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PROSPECTS FOR REDUCED ENERGY TRANSPORTS - A PRELIMINARY ANALYSIS

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SUMMARY

The recent "energy crisis" and subsequent substantial increase in fuel prices have provided increased incentive to reduce the fuel consumption of civil transport aircraft. At the present time many changes in operational procedures have been introduced to decrease fuel consumption of the existing fleet. 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 preliminary 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 on economic performance. For each design, the wing geometry was optimized to give maximum return on investment at a particular fuel cost. Based on the results of the parametric study, a nominal 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 lower Mach number. It has about 30% less fuel consumption on a seat-mile basis. At current fuel prices (about \$52.84/m^3 (20¢/gal)), the reduced energy configuration has about the same economic performance as existing designs but at higher fuel prices, the economic performance is superior.

INTRODUCTION

The "energy crisis" of 1973-74 highlighted a serious problem that has been developing for many 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, and particularly aircraft transportation, was affected most severely by these restrictions.

Although the severe restrictions on the use of fuel for aircraft transportation were lifted to a great degree following the end of the crisis, it is clear that the limited availability 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 system can be reduced and most of these are under study at the present time. These range from changes in the cruise altitude and Mach number of current aircraft, to the development of new "far term" aircraft designs employing advanced technology and designed for minimum fuel consumption. The study reported herein considered only one of these approaches to decreasing fuel consumption -- the design of a new "near term" aircraft, that is a design employing existing technology.

The primary tool used to generate the data for this study is computer program -- TRANsport SYNthesis. This program is basically a computerized, integrated form of the aircraft preliminary design process. The program consists of a control module and discipline area modules to perform the required geometry, aerodynamics, propulsion, structures, weight, volume, and economics computations. In the present study, a parameter optimization module was used to "optimally shape" the wing planforms of the vehicles. Currently, the flutter and aeroelastic computations are not an integral part of the TRANSYN program; these computations are performed exterior to the program for selected vehicles. TRANSYN has been used extensively in the past for similar studies.(1,2)

STUDY GROUND RULES AND CONSTRAINTS

The study ground rules are presented in Figure 1. The aircraft selected for study has a passenger capacity of 200 and a range of 5000 km (2700 n.mi.). Such an aircraft would be a replacement for the older, first-generation jet transports. This size aircraft results in favorable economics and fuel economy in the medium density continental market. In high density markets, it allows increased scheduling flexibility that can be used to increase frequencies and/or load factors compared with larger aircraft. The study assumption of fixed utilization means that faster aircraft will have higher productivity (i.e., greater seat miles per day). The nominal fuel cost, \$85.87/m^3 (32.50¢/gal) in 1974 dollars, is representative of the probable prices in the 1980's when this aircraft would be operating and is based on the costs of obtaining fuel from the gasification of coal or shale oil.

The technology ground rules reflect the assumed 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 more likely that the next generation of transport aircraft will be conventional configurations. The JT-10D engine cycle and weights were adopted as representative of an advanced but current engine design. For the purpose of this study, the engine thrust and weight were scaled as required to match the mission requirements. In an actual design the aircraft capacity and number of engines would be matched to the specific engine. The latest supercritical wing data were used for the aerodynamic analyses. These data indicated that Mach numbers up to 0.8 measured perpendicular to the wing semichord are possible without drag rise. Conventional state-of-the-art aluminum structure was assumed. To examine the effect of applying an advanced technology, a design employing a graphite/epoxy wing was also assessed.

One of the most important parameters influencing transport economics and fuel consumption is cruise Mach number. Therefore, one of the principle aims of the current study was to examine aircraft designed for a range of cruise Mach numbers from 0.70 to 0.90. The constraints imposed when sizing these aircraft are shown on Figure 2. Restricting the Mach number perpendicular to the semi-chord at 0.80 or less fixes the sweep for cruise speeds greater than 0.80 Mach number; aircraft with cruise speeds less than 0.80 Mach number would have straight wings. The wing thickness-to-chord ratio was constrained at the maximum value consistent with good aerodynamic characteristics. For the lower speed, straight wing aircraft, it was necessary to impose a lower limit on cruise altitude of 9144 m (30,000 ft) and an upper limit on section lift coefficient of 0.60. The altitude limit is necessary to avoid delays due to weather and the lift coefficient limit avoids drag rise and assures adequate margins for maneuvering. The higher speed, swept wing aircraft are subject to a fuel volume constraint due to the study assumption that all fuel is required to be carried in the wing.

To properly reflect the importance of fuel cost on aircraft design, maximization of the rate of return on investment (ROI) was selected as the design goal. This implicitly assumes that fuel will be available although possibly at a high price. Since the engine cycle is fixed, the optimization involves only the wing aspect ratio (AR) and the wing loading (W/S). Therefore, the aircraft of this study have been sized by maximizing the ROI with respect to AR and W/S subject to the constraints previously described. This maximization was done at different specified cruise speeds and fuel prices.

RESULTS

Effect of Cruise Mach Number

Higher fuel costs may well alter the selection of cruise Mach number (M). To determine the effects of M on performance and economics and to aid in selecting the best value, six aircraft with values of M from 0.70 to 0.90 were sized for a fuel cost of $\$85.87/m^3$ (32.50¢/gal) according to the criteria discussed earlier. The resulting values of AR and W/S are shown on Figure 3. As M decreases, the AR increases because the difference between the structural and aerodynamic aspect ratios decreases (the optimum structural aspect ratio 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. The optimum aspect ratio of the straight wing designs is about 14.

The optimum wing loading remains nearly constant at a value of 6224 N/m^2 (130 lb/ft^2), primarily due to the constraints. The range of influence of each of the constraints is also indicated on Figure 3. The wing loading would tend to be higher (smaller wing) if the constraints were relaxed. However, the sensitivity of aircraft performance to wing loading is very small about the optimum value and the relaxation of the constraints would have very little effect.

A preliminary flutter analysis indicates that all configurations represented on Figure 3 are flutter-free although several are probably marginal. There may well 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 will be discussed later.

The optimum configuration with the graphite/epoxy wing, designed for $M = 0.80$, has an AR of 16.5 and a W/S of 5985 N/m^2 (125 lb/ft^2). Thus, advantage has been taken of the lighter weight material to further increase the aerodynamic efficiency.

The effect of M on the aircraft gross take-off weight (W_{GTO}) and mission fuel weight (W_{FUEL}) for the design range of 5000 km (2700 n.mi.) at full payload is shown in Figure 4. As M decreases from 0.90, W_{GTO} and W_{FUEL} decrease due to decreasing wing sweep and 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. This is partly due to use of an engine cycle designed for 0.85 M; if the engine were optimized for each value of M, W_{GTO} and W_{FUEL} would be very nearly constant for all the straight wing designs. The optimum 0.80 M configuration consumes about 25% less fuel than does the optimum 0.90 M configuration. It should be noted that all the designs on Figure 4 have very low values of W_{GTO} compared with existing or recent study designs for the same mission. For example, the 0.80 M design of Reference 2 is about 111,200 N (25,000 lb) heavier in gross take-off weight than the 0.80 M design of the current study. This difference is primarily due to the use of more recent super-critical wing aerodynamic data. The lift-to-drag ratio of the 0.80 M straight wing configuration in this study is 22. Figure 4 shows that the graphite/epoxy wing design has 5% less W_{GTO} and uses 10% less fuel than the corresponding all-aluminum design.

Of course, the cruise Mach number selection cannot be based on weights alone; the increased productivity of the faster designs must also be accounted for. Because it includes productivity, ROI is used as a basis of comparison in Figure 5 where ROI is shown as a function of M for three values of fuel cost. The lowest cost of $42.93/m^3$ (16.25¢/gal) is slightly higher than pre-energy crises fuel costs, the middle cost of $85.87/m^3$ (32.5¢/gal) is the nominal value discussed previously, and the high cost of $171.73/m^3$ (65¢/gal) is representative of values which may occur in extreme cases. To put these fuel costs in perspective, the average fuel cost for domestic aircraft operations was $58.12/m^3$ (22¢/gal) as of May 1974. To obtain the curves shown in Figure 5 the configurations were optimized at each value of M for the nominal fuel cost, and the ROI was computed for these configurations at the three fuel costs.

At the lowest fuel cost, the swept wing configurations (0.80 M to 0.90 M) all have about the same ROI which is superior to that of the straight wings. At "pre-energy crisis" values of $26.42 - 31.70/m^3$ (10 - 12¢/gal), the 0.90 M design would have the best ROI. 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 approaching 0.90. As fuel cost increases, the ROI of the swept wing designs decreases more rapidly than does that of the straight wing designs because of their relatively high fuel fractions. The slower straight wing designs below 0.8 M suffer from lower productivity and under the ground rules of this study there seems to be no reason to consider values of M below 0.80. The 0.80 M configuration clearly becomes superior at higher fuel costs. The figure also shows that the graphite/epoxy wing gives an incremental improvement in ROI of about 1/2%.

Figure 6 is a cross-plot of the data from Figure 5 showing ROI as a function of fuel cost for the 0.80 M and 0.90 M aluminum configurations and the 0.80 M with graphite/epoxy wing configuration. The cross-over point at which the straight wing 0.80 M design becomes superior to the 0.90 M design occurs at a fuel cost of about \$42.27/m^3 (16¢/gal). The sensitivity (slope) of the 0.90 M design is greater due to its higher fuel consumption. Figure 7 presents direct operating cost (DOC) data for the 0.80 M and 0.90 M aluminum designs. At pre-energy crisis fuel costs, fuel cost accounted for about 10% of the DOC whereas at anticipated future costs it may account for as much as 25% of the DOC. This illustrates again that fuel conservative aircraft will have superior economics at higher fuel costs.

Effect of Fuel Cost

A parametric study was undertaken to investigate the effects of fuel cost on the configuration geometry and the performance. As before, the wing geometry of each configuration was selected to give the maximum ROI. A cruise Mach number of 0.80 was selected as the best value for fuel economy based on the results of the previous section. Figure 8 shows how the optimum wing geometry changes as the fuel cost is varied. The aspect ratio and wing area tend 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 strength-designed and that flutter and other aeroelastic phenomena have not been checked for the wings which have AR greater than 14. In view of the marginal flutter characteristics of the 14 AR design, the wings with greater AR are certain to have some weight penalty due to aeroelastic effects. This would tend to lower the values of optimum aspect ratios for those wings above 14 AR. Since the sensitivity to changes in aspect ratio above 12 AR is small, this would have only a small effect on performance. The optimum wing area increases with higher AR because of the constraint imposed of carrying all the fuel in the wing.

The effect of fuel cost on W_{GTO} is shown on Figure 9. 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. W_{FUEL} decreases with increasing fuel cost, as expected. Since W_{GTO} is remaining constant, empty weight (and therefore also aquisition cost) increases as fuel cost increases.

The sensitivities of DOC and ROI to fuel cost is shown on Figure 10. Two cases have been computed: First, the solid line shows the sensitivities if the wing geometry is optimized at each value of fuel cost. Second, the dashed line shows the sensitivities if the wing design is held fixed at the design optimized at the nominal fuel cost of $85.87/m^3 (32.50¢/gal). The figure 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, 14 AR 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.

To place the effect of fuel cost in perspective with the effects of other important economic parameters, Figure 11 compares the effects of fuel cost and load factor on ROI. As shown on this figure, an increase in load factor from 50 to 60% can nullify 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.

Low Fuel Consumption Configuration

Based on the discussions of the previous two sections, the most promising low fuel consumption configuration identified in this study has a cruise Mach number of 0.80 and an aspect ratio 14 straight wing. A three-view of this configuration is shown on Figure 12. Such a design would have significantly better fuel economy than existing transport designs and may also have better economics at higher future fuel costs.

Figure 13 compares the fuel consumption of the low fuel consumption configuration to that of existing transports. The fuel consumptions are computed in terms of seat-kilometer/meter^3 (seat-n.mi./gal) for design ranges and would be higher for shorter stage lengths. The historical base is indicative of existing transport designs operating in a "pre-energy crisis" environment. If these transports are operated in a manner to minimize fuel consumption, estimates indicate that a 14% improvement in fuel consumption may be possible. A portion of this 14% is actually being achieved at the present time. If super-critical airfoils are substituted for current wing designs, an additional 14% improvement in fuel consumption would be obtained. Finally, the replacement of existing designs with the 0.80 M, 14 AR, straight wing design would save another 44%. The cumulative result is a 72% improvement in fuel economy relative to the historical base. Thus, new transport designs offer the possibility of substantial improvements in fuel economy.

In addition to improved fuel economy, the low fuel consumption design has some other attractive features. Aircraft noise reduction is inherent in the new design and the goal of FAR 36-10 is easily met by the basic engine with minimum wall treatment only. Also, due to the high aspect ratio, field length was 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. Finally, a straight wing should also be slightly cheaper to build and maintain than a swept one.

On the other hand, a high aspect ratio straight wing design may introduce some new problems and constraints. Many of these may turn out to be relatively unimportant, but all should be investigated. For example, as mentioned earlier, this design is 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 wing spans. This could lead to gate spacing incompatability with existing swept wing aircraft. A planform comparison of a swept and a straight wing configuration is shown on Figure 14. 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 catastrophic 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 due to other aeroelastic constraints. Further, the high lift curve slope of the straight wing makes the configuration susceptable to gust loads and could result in a high fatigue environment. (Such an airplane may be a good candidate for load alleviation by active controls.) Because of these factors, a practical design might have a slightly lower aspect ratio of about 12 and a nominal amount of semi-chord sweep of about 15°. Such a design would have slightly greater fuel consumption and about the same economic performance when compared with the low fuel consumption design discussed above. In addition to having a wing less prone to flexibility effects and gust loading, such a configuration would also benefit from allowing a staggered engine placement to avoid engine failure coupling.

CONCLUDING REMARKS

New transport aircraft designs appropriate for an environment of high fuel costs have been investigated. The designs are "near term" in that they employ existing technology. The following results were found:

1. The most promising reduced energy configuration has a high aspect ratio (12-14), nearly straight (0° - 15° sweep) supercritical wing and a cruise Mach number of about 0.80. Such a configuration would have good economic performance across a wide range of fuel prices.

2. Supercritical technology alone has the potential of giving about a 12 - 14% improvement in fuel economy.

3. The reduced energy configuration results in approximately a 28% improvement in fuel economy compared with a swept wing design of the same technology level operated in the same manner. When compared with current transports operated in a "pre-energy crisis" manner, the improvement is 72%.

4. For pre-energy crisis fuel costs, there would be a small economic penalty associated with the reduced energy configuration. At higher future fuel costs, there may be a small advantage in operational economics. However, the economic advantage is too small at the present time to induce the commercial transport operators to replace their existing equipment.

REFERENCES

1. Ardema, M. D., and Williams, L. J.: "Automated Synthesis of Transonic Transports," AIAA Paper No. 72-794; Presented at the 4th Aircraft Design, Flight Test, and Operations Meeting, Los Angeles, CA, August 1972.

2. Ardema, M. D.: "Sensitivity of Transport Aircraft Performance and Economics to Advanced Technology and Cruise Mach Number," NASA TM X-62,336, February 1974.

- MISSION AND ECONOMIC
  - 200 PAX, 5000 KILOMETERS (2700 N.MI.)
  - 1974 DOLLARS
  - 250 FLEET SIZE
  - 3290 HOURS/YEAR UTILIZATION
  - 0.5 LOAD FACTOR
  - NOMINALLY 85.87 \$/meters^3 (32.50 ¢/gallon) FUEL COST
- TECHNOLOGY
  - CONVENTIONAL FOUR ENGINE CONFIGURATION
  - JT10D ENGINE CYCLE WITH SCALED THRUST AND WEIGHT
  - FAR 36–10 NOISE LEVEL
  - SUPERCRITICAL AIRFOILS
  - NOMINALLY CONVENTIONAL ALUMINUM STRUCTURE

Figure 1. Study Ground Rules

- **CONSTRAINTS**

  $M_{\perp C/2} \leq 0.80$

  $$(t/c)_{\perp C/2} = \begin{cases} 0.1, & 0.8 \leq M_{CRUISE} \leq 0.9 \\ 0.9 - M_{CRUISE}, & 0.7 \leq M_{CRUISE} < 0.8 \end{cases}$$

  $h_{CRUISE} \geq 9144$ meters (30,000')

  $c_{l_{SECTION}} \leq 0.60$

  $VOL_{WING} \geq VOL_{FUEL}$

- **CRITERIA**

  MAXIMIZE ROI WITH RESPECT TO Æ AND W/S

Figure 2. Sizing

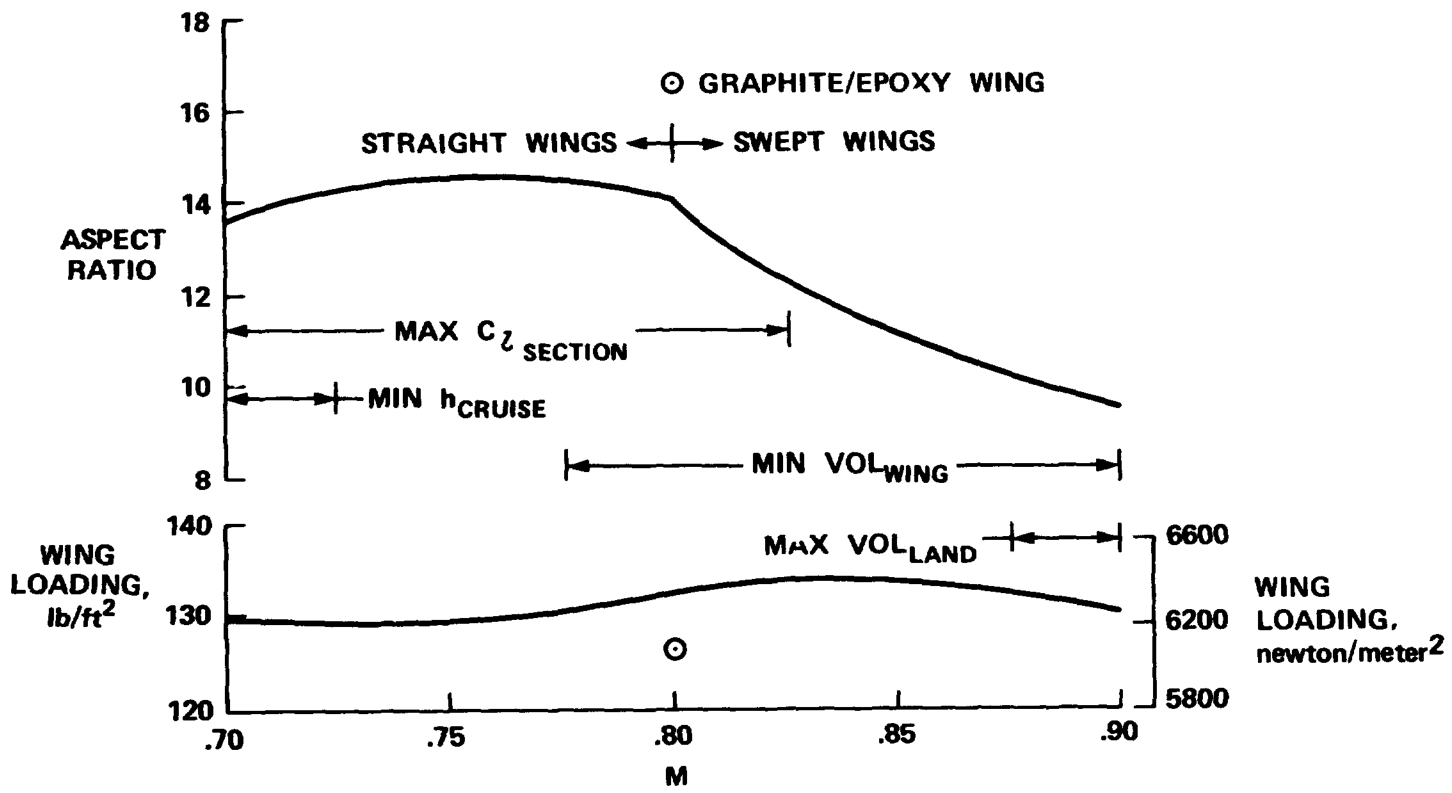

Figure 3. Effect of Cruise Mach Number on Wing Geometry

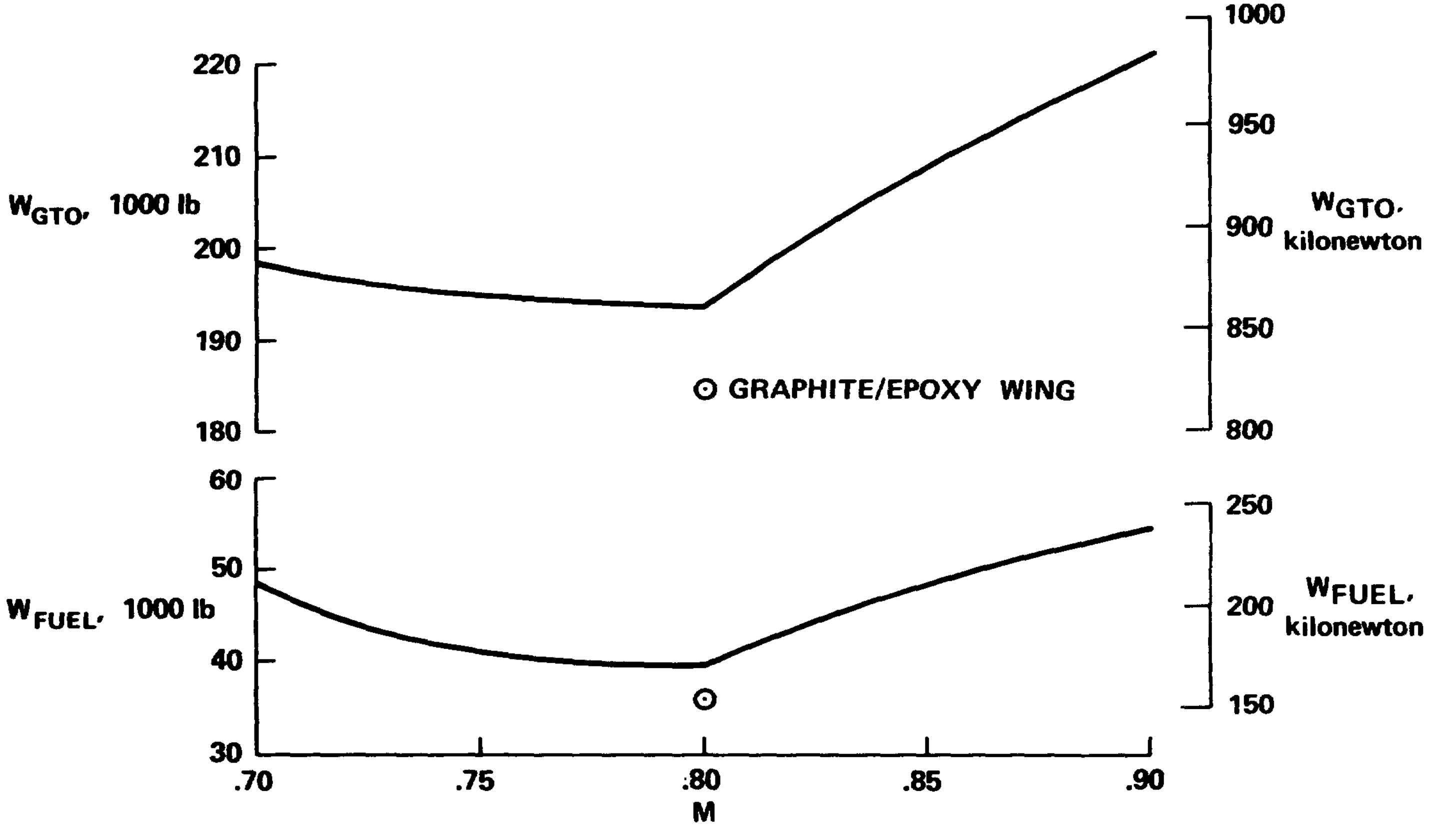

Figure 4. Effect of Cruise Mach Number on Weights

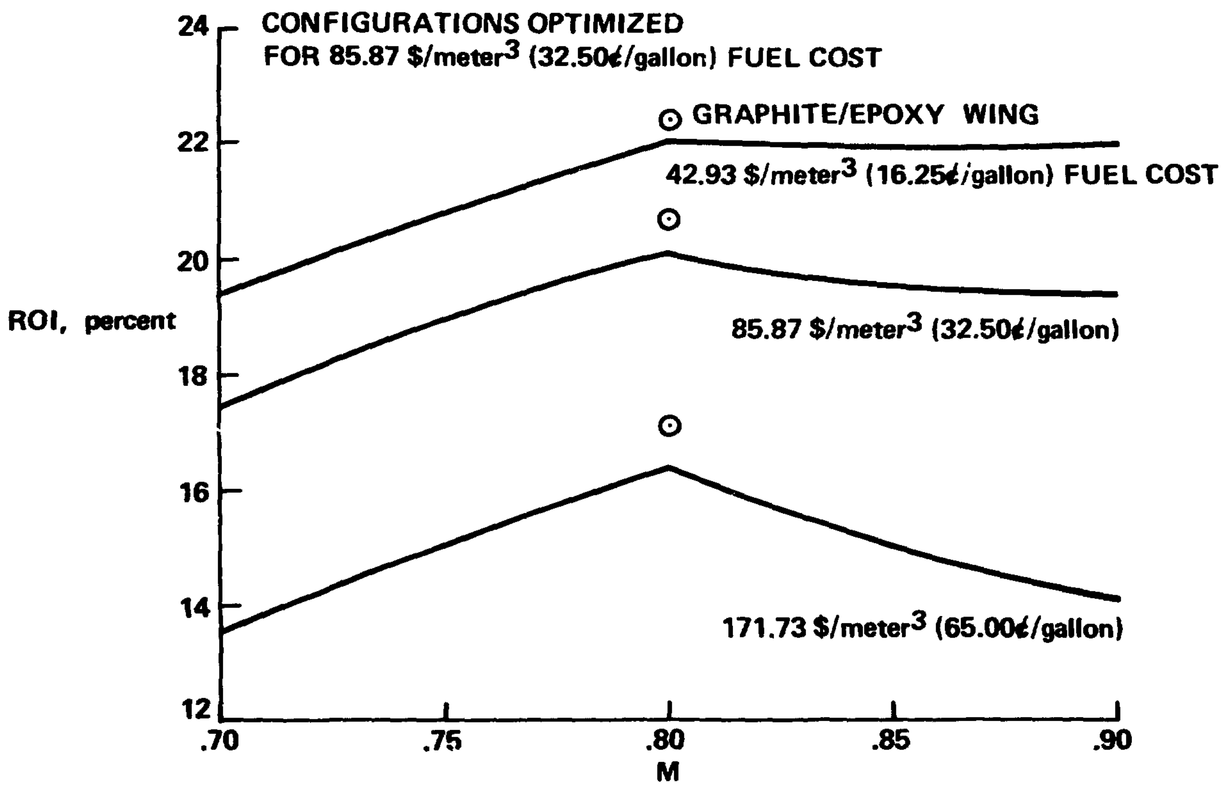

Figure 5. Effect of Cruise Mach Number on Return on Investment

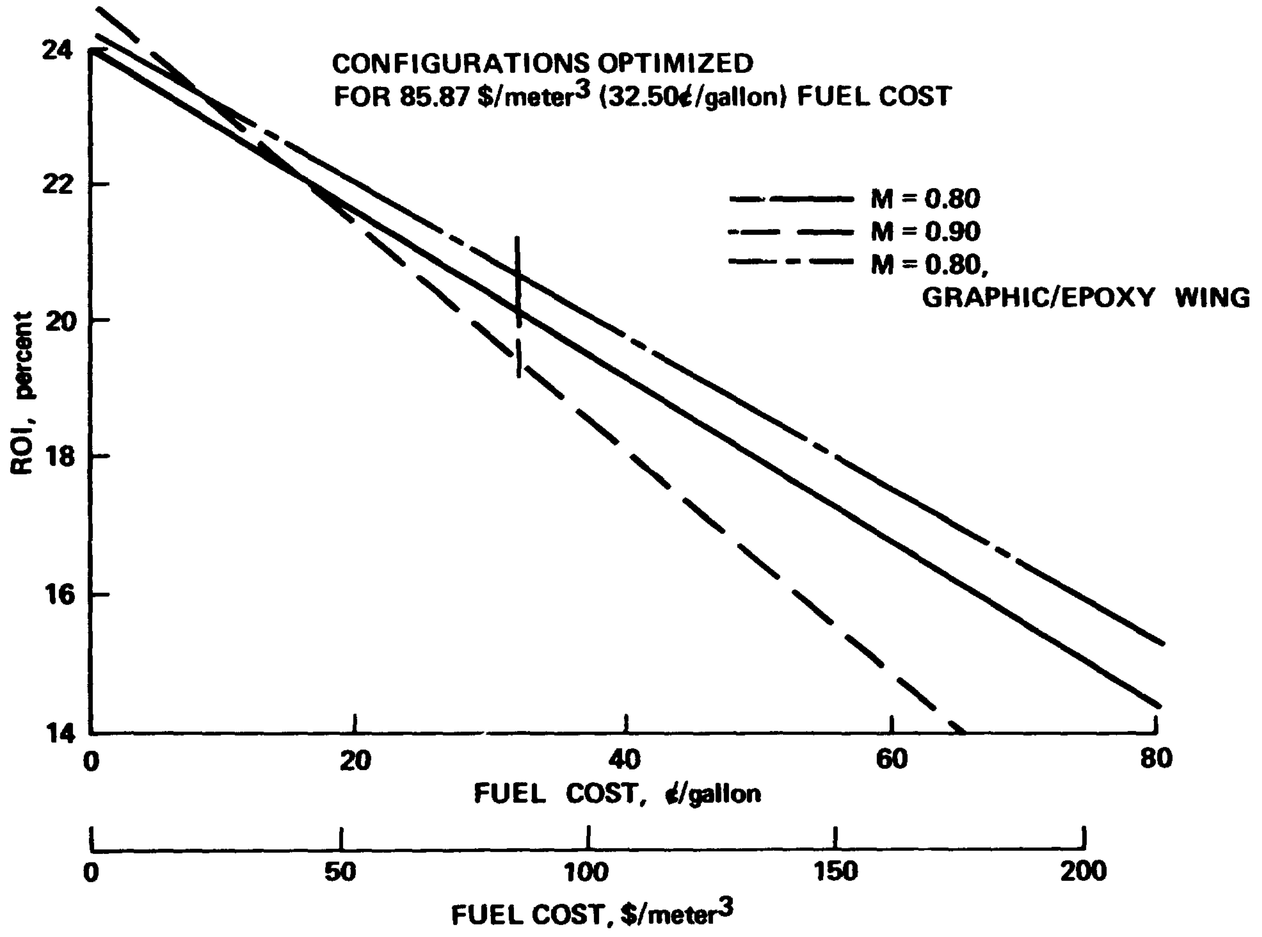

Figure 6. Effect of Fuel Cost on Return on Investment

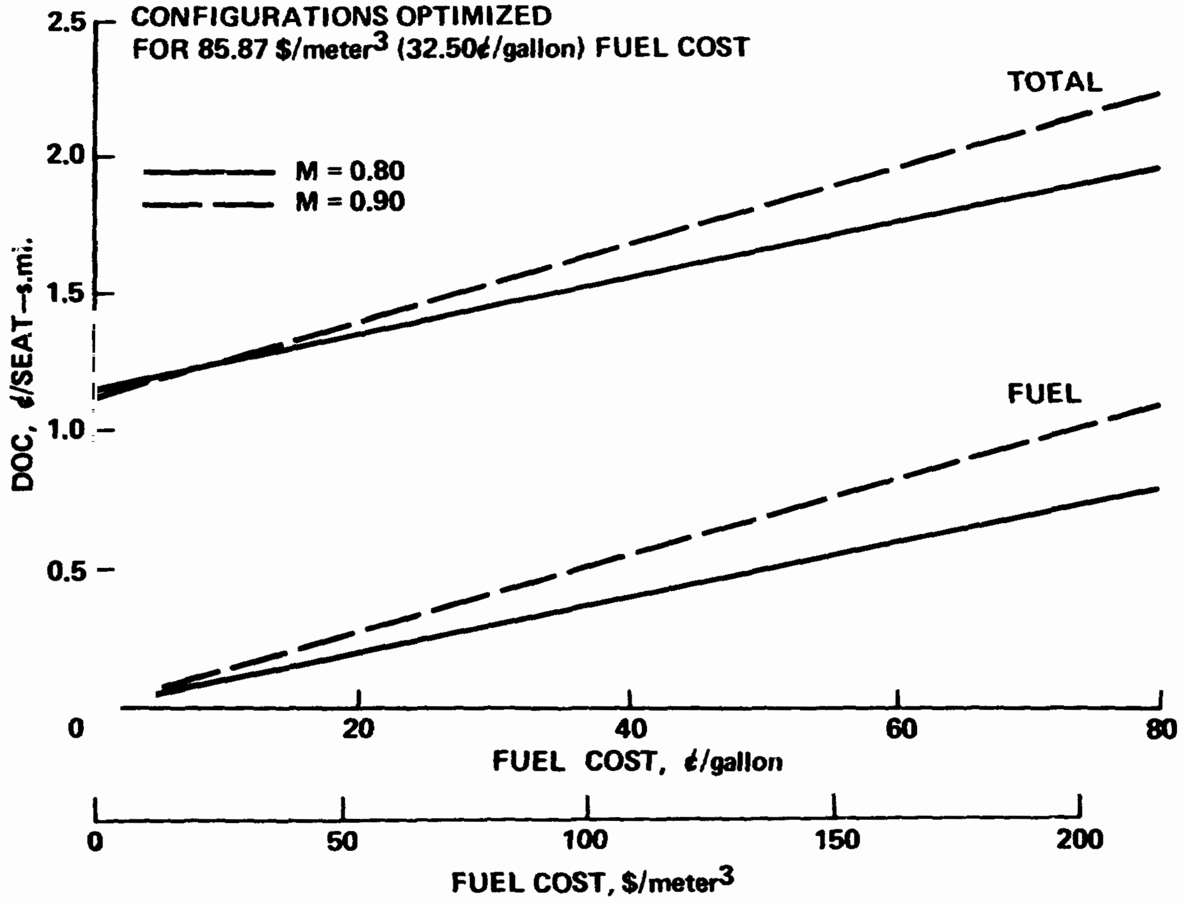

Figure 7. Effect of Fuel Cost on Direct Operating Costs

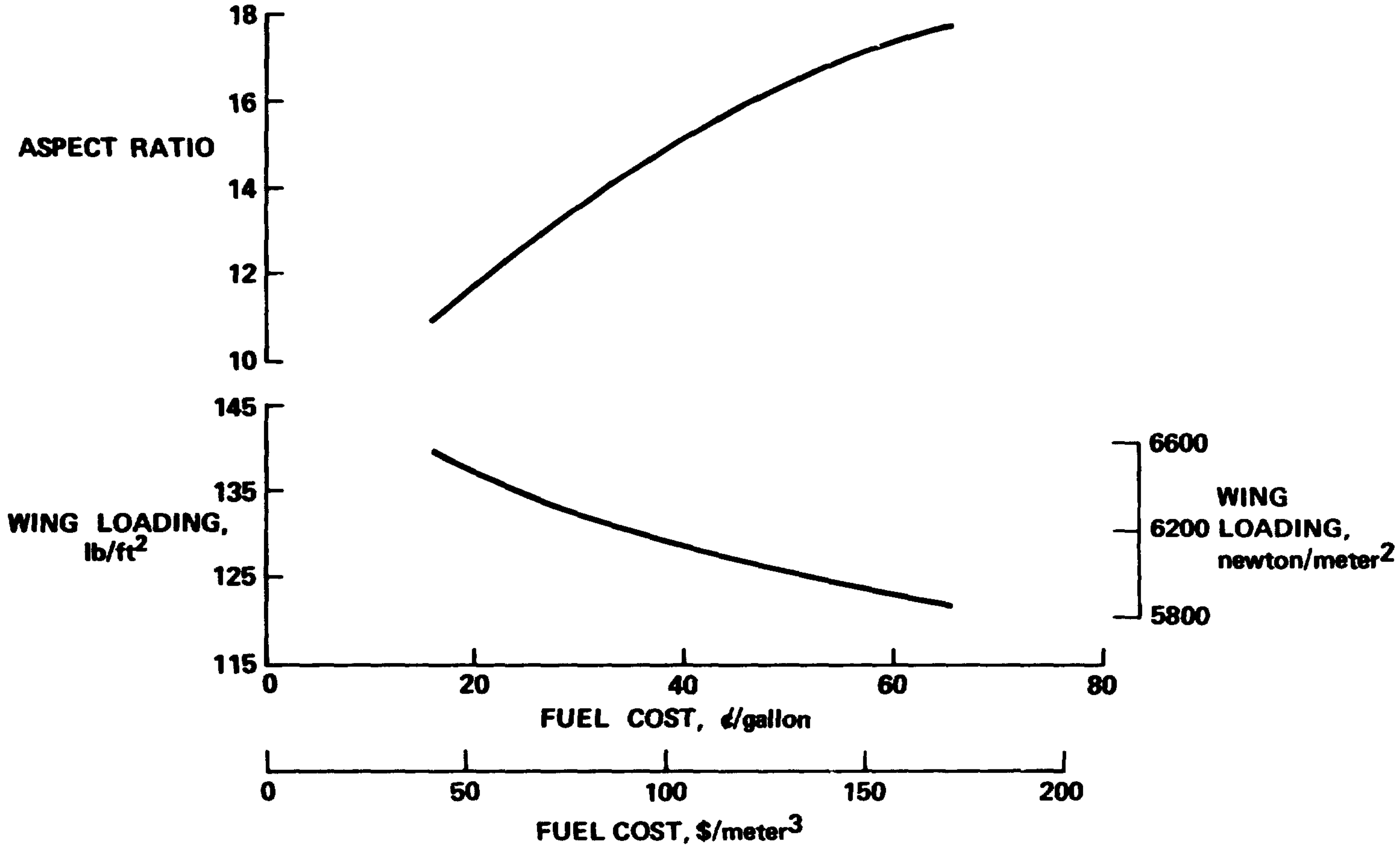

Figure 8. Effect of Fuel Cost on Wing Geometry, M = 0.80

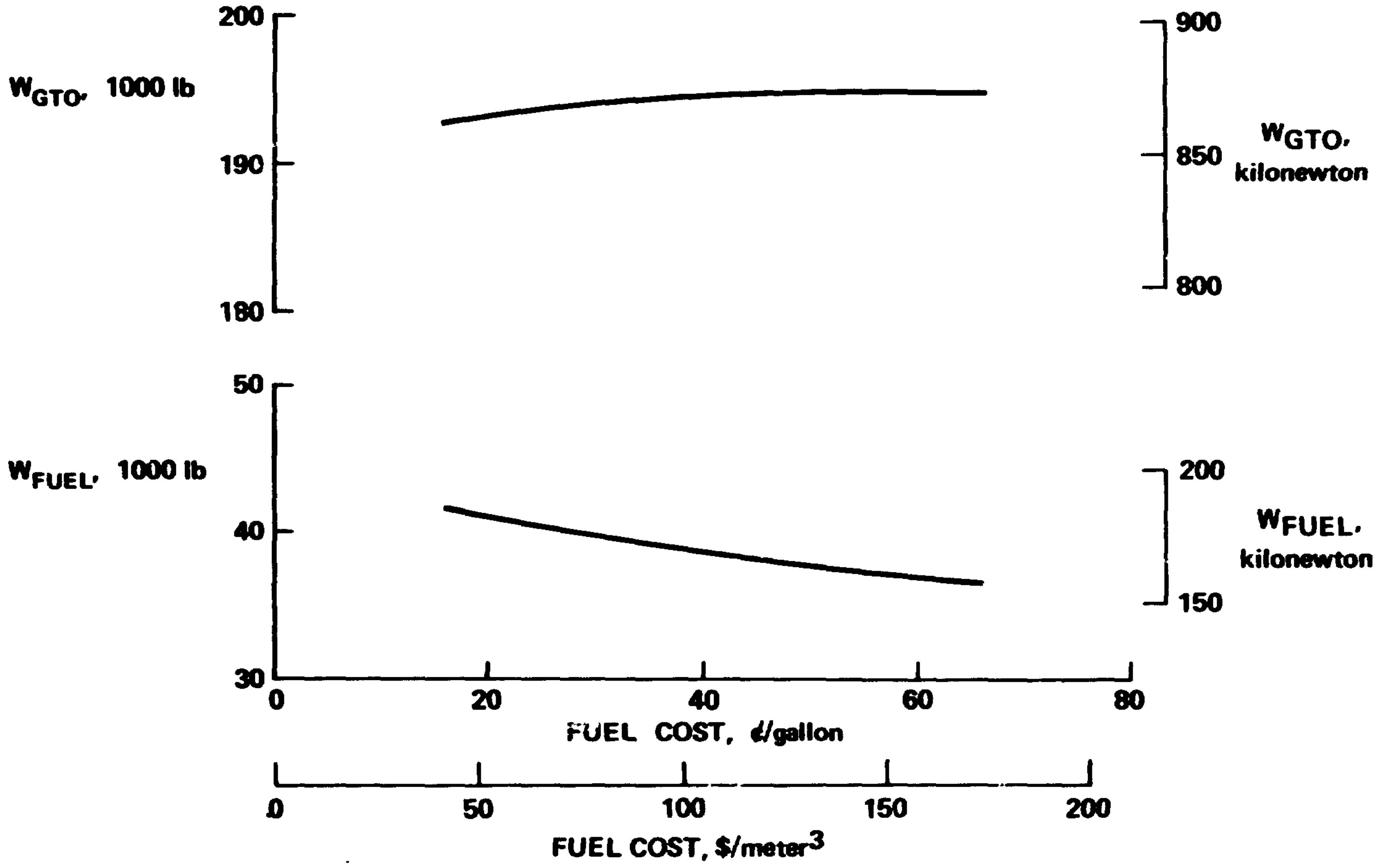

Figure 9. Effect of Fuel Cost on Weights, M = 0.80

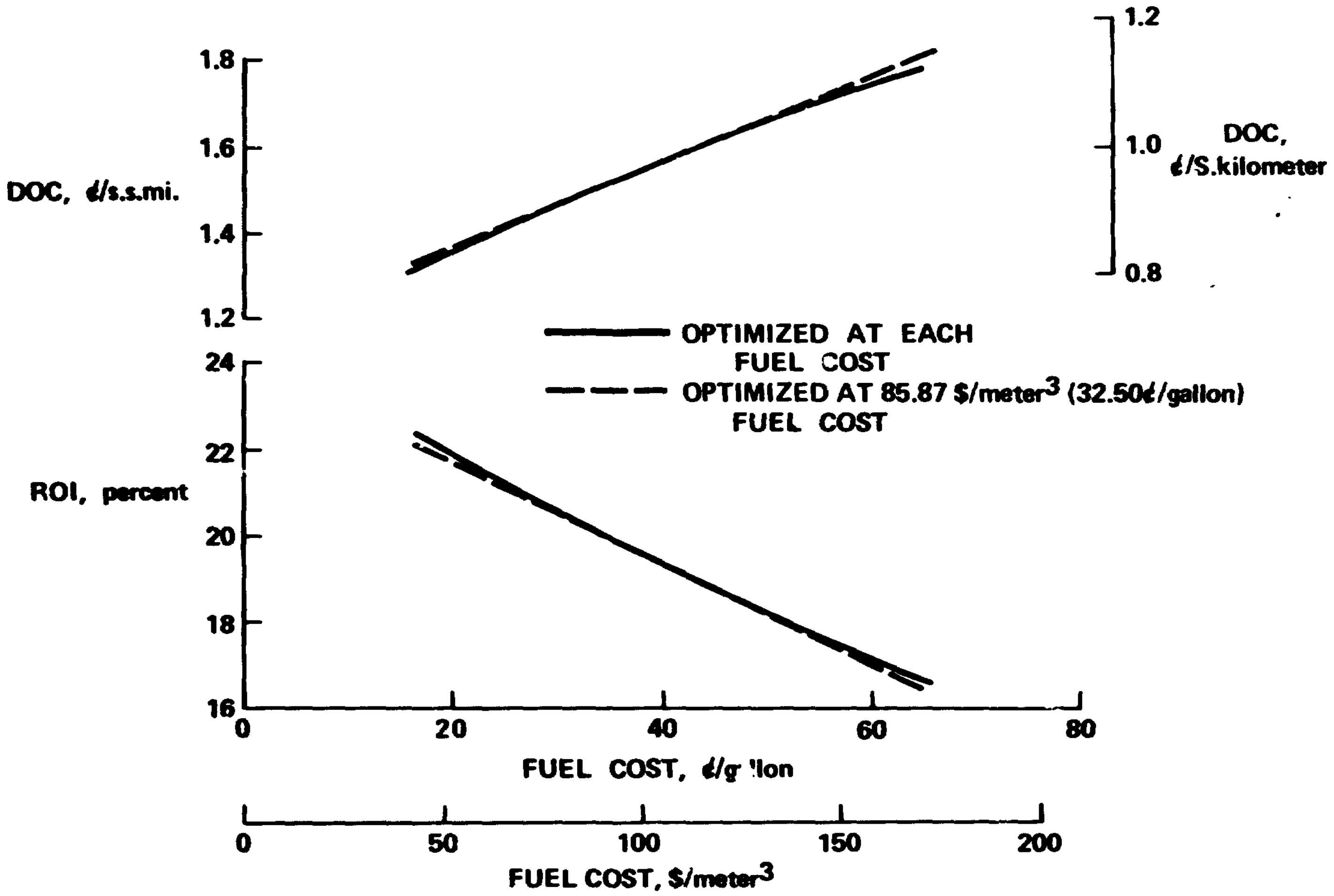

Figure 10. Effect of Fuel Cost on Economics, M = 0.80

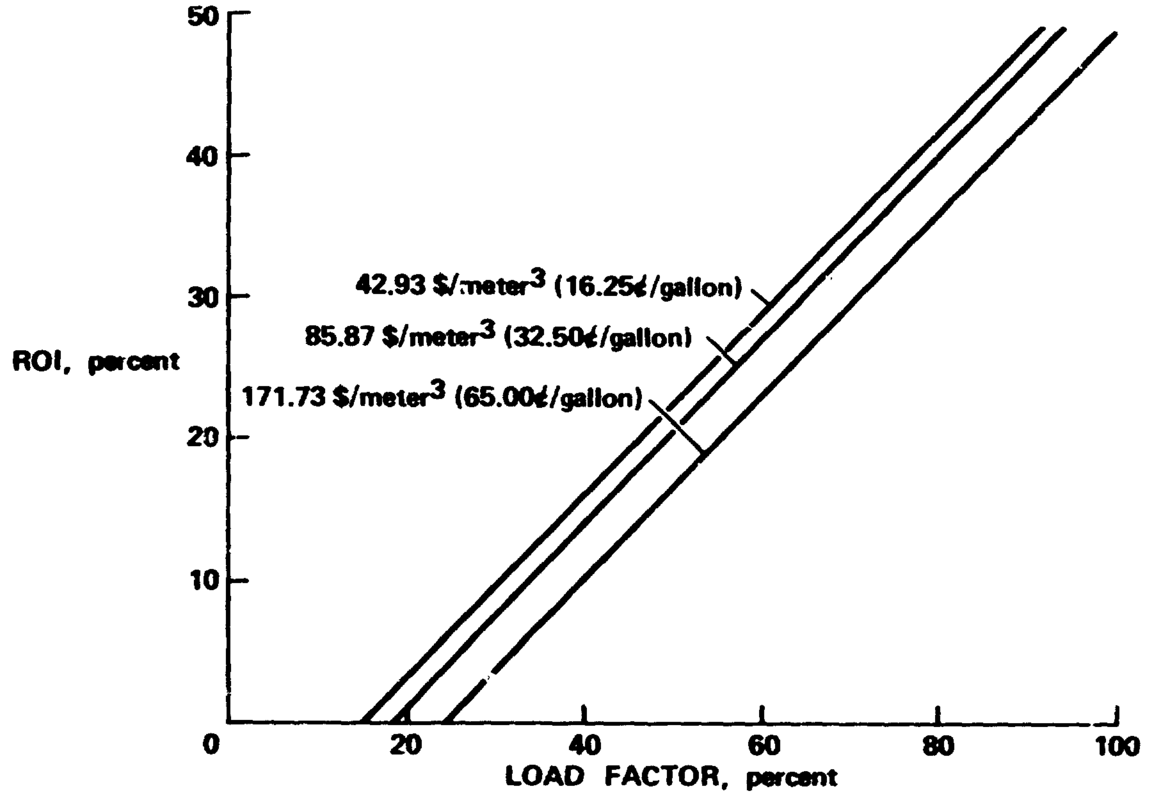

Figure 11. Effect of Fuel Cost and Load Factor on Return on Investment, M = 0.80

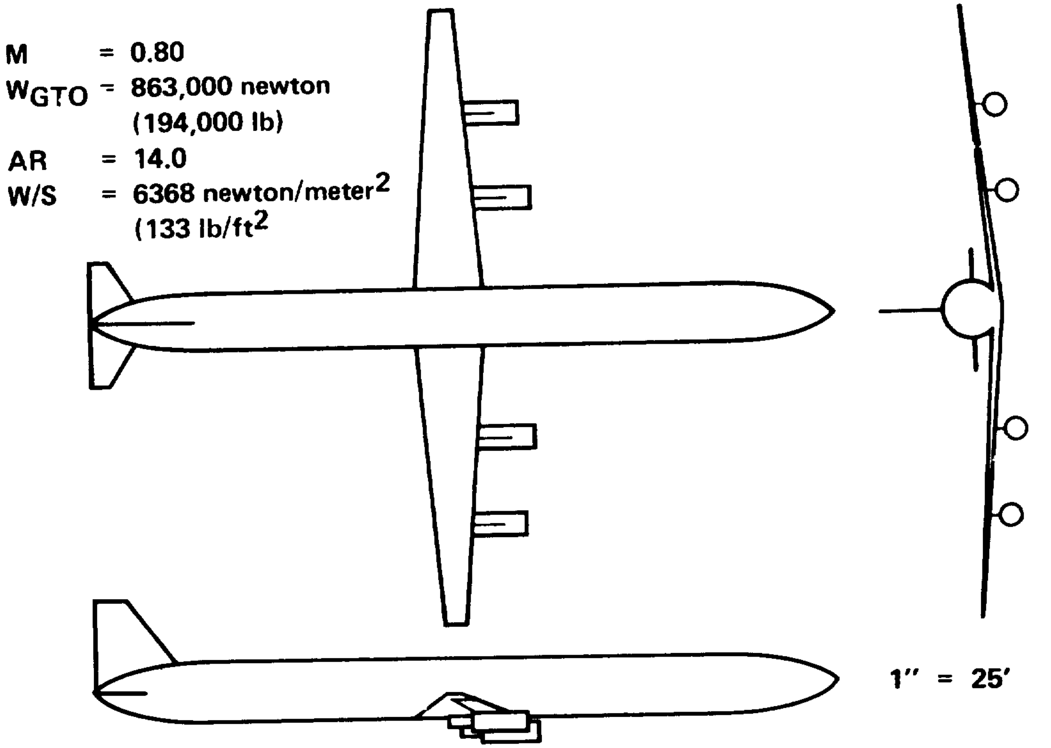

Figure 12. Low Fuel Consumption Transport Configuration

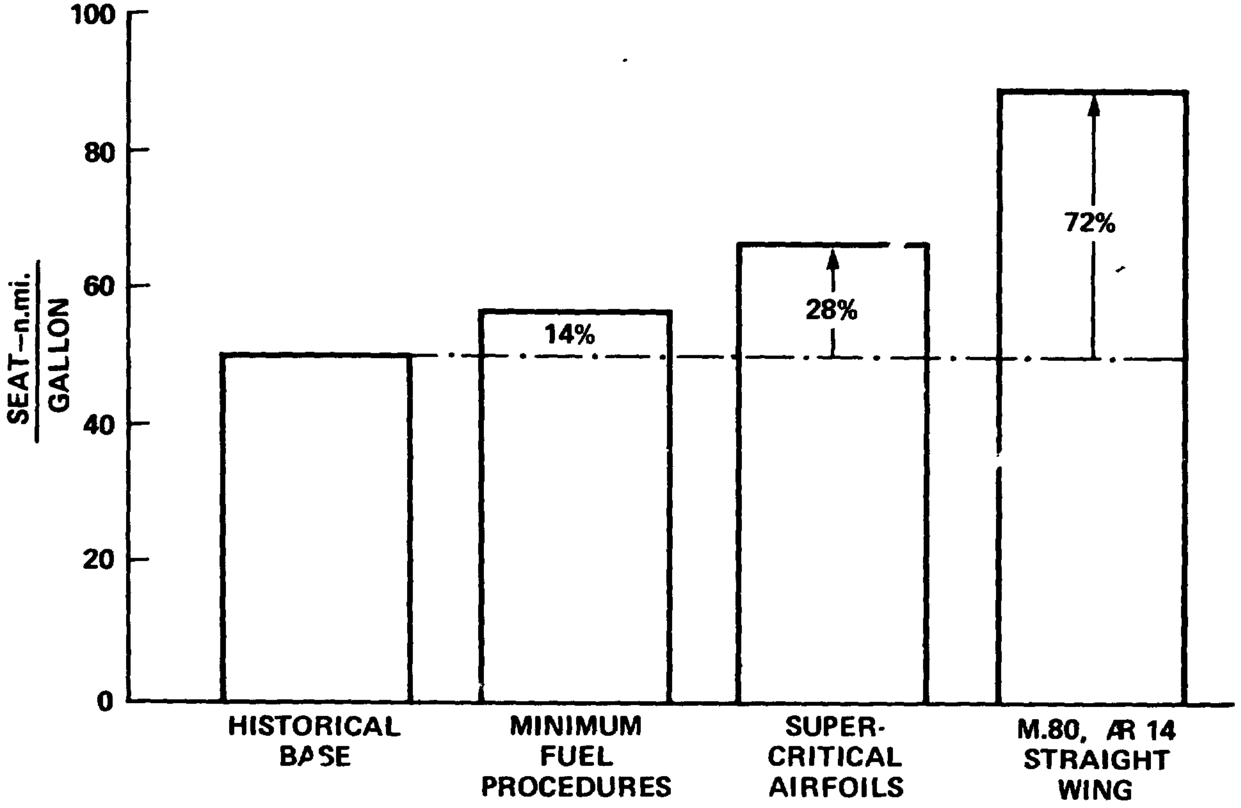

Figure 13. Relative Fuel Consumption Cumulative Changes

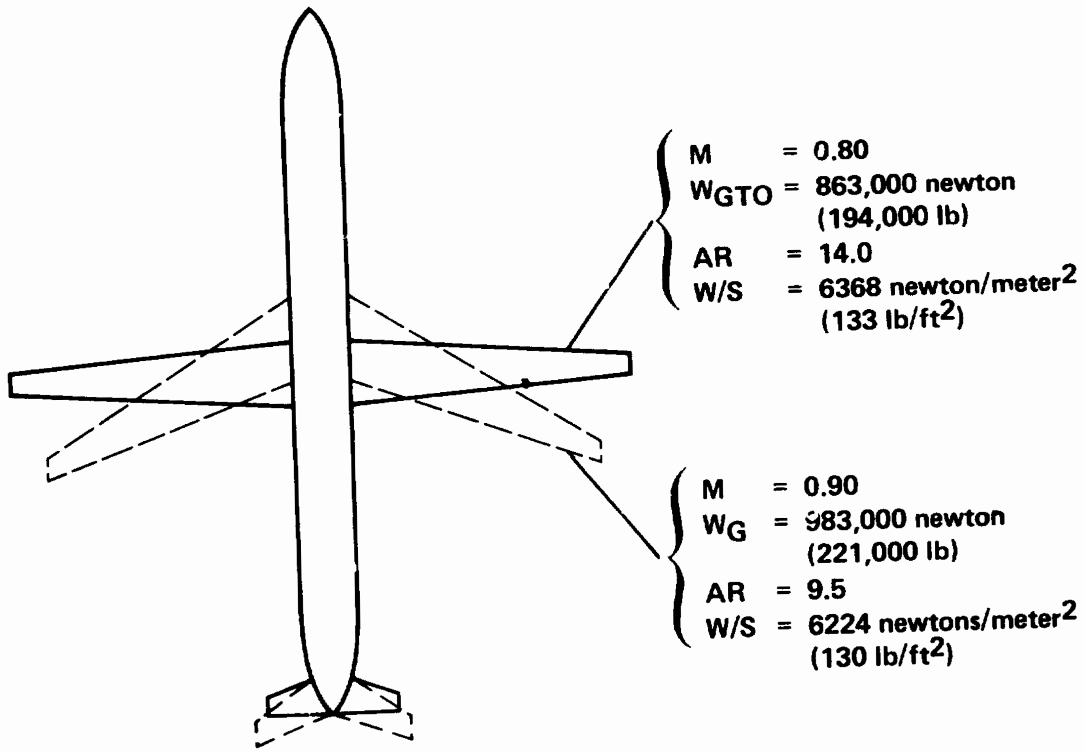

Figure 14. Planform Comparison