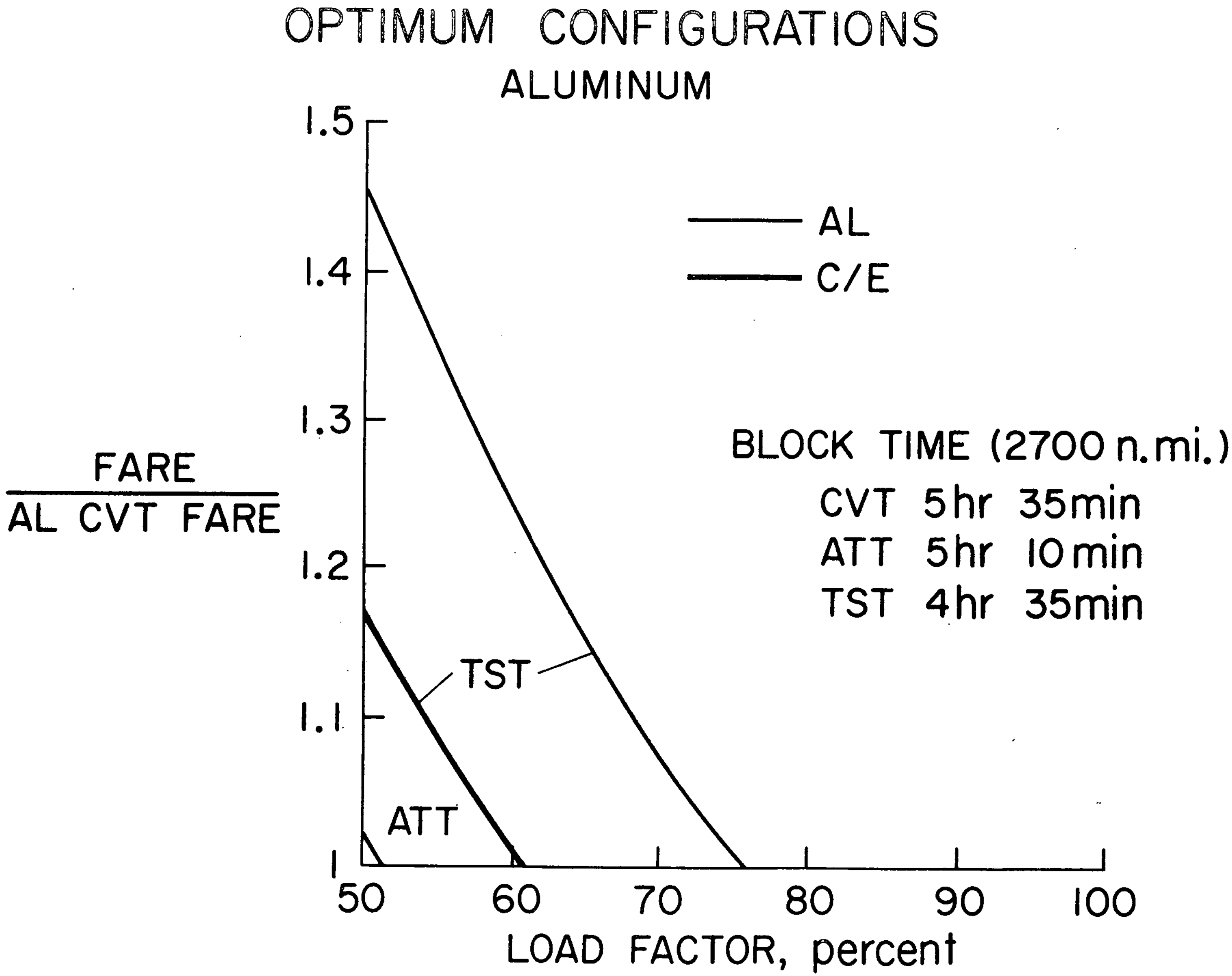


Figure 16.- Fare Required for Equal Return on Investment.

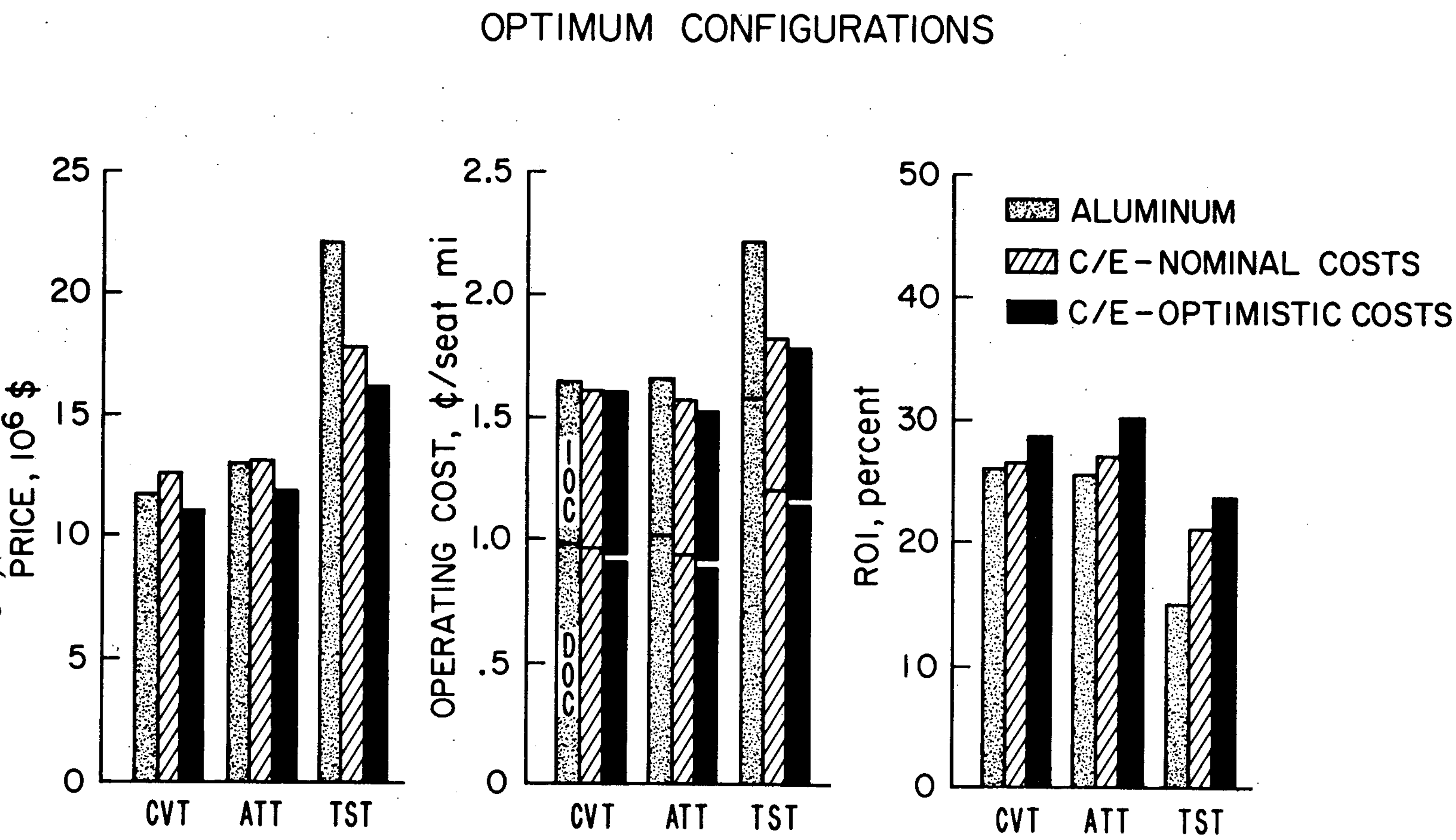


Figure 17.- Aircraft Economics.