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COMPARISON OF ADVANCED TURBOPROP AND TURBOFAN AIRPLANES

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SUMMARY

Results of a parametric study to determine the effects of design variables and penalties on the fuel efficiency of Mach 0.8, 125-passenger, advanced turboprop airplanes show that propeller-wing interference penalty has a major effect. Propeller tip speed has a minor effect, and could be decreased to alleviate the noise problem without significant effects on fuel efficiency. The anticipated noise levels produced by the propfan will require additional acoustical treatment for the fuselage; this additional weight can have a significant effect on fuel efficiency. The propfan advantage over an equivalent technology turbofan is strongly dependent on the interference penalty and acoustical treatment weight. Lowering the cruise Mach number to around 0.73 would result in greatly increased fuel efficiency.

INTRODUCTION

The motivation for the current emphasis on high-speed turboprop airplanes (M = 0.8) is improved fuel efficiency. Comparison of the potential fuel-saving benefits of various technology advances, when applied to a short to medium range aircraft of 100 to 150 passengers, is shown in figure 1 (ref. 1). The fuel savings for each technology item, applied separately to a current technology turbofan aircraft are shown. These technology items are expected to be available for commercial transports in the 1990's. Of those items shown, the advanced turboprop propulsion system offers the greatest gain, as much as a possible 20-percent reduction in fuel usage.

The results of figure 1 were obtained under relatively ideal conditions. The actual gain will depend on design constraints and installation effects; therefore, a parametric study has been conducted to determine the effects of design variables and penalties associated with advanced turboprop airplanes on the fuel efficiency of the configurations. The parameters examined include propeller tip speed, propeller-wing interference penalty, acoustical treatment weight penalty, and lower cruise Mach numbers. The effects of these parameters are examined on both a baseline airplane (constant gross weight, wing loading, and power-to-weight ratio) and on configurations which have been sized for the same mission in an attempt to demonstrate the consequence of sizing on the effects of the parameters. For comparison, both an equivalent technology and a current technology turbofan are also considered.

Study Parameters

Propeller tip speed plays a key role in the performance of the turboprop propulsion system, in the component weights of the propulsion system, and in the noise produced by the propulsion system. In general, with increasing tip speed the efficiencies of the system increase, the propeller diameter decreases, and the component weights (except the propeller) decrease; however, increasing tip speed also causes increased noise which will affect both community and passenger cabin noise. At a Mach number of 0.8 and an altitude of 30,000 feet, a tip speed of 800 feet per second is supersonic, and the propeller will be noisy. No attempt is made herein to predict the noise produced by the propulsion system. The intent is to show the effects on the overall configuration of reducing tip speed to minimize noise.

The actual losses due to the propeller slipstream interaction with the wing are presently uncertain. These losses are referred to herein as the propeller-wing interference penalty. Figure 2(a) illustrates a typical wing-nacelle geometry. The nacelle drag is already accounted for in the airplane aerodynamic characteristics. It is not part of the propeller-wing interference penalty as defined herein. The interference penalty is caused by the propeller slipstream (fig. 2(b)). The slipstream interaction with the wing increases the dynamic pressure over the wing; thus producing increased scrubbing and compressibility drag. The slipstream also changes the local effective angle of attack which affects the parasite and, directly, as well as by virtue of an altered span load distribution, the induced drag. The magnitudes of these changes are functions of the strength of the slipstream, which, in turn, is a function of the throttle setting. For this reason, the propeller-wing interference penalty is treated as a constant percent thrust decrement across the entire Mach number and altitude range of the propulsion system. No attempt is made herein to predict or reduce the interference penalty; rather it is treated parametrically to determine its effect on the airplane fuel efficiency.

There is greater interior noise with the turboprop propulsive system than with turbofan. An increase in acoustical treatment of the fuselage will be required to reduce interior noise levels to acceptable limits. Currently the noise levels and the associated acoustical treatment weights of the turboprop are uncertain. Recent predictions estimate the acoustical treatment weight at about two percent of takeoff gross weight (ref. 2). The acoustical treatment weight is varied parametrically to determine its effect on the fuel efficiency of the configurations.

Current emphasis is on an airplane designed for a cruise Mach number of 0.8. The fuel efficiency of a turboprop airplane is strongly influenced by the design cruise speed; therefore, the effect of lower cruise Mach numbers on fuel efficiency is examined. The propeller was designed for a cruise Mach number of 0.8; however, since no design point propeller data exist for lower Mach numbers, the Mach 0.8 propeller design is used throughout the study. With a propeller designed for lower Mach numbers, further improvements in propeller efficiency and weight should be possible. No attempt is made herein to redesign the airplane for slower speeds by modifying wing-sweep angle or weights. The baseline airplane is flying in the transonic drag rise region at Mach 0.8. To isolate the effects of the propulsion system compressibility effects at lower Mach numbers, the wing aerodynamic characteristics are altered arbitrarily to raise the critical Mach number above the area of interest for this portion of the study.

Study Ground Rules

The configuration used in the study is a 125-passenger, twin-engine subsonic transport. The airframe technology level is representative of a current airline aircraft. Greater gains in fuel efficiency should be possible with an advanced technology airframe. Such effects are not considered herein since the intent is to illustrate the effects of the propulsion system on the overall configuration, not to predict the fuel efficiency of an advanced technology design.

The engines are located on the wing, with the turbofan mounted under the wing and the propfan over the wing (fig. 3). The turboprop system consists of a 1990-technology turboshaft engine (P&WA STS-589) and an eight-blade advanced technology highly-loaded swept propeller (ref. 3). Two different technology level turbofan engines are considered. A current technology turbofan engine (JT8D-7) is used for reference; however, comparing 1960's and 1990's technology is not a legitimate comparison. A 1990 technology turbofan engine (P&WA STF-592) is considered to establish the comparative "goodness" of the turboprop propulsion system.

Except for the case where the effect of lower cruise Mach number is investigated, the mission required a cruise Mach number of 0.8. During climb, the best Breguet factor is sought constantly. For all missions, the start of cruise altitude is determined by either the best Breguet factor or a minimum available rate of climb during cruise of 300 feet per minute, depending on which condition is reached first. In the latter case, cruise begins at the altitude at which the rate of climb limitation is encountered. The result of this method of fixing the altitude for start of cruise is that the airplanes are not all flying at the same cruise altitude. Those at lower altitudes are flying at higher cruise speeds than those at higher altitudes since the Mach number is constant.

The configurations are designed for a particular mission to examine the effects of the turboprop propulsion system on fuel efficiency. The design mission consists of takeoff, climb, cruise at the required Mach number and at the altitude described above, descent, and landing. The required reserves are missed approach, flight to an alternate airport 200 nautical miles away, and one hour of flight with fuel flow of start of cruise. In addition, the configurations are sized for a minimum gross weight based on a design range of 1000 nautical miles, a maximum takeoff field length of 6000 feet, and a maximum approach speed of 135 knots. Identical conditions are used for both the turboprop and turbofan configurations. The design mission is typical of that envisioned for this type of configuration. Changing the design mission should not affect the study-parameter trends presented herein; however, the comparison between the propfan and turbofan could be affected to a major degree.

Mission analysis is done using the ASP (Airplane Sizing and Performance) program (ref. 4). Since the publication of reference 4, this program has been extensively modified in order to treat subsonic, as well as supersonic, configurations. Further modifications were made to ASP to incorporate turboprop propulsion system capability. The configuration description necessary for ASP consists of fairly detailed geometry, aerodynamic characteristics, weights, and propulsion data (fig. 4). The propulsion system data supplied to ASP is generated (by the method of ref. 5) from a turboshaft engine data deck and propeller data decks supplied by the engine and propeller companies.

Results and Discussion

Baseline airplane.- A matrix of propeller tip speeds and propeller-wing interference penalties were considered using the baseline turboprop configuration at a constant power-to-weight ratio of 0.3 horsepower/pound, a wing loading of 104.5 pounds/square foot, and a takeoff gross weight of 104,000 pounds. No acoustical treatment weight was included. Figure 5(a) shows that range decreased significantly with increasing propeller-wing interference propeller tip speed. The interference penalty has a significant effect on passenger miles per gallon, while tip speed again has a small effect (fig. 5(b)).

As the propeller-wing interference penalty increases, the amount of thrust available is reduced. The decreased thrust results in much lower cruise altitudes (fig. 5(c)) leading in turn to a much less efficient cruise; the throttle setting must be increased (fig. 5(d)), and the thrust specific fuel consumption increases (fig. 5(e)). The net result is a large decrease in range, and, therefore, passenger miles per gallon, as the propeller-wing interference penalty increases.

At higher propeller tip speeds, the turboprop propulsion system is more efficient and produces slightly more thrust. As seen in figures 5(a) to 5(e), the increase in thrust results in a very modest reduction in the thrust specific fuel consumption. Higher tip speeds also result in slightly reduced propulsion system weight. (The propeller weight increases, but other component weights decrease more than enough to compensate for the increase in propeller weight.) The reduced propulsion system weight allows the total fuel weight to increase since the gross weight is constant. The net result of higher tip speed is a minor improvement in range and passenger miles per gallon.

Airplane sizing.- All configurations were sized for minimum takeoff gross weight for the design mission. Figure 6 shows a sample thumbprint used to size a propfan configuration with a propeller tip speed of 750 feet/second and no propeller-wing interference penalty or acoustical treatment weight. The only design constraint that appears on figure 6 is maximum approach speed. This was the case for both the propfan and turbofan configurations. The cruise Mach number, range, and minimum rate of climb constraints are met by all points on the thumbprint. The takeoff field length constraint was not a factor for any configuration considered.

A matrix of configurations were sized in a similar manner. Changes in any part of the design mission could result in a change in the critical sizing point(s) for either the propfan or the turbofan or both. The power-weight ratio (or thrust-weight ratio for the turbofans), wing loading, and takeoff gross weight of the sized configurations are given in Table 1.

Design airplanes.- The sized configurations are compared to each other in figures 7(a) to (7d). It is evident from these figures that sizing the configurations for a design mission does not alleviate the effects of the propeller-wing interference penalty. As with the baseline airplanes, the interference penalty drastically reduces the passenger miles per gallon of the turboprop configurations (fig. 7(a)). The increase in fuel efficiency due solely to technology level may be seen by noting the low-passenger miles per gallon of the current turbofan as compared to all other configurations. The advanced turbofan is roughly equivalent to a turboprop configuration with a ten-percent interference penalty.

The large effect of propeller-wing interference penalty on the takeoff gross weight of the turboprops is evident in figure 7(b). It is interesting to observe that the takeoff gross weight of the current turbofan is approximately the same as that of the propfan with a twenty-percent interference penalty while the advanced turbofan is actually lighter than any of the turboprop configurations. The turboprops require less fuel than the turbofans for the design range but the increased propulsion system weight of the propfans more than compensates for the reduced fuel weight.

As would be expected, increasing propeller-wing interference penalty requires greater shaft horsepower (fig. 7(c)). The greater power results in higher values of thrust specific fuel consumption. As a consequence, the average cruise Breguet factor decreases substantially with increasing interference penalty (fig. 7(d)). The large increase due to technology level can be observed once more; the current turbofan has an average cruise Breguet factor well below that of any of the configurations, while the advanced turbofan is roughly equivalent to the propfan with ten-percent interference penalty.

For the sized configurations, the small effect of propeller tip speed is evident throughout these figures, indicating that it would be possible to decrease tip speed without significant effects on fuel efficiency. Decreased tip speed may be necessary to alleviate the noise problem. Because of the fuel efficiency of those sized configurations with reduced propeller tip speed, all remaining propfan results will be presented only for a tip speed of 750 feet/second.

Acoustical treatment weight penalty.- The effect of additional weight for acoustical treatment of the propfan fuselage is evaluated to determine the amount of weight that could be added to the propfan configuration before the fuel efficiency is degraded to that of the advanced turbofan. Figure 8(a) shows the takeoff gross weight of the sized propfan configurations as a function of weight increase for acoustical treatment. Every pound of acoustical treatment added results in another pound of airplane (distributed between fuel, propulsion system, structure, etc.) to meet the design mission. For reference, the takeoff gross weights of the current and advanced turbofans are also indicated. The total mission fuel required by the turboprops for the design mission is shown in figure 8(b), again as a function of weight increase. As a point of reference, the total fuel required for the advanced and current turbofans is also shown. Figures 8(a) and 8(b) show once more that propfans require less fuel than turbofans, but have comparable takeoff gross weights because of substantially increased propulsion system weight.

Current estimates for the additional turboprop acoustical treatment weight vary from two to four percent of takeoff gross weight. It is evident, from figure 8(b), that for propeller-wing interference penalties up to almost ten percent, even with additional acoustical treatment, the fuel required is less than that of the advanced turbofan. For interference penalties above ten percent, the fuel required, even with only two-percent acoustical treatment weight, is greater than that required by the advanced turbofan.

Comparison of turboprops and turbofans.- A comparison of takeoff gross weight (fig. 9(a)) shows that the current technology turbofan has the highest weight while the advanced technology turbofan has the lowest. The propfan with no propeller-wing interference penalty has a takeoff gross weight slightly higher than the advanced turbofan; the propfan with twenty-percent propeller-wing interference penalty has a weight almost as great as the current technology turbofan. The turboprops with two-percent acoustical treatment weight penalty have higher gross weights; the twenty-percent propeller-wing interference penalty configuration weighs even more than the current technology turbofan.

A comparison of the fuel efficiencies of these configurations is shown in figure 9(b). As seen before, there is a significant increase in passenger miles per gallon due solely to the increase in technology level. The advanced turboprop demonstrates an increase in fuel efficiency for no interference penalty, about the same fuel efficiency for ten-percent interference penalty, and a decrease in fuel efficiency for twenty-percent interference penalty compared to the advanced turbofan. For two-percent acoustical treatment weight penalty, the fuel efficiency of all propfans is reduced. If the propeller-wing interference penalty is as great as ten percent, the fuel efficiency is inferior to that of the advanced turbofan.

Effect of lower cruise mach number.- The effects of lower cruise Mach number were investigated for a turboprop configuration sized for the design mission with a propeller tip speed of 750 feet/second, no propeller-wing interference penalty, and no acoustical treatment weight penalty. No change was made in the wing sweep or weight with changing Mach number. The main study was done for $M = 0.8$, since that was the Mach number for the available propeller data; however, at this Mach number, the airplane configuration was already beyond the transonic drag rise. In an attempt to isolate the propulsion system effects from compressibility effects, the configuration aerodynamics were upgraded to increase the critical Mach number to well above 0.8 by reducing the thickness of the wing. This improved configuration was sized for the design mission at Mach 0.8.

Reducing the cruise Mach number results in large increases in the range of the baseline airplane (fig. 10(a)). The improved configuration also has increased range at lower cruise Mach numbers, but the increase is not as great as for the baseline aircraft. This result is obtained because the improved configuration is a smaller airplane (takeoff gross weight of 101,900 pounds and power-weight ratio of 0.25 horsepower/pound as compared to 105,111 pounds and 0.26 horsepower/pound for the baseline) since it has less drag without the compressibility effects. For both configurations, the propulsion system is more efficient at lower cruise Mach numbers, with the maximum range occurring around $M = 0.73$. Reducing cruise Mach number also results in an increase in passenger miles per gallon for both configurations, with the maximum occurring around $M = 0.72$. At $M = 0.8$, the improved configuration exhibits better fuel efficiency than the baseline configuration (fig. 10(b)) again due to the lesser drag of the improved configuration. As cruise Mach number is reduced, the baseline configuration exhibits a larger increase in passenger miles per gallon than the improved configuration since the baseline can use the fuel that was overcoming compressibility at $M = 0.8$ to gain extra range at lower speeds. A propeller designed for a Mach number of 0.7 or 0.75 should result in even better fuel efficiencies than shown here; however, data for such propellers do not exist at present.

CONCLUSIONS

Results from a parametric study of the factors affecting the fuel efficiency of advanced turboprop airplanes have shown that:

1. Propeller-wing interference has a major effect on fuel efficiency and takeoff gross weight; however, propeller tip-speed has a minor effect on these quantities. It could be lowered for noise reduction with little effect.

2. When combined with propeller-wing interference, additional turboprop acoustic treatment weight can have a significant effect on the relative efficiencies of turboprop and turbofan aircraft with engines of comparable technology level.

3. Lower cruise Mach numbers ($M \approx .73$ vs $M = .8$) greatly improve the fuel efficiency of turboprop aircraft. There is need for data on propellers designed for these lower Mach numbers.

REFERENCES

1. Booth, Murray A.: Advanced Turboprop Transport Development - A Perspective. ICAS Paper 82-1.8.2 presented at the 13th Congress of the International Council of Aeronautical Sciences, Seattle, Washington, August 22-27, 1982.

2. Revell, J. D.; Balena, F. J.; and Prydry, R. A.: Cabin Noise Weight Penalty Requirements for a High-Speed Propfan-Powered Aircraft - A Progress Report. SAE Paper 821360 presented at the Aerospace Congress and Exposition, Anaheim, California, October 25-28, 1982.

3. Baum, J. A., et al: Propfan Data Support Study Technical Report. NASA CR-152141, 1978.

4. Fetterman, David E., Jr.: Preliminary Sizing and Performance Evaluation of Supersonic Cruise Aircraft. NASA TM X-73936, 1976.

5. Morris, Shelby J., Jr.: Performance Estimation for a Highly Loaded Eight-Blade Propeller Combined with an Advanced Technology Turboshaft Engine. NASA TM-80075, 1979.

(a) Propfan Airplanes.

V_{tip}	Prop-wing int. (%T)	P/W (lb_f/hp)	W/S (lb_f/ft^2)	WG (lb_f)
700	0	.26	93.7	106037
700	10	.30	94.0	115464
700	20	.32	95.8	125200
750	0	.26	93.7	105111
750	10	.30	94.0	114462
750	20	.32	95.5	123852
800	0	.25	93.7	104222
800	10	.28	94.2	111560
800	20	.31	94.5	122416

(b) Turbofan Airplanes.

Description	T/W (lb_f/lb_f)	W/S (lb_f/ft^2)	WG (lb_f)
Current Technology Turbofan	.33	99.5	124244
Advanced Technology Turbofan	.33	95.6	102770

Table 1.- Sized configuration data.

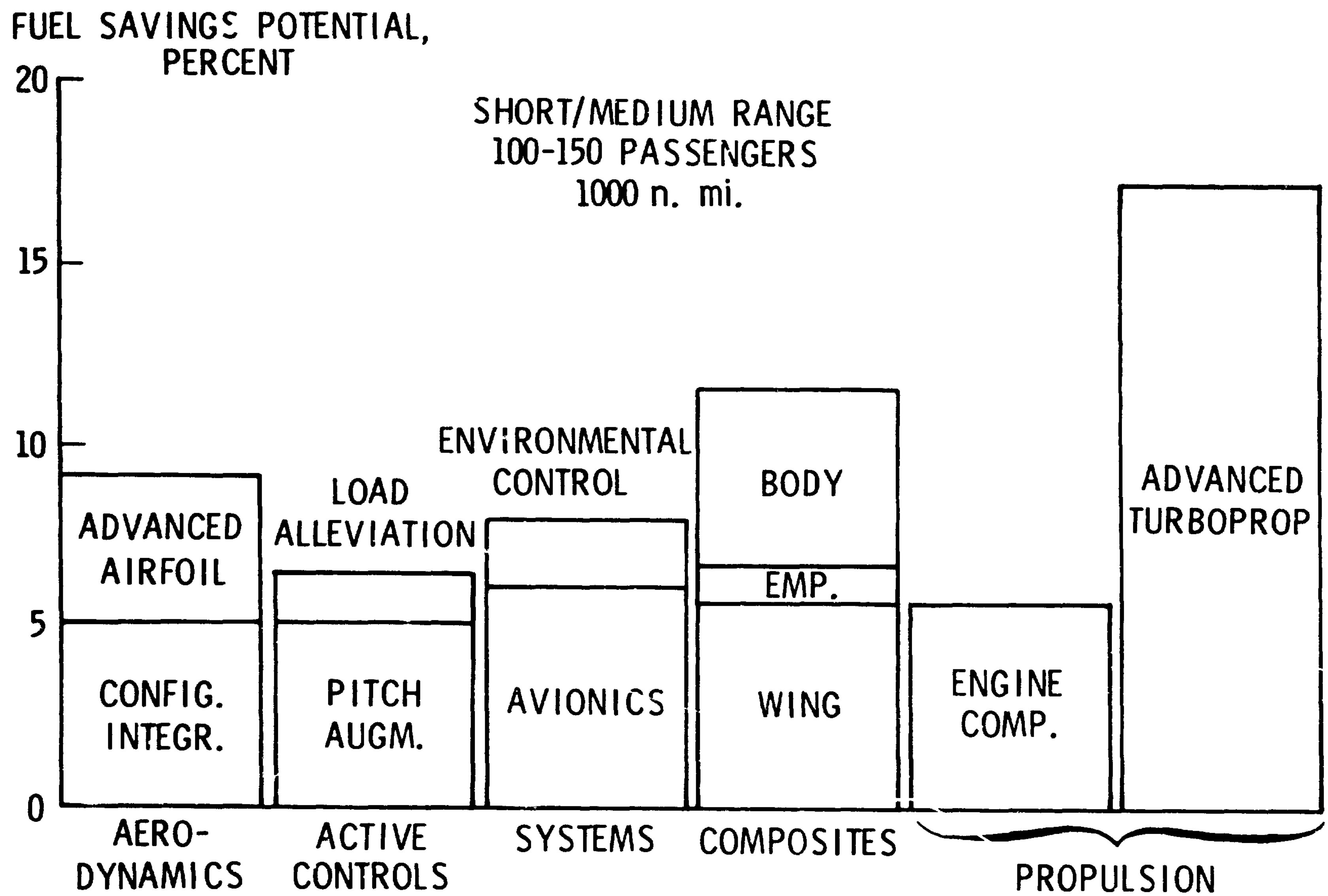
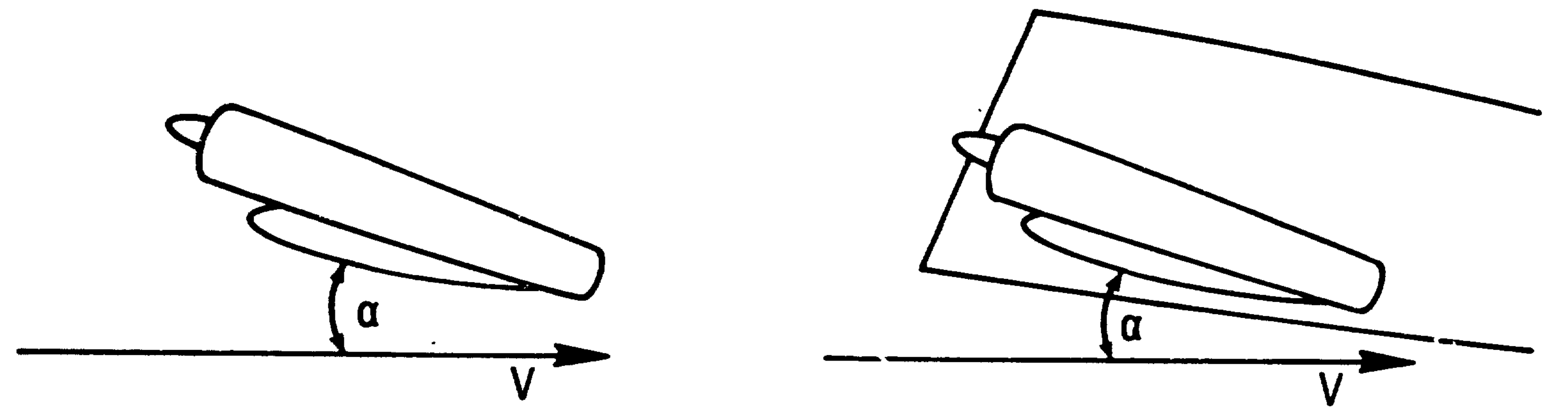


Figure 1.- Advanced technology benefits (current turbofan baseline).



(a) Aerodynamics for this geometry included in airplane aerodynamics.

(b) Slipstream from propeller causes interference penalty.

Figure 2.- Bookkeeping for the prop ller-wing interference penalty.

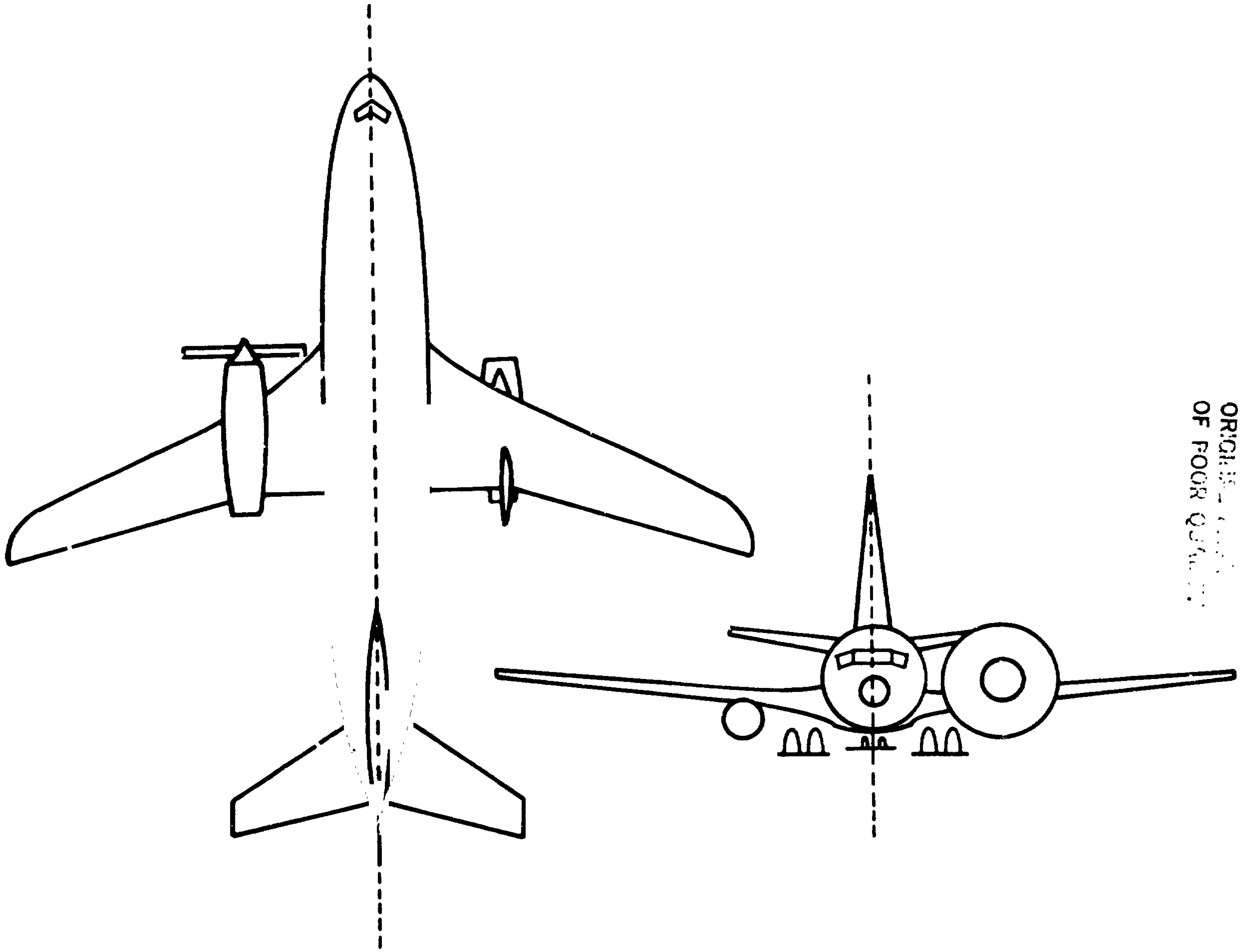


Figure 3.- Baseline configuration with turbofan and propfan engines.

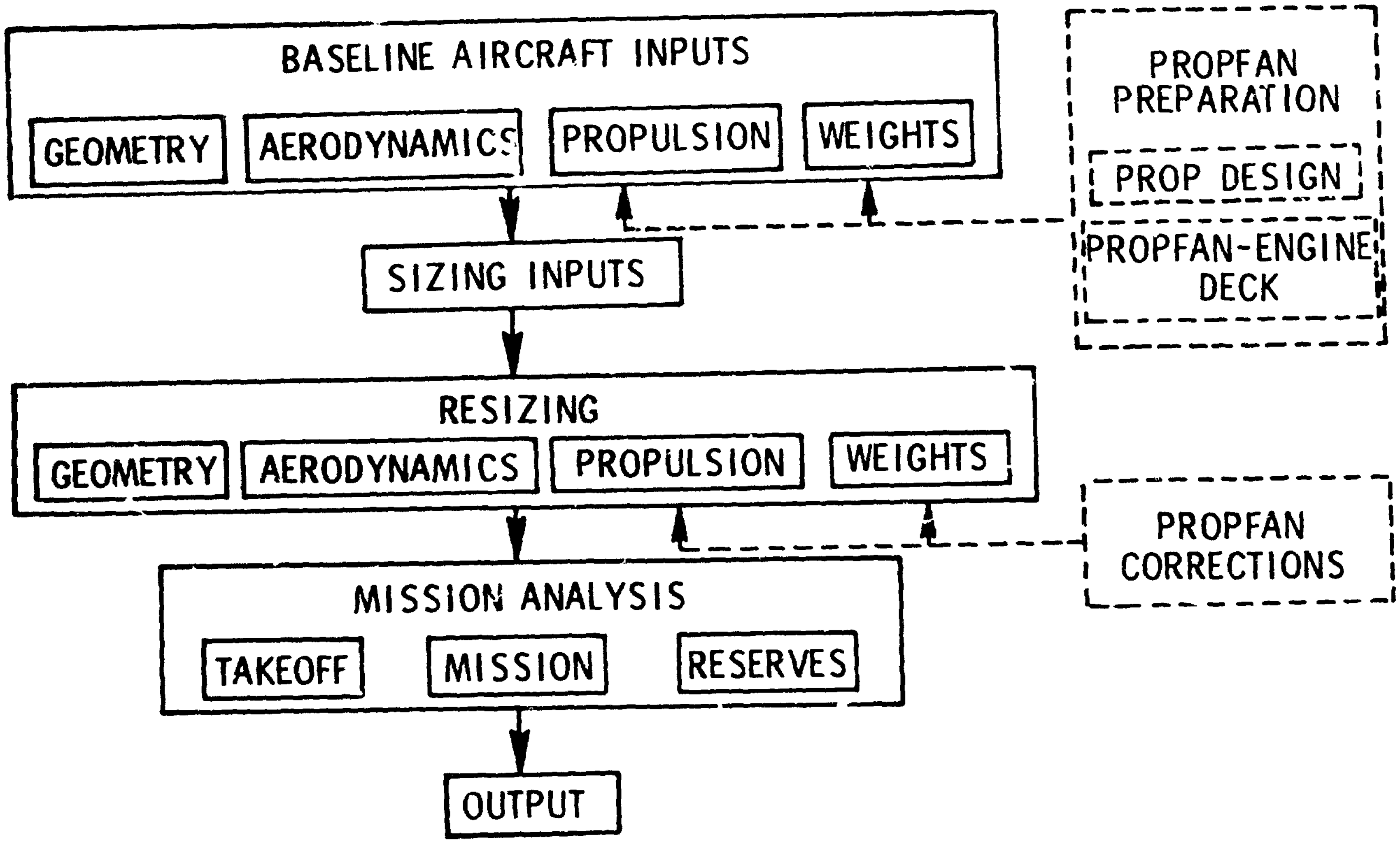
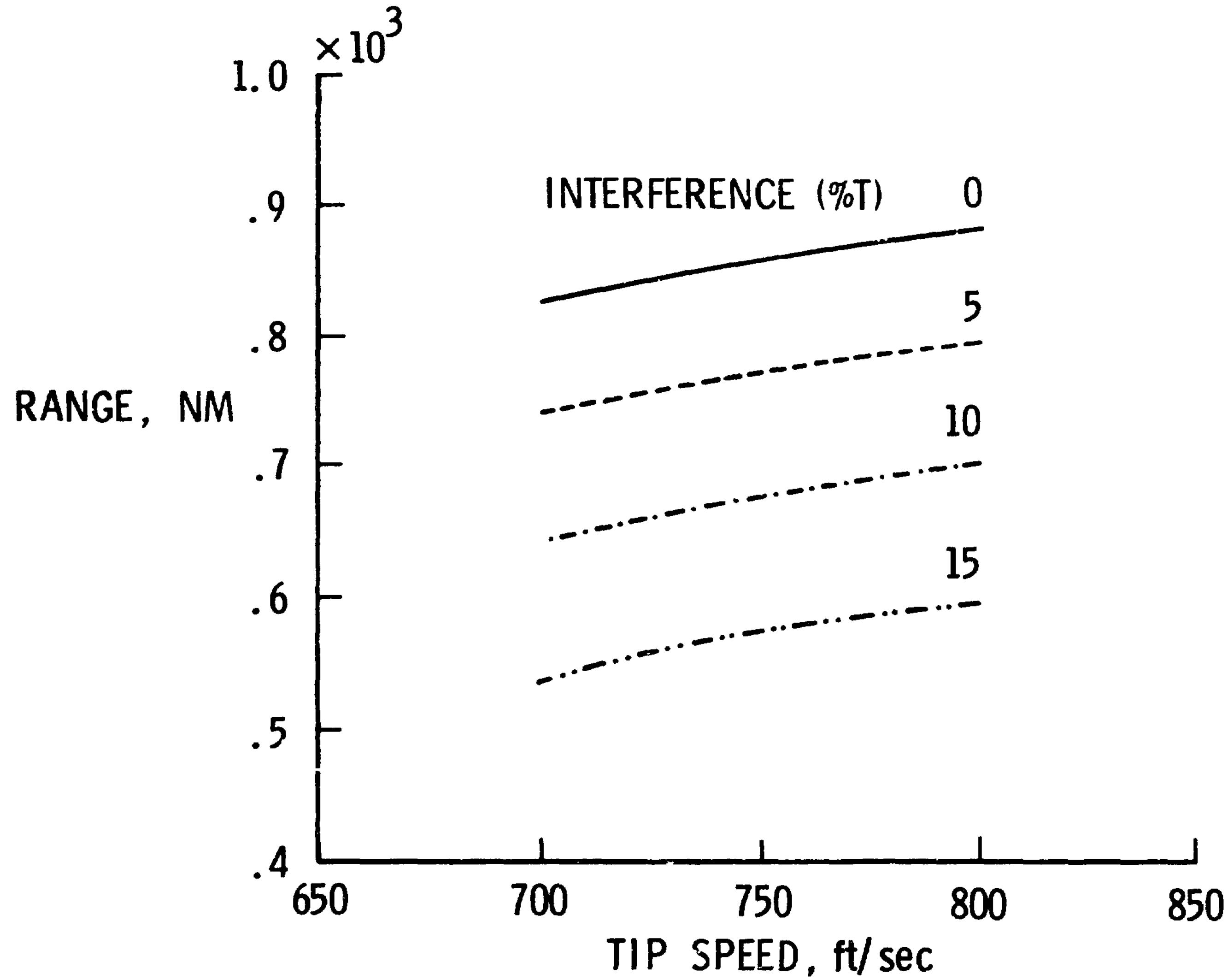
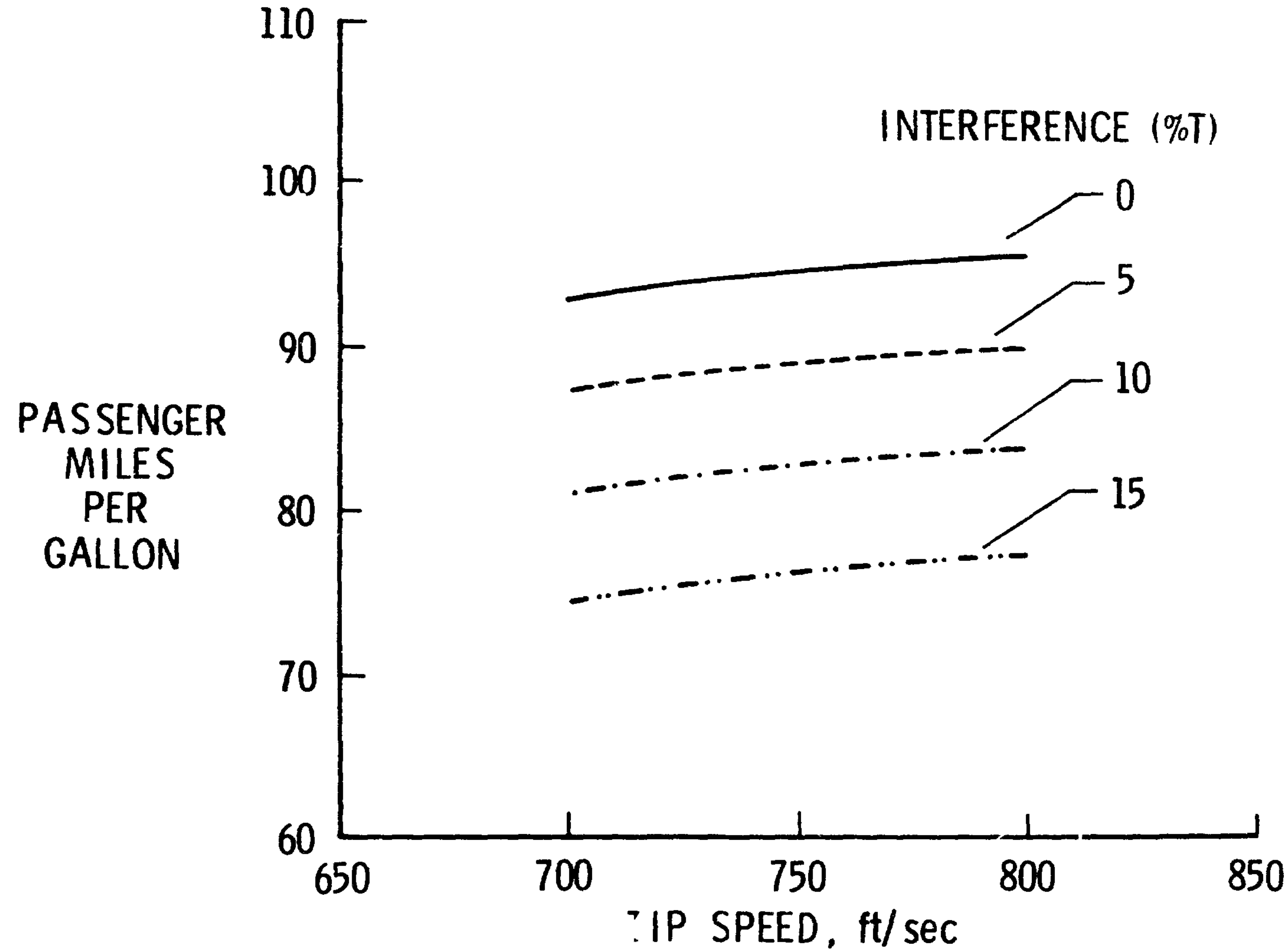


Figure 4.- Airplane Sizing and Performance Program flow.



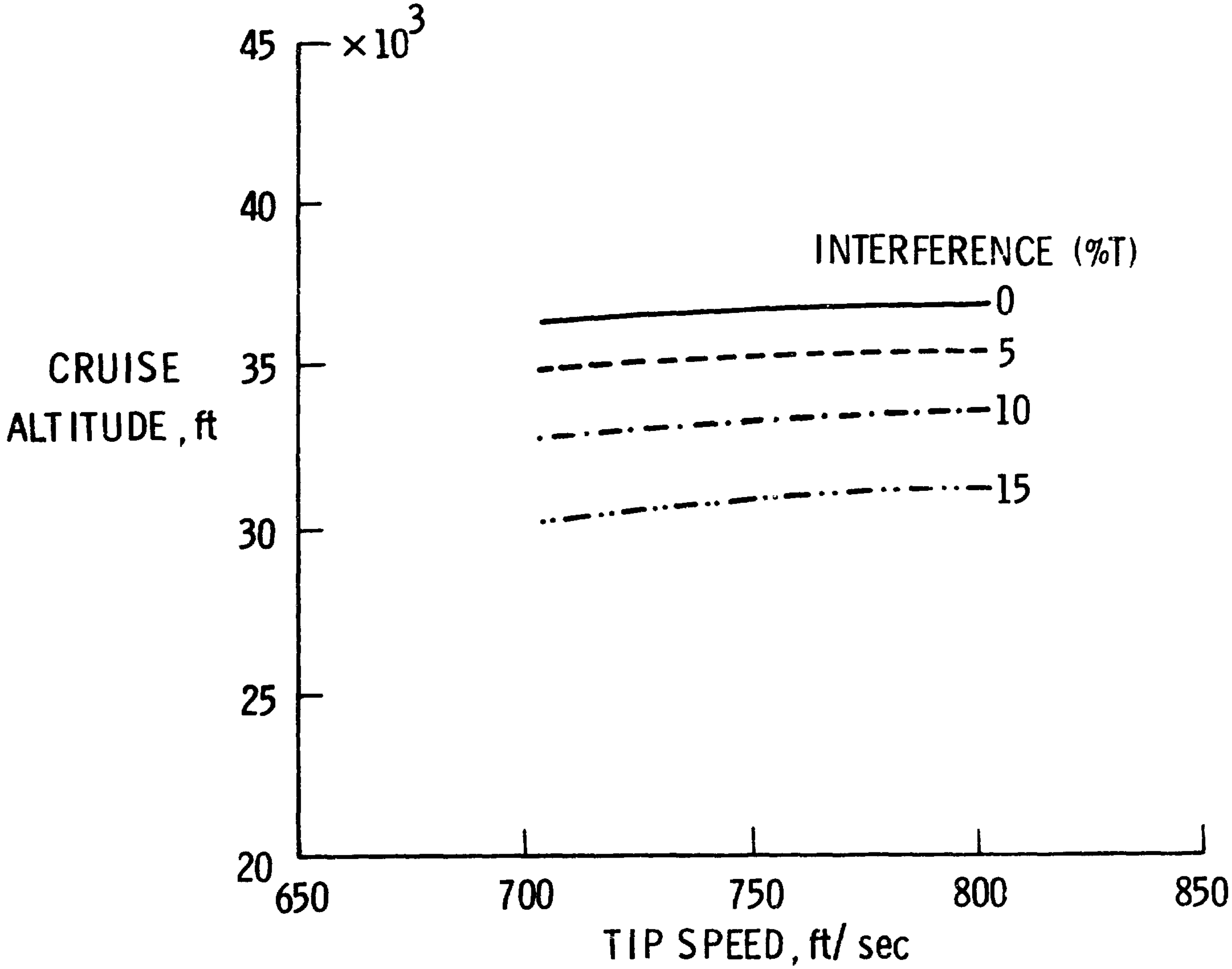
(a) Range.

Figure 5.- Effect of propeller-wing interference and propeller tip speed on baseline airplane.



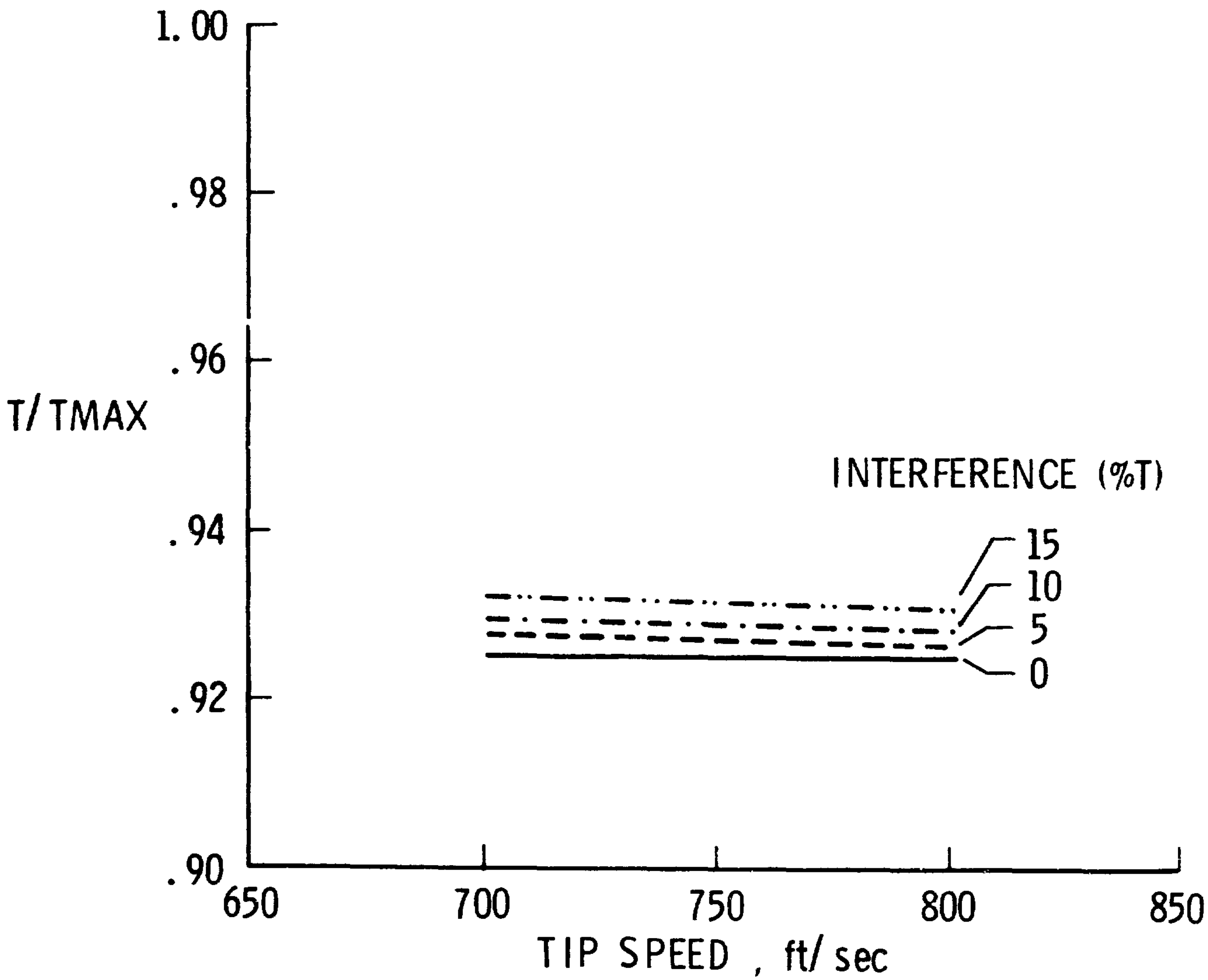
(b) Passenger miles per gallon.

Figure 5.- Continued.



(c) Average cruise altitude.

Figure 5.- Continued.



(d) Throttle setting.

Figure 5.- Continued.

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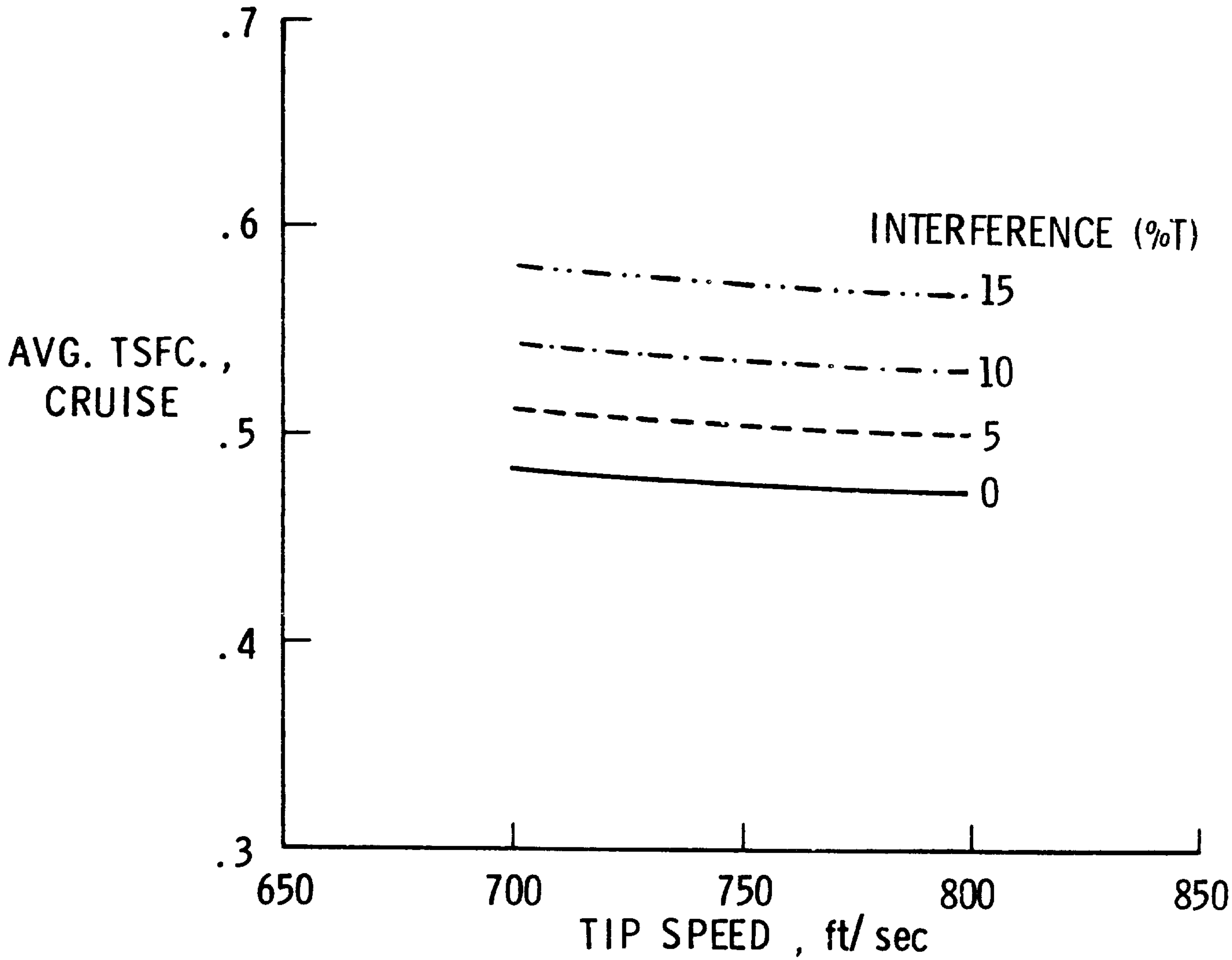


(e) Average thrust specific fuel consumption.

Figure 5.- Concluded.

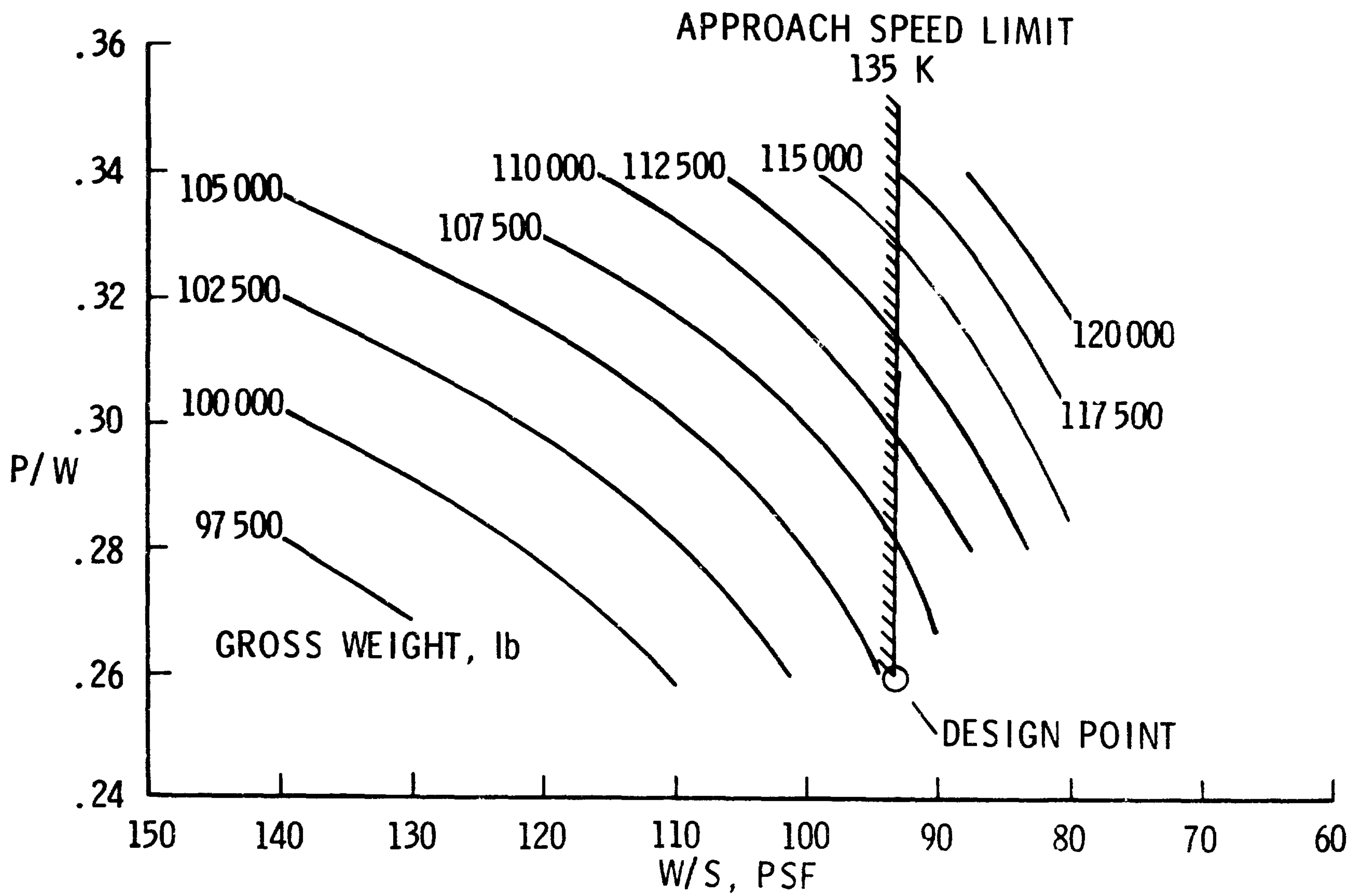
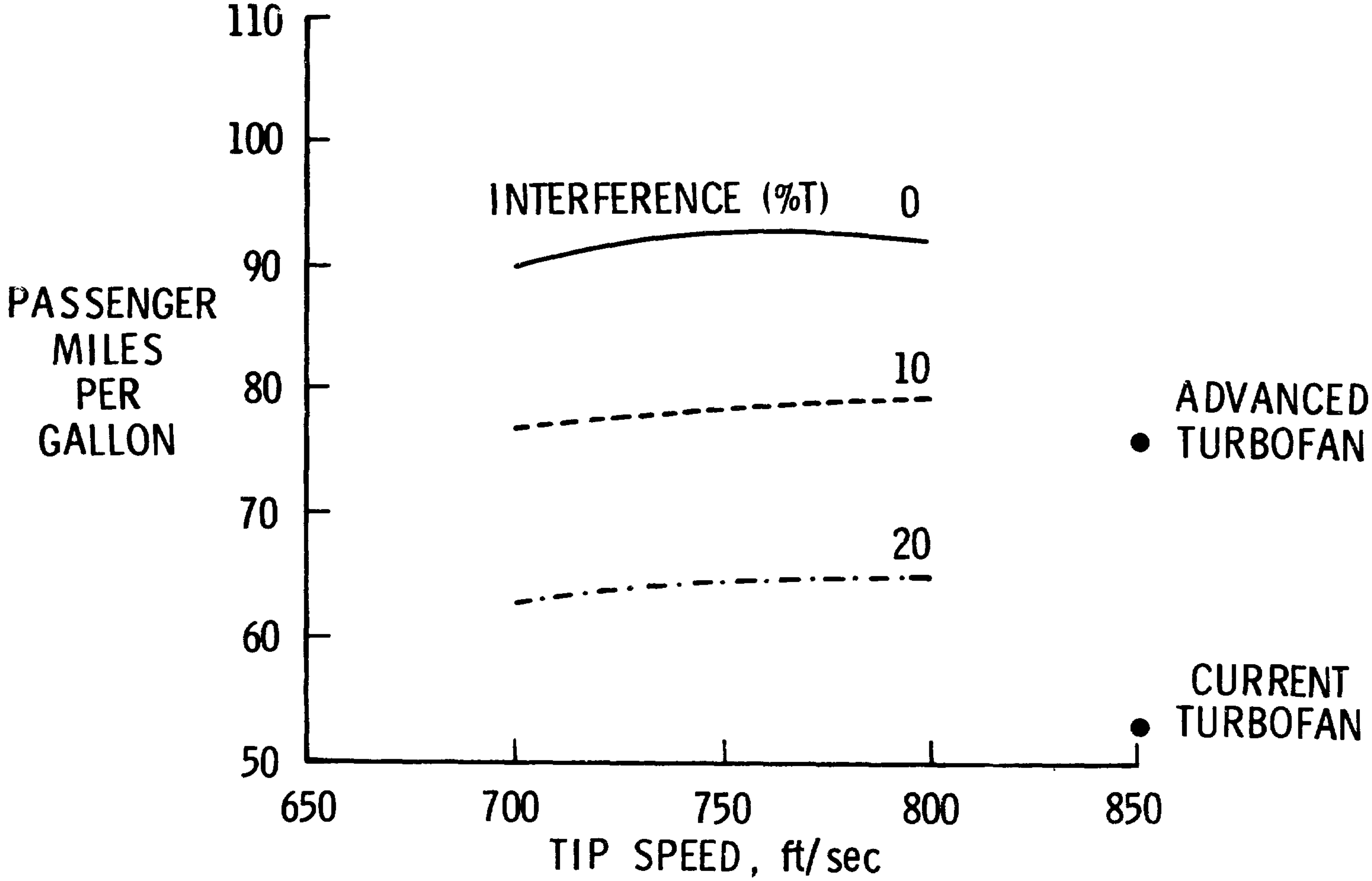
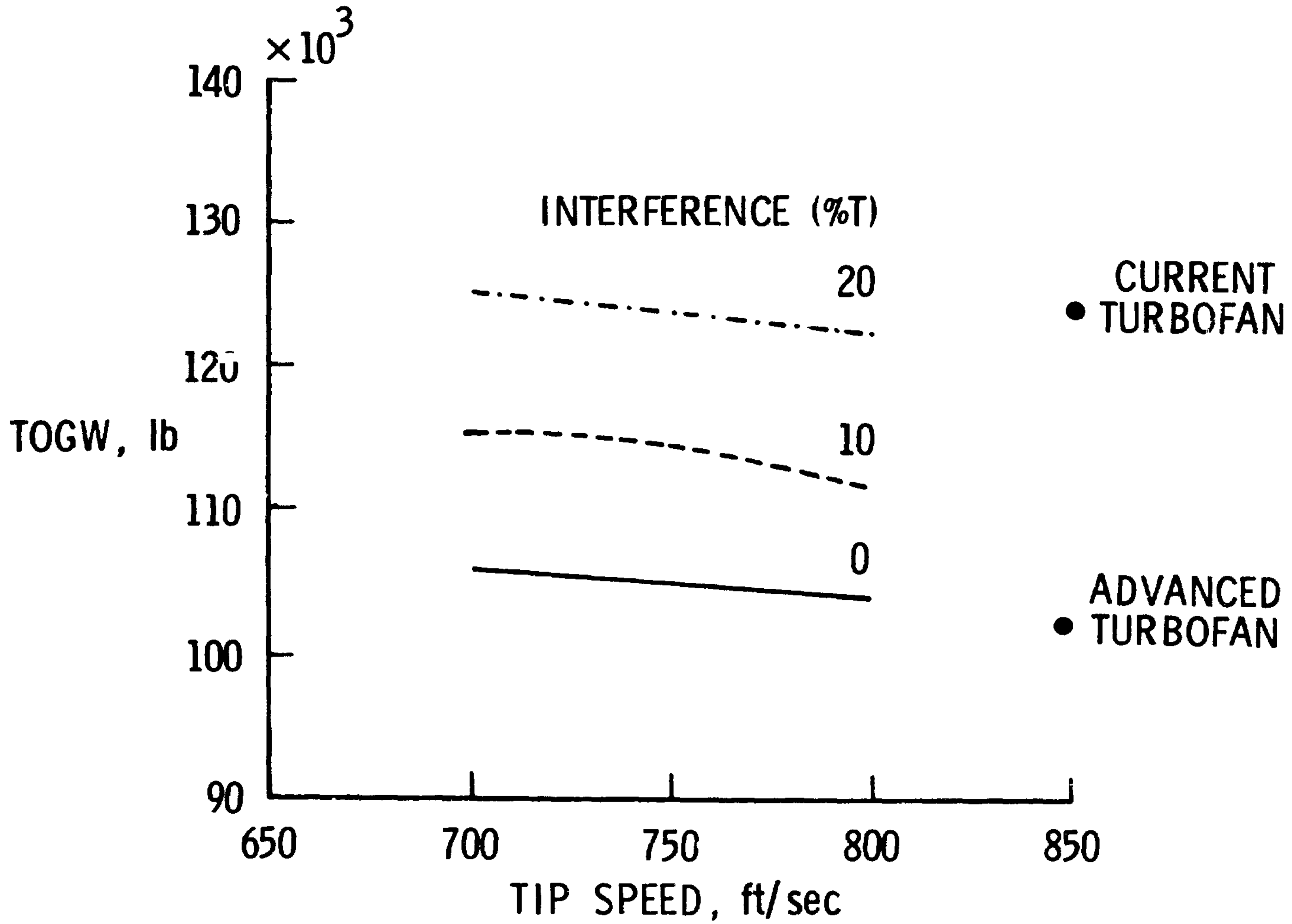


Figure 6.- Sample propfan sizing thumbprint (tip speed 750 ft/sec, prop-wing interference penalty 0%)



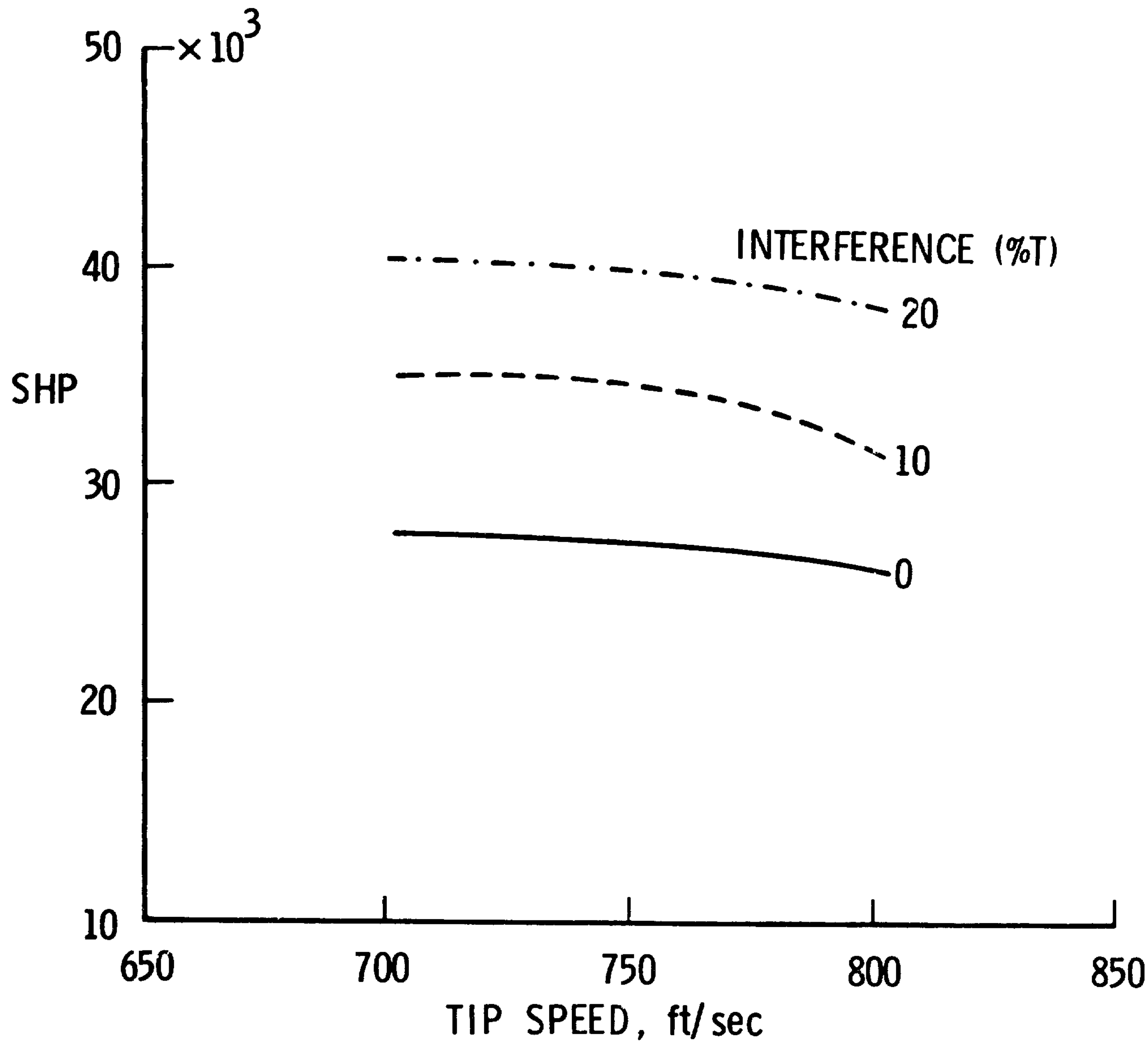
(a) Passenger miles per gallon.

Figure 7.- Effect of propeller-wing interference and propeller tip speed on sized turboprop.



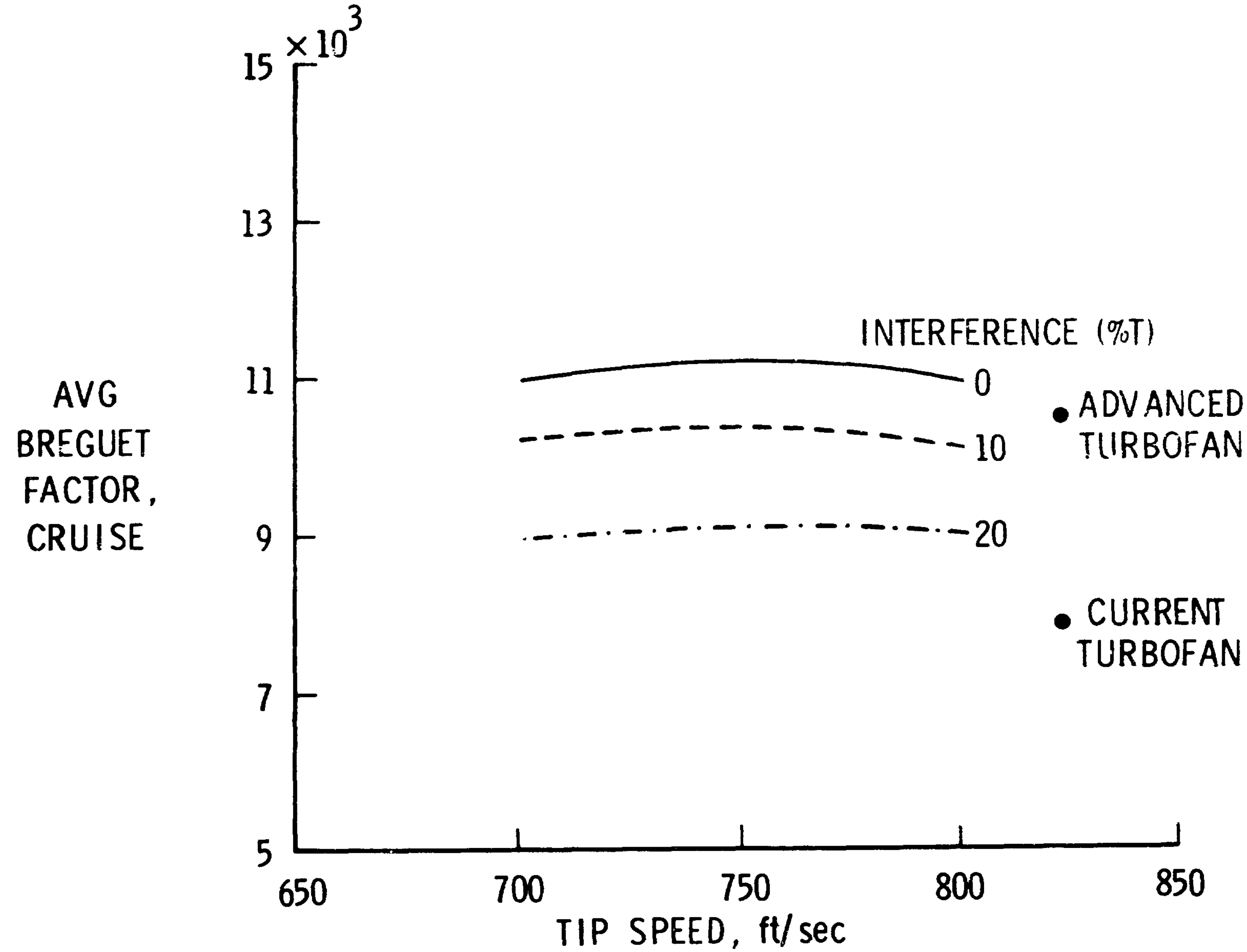
(b) Takeoff gross weight.

Figure 7.- Continued.



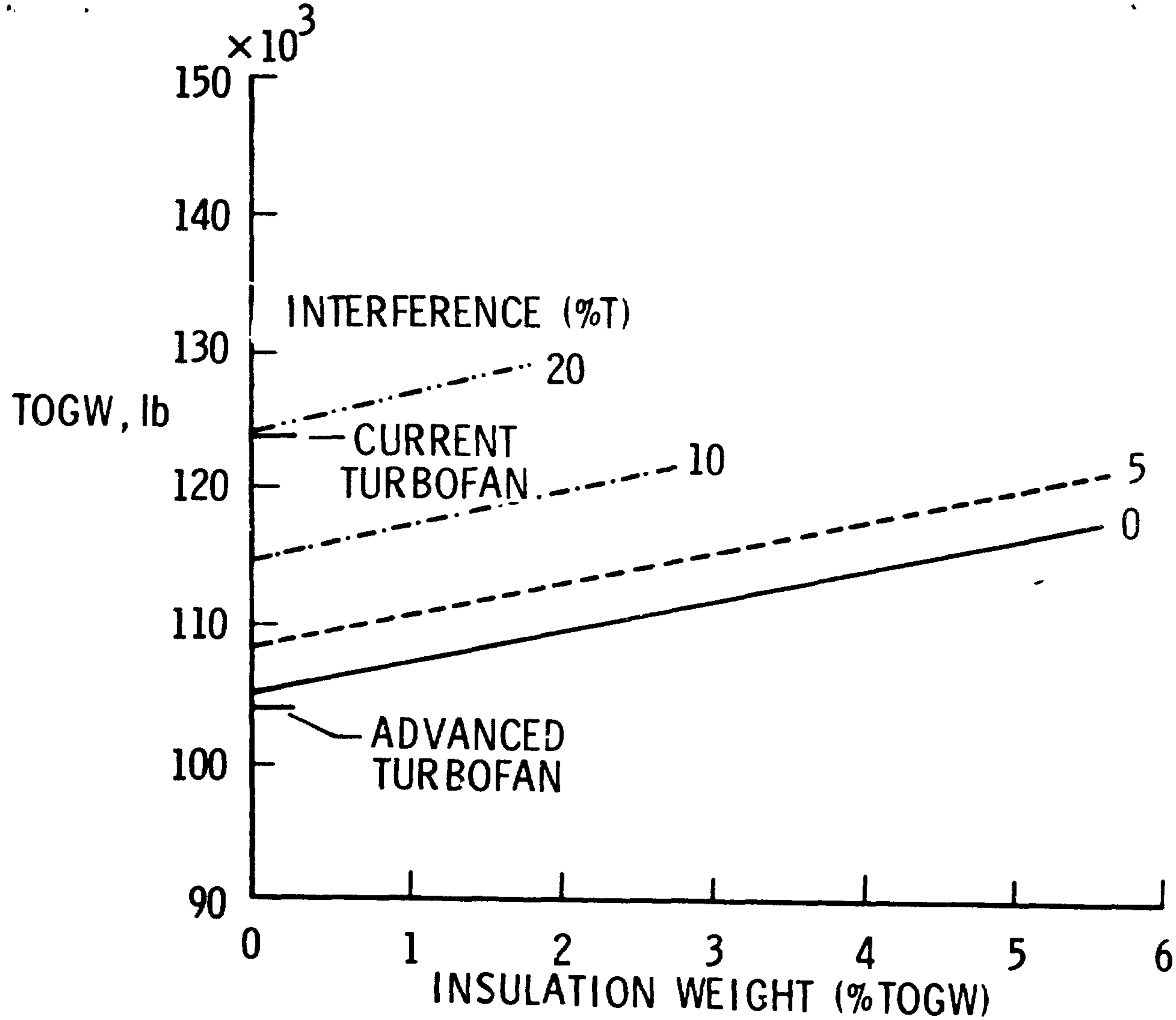
(c) Shaft horsepower.

Figure 7.- Continued.



(d) Average cruise Brequet factor.

Figure 7.- Concluded.



(a) Takeoff gross weight.

Figure 8.- Effect of acoustical treatment weight and propeller-wing interference on sized turboprop.

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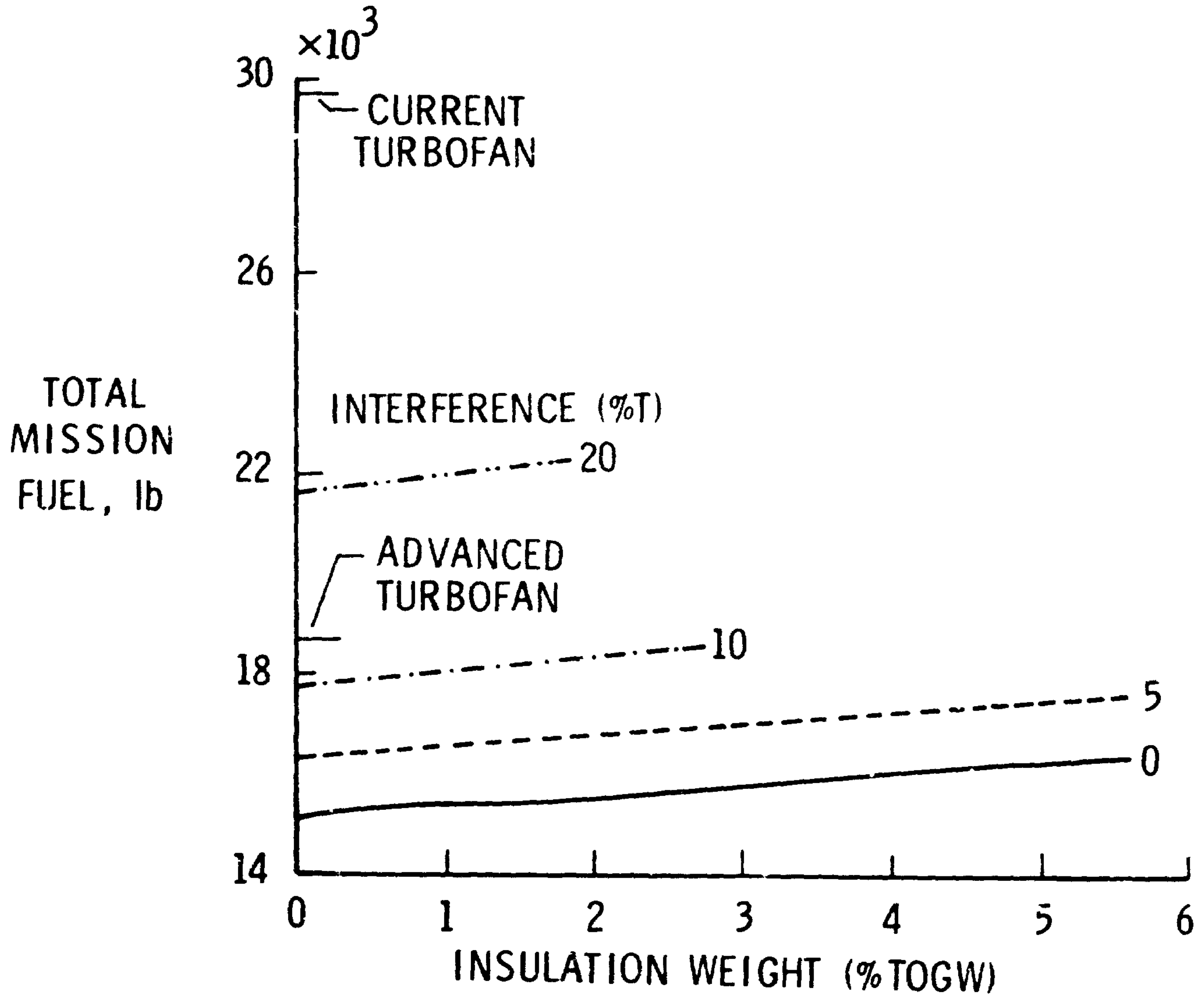
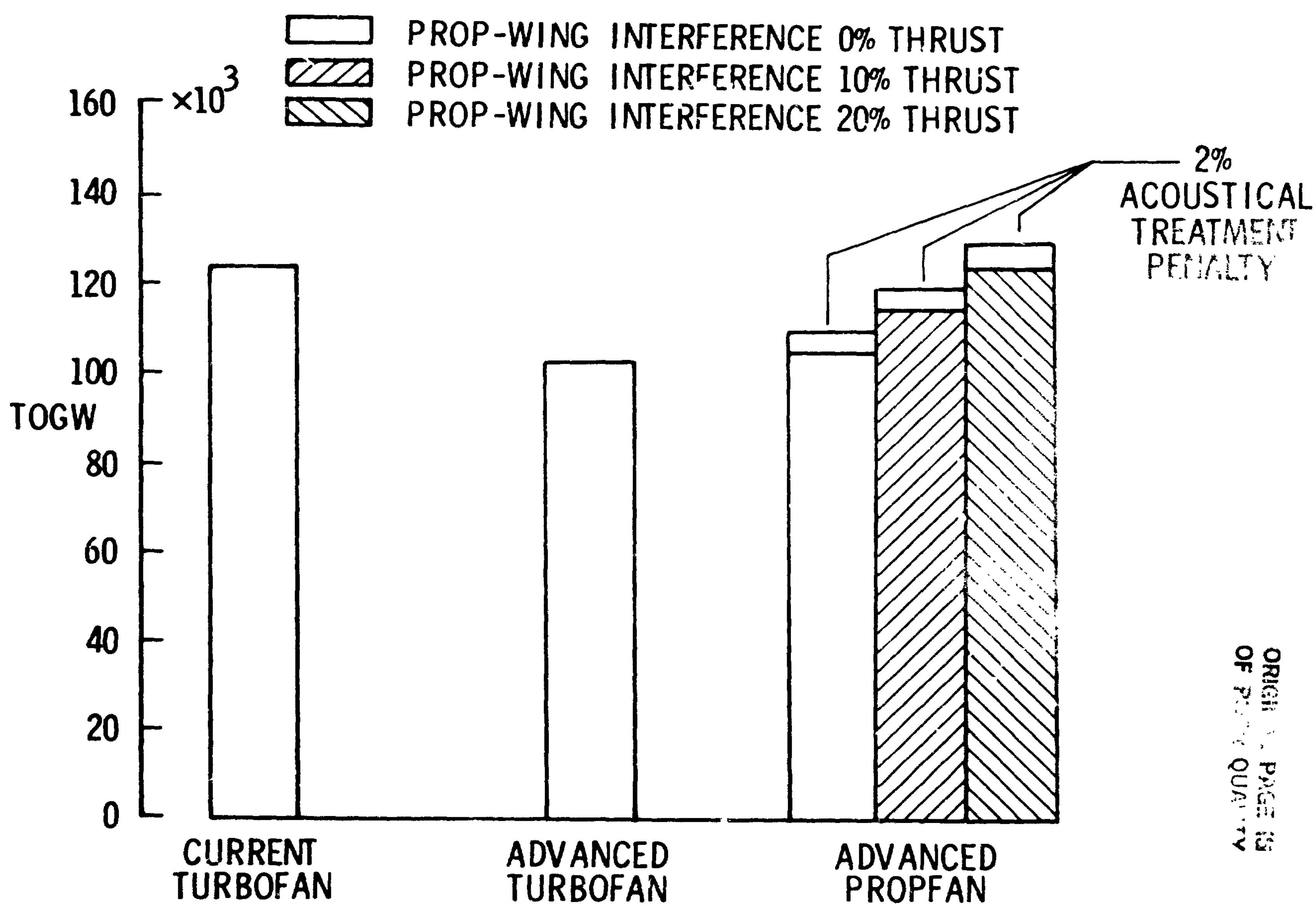


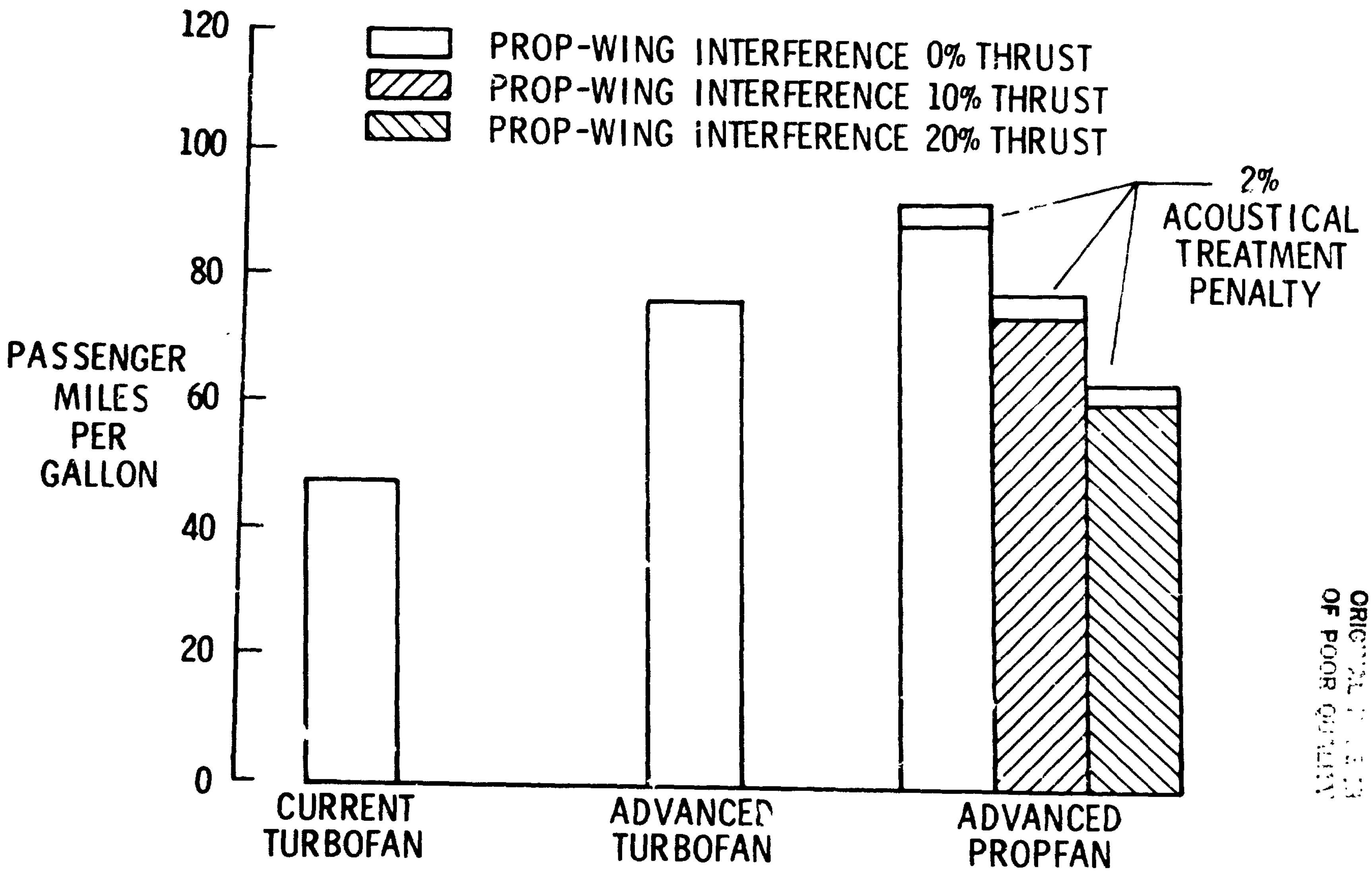
(b) Total mission fuel.

Figure 8.- Concluded.



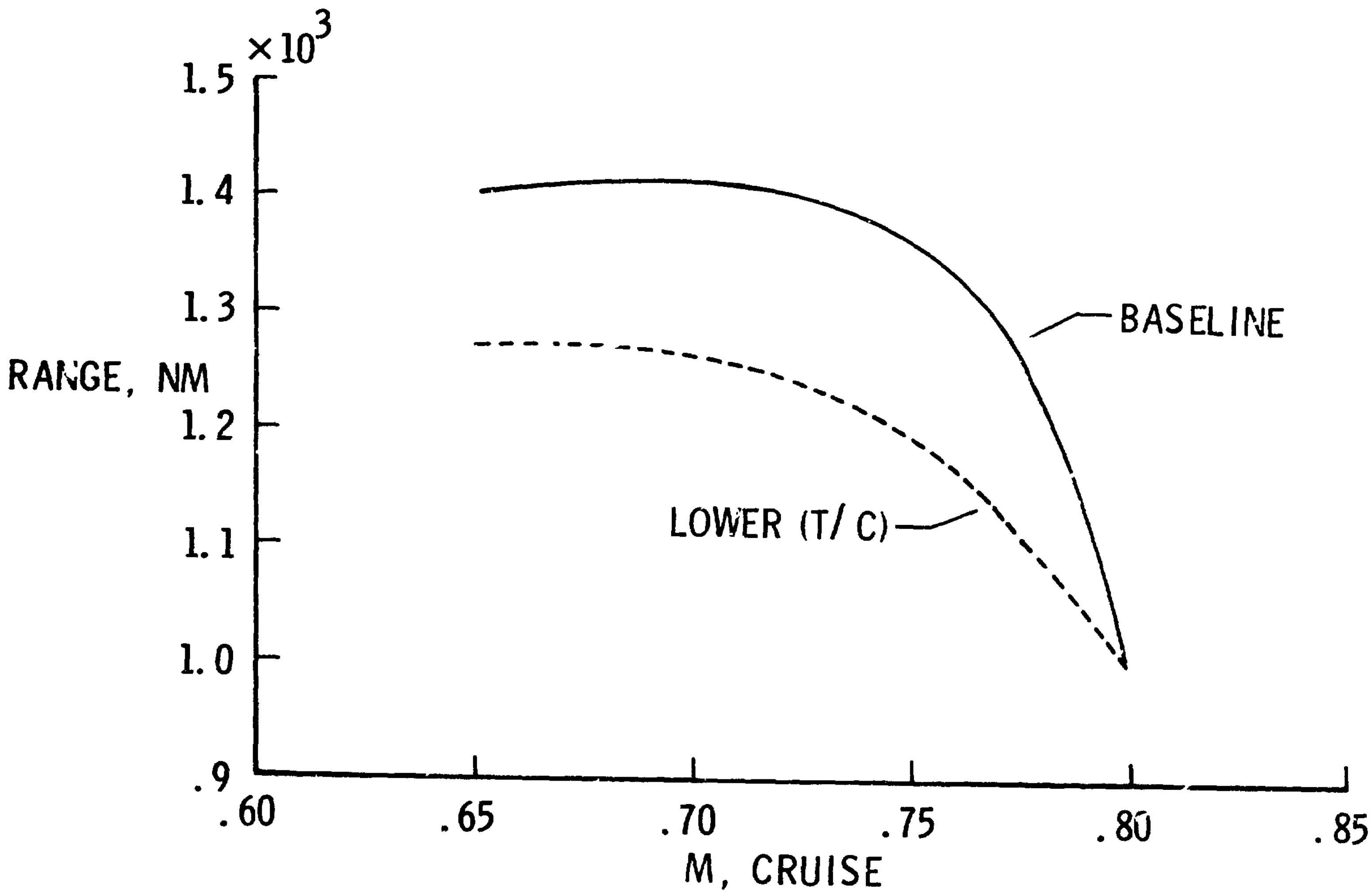
(a) Takeoff gross weight.

Figure 9.- Comparison of propfan with turbofan (range = 1000 n.mi.).



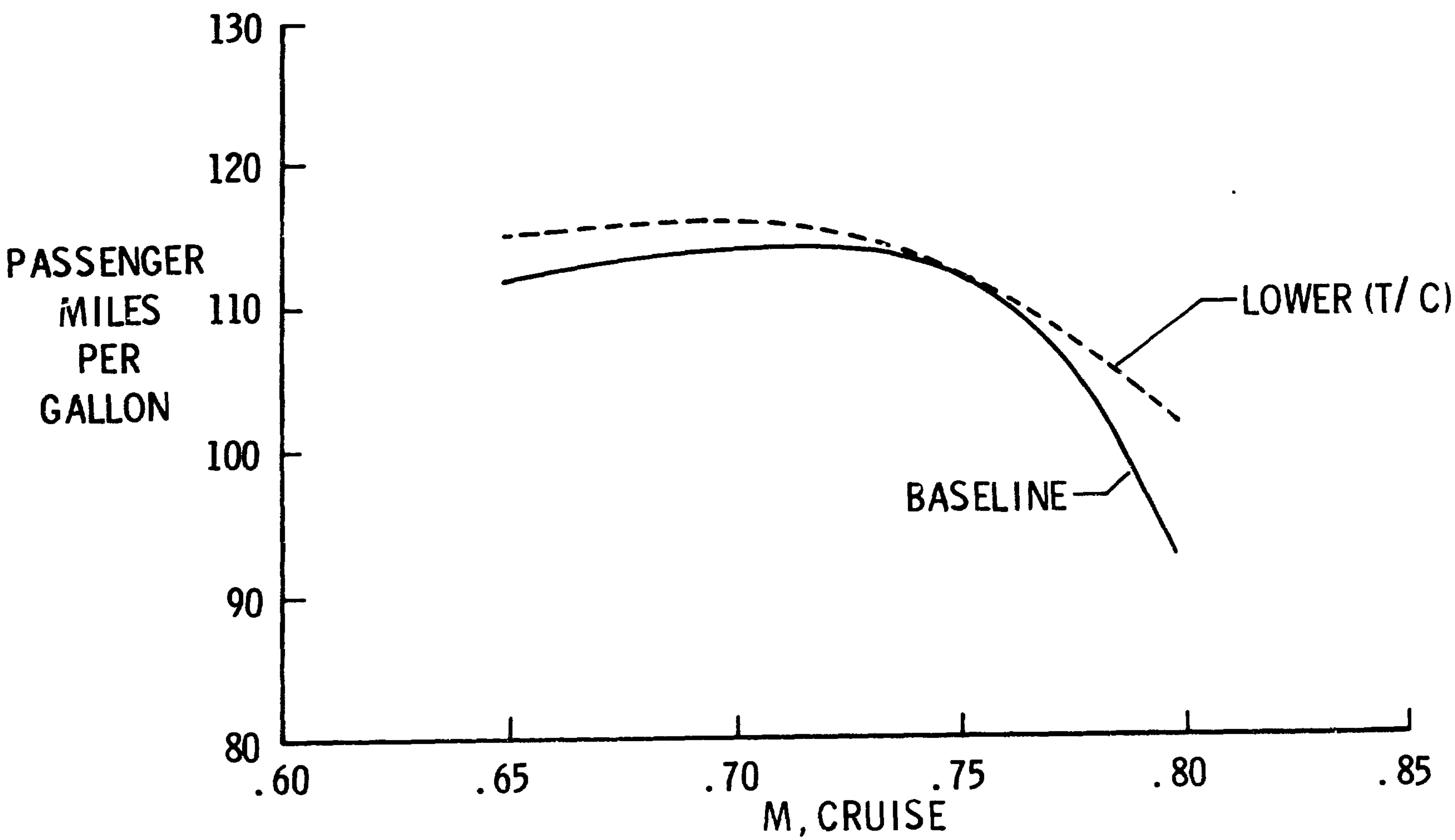
(b) Passenger miles per gallon.

Figure 9.- Concluded.



(a) Range.

Figure 10.- Effect of lower cruise Mach number (tip speed 750 ft/sec, prop-wing interference penalty 0%).



(b) Passenger miles per gallon.

Figure 10.- Concluded.