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ENERGY AND ECONOMIC TRADE OFFS FOR
ADVANCED TECHNOLOGY SUBSONIC AIRCRAFT

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APRIL 1, 1976

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ENERGY AND ECONOMIC TRADE OFFS FOR ADVANCED TECHNOLOGY SUBSONIC AIRCRAFT

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Summary

Changes in future aircraft technology which conserve energy are studied, along with the effect of these changes on economic performance. Among the new technologies considered are laminar-flow control, composite materials with and without laminar-flow control, and advanced airfoils. Aircraft design features studied include high-aspect-ratio wings, thickness ratio, and range. Engine technology is held constant at the JT9D level.

It is concluded that wing aspect ratios of future aircraft are likely to significantly increase as a result of new technology and the push of higher fuel prices. Whereas current airplanes have been designed for AR = 7, supercritical technology and much higher fuel prices will drive aspect ratio to the AR = 9-10 range. Composite materials may raise aspect ratio to about 11-12 and practical laminar flow-control systems may further increase aspect ratio to 14 or more. Advanced technology provides significant reductions in aircraft take-off gross weight, energy consumption, and direct operating cost.

Introduction

In January 1973, U.S. airlines paid about 12 cents per gallon for their fuel. By October of 1975, U.S. domestic airlines were paying almost 30 cents per gallon and U.S. international airlines were paying about 37 cents per gallon (Fig. 1). By the end of 1975, OPEC crude oil price increases and gradual removal of domestic price controls suggest that fuel prices may rise again. Increases in fuel price such as those experienced over the past few years mean that significant improvement must occur in the energy performance of future aircraft. The impact on the design of aircraft will be great.¹⁻⁸ This paper presents an overview of what the development of new technologies such as laminar-flow control (LFC), composite materials, and new airfoils may mean to future aircraft design.

Studies were accomplished by the development of a computer program capable of sizing aircraft for minimum fuel consumption. With this tool, it is possible to take a broad look at technologies and parameters which influence aircraft weight, fuel usage, and other operating cost components. The assumptions on which the program is based limit its use to defining broad effects of aircraft design rather than conducting detailed point designs. Experience to date indicates that this program can be quite useful in making broad assessments of the value of new aircraft technology.

Symbols

| | |
|----------------------------|---------------------------|
| AR | Aspect ratio |
| c | Section chord, ft |
| C _D | Total drag coefficient |
| C _{D_i} | Induced drag coefficient |
| C _{D_o} | Friction drag coefficient |
| C _L | Cruise lift coefficient |

| | |
|--------------------|---|
| COMP | Composite material |
| DOC | Direct operating cost, cents per seat statute mile |
| ENERGY | Energy use, Btu's per seat mile |
| e = 0.8 | Span efficiency factor |
| L/D | Lift-to-drag ratio |
| LFC | Laminar-flow control used on wing and tail |
| M | Mach number |
| OEW | Operating empty weight, lb |
| PAX | Number of passengers |
| R | Range, n. mi. |
| ROI | Return on investment, percent |
| S _{wing} | Wing area, ft ² |
| t/c | Average thickness ratio, percent |
| (t/c) _D | Average thickness ratio consistent with drag divergence Mach number |
| TOGW | Take-off gross weight, lb |
| TURB | Turbulent flow |
| UW | Unit weight, lb per ft ² (laminarized wetted area) |
| W _{wing} | Wing weight, lb |
| α | Angle of attack, radians |
| Λ | Wing sweep angle, degrees |
| λ = 0.27 | Wing taper ratio |

Description of Minimum Energy Aircraft Program

Appendix A summarizes the important equations used in the development of the program. Program logic is shown in Figure 2. Passenger number, range, and Mach number are specified. An initial fuel weight and take-off gross weight (TOGW) is assumed. The fuselage is sized to accommodate the payload. Empirical equations (Appendix A) are used to weigh major aircraft components such as the wing and fuselage (with appropriate modifications for high-aspect ratio and advanced technology). A first guess of wing area is made and first-order (no wing-body interference effects) aerodynamics⁹ used to calculate cruise performance at (L/D)_{max}. Engine size is then determined by weighing cruise thrust requirements against the thrust requirements imposed by a 10,500-foot runway. A climb performance routine is calculated¹⁰ and the engine resized, if necessary, to achieve adequate climb performance. The calculations are then iterated until a convergence is reached which defines the aircraft and its performance for the selected wing area. Wing area is then varied in a search for the aircraft with maximum range.

given the assumed fuel load. The optimum energy airplane to meet the required range is then found by repeating the wing area search for different assumed fuel weights. This part of the program, which defines the optimum energy airplane, provides inputs for the next section of the program to calculate airplane economics.

Economic results are expressed in terms of Direct Operating Costs (DOC), Indirect Operating Costs (IOC), and Return on Investment (ROI). DOC calculations are based on the Air Transport Association model¹¹ updated to 1975 cost experience.* Indirect Operating Costs are based on a Lockheed Aircraft Corporation model.¹² The ROI calculations utilize discounted cash flow methodology. Baseline fuel price is 30 cents per gallon.

Off-design performance (block fuel and DOC) is then calculated by assuming a full payload and design fuel load for stage lengths less than design range. Approximately 40 seconds of run time on the CDC 6600 computer are needed to define an optimum airplane and determine its economic and off-design performance.

Major assumptions made in developing the program are listed in Figure 3. Table 1 compares a representative trijet configuration¹³ with results predicted by the program for a minimum fuel consumption aircraft. Weights, geometry, and mission performance data are given. Even though many parameters, other than fuel consumption, were considered in the trijet design (for example, economic performance), the comparison indicates that realistic aircraft characteristics evolve from the program.

Results

Baseline Airplane

A 200-passenger airplane with 10,000 pounds of cargo load flying at $M = 0.8$ was chosen as a baseline. Additional characteristics of this airplane are given in Table 2, which also includes the baseline characteristics of the laminar-flow control (LFC) configuration. Design parameters studied with the baseline airplane include thickness ratio, aspect ratio, and range. Studies of new technology airplanes are also referenced to this baseline. A high bypass ratio engine is assumed with technology level held constant; the technology level is about that of a JT-9D engine.

Airfoil Model

The baseline configuration was used to study the effects of thickness ratio at various aspect ratios and $R = 3000$ n. mi. TOGW, ENERGY, and DOC results are given in Figure 4. Use of a constant wing thickness ratio yields a continuous decrease in energy requirements as aspect ratio is increased; however, trends in TOGW and DOC with aspect ratio (AR) are strongly dependent on the assumed thickness ratio.

Minimum energy aircraft with thick wings have their minimum TOGW at higher aspect ratios than do aircraft with thin wings. Thick wing aircraft also have lower TOGW, as would be expected from inspection of the wing weight equation used (see Appendix A) which shows decreasing wing weight with increasing thickness ratio. However, these constant thickness ratio results are misleading. For example, the decrease in DOC that occurs with increasing aspect ratio for $t/c \geq 12$ may be erroneous since these airfoils may not be able to meet a drag divergence criterion. A bad estimate as to the absolute level of average thickness ratio could also lead to significant error.

For these reasons, Reference 14 was used to determine the variation of average wing thickness ratio, $(t/c)_{M_D}$, consistent with a drag divergence Mach number

and required wing lift coefficient. It is important to realize that this relationship does not necessarily represent an attainable supercritical technology for the airfoil section, but only serves as a model for the relationship between wing thickness, wing lift coefficient, and Mach number. With this criterion, the wing thickness ratio compatible with drag divergence Mach number (i.e., a 20-count drag rise) varies from 14.1% to 7.8% over the AR range (see $(t/c)_{M_D}$ curve in

Fig. 4). The result is an increase in wing weight (at high aspect ratios) which is above and beyond the $(AR)^{1.5}$ penalty (see wing weight equation in Appendix A). Consequently, at high aspect ratios, large penalties occur in TOGW and DOC (Fig. 4).

In addition, at high aspect ratios, the varying thickness ratio compounded the problem of getting enough fuel in the wing; for these aircraft, adequate fuel storage volume in the wing could present a design problem above $AR = 10$.

Turbulent Airplane Studies

Design Range. The effect of design range on the baseline aircraft is given in Figure 5 for aspect ratios of 7 and 14. As range increases, the extra fuel required to meet mission requirements combines with increases in structural weight to raise take-off gross weight. At $AR = 7$, which is typical of current commercial transports, energy requirements increase continuously with range; high AR aircraft ($AR = 14$) show a minimum energy consumption at a design range of about 2200 n. mi. Relative to the $AR = 7$ aircraft, energy saved with an $AR = 14$ design is greatest at long range. Best economic performance occurs at ranges between 2000 n. mi. and 3000 n. mi. with best economics at a somewhat higher range for the highest AR. Severe penalties are encountered with long-range capability (3500 n. mi.) in terms of both energy use and DOC.

Aspect Ratio. The effect of aspect ratio is shown in Figure 6 for ranges of 1000, 3000, and 5000 n. mi. Effects of increased aspect ratio result from a trade of improved aerodynamic efficiency for added structural wing weight (see Appendix A). Up to AR of about 12, this trade is favorable at all ranges in the sense that energy requirements are reduced. At a range of 1000 n. mi., however, the resulting TOGW increase, with increasing AR. At 5000 n. mi. range, the fuel saved with increased AR more than offset the structural weight penalty and TOGW decreases when AR is increased from 7 to 10. Above AR of about 12, the trade is not favorable and TOGW and fuel usage begin to increase with AR. Lowest DOC's are obtained at aspect ratios between 9 and 10. These optimum DOC's occur at a higher aspect ratio than today's $AR \approx 7$ designs because of the sharp fuel price increases which have occurred during the past 2-1/2 years (the present study uses a fuel price of 30 cents per gallon compared to an earlier 12 cents per gallon) and the existence of supercritical airfoil technology. For the three ranges shown, the lowest DOC's occur with $R = 3000$ n. mi. for all as. ar ratios. DOC increases rapidly when $AR > 11$ because of the extra fuel and purchase price increase resulting from the much increased structural weight.

*APPENDIX B.

Laminar-Flow Control

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Controlling the boundary layer to maintain laminar flow on an airplane can offer large benefits. Laminar-Flow Control (LFC) results in much lower friction drag and therefore reduced fuel use. Figure 7 illustrates the concept of using suction to stabilize the initial laminar boundary layer such that laminar flow can be maintained far beyond the length normally observed for transition to turbulent flow. Suction power requirements are small compared to the reductions obtained in propulsive power. Much significant work in LFC using the suction concept was accomplished with the X-21 flight tests made between 1962-1965.¹⁵⁻¹⁹ This work showed that LFC could, in fact, be achieved in flight. Remaining uncertainties revolve largely around questions of reliability, maintenance, and cost.

As a result of the national energy crisis, NASA is taking a fresh look at LFC's potential and problems.²⁰ Two studies by Lockheed²¹ and Boeing²² have recently been completed under NASA sponsorship. Because of the potential for energy conservation with LFC technology, the present study has also looked at some of the major questions which surround the application of LFC to commercial transport aircraft.

LFC Configuration. For comparison to the baseline turbulent airplane, LFC airplanes were studied assuming laminar flow exists over the wing and tail of the aircraft (see Table 3 for a typical configuration comparison). The LFC system is turned on once the aircraft reaches cruise altitude. The propulsion system was sized to include the power required to run the LFC system pumps.

Figure 8 shows the effect of LFC with range. LFC benefits in reduced weight, energy, and direct operating cost grow rapidly as range increases because of the greater importance of aerodynamic efficiency at long range. LFC also increases the range at which minimum DOC occurs. The effect of AR for aircraft designed for LFC relative to the turbulent baseline at R = 3000 n. mi. is shown in Figure 9. LFC delays the TOGW increase which occurs at AR = 10 with the turbulent airplanes. In addition, the weight penalty paid with the turbulent airplane at AR = 14 is greatly reduced with LFC. LFC aircraft energy requirements continually decrease as AR increases from 7 to 14, whereas the AR = 14 turbulent airplane shows increased energy requirements relative to lower aspect ratios. LFC reduced direct operating costs at all aspect ratios studied. Even the DOC penalty from an AR = 14 configuration is largely eliminated with LFC. These favorable results using LFC occur despite built-in economic penalties equal to 17% higher maintenance and 3% higher purchase price assumed for the LFC airplane (Table 3), based on the results of Reference 21.

LFC wings have lower lift coefficients and hence greater thickness ratios than their turbulent counterparts (Fig. 10). This follows since at $(L/D)_{max}$, $C_L = \sqrt{AR C_{D_0}}$; since LFC reduces C_{D_0} , C_L is also reduced and the wing can have a larger thickness ratio for the same drag divergence Mach number. As aspect ratio increased, wing thickness ratio for the optimum turbulent configuration decreased (Fig. 10), and fuel volume efficiency decreased. For turbulent airplanes with AR = 10, not enough wing volume was available to store the fuel needed for long-range missions. Turbulent airplanes of high aspect ratio and low passenger capacity may therefore require wing pod tanks²¹ or fuel storage in the fuselage. In contrast, no fuel volume problems were encountered with the AR = 14, R = 3000 n. mi., LFC configuration. LFC airplanes,

therefore, may offer this potential design simplification although LFC ducting volume requirements present an added problem. Wing box volume was estimated assuming a spar separation distance of one-half the chord length, and fuel volume was taken as 70% of the wing box volume.

The effect of LFC system unit weight (UW in lb per sq ft of laminarized area) is given in Figure 11 for varying AR and R = 3000 n. mi. Baseline unit weight (1.26 from Ref. 21) was varied from 2.52 to 0.63 (not shown). Relative to the baseline, UW = 0.63 provided only minor reductions in TOGW, whereas UW = 2.52 wipes out much (but not all) of the TOGW savings possible at low AR with LFC. Energy consumption is relatively unaffected by unit weight changes and large energy savings result even if UW = 2.52. In contrast to the turbulent configuration, the UW = 2.52 airplane used less energy at AR = 14 than at lower aspect ratios. Economic performance is best at UW = 1.26, but even the UW = 2.52 airplane has a lower DOC than the turbulent baseline. Further work on LFC designs may enable the unit weight penalty to be reduced below 1.26, as design techniques are developed which use the LFC suction surfaces and ducting to help carry structural loads.²²

Composites

Figures 12 and 13 show the benefit which composite materials will have on the baseline turbulent and LFC configurations. Estimates of wing, tail, fuselage, and landing-gear weight resulting from application of composite material were obtained from Reference 23 (see Table 4). It is thought that this degree of composite application (~40%) might be applied to an airplane introduced in 1985. Significant reductions in TOGW, energy, and DOC occur with introduction of composite material. Figure 12 shows that at R = 3000 n. mi., composites have a bigger effect on TOGW than does LFC; however, LFC saves more energy and has better economic performance than does composites. At R = 5000 n. mi., LFC reduces both TOGW and energy to a greater extent than does composites (Fig. 12). With varying aspect ratio (Fig. 13) and R = 3000 n. mi., an LFC airplane made of composite materials eliminates the TOGW and DOC penalty paid for the AR = 14 design (relative to AR = 11). These calculations must be viewed with caution, however, since wing weights are estimated using a correlation of historical data based on aluminum aircraft and then corrected to expected composite material weight. Best economic performance is obtained with an LFC airplane built of advanced materials. The price of composite airplanes is found by calculating price as if an aluminum airplane were being costed, and then adding 10% to this value; the resulting composite airplane price is typically about 12-5% under the price of an equivalent aluminum airplane. Maintenance characteristics are assumed equivalent to that of aluminum airplanes based on the encouraging (but limited) data obtained to date through in-service flight tests made with composite materials on secondary structures. Since energy use is decreasing even at AR = 14, other advanced technology (which lowers structural weight) beyond that discussed in this paper may eventually lead to practical configurations with aspect ratios above 14. Examples of such technologies include more advanced airfoils, greater composite application, laminarized strut-braced wings of very high AR, and active control systems.

Advanced Airfoils

The effect of advanced airfoil technology is illustrated in Figure 14. The advanced configuration represents airfoils with drag divergence Mach numbers 0.925

and 0.05 greater than that attained by supercritical airfoils in Reference 14. Admittedly, attainment of the benefits represented by these cases is a difficult goal to reach if, in fact, reachable. The impact of such an airfoil is relatively small at low aspect ratios. However, the TOGW, energy, and DOC benefits are sizable at high aspect ratios.

These results have an interesting implication for LFC aircraft. Laminar-flow control thins the airfoil boundary layer and thus permits a thicker, lighter-weight wing to be used (without a drag penalty). Therefore, LFC will provide an additional synergistic benefit perhaps comparable to that shown in Figure 14 for the 0.025 Mach number increase. No benefit was taken for this effect in the LFC calculations made in this paper.

In addition, high-aspect-ratio airplanes (turbulent or laminar) require cruise lift coefficients that will be difficult to achieve even with advanced airfoil technology. LFC, with lower required lift coefficients, alleviates this problem (Fig. 10).

Economics

Turbulent Configuration. The effect of aspect ratio on DOC for various fuel prices and ranges is shown in Figure 15. Clearly, if fuel prices continue to rise relative to other costs, higher AR will be economically desirable for future aircraft. At all ranges, the effect of increasing fuel price is to increase the aspect ratio at which minimum DOC occurs. Also, at a constant fuel price, increasing the design range increases the need for improved aerodynamics and, therefore, increases the AR at which minimum DOC occurs. Dramatic changes in airplane design can occur as a result of the interaction of these parameters. For example, at $R = 1000$ n. mi. and 30 cents per gallon fuel, an $AR \approx 8$ airplane has the lowest DOC, and DOC varies little between $AR = 7-11$. In contrast, at $R = 5000$ n. mi. and \$1.20 per gallon fuel, an $AR = 11$ airplane clearly has the lowest DOC.

Laminar-Flow Control. The effect of increases in purchase price and maintenance cost for the LFC airplane is shown in Figure 16. With $AR = 10$ and 30 cents per gallon fuel, the LFC airplane must cost 11% more than expected (or have an 18% higher maintenance cost) for the airplane's DOC to be equal to the turbulent airplane's DOC. If fuel costs 60 cents per gallon, it would take either a 37% increase in purchase price or a 50% increase in maintenance cost to wipe out the LFC benefits. At $AR = 14$, LFC cost increases must be even greater to eliminate the anticipated savings. It is evident that the payoff from LFC is large enough to overshadow possible maintenance and purchase price increases.

The relative contribution which different costs make to DOC is given in Table 5 for turbulent and LFC airplanes at fuel prices of 30 cents and 60 cents per gallon. As aspect ratio increases, fuel cost becomes less important and purchase price becomes more significant. Laminar-flow control significantly reduces the importance of fuel costs to DOC. In every case listed in Table 5, except two, fuel cost is seen to be the major element of DOC. Therefore, technology which reduces fuel cost is likely to be more important in the future than in the past.

Conclusions

A broad look was taken at how changes in future aircraft design and technology might impact commercial

aircraft trade offs between TOGW, energy use, and DOC. Subject to the ground rules and assumptions on which the study was based, the following conclusions were reached:

Turbulent Airplanes. Energy use per passenger mile is lowest at $R \leq 3000$ n. mi. Best DOC's are obtained between ranges of 2000 n. mi. and 3000 n. mi. at all aspect ratios. Severe penalties occur at long range ($R \approx 5000$ n. mi.) in terms of both energy use and direct operating cost. High aspect ratio, long-range ($AR \approx 10$, $R = 5000$ n. mi.) aircraft can conceivably show lower TOGW than $AR = 7$ aircraft.

Laminar-Flow Control. LFC systems provide significant energy savings when applied to current $AR = 7$ aircraft. TOGW, energy, and DOC savings increase dramatically with design range. LFC will be of even more value to the high aspect ratio ($AR = 10-14$) aircraft of the future because the greater aerodynamic efficiency realized with LFC systems reduce the total drag and, consequently, negate further the weight penalties that must be paid for high-aspect-ratio design. Successful application of LFC systems, therefore, will tend to increase the aspect ratios of future airplanes. Aircraft energy requirements for LFC configurations continually decreased as AR was increased from 7 to 14 in contrast to the turbulent airplane results. LFC benefits are greatest at high range and high aspect ratio. Unit weight (lb/ft²) of the LFC system has a small effect on energy saved but increased LFC unit weight penalties are more significant in TOGW and DOC results.

Composites. Significant reductions in TOGW, energy, and DOC occur with introduction of composite material. At $R = 3000$ n. mi., composites had a larger effect on TOGW than did LFC, although LFC saved more energy and had a lower DOC than did composites. Also, at $R = 3000$ n. mi., an LFC composite airplane nearly eliminated the TOGW and DOC penalty paid for an $AR = 14$ design. Best economic performance was obtained with an LFC airplane built of advanced materials.

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Appendix A. Main Equations Used in Minimum Energy Aircraft Program

Aerodynamics

$$C_L = \left(\frac{dC_L}{d\alpha} \right) \alpha ; \frac{dC_L}{d\alpha} = \frac{2\pi}{\sqrt{1-M^2}} (\cos \Lambda) \left\{ \frac{F}{2 + F \sqrt{1 + 4/F^2}} \right\} \quad \text{where } F = \frac{AR \sqrt{1-M^2}}{\cos \Lambda}$$

$$C_{D_i} = \frac{C_L^2}{\pi e AR} ; (L/D)_{\max} = 0.5 \sqrt{(\pi AR e)/C_{D_0}}$$

$$(C_L)_{(L/D)_{\max}} = \sqrt{\pi AR e C_{D_0}}$$

$$C_{D_0} = K \sum C_F \text{ (wetted area/wing area)} \quad \text{where } K = 1.15 \text{ (correction factor for parasite drag)}$$

C_F - Laminar: Blasius

C_F - Turbulent: Prandtl-Schlichting

Weights

$$\text{Fuselage weight}^{**} = (\text{WOSB}) (\text{body area}) \quad \text{where } \text{WOSB} = 2.6 \sqrt{3.75 \times \text{TOGW} \times 10^{-6}}, \text{ or} \\ = 4.75 \text{ minimum (selected minimum gage)}$$

$$\text{Wing weight}^{***} = 3534 + 3.847 \left[S_{\text{wing}} + 0.3 K_w \left(\frac{\text{TOGW}}{S_{\text{wing}}} \right) (S_{\text{wing}})^{1.5} \times 10^{-6} \right]$$

$$\text{where } K_w = \frac{3.75 (AR)^{1.5} (KZF)^{0.5} (1 + 2\lambda)}{(t/c)(1 + \lambda) \cos^2 \Lambda} ; KZF = \frac{\text{Zero fuel weight}}{\text{TOGW}}$$

* Shapiro, p. 422.

** Correlation of historical data by L. Robert Jackson, NASA High-Speed Aerodynamics Division, Design Concepts Group, Langley Research Center.

*** Obtained from McDonnell Douglas Corporation, NAS1-13964.

APPENDIX B.- EQUATIONS USED TO CALCULATE DIRECT
OPERATING COST - 1975 COEFFICIENTS*

| | |
|--|--|
| CREW PAY (\$/BLOCK HOUR) | |
| 3 MAN JET | $24.261 \left(V_c \times \frac{TOGW}{10^5} \right)^{.3} + 57.620$ |
| NON-REVENUE FACTOR | |
| | 1.00 ON FUEL AND MAINTENANCE |
| AIRFRAME MAINTENANCE-CYCLE | |
| MATERIAL (\$/CYCLE) | $1.9229 (Ca/10^6) + 2.2504$ |
| DIRECT LABOR (MH/CYCLE) | $.21256 [\text{Log}_{10} (Wa/1000)]^{3.7375}$ |
| AIRFRAME MAINTENANCE - FLIGHT HOUR | |
| MATERIAL (\$/FH) | $1.5994 Ca/10^6 + 3.4263$ |
| DIRECT LABOR (MH/FH) | $4.9169 [\text{Log}_{10} (Wa/1000)] - 6.425$ |
| ENGINE MAINTENANCE - CYCLE | |
| MATERIAL (\$/CYCLE) | $[3.6698 (Ce/10^6) + 1.3655] Ne$ |
| DIRECT LABOR (MH/CYCLE) | $.20 Ne$ |
| ENGINE MAINTENANCE - FLIGHT HOUR | |
| MATERIAL (\$/FH) | $[28.2353 (Ce/10^6) - 6.5176] Ne$ |
| DIRECT LABOR (MH/FH) | $[7/10^3 / (.82715 7/10^3 + 13.639)] Ne$ |
| BURDEN \$/DIRECT MAINTENANCE \$ | 1.00 |
| MAINTENANCE LABOR RATE (\$/MANHOUR) | 8.60 |
| INSURANCE (% PRICE/YEAR) | 1.0 |
| INVESTMENT SPARES RATIO (X) | |
| AIRFRAME | 6 |
| ENGINE | 30 |
| DEPRECIATION SCHEDULE (YEARS/RESIDUAL VALUE) | |
| | 14/0 |
| TOGW - Maximum Takeoff Gross Weight - lbs. | Wa - Airframe Weight - lbs. |
| Ca - Airframe Price - \$ | M - Mach No. |
| Ce - Engine Price - \$ (Excluding Reverser) | FH - Flight Hours |
| Ne - Number of Engines | MH - Manhours |
| $V_c = 715 \times M - 75 \times M^2$ (Mk.9) | T - Sea Level Static Thrust - lbs. |

*Obtained from Boeing Commercial Aircraft Company

TABLE 1. COMPARISON OF REPRESENTATIVE WIDE BODY TRIJET WITH PRESENT STUDY RESULTS

| | Trijet | Present study |
|---------------------------------------|--------|---------------|
| Weight, lb | | |
| TOGW | 555000 | 533600 |
| Wing | 57878 | 56875 |
| Fuel | 187000 | 183170 |
| Tail | 10000 | 8927 |
| Engine | 48856 | 52019 |
| Body | 46275 | 46738 |
| Empty | 349955 | 352430 |
| Fixed | 76288 | 83910 |
| Payload (inc. cargo) | 104573 | 103960 |
| Number of passengers | 376 | 376 |
| Altitude, ft | 31000 | 37619 |
| Length, ft | 182 | 178 |
| Wing loading, lb per ft ² | 152 | 142 |
| Wing area, ft ² | 3647 | 3774 |
| Span, ft | 165 | 155 |
| Horizontal tail area, ft ² | 1336 | 1080 |
| Vertical tail area, ft ² | 605 | 651 |
| Climb range, n. mi. | 193 | 175 |
| Climb time, minutes | 26.4 | 23.9 |
| Available fuel storage, lb | 240000 | 211000 |
| Take-off thrust, lb | 153000 | 176000 |
| Average t/c, percent | 11.2 | 10.4 |

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TABLE 2. BASELINE TURBULENCE/LFC AIRPLANE CHARACTERISTICS

| | |
|--|-------------|
| Mach number | 0.8 |
| Seats | 290 |
| Cargo load, lb | 10000 |
| Sweep, deg | 25 |
| Aspect ratio | 7 |
| Runway length, ft | 10500 |
| Reserve fuel, as percent of total fuel | 18 |
| Airframe material | Aluminum |
| Engine technology | 37-90 |
| Engine number | 4 |
| Fuel cost, cents per gallon | 30 |
| Passenger weight + baggage, lb | 210 |
| LFC components | Wing + tail |
| Wing and tail area with LFC, percent | 190 |

TABLE 3. COMPARISON OF NOMINAL TURBULENT AIRPLANES TO LFC AIRPLANES

M = 0.8
 Range = 3000 n. mi.
 PAX = 200
 A = 25°

| | AR = 7 | | AR = 14 | |
|--|-----------|--------|-----------|--------|
| | Turbulent | LFC | Turbulent | LFC |
| TOGW, lb | 224070 | 213437 | 261440 | 221100 |
| OEW, lb | 102530 | 107788 | 147540 | 125090 |
| Wing wt, lb | 16641 | 21161 | 55511 | 39482 |
| Body wt, lb | 43189 | 43189 | 43189 | 43189 |
| Engine wt, lb | 20247 | 17949 | 23555 | 18119 |
| LFC system wt, lb | ----- | 5920 | ----- | 4833 |
| Block fuel, lb | 58960 | 47470 | 52609 | 37420 |
| Span, ft | 109 | 178 | 167 | 164 |
| Length, ft | 151 | 151 | 151 | 151 |
| Wing area, ft ² | 1708 | 1992 | 1999 | 1918 |
| Cruise altitude, ft | 35260 | 4998 | 42662 | 40654 |
| Cruise L/D | 15.2 | 19.8 | 21.1 | 26.8 |
| Wing loading, lb per ft ² | 131 | 107 | 131 | 115 |
| Airplane price, \$ x 10 ⁶ | 9.36 | 9.91 | 12.37 | 10.98 |
| DOC | 1.085 | 1.036 | 1.169 | 1.036 |
| Relative LFC maintenance, percent | ----- | 17 | ----- | 17 |
| Relative LFC purchase price, percent | ----- | 1 | ----- | 3 |
| LFC system unit weight, lb per ft ² | ----- | 1.26 | ----- | 1.26 |

TABLE 4. COMPOSITE MATERIAL COMPONENT WEIGHT AS A PERCENT OF CONVENTIONAL FLIGHT

| | |
|--------------|------|
| Wing | 71.5 |
| Body | 76.2 |
| Tail | 78.0 |
| Landing gear | 86.0 |

Source: Reference 23

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TABLE 5. COST AS A PERCENT OF DIRECT OPERATING COST
 Range = 3000 n. mi.

| | Turbulent | | | | | | Laminar | | | | | |
|--------------------------|--------------|------|------|--------------|------|------|--------------|------|------|--------------|------|------|
| | 30 cents/gal | | | 60 cents/gal | | | 30 cents/gal | | | 60 cents/gal | | |
| | AR | | AR | AR | | AR | AR | | AR | AR | | AR |
| | 7 | 10 | 14 | 7 | 10 | 14 | 7 | 10 | 14 | 7 | 10 | 14 |
| Fuel | 36.0 | 32.6 | 29.8 | 52.9 | 49.1 | 46.0 | 29.2 | 26.3 | 24.0 | 45.2 | 41.6 | 38.7 |
| Maintenance | 18.4 | 19.4 | 20.6 | 13.5 | 14.7 | 15.9 | 22.2 | 23.1 | 23.9 | 17.2 | 18.3 | 19.3 |
| Crew | 25.9 | 26.7 | 25.3 | 19.1 | 20.1 | 19.5 | 26.9 | 27.7 | 27.7 | 20.8 | 21.9 | 22.3 |
| Depreciation + Insurance | 19.7 | 21.3 | 24.3 | 14.5 | 16.1 | 18.6 | 21.7 | 22.9 | 24.4 | 16.8 | 18.2 | 19.7 |

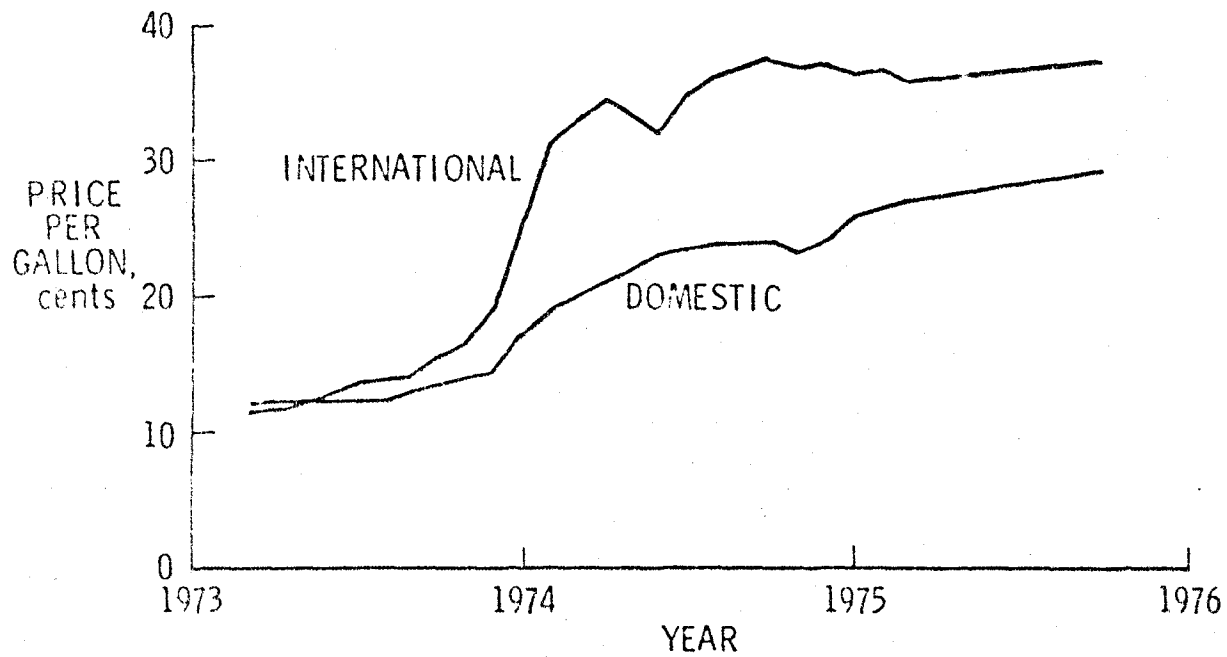


Figure 1. Average U.S. commercial jet fuel price.

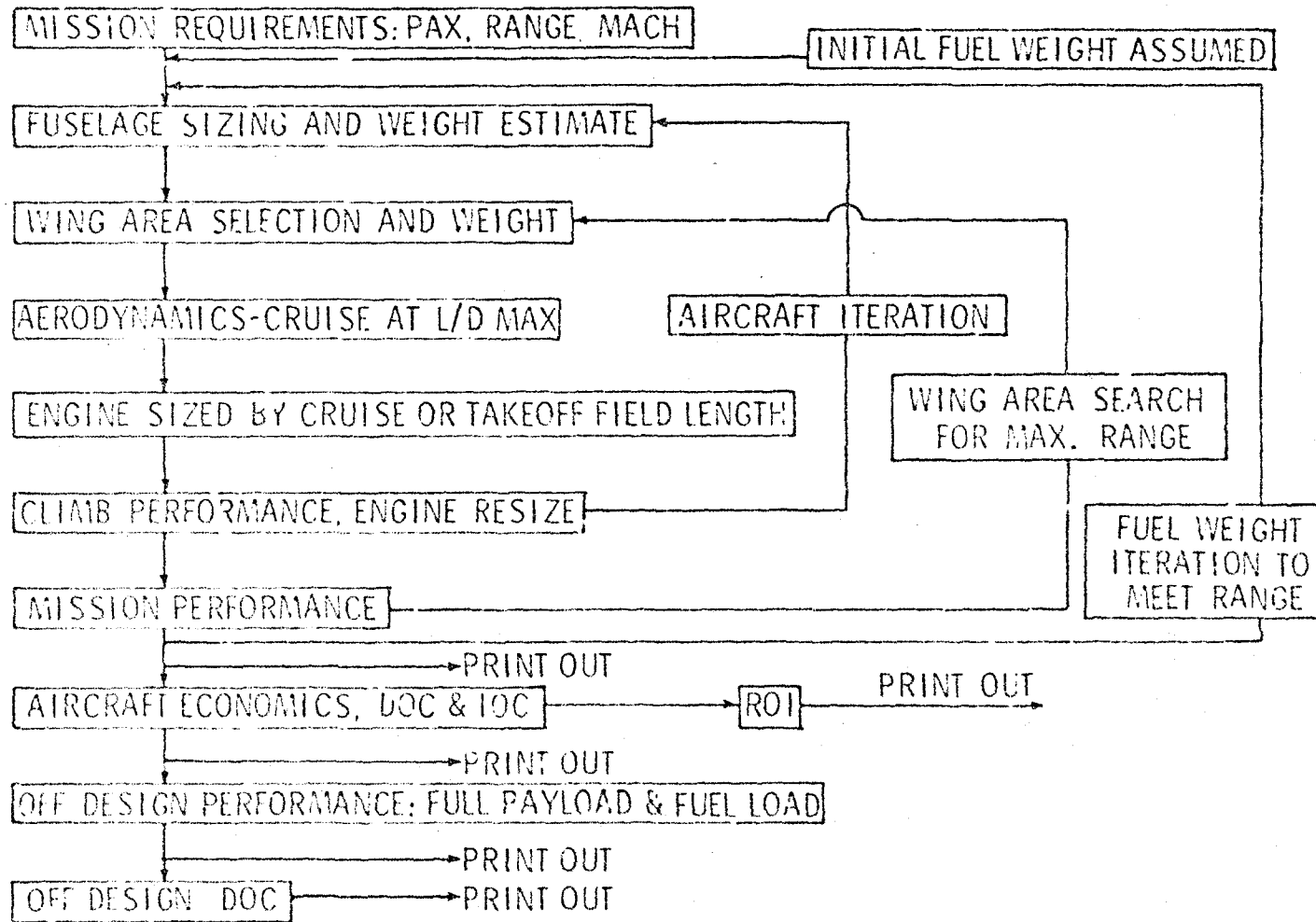


Figure 2. Minimum energy aircraft program logic.

FIRST ORDER AERODYNAMICS

TRIM OR BALANCE NOT CONSIDERED

HISTORICAL PARAMETRIC WEIGHTS - ALUMINUM
- EXTRAPOLATED TO HIGH ASPECT RATIO

WEIGHT REDUCTION FACTORS USED FOR COMPOSITE MATERIALS

EMPENNAGE SIZED BY TAIL VOLUME COEFFICIENTS

HIGH BYPASS RATIO ENGINE MODEL - CONSTANT TECHNOLOGY

Figure 3. Major program assumptions.

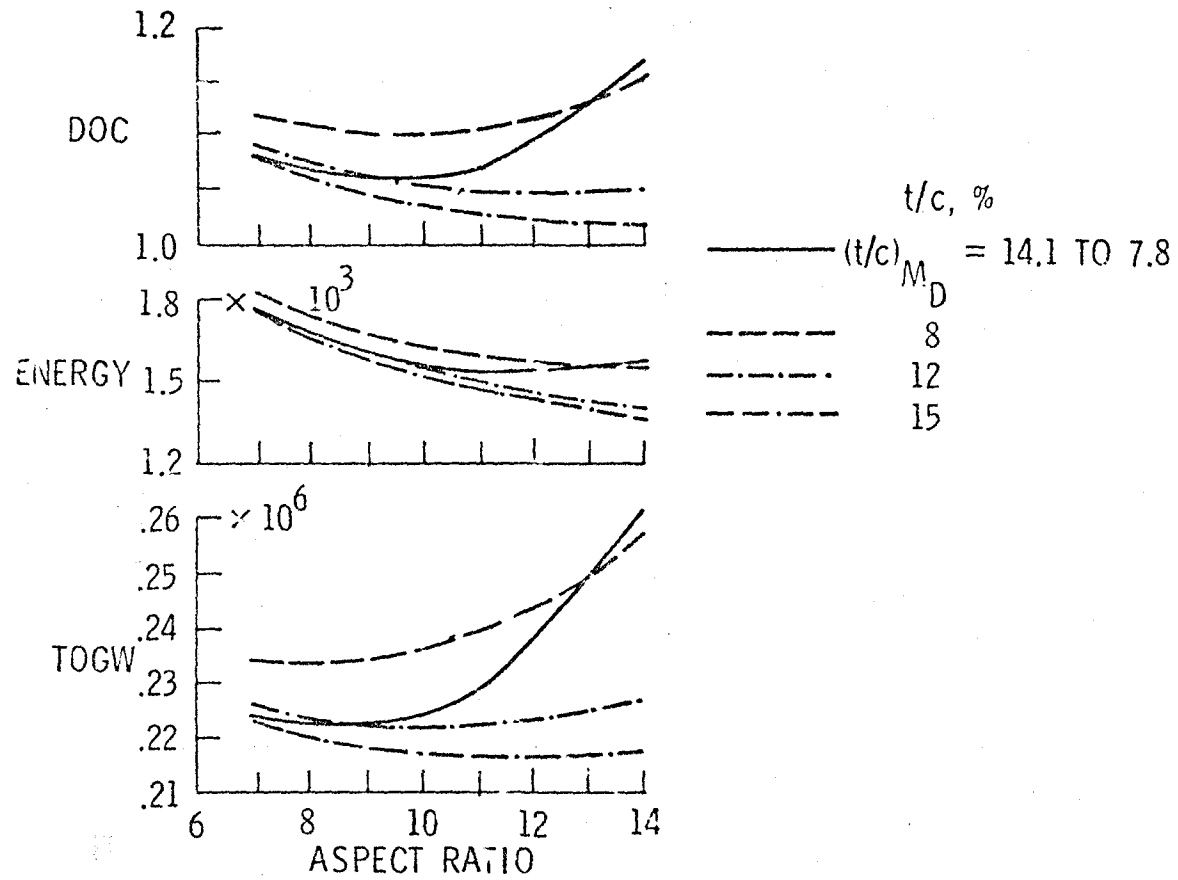


Figure 4. Wing thickness ratio and aspect-ratio effects at $R = 3000$ n.mi. for turbulent flow aircraft.

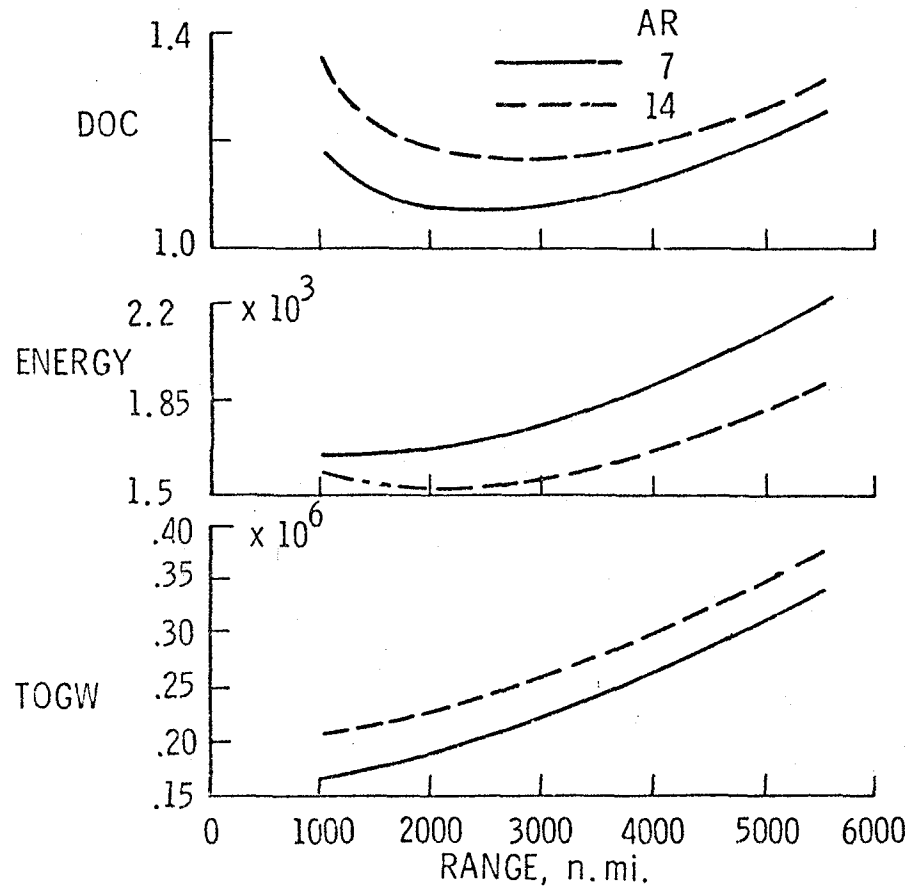


Figure 5. Design range effects for turbulent flow aircraft.

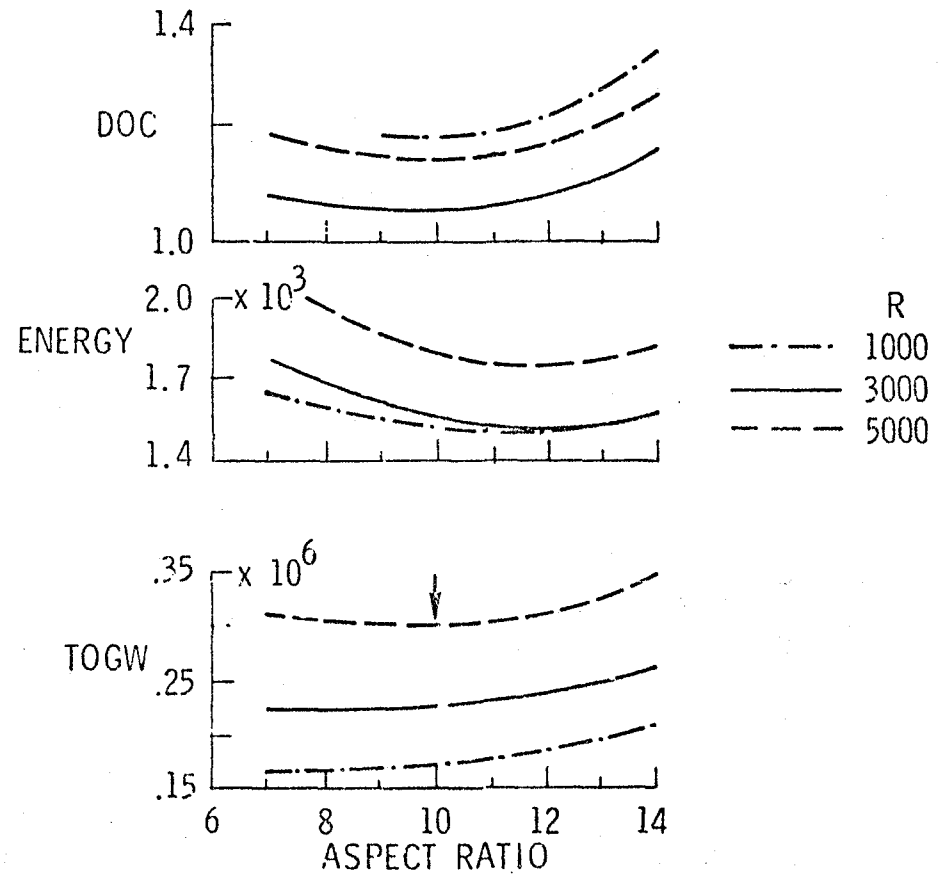


Figure 6. Aspect-ratio effects for turbulent flow aircraft.

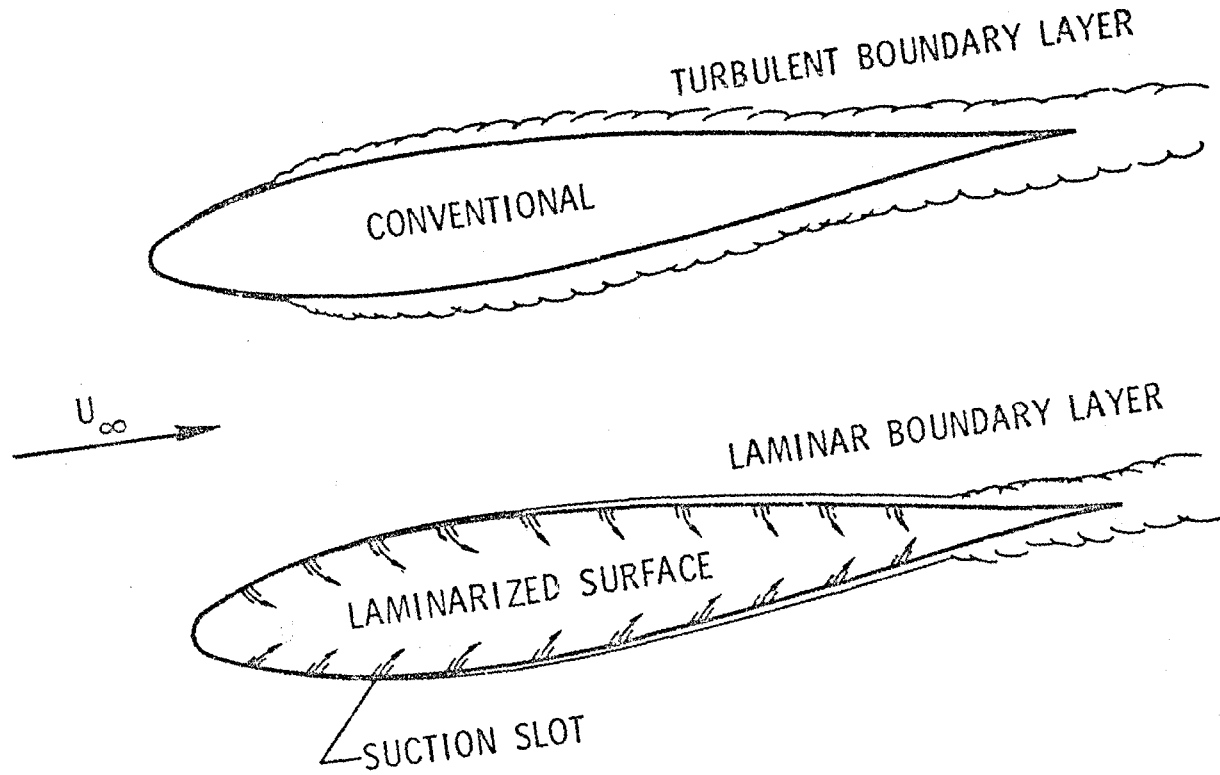


Figure 7. Laminar flow control concept using suction.

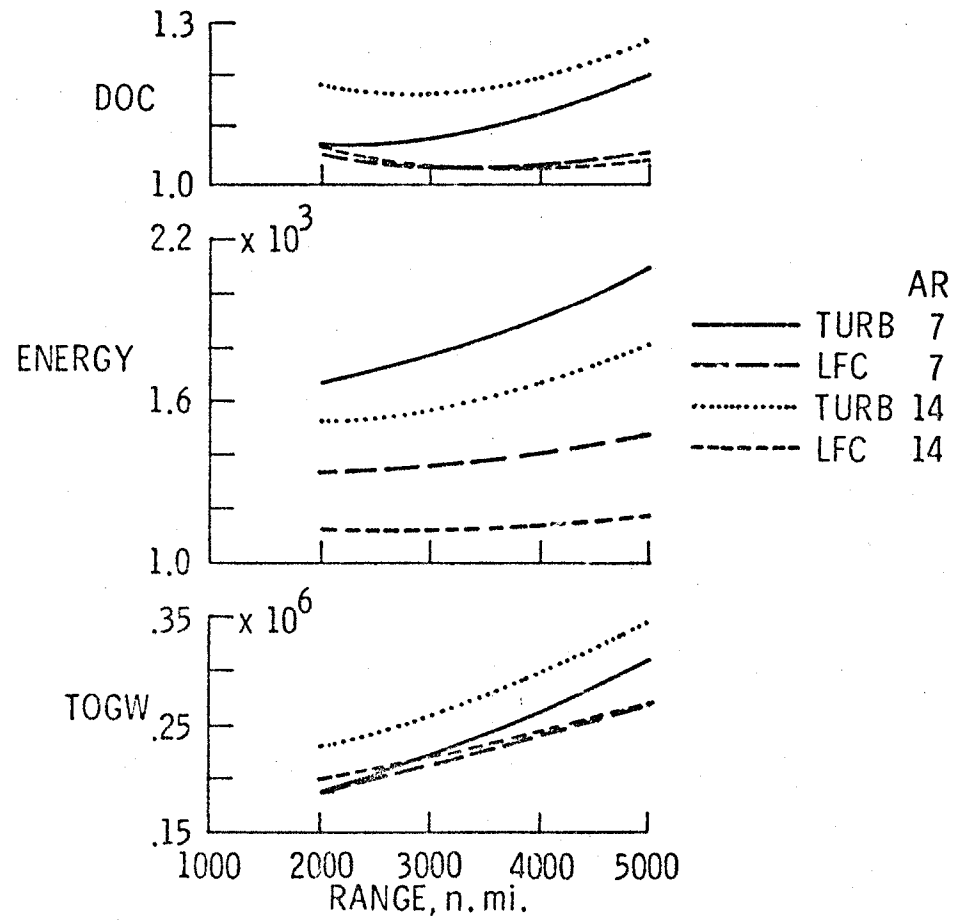


Figure 8. Effect of laminar flow control and range.

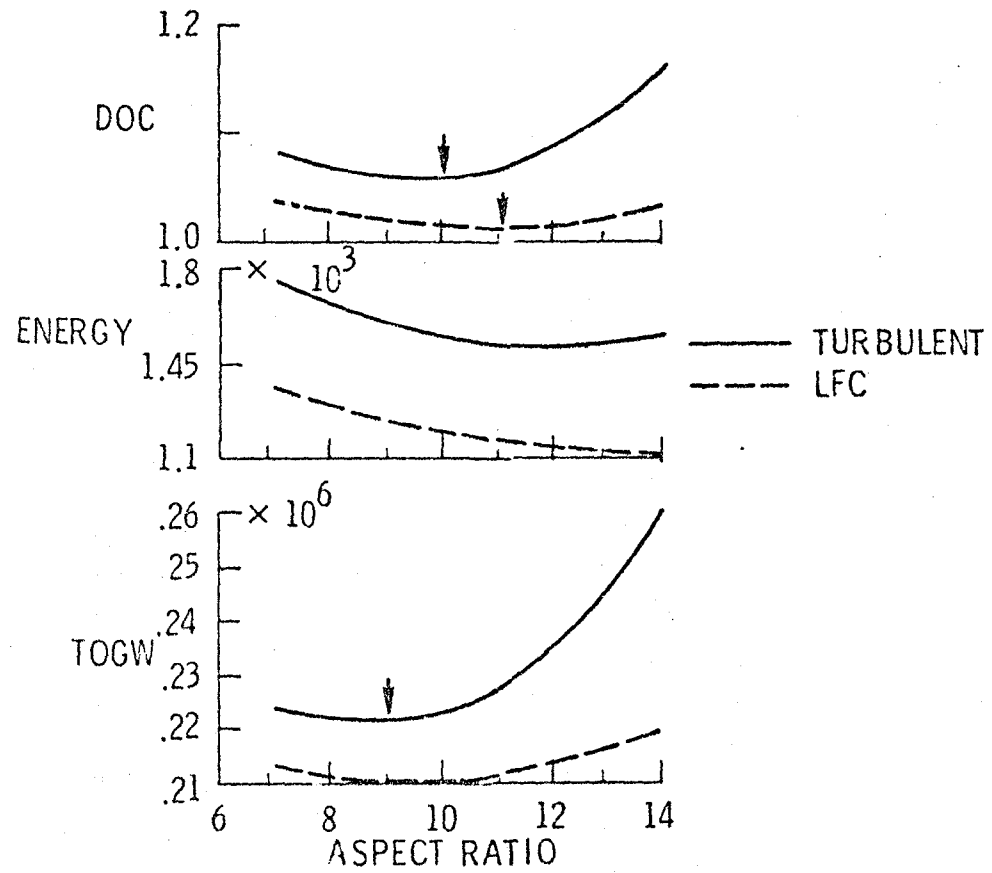


Figure 9. Effect of laminar flow control and aspect ratio at $R = 3000$ n.mi.

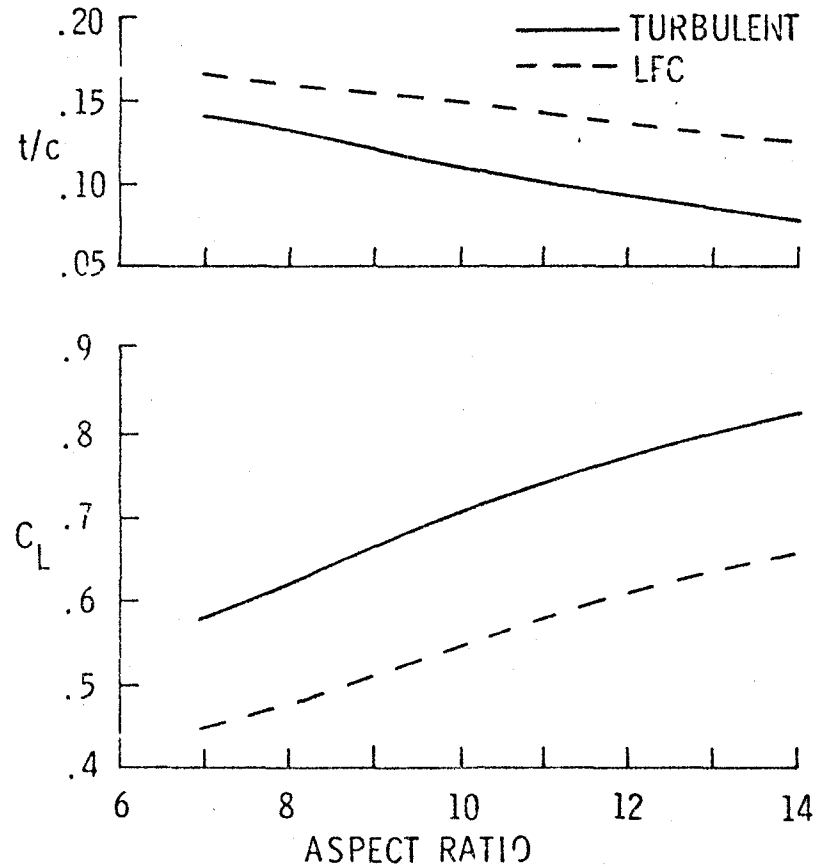


Figure 10. Wing thickness ratio and cruise lift coefficient for LFC aircraft at R = 3000 n.mi.

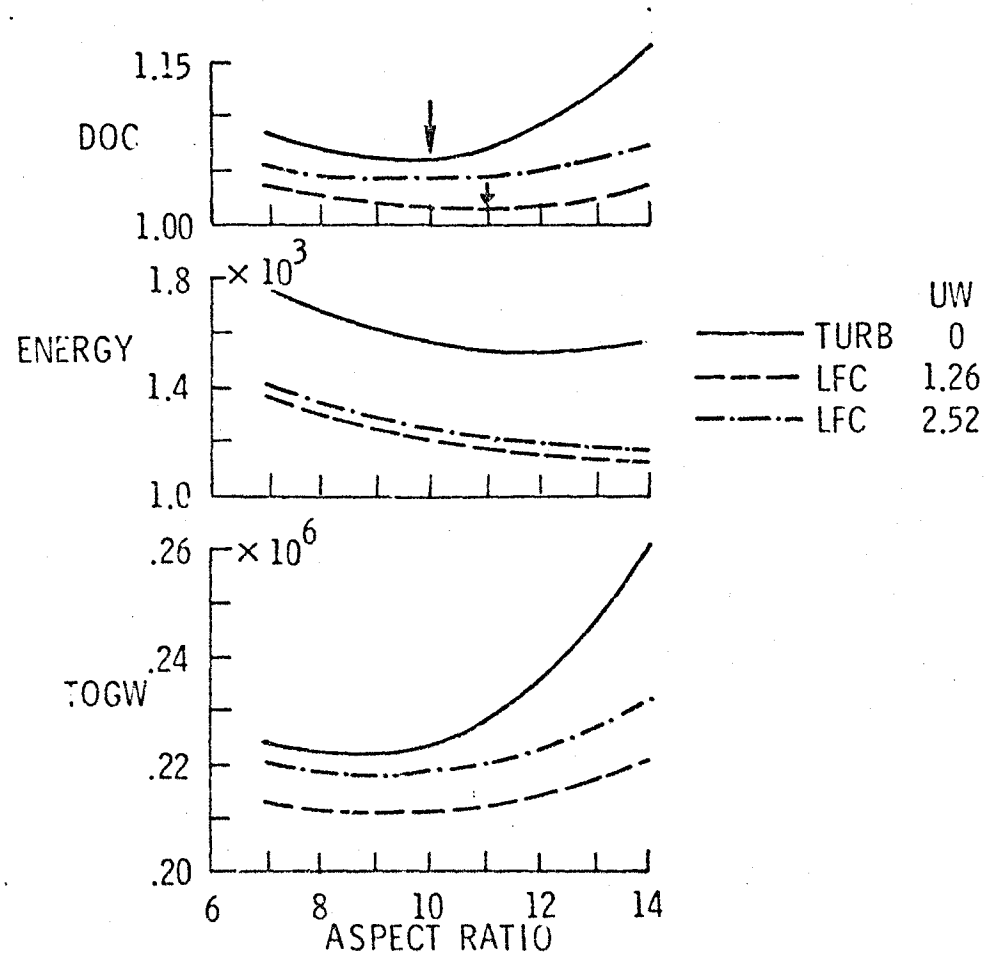


Figure 11. Effect of laminar flow control system unit weight on aluminum aircraft at $R = 3000$ n.mi.

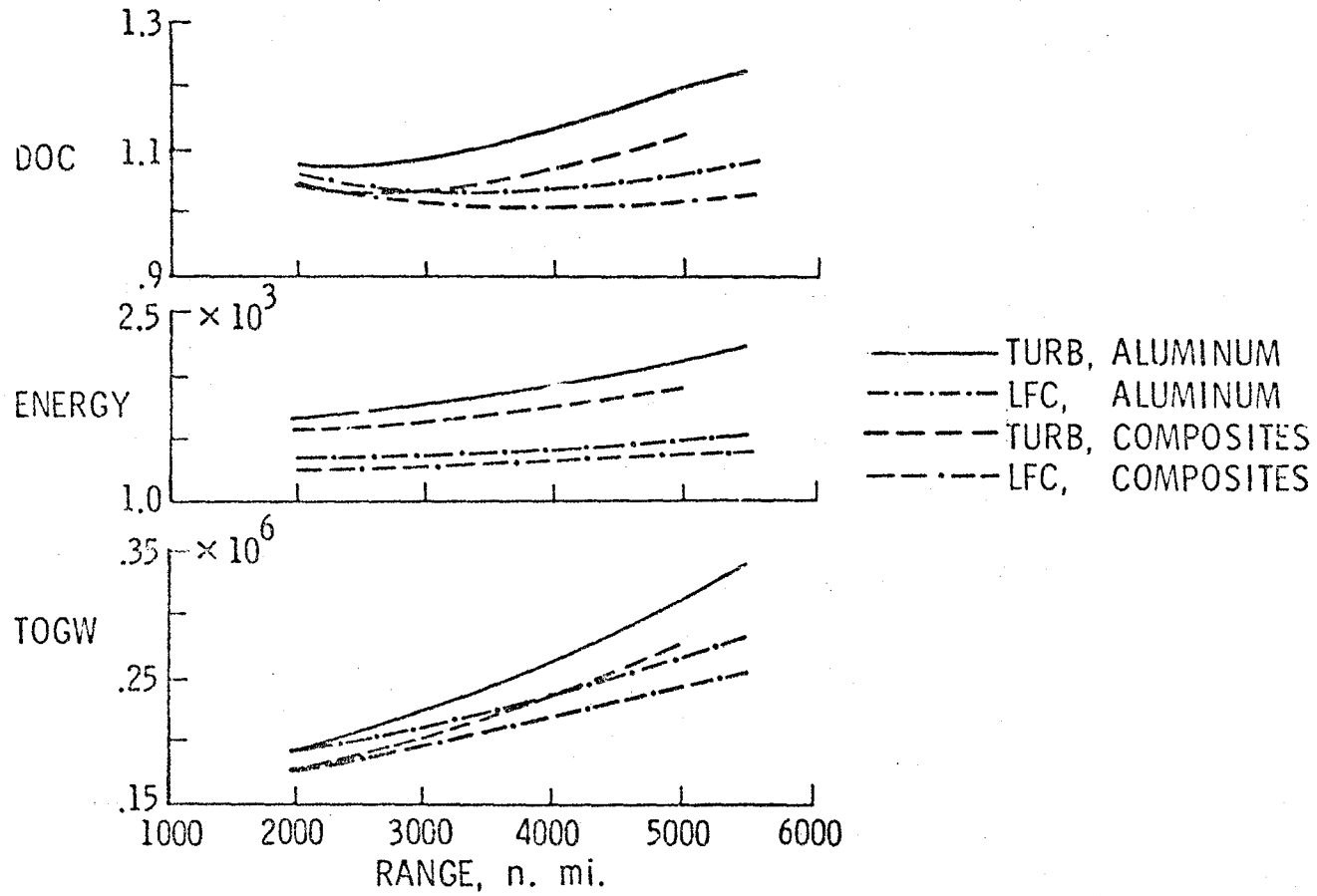


Figure 12. Laminar flow control and composite material effects on aircraft with AR = 7 for various design ranges.

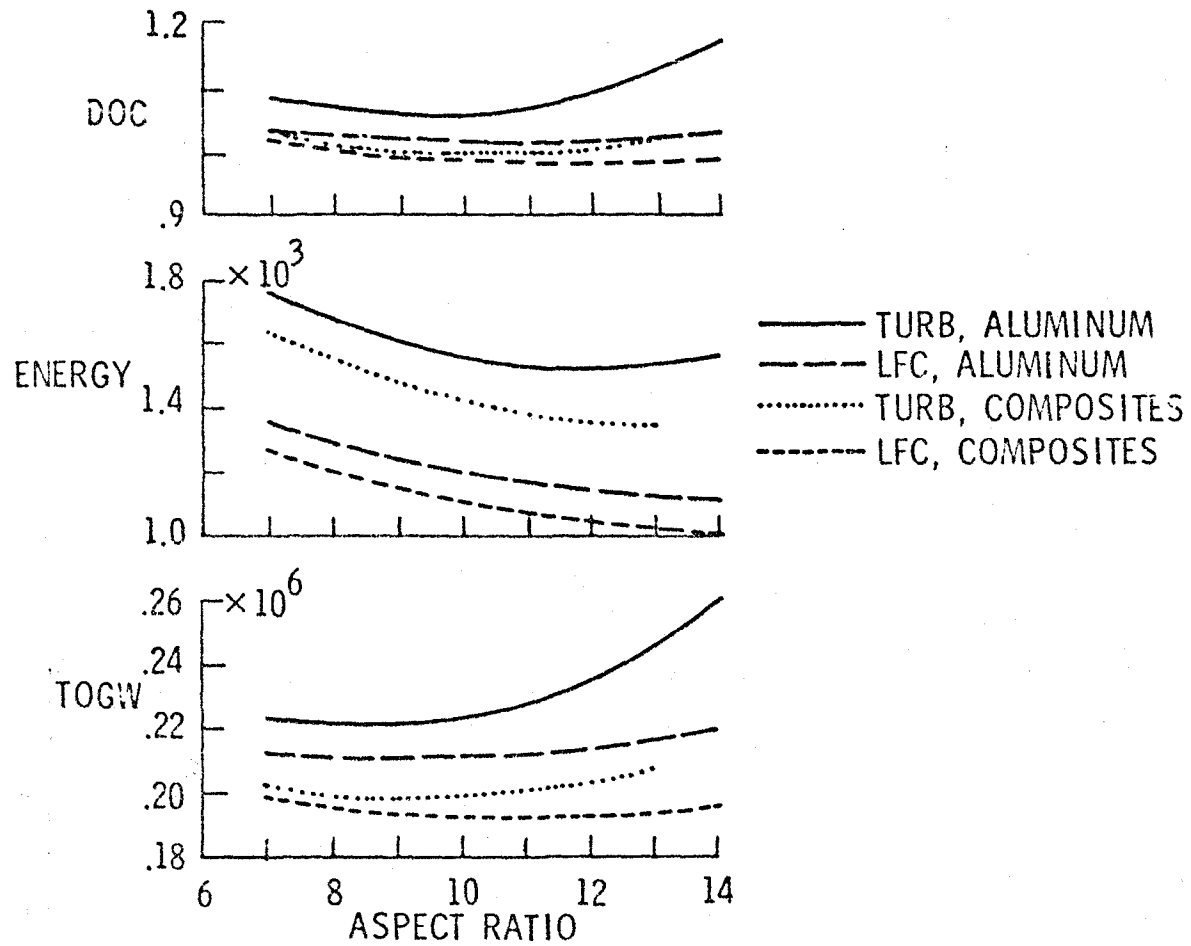


Figure 13. Effects of laminar flow control and composite material on aircraft at $R = 3000$ n.mi. for various aspect ratios.

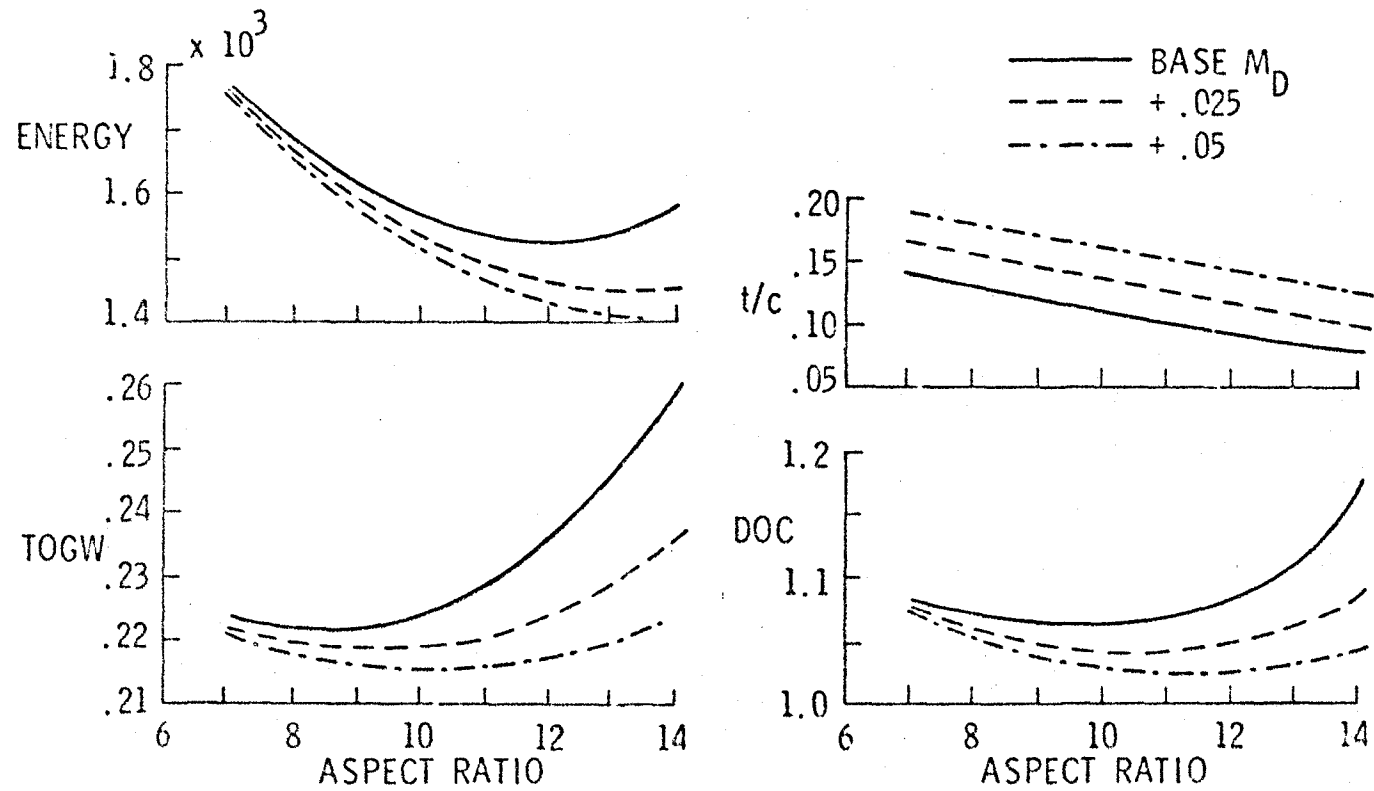


Figure 14. Effect of advanced airfoil technology at $R = 3000$ n.mi. in turbulent flow.

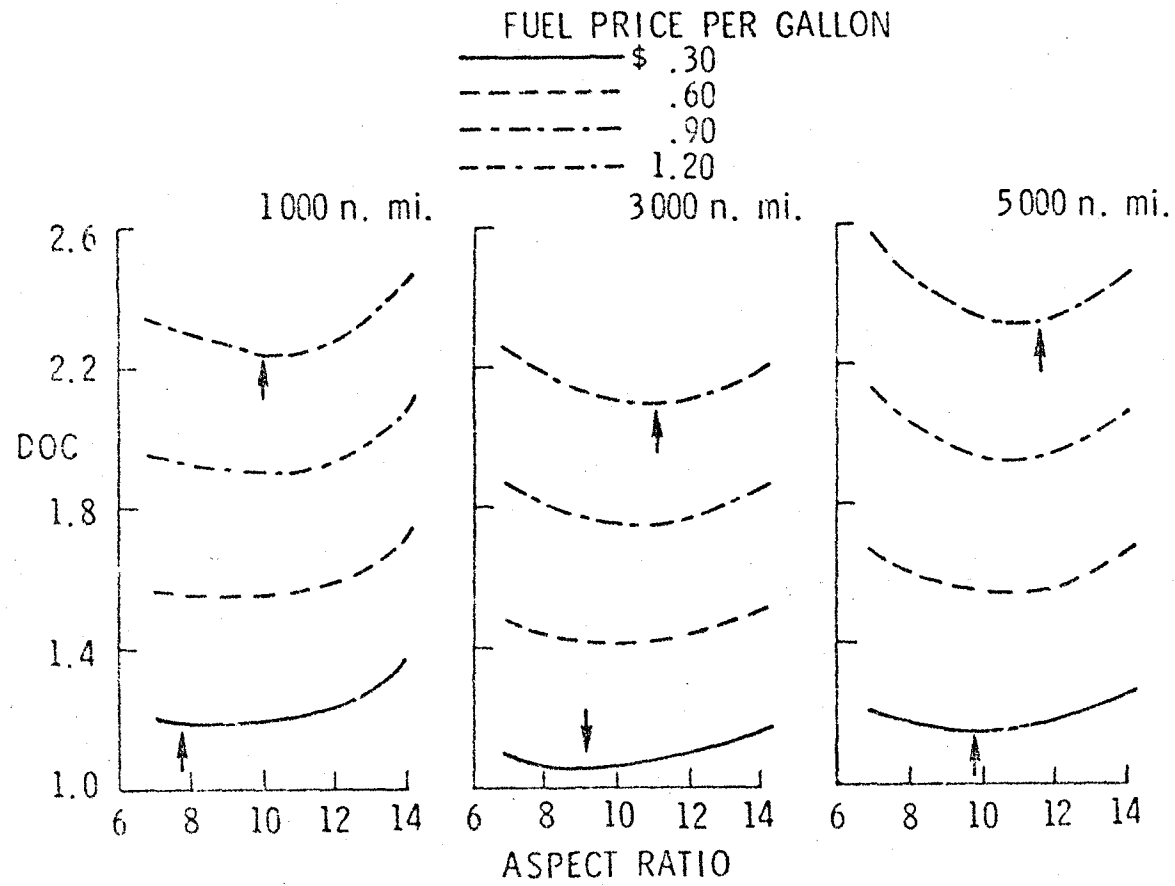


Figure 15. Effect of aspect ratio and fuel price versus minimum DOC in turbulent flow.

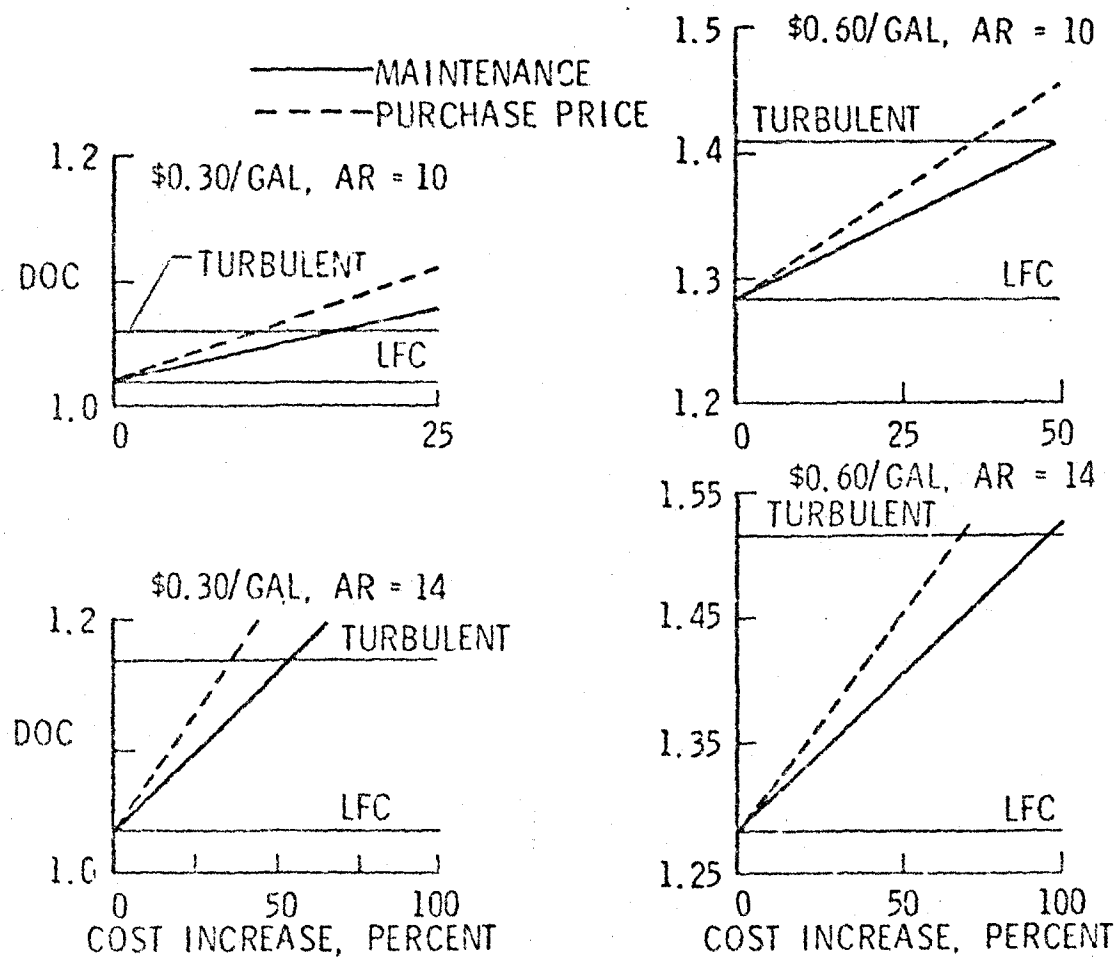


Figure 16. Effect of purchase price and maintenance cost increases on LFC economics at $R = 3000$ n.mi.