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ADDITIONAL STUDIES ON THE FEASIBILITY OF V/STOL CONCEPTS FOR SHORT-HAUL TRANSPORT AIRCRAFT

by K. R. Marsh

Prepared by
LTV AEROSPACE CORPORATION
Dallas, Texas
for Ames Research Center

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INTRODUCTION

Under contract to the National Aeronautics and Space Administration, Vought Aeronautics Division of LTV Aerospace Corporation developed a number of V/STOL Short-Haul Transport aircraft designs around a set of common design criteria. These design criteria are summarized in Table 1. These designs used turboprop, fan-in-wing, and propulsive wing propulsion system arrangements for attaining the design V/STOL capabilities. For the turboprop and fan-in-wing propulsion system concepts, VTOL, V/STOL, and STOL airplanes were developed; for the propulsive wing concept, only STOL airplanes were developed. STOL airplanes were developed for operation from 1,000-foot and 2,000-foot runways, and all airplanes were optimized to give a minimum direct operating cost on a 500-statute-mile stage length. The results of this design effort are summarized in Reference 1.

As a result of the findings gleaned from the work effort reported in Reference 1, further studies were made of the performance of these V/STOL short-haul transport aircraft when operated at off-design conditions and of design changes resulting from using different design criteria. Some of the basic aerodynamic input data that were utilized in developing these designs, and the noise characteristics of some of the designs, were evaluated. These additional studies are summarized herein.

STUDY RESULTS

Sensitivity of Airplanes to Off-Design Operations

Reduced cruise altitude effects. The airplanes designed for the study of Reference 2 were optimized to give a minimum direct operating cost at a 500-mile stage length, and cruise altitudes were high (25,000 to 35,000 feet); therefore, the resulting design limit equivalent airspeeds (EAS) were considerably less than the cruise speed capability of these airplanes for operations at low altitudes. The study assumed that there would be no air traffic control problems or operational problems that would prevent these V/STOL short-haul transport aircraft from operating at optimum cruise conditions. While such an operation is desired, it may not be achieved during the time period being considered for these vehicles. Hence, the effects of imposing lower cruise altitude limits were evaluated on some of these airplanes. The effects of lowering cruise altitude on performance and direct operating cost were studied for the turboprop VTOL, turboprop 2,000-foot STOL, and propulsive wing 2,000-foot STOL airplanes.

The turboprop VTOL airplane was designed for a 285 knot limit EAS and with an ultimate limit load factor of 4.07. The turboprop 2,000-foot STOL airplane was designed for a 282 knot limit EAS and an ultimate load factor of 4.07. The propulsive wing 2,000-foot STOL airplane was designed for a 365 knot limit EAS with an ultimate load factor of 4.05. These design limit equivalent airspeeds and ultimate load factors were selected after evaluating the effects of the 50-foot-per-second and 66-foot-per-second gust conditions on the operational limits and direct operating costs of these airplanes during the cruise, climb, and let-down portions for the design stage length.

Figure 1 presents the effect of cruise altitude on the normal rated power (NRP) cruise speed for each of these three airplanes. The turboprop VTOL and propulsive wing 2,000-foot STOL airplanes have a design cruise altitude of 35,000 feet. The turboprop 2,000-foot STOL airplane has a design cruise altitude of 25,000 feet. From Figure 1 it can be seen that the propulsive wing 2,000-foot STOL airplane can cruise with NRP down to altitudes as low as approximately 24,000 feet before encountering the limiting EAS. The turboprop VTOL airplane can cruise with NRP down to an altitude of approximately 22,000 feet before encountering the limiting EAS. The turboprop 2,000-foot STOL airplane can cruise with NRP down to an altitude of approximately 19,000 feet before encountering the limiting EAS. To use an NRP cruise capability at altitudes below these limiting altitudes will require an increase in the airplane design ultimate load factor and an increase in the airplane empty weight.

Figure 1a presents the required variations in the design ultimate load factor if these three airplanes are to be permitted to cruise with NRP at an altitude lower than those that were found to be critical. This figure shows that the ultimate load factor continues to increase for the turboprop airplanes all the way to a sea level cruise altitude. By contrast, the propulsive wing 2,000-foot STOL airplane reaches a maximum ultimate load factor at an altitude of approximately 5,000 feet. At lower cruise altitudes, the ultimate load factor begins to decrease. Although the cruise speed capability of the propulsive wing 2,000-foot STOL airplane is considerably higher than the cruise speed capabilities of the two turboprop powered airplanes, the lower aspect ratio of the wing of the propulsive wing airplane is sufficient to keep the load factor for this airplane at approximately the same level as that which has been found to be adequate for the turboprop airplanes.

Figure 2 presents a variation of direct operating costs (DOC) with the variation in cruise altitude for the 60-passenger turboprop VTOL airplane at stage lengths of 150 and 250 statute miles. It shows the difference in direct operating costs when flying at the limit EAS compared to flying at the airspeed with NRP. The curves for cruising with NRP are the dash lines below the critical altitude. (The design takeoff weights of these aircraft were unchanged; however, a structural weight penalty has been applied to permit cruising at the higher speeds that are compatible when using NRP at the lower altitudes. The airplane fuel availables have been reduced by the amount of the structural weight penalty.) The NRP curve for the 250-mile stage length condition is terminated at an altitude of approximately 12,000 feet because, at altitudes below this, the airplane does not have sufficient fuel to permit flying the 250-mile stage length. This figure shows the benefits, in terms of DOC, for being able to cruise with NRP if lower than optimum cruise altitude limits are imposed.

Figure 3 is similar to Figure 2 except that it is for the turboprop 2,000-foot STOL airplane. These curves are similar in shape to those that were developed for the turboprop VTOL airplane, but the effects of stage length are less pronounced and the variation of DOC with cruise altitude does not have as steep a slope for cruising at altitudes below the critical altitude. Both Figures 2 and 3 show that the DOC decrease slightly as the cruise altitude is reduced from the design cruise altitude to the critical cruise altitude. Below the critical altitude, the DOC for NRP cruise is approximately constant to an altitude of approximately 10,000 feet, and then it begins to increase at the lower altitudes. Cruise at the limit EAS below the critical altitude results in increased DOC.

Figure 4 has been developed to show the variation of DOC with cruise altitude for the propulsive wing 2,000-foot STOL airplane. This curve shows that the variation of direct operating costs with cruise altitude has only a negligible variation until the critical altitude is reached. The variation of direct operating costs with cruise altitude below the critical altitude is not as pronounced for the propulsive wing 2,000-foot STOL airplane as for two turboprop airplanes.

In summary, then, these studies have shown that if it is required that V/STOL short-haul transport aircraft operate at less than optimum cruise altitudes, it will probably be profitable to compromise these airplanes for cruising at lower than optimum cruise altitudes by designing for a higher EAS.

Effects of varying the operating range. - Although the airplanes designed for the ground rules specified in Reference 1 had a design stage length of 500 statute miles, it is realized such vehicles would seldom be operated at this specific stage length. Hence, the effects of operating at other stage lengths on the takeoff performance were determined for some of these aircraft, assuming that the lower structural load factors would be acceptable. Figures 5 through 8 present the results of these studies for the turboprop VTOL, the turboprop 1,000-foot STOL, the fan-in-wing V/STOL, and the propulsive wing 1,000-foot STOL airplanes.

Figures 5 through 8 present plots of takeoff distance and gross weight versus the operational range for these four aircraft. The takeoff performance shown is the total distance required to clear a 50-foot obstacle on a sea level, 86°F day with one engine failed. Figure 5 shows that the turboprop VTOL airplane, with one engine failed, has a VTOL capability sufficient to permit flying up to a 500-mile stage length (the design point for this aircraft). If, instead of using a vertical takeoff for the 500-mile stage length, this airplane, operated in the STOL mode for takeoff, would have a takeoff distance of less than 250 feet to clear a 50-foot obstacle. This airplane could also have an operational range of 1,000 miles and still require less than 300 feet to clear a 50-foot obstacle. If it should be so desired, instead of using a short takeoff run when flying a stage length of 1,000 miles, this airplane could have its passenger load reduced from the design number of 60 to 44 and still use vertical takeoff for the 1,000-mile stage length. The economy of the turboprop propulsion system is shown on this figure in that only approximately 7,500 pounds of fuel are required to extend the operational range from 50 miles to 1,000 miles. It has been assumed for these analyses that adequate space is available for such fuel.

Figure 6 presents a comparable curve to Figure 5, except it is for the turboprop 1,000-foot STOL airplane. It is seen that a large change in range has little effect on takeoff distance. The takeoff performance presented in this figure assumes that the airplane does not use any wing tilt. A wing tilting capability of 20° is available (this 20° capability was put in to permit the airplane to meet its design landing requirements), and the use of this 20° wing tilt could permit this takeoff distance to be considerably shorter. This figure again shows the efficiency of the turboprop propulsion system in that less than 7,000 pounds of fuel are required to extend the operational range from 50 statute miles to 1,000 statute miles.

Figure 7 presents the effects of takeoff distance on the operational range for the fan-in-wing V/STOL airplane. This figure shows that the VTOL capability of this airplane will permit it to fly a 50-mile stage length; but if the stage length exceeds 50 miles, the airplane must use a short takeoff run. This figure also shows that approximately 16,000 pounds of fuel are required to extend the operational range from 50 statute miles to 1,000 statute miles. It can be found from this figure that this airplane can fly a 500-mile stage length using its VTOL capability if the passenger load is reduced from the design value of 60 to a level of 22.

Figure 8 presents the effect of takeoff distance on the operational range for the propulsive wing 1,000-foot STOL airplane. This figure shows that increasing the operational range from 50 statute miles to 1,000 statute miles increases the fuel required by approximately 10,000 pounds - not quite as efficient as the turboprop propulsion system but considerably more efficient than the fan-in-wing propulsion system. A comparison of the data presented in Figure 8a with the comparable data presented in Figures 5a through 7a shows that the variation of takeoff distance with range is not nearly so linear for the propulsive wing airplane as for the turboprop or fan-in-wing airplanes.

Sensitivity of Airplane Designs to Alternate Design Criteria

Sensitivity of airplanes design to design stage length. - In order to determine the sensitivity of the airplanes designed under Reference 2 to the design stage length, a study has been made on the tilt-wing VTOL airplane and the fan-and-wing V/STOL airplanes. For this study the design range was reduced to 300 statute miles, and the fuel reserves were reduced to simply that fuel required for entering the traffic pattern and making a landing on the first pass. It is considered that the resulting airplanes represent the minimum practical sizes. One other change in design criteria made for these airplanes was that the VTOL design criteria were applied only at the landing condition after a 50-mile mission.

Table 2 presents a comparison of some of the more important characteristics of the airplanes which have been optimized for the 300- and 500-mile stage length. A close analysis of the data presented in this table will show that the weight of the turboprop VTOL airplane designed for 300 miles is approximately 90% of that for the airplane designed for 500 miles. By contrast, the fan-in-wing V/STOL airplane designed for 300 miles weighs approximately 80% as much as the airplane which was designed for 500 miles. The reason for this difference in gross weight ratio comes about as a result of the reduction in the quantity of fuel required. The turboprop VTOL airplane optimized for a stage length of 300 miles will have an optimum cruise altitude of 25,000 feet. A projection of the data presented in this table will show that the weight of the fan-and-wing V/STOL airplane would equal the weight of the turboprop VTOL airplane at a design stage length of approximately 175 statute miles.

Propulsive wing V/STOL airplane. - During the study reported in Reference 1, only STOL propulsive wing airplane designs were developed. As a result of the promise of these STOL designs, it was considered appropriate to develop a V/STOL propulsive wing airplane to the same design criteria used for the designs of Reference 1. A three-view drawing of the resulting propulsive wing V/STOL airplane is presented in Figure 9. This airplane is fitted with four gas generators driving four wing fans. The gas generators are connected to the turbines which drive these wing fans with an interconnecting hot-gas duct system. The design gross weight of the airplane is 73,300 pounds, and the airplane has a design cruise Mach number of 0.9 at its design cruise altitude of 40,000 feet. This airplane uses 59.5-inch diameter fans. The four main gas generators produce 6,380 pounds of thrust each. The airplane also has two lift-type gas generators located in the nose of the fuselage to provide hover and slow speed pitch trim and control. The pitch engines are sized so that each is capable of providing the maximum longitudinal trim for the hover mode, plus 20 percent of the hover pitch control requirements, and the resulting engines are capable of developing 15,250 pounds of thrust each. The exhaust system for these engines is arranged so that they are run at full thrust when in use. The gas exhaust from these engines is varied between the front and aft outlets in order to vary the pitching moment. A weight breakdown of the propulsive wing V/STOL airplane is presented in Table 3.

Direct operating cost comparisons between the propulsive wing 1,000-foot STOL airplane and the propulsive wing V/STOL airplane have been made using parametric-type costing equations rather than the modified ATA costing methodology used in Reference 1. The parametric costing equations show that direct operating costs for the V/STOL airplane were just slightly higher than those of a 1,000-foot STOL airplane. Since the V/STOL airplane is approximately 10% heavier than the 1,000-foot STOL airplane, the depreciation costs should be approximately 10% greater than the depreciation costs of the propulsive wing 1,000-foot STOL airplane. The fuel required is approximately 18% greater for the propulsive wing V/STOL airplane than for the propulsive wing 1,000-foot STOL airplane; therefore, the flying operations costs will be higher (to a lesser percentage). Maintenance costs would approximately equal the maintenance costs that were determined for the propulsive wing 1,000-foot STOL airplane. As a result of these considerations, it is projected that a detailed costing analysis of the propulsive wing V/STOL airplane would show direct operating costs were between 10 and 15 percent greater for the propulsive wing V/STOL airplane than for propulsive wing 1,000-foot STOL airplane.

Propeller RPM-Engine RPM Match

In the study of Reference 1, the propellers of all the turboprop aircraft were designed for maximum static thrust. Maximum static thrust was obtained with a propeller tip speed of 1,000 feet per second (fps). It was found during the course of the study that cruise performance, rather than takeoff performance, was critical for sizing the propulsion system of the turboprop STOL aircraft. The best cruise speed occurred for an NRP setting and at a propeller RPM that was between 70 and 80 percent of the RPM needed to give a 1,000 fps propeller tip speed at takeoff. The use of this low percentage of the design engine free-turbine RPM caused the engine performance to be penalized; consequently, a study was made of different takeoff propeller tip speeds coupled with 100 percent engine free-turbine RPM (i.e., different engine free-turbine to propeller gear ratios) with different propeller activity factors and integrated design lift coefficients. By matching the 100 percent engine free-turbine RPM with an 800 fps propeller tip speed instead of the original 1000 fps propeller tip speed, the cruise speed was increased from 340 knots to 370 knots with a negligible change in takeoff performance for both the turboprop 1,000-foot STOL and 2,000-foot STOL airplanes (Reference 1). This reduction in propeller takeoff tip speed would also provide a large reduction in propeller noise during takeoff, and these effects will be discussed later.

In light of these performance improvements for the turboprop STOL airplanes, an additional study was conducted to determine if similar improvements could be obtained for the turboprop VTOL 60-passenger airplane by rematching the propeller takeoff RPM with the engine free-turbine RPM. Figures 10 through 14 summarize the results of varying the propeller takeoff tip speed, the engine free-turbine RPM during takeoff (the engine free-turbine can be operated at 125 percent of the design RPM without adversely affecting the structural integrity of the engine), and the engine shaft horsepower (SHP) level. The effects of these variables on payload are presented in Figure 10, on takeoff weight in Figure 11, and on cruise speed in Figure 12. The resulting change in operating costs is given in Figures 13 and 14. Reducing the propeller takeoff tip speed from 1000 fps to 900 fps for the engine free-turbine operating at 100 percent RPM reduces the VTOL takeoff weight (because of the reduction in static thrust) and payload by 3,200 pounds and increases the cruise speed from 339 knots to 362 knots (because of a better propeller RPM-engine free-turbine RPM match at cruise). By using the gear ratio which gives a propeller tip speed of 900 fps at

100 percent engine free-turbine RPM and overspeeding the engine free-turbine at takeoff to 111 percent (in order to get a takeoff propeller tip speed of 1,000 fps), the takeoff weight and payload are reduced by only 450 pounds and the cruise speed is increased from 339 knots to 357 knots. Further overspeeding of the engine free-turbine for takeoff while maintaining a 1,000 fps propeller tip speed would cause a more rapid drop in payload.

Increasing the installed engine shaft horsepower makes possible the use of lower propeller takeoff tip speeds and/or further overspeeding of the engine free-turbine during takeoff in order to provide a better match between the hover and cruise thrust requirements while still maintaining a constant passenger load.

Figure 13 presents the relative direct operating costs on a cost-per-airplane-mile basis associated with rematching the propeller takeoff tip speed, the engine free-turbine RPM during takeoff, and the percentage increase in shaft horsepower over that used for the basic design. This figure shows that overspeeding the engine free-turbine for takeoff and reducing the takeoff propeller tip speed significantly reduces the direct operating costs on a per-airplane-mile basis; but increasing the engine shaft horsepower does not make an appreciable (less than one percent) effect.

If the VTOL ground rules are retained and accounting for the change in payload is made by varying the passenger load (assuming space is available for additional passengers and/or fuel, as appropriate), the effects on the relative direct operating costs on a cost-per-seat-mile basis are shown in Figure 14. This curve has been developed assuming the number of passengers carried equals the payload (Figure 10) divided by 220 (the weight allowance per passenger, including baggage and revenue cargo).

These curves show that a better match between engine and propeller RPM can be made for turboprop V/STOL short-haul transport aircraft than was used for the turboprop point design aircraft of Reference 1. As an example, reducing the takeoff propeller tip speed to 950 fps, increasing the engine takeoff free-turbine speed to 118 percent of its design value, and increasing the installed shaft horsepower by 10% over the value used in Reference 1 would reduce the direct operating costs per-seat-mile by approximately seven percent compared to those costs determined in Reference 1.

Drag Polars

In order to provide a more basic understanding of some of the fundamental aerodynamic characteristics used in configuring the airplanes developed in response to Reference 2, landing drag polars have been developed for four of these airplanes and are presented in Figures 15 through 18. These landing polars are for operating on sea level, 86°F day ambient atmospheric conditions.

Figure 15 presents the landing drag polar for the turboprop V/STOL airplane. This polar is for a condition where the wing is tilted up 20 degrees and the 48 percent chord, full span, double-slotted flaps are deflected 60 degrees. The angles of attack are varied from zero degree to a positive 12 degrees, and the thrust coefficient, based on slipstream dynamic pressure, is varied from 0.5 to 0.8. The symbol in this figure, located at a lift coefficient of approximately 10 and a drag coefficient of approximately 1.5, represents the condition for an 800-foot-per-minute rate of descent at a 54-knot flight speed. This condition represents the critical STOL landing conditions as specified by Reference 2. It can be seen from this figure that at this landing condition, and with this wing incidence and flap configuration, the airplane is operating close to the buffet onset boundary. Flight experience with the XC-142A airplane shows that the initial buffet is mild. This curve shows that increasing the thrust coefficient from .65 to .75 (the equivalent to increasing the engine power from approximately 30% to 40%) will give a normal acceleration increase of 0.30 g's. If a pilot should encounter an undesirable flight condition while flying so close to the buffet onset boundary, a light application of power will correct it; therefore, it is expected that the airplane would be safe for such operations.

Figure 16 presents the landing drag polar for the turboprop 2,000-foot STOL airplane. For this curve, the angles of attack are varied from zero degree to a positive 12 degrees, and the thrust coefficients are varied from 0.1 to 0.7. The symbol shown at a lift coefficient of approximately 3.7 and a drag coefficient of approximately 0.4 represents the aerodynamic conditions that are required for descending at 800 feet per minute while flying at 86 knots, the critical landing condition specified by Reference 2 for this airplane. From this figure it can be determined that increasing the angle of attack from approximately six degrees to approximately 8.5 degrees will provide an 0.1g normal acceleration as required by Reference 2 for this situation where one engine has failed. It can be also seen from this figure that increasing the thrust coefficient from approximately .25 to approximately .29 will also give an 0.1g normal acceleration capability to the airplane, another alternate design condition specified by Reference 2. For the same flight condition, increasing the angle of attack from 6 degrees to approximately ten degrees and increasing the thrust coefficient from approximately .25 to approximately .35, or simply increasing the thrust coefficient to .45 with no angle of attack change, will give an increase in the normal force coefficient of 0.3, another of the requirements of Reference 2. In summary then, it can be seen that this airplane has adequate margin in all of the critical conditions of the landing mode of operation.

Since the wing geometry for the turboprop V/STOL airplane and the turboprop 2,000-foot STOL airplane are similar, the polars for these airplanes will be similar for comparable wing incidences and flap deflection conditions. A comparison of Figures 15 and 16 gives an indication of the effects of wing tilt on these polars. As an example, Figure 16, a zero wing tilt condition, shows that at a thrust coefficient of 0.7 and an angle of attack of 8°, this airplane will have a lift coefficient of approximately

7.5 and a drag coefficient of approximately -1.2. Figure 15, for a wing tilt wing condition of 20 degrees, shows that at the same thrust coefficient and angle of attack, the airplane develops a lift coefficient of approximately 10.7 and a drag coefficient of a positive 1.4; therefore, adding 20 degrees of wing incidence has increased the trimmed lift coefficient by over 3.2, and the drag coefficient has increased by approximately 2.6. Thus, these two figures illustrate the operational flexibility available to the pilot of a tilt wing V/STOL airplane. The pilot of such an airplane has the ability to adjust his wing tilt to provide a wide latitude of safe flight conditions in the slow speed flight modes.

Figure 17 presents the landing drag polar for the fan-in-wing V/STOL airplane developed in response to Reference 2. This drag polar is specifically for a condition of flying at 54 knots at sea level on an 86°F day. The symbol located at a lift coefficient of approximately 7.0 and a drag coefficient of approximately 1.25 indicates the flight conditions for making an 800-foot-per-minute rate of descent at a 54-knot flight condition. It should be kept in mind, while referring to this figure, that this polar assumes the nose fan is not operative, and the nose fan makes a large contribution to the normal force on this airplane. (The nose fan lift will provide a lift coefficient change of approximately 1.5 at this flight condition.) This figure shows that increasing the wing fan thrust from approximately 60% to approximately 75% for the condition where the wing fan louvers are deflected aft by 10° will provide 0.1g normal acceleration required by Reference 2 for the engine-out flight situation. It can also be seen from this figure that increasing the power to 90 percent at a constant angle of attack will increase the lift coefficient to approximately 9.5, a value needed to provide a .3g normal acceleration with all engines operating, another of the conditions specified by Reference 2. It does not appear from this figure that increasing the angle of attack, alone, will provide the capability of increasing the normal force coefficient by 0.1, one of the alternatives specified by Reference 2.

Figure 18 presents the landing drag polar for the propulsive wing 2,000-foot STOL airplane. This landing drag polar is specifically for the operational conditions on a sea level, 86°F day, and it is for the nose fan inoperative case. The symbol shown at a lift coefficient of approximately 3.4 at a drag coefficient of approximately 0.4 indicates the operational condition for an 800-foot-per-minute rate of sink at a flight condition of 86 knots. (The nose fan lift will provide a lift coefficient increase of approximately 0.6 at this flight condition.) From this curve, it can be seen that the airplane can increase its angle of attack at a constant power setting to give a change in normal acceleration of 0.1 with a flap deflection of 90° - one of the engine-out requirements specified by Reference 2. The propulsion system can maintain 80% thrust with one engine failed by operating the engines at emergency power. The airplane can increase power and angle of attack to get the increase in normal acceleration of 0.3 to satisfy the margin requirements for all engines operating as specified by Reference 2.

Noise

Effects of aircraft size. - Under Reference 2, 60-, 90-, and 120-passenger airplanes were developed for selected turboprop, fan-in-wing, propulsive wing V/STOL designs. Figures 19 through 21 present perceived noise level contours during the takeoff mode of flight for 60- and 120-passenger aircraft designed around each of these three V/STOL concepts. These contours describe the noise levels for ground-based observers with an assumed climbout angle of 20°. Figure 19 shows the effect of aircraft size on perceived noise level for the turboprop VTOL airplane. This curve shows that for the turboprop concept, the noise level at most distances from the source for the 120-passenger airplane is from 5 to 7 PNdb higher than for the 60-passenger aircraft.

Figure 20 presents the effect of size on the perceived noise level for the fan-in-wing V/STOL airplane during the takeoff flight mode. This figure shows that the perceived noise level is approximately 10 decibels higher for the 120-passenger airplane than it is for the 60-passenger airplane.

Figure 21 presents the effects of size on perceived noise level for the propulsive wing 2,000-foot STOL airplane during takeoff. This curve shows different results than have the two previous curves in that the perceived noise level for the larger airplane is lower than it is for the smaller airplane. This unusual change in trend occurs because the jet engine RPM increases as the airplane size increases from the 60-passenger size to a 120-passenger size. This increase in engine RPM shifts the spectrum peak beyond the last octave band; thus, the perceived noise level effects from the higher octave bands are lowered.

Effect of reduced propeller tip speed. - It has been mentioned previously that for the turboprop 2,000-foot STOL airplane, the propeller tip speed can be reduced and provide a more efficient match between the desired propeller performance characteristics for takeoff and cruise flight conditions. Another benefit that can be derived from reducing the takeoff propeller tip speed is a reduction in the propeller noise in the takeoff mode of flight. Figure 22 presents a description of the effects of the propeller tip speed on the perceived noise level contours for the turboprop 2,000-foot STOL airplane during a takeoff. This curve shows perceived noise level contours for both 1,000-foot-per-second propeller tip speeds and 800-foot-per-second propeller tip speeds. This curve shows that for the airplane fitted with propellers having an 800-foot-per-second tip speed, the perceived noise level is nearly 10 decibels lower than for the airplane fitted with propellers using a 1,000-foot-per-second tip speed.

Figure 23 also shows the effects of the propeller tip speed on noise during the takeoff mode. This curve presents the maximum radial distance from the airplane at which a given perceived noise level is detected. Curves are presented for the turboprop V/STOL airplane fitted with propellers rotating at a 1,000-foot-per-second tip speed and for the turboprop 2,000-foot STOL airplane fitted with propellers rotating with propeller tip speeds of 1,000-foot-per-second and 800-foot-per-second. The primary difference between noise level for the turboprop V/STOL airplane and the turboprop 2,000-foot STOL airplane fitted with a propeller rotating at 1,000-foot-per-second tip speeds are the power differences between these two airplanes. The engines of the turboprop V/STOL airplane develop approximately 60% more power than do the engines of the turboprop 2,000-foot STOL airplane.

It is important to note that while the source noise level between using 1,000-foot-per-second and 800-foot-per-second tip speed is not great at distances very close to the airplane, sharp reductions in noise do occur as the distance from the airplane is increased. These reductions occur primarily because the low frequency band noise levels have been reduced for the propeller having an 800 fps tip speed. The higher frequency noise levels, which have not been appreciably reduced, attenuate much more rapidly than do the lower frequency noises.

Accuracy of noise predictions methods. - In order to get an assessment of the accuracy of the noise prediction methods that have been utilized in this study and the study reported in Reference 1, a comparison has been made of measured and calculated perceived noise levels for the XC-142A airplane and the Breguet 941 airplane. Figure 24 presents a comparison of the measured and calculated perceived noise levels for the XC-142A airplane in hover. The calculated curves come out as pure circles about the hover point, whereas the measured data have lobes located 45 degrees to left or right in front and aft around the airplane.

Figure 24 shows that these lobes in the quadrants aft of the airplane for the 80 PNdb noise level go beyond the calculated lines slightly. The lobes in the forward quadrants of the airplane do not extend to the calculated lines. For the 90 PNdb level, the measured lobes extend to the calculated lines in the aft quadrant and again do not extend to the calculated levels in the forward positions. When the measured lines extend beyond the calculated lines, the noise is greater than would be calculated. These curves show that the calculations can be as much as 7 decibels in error for this particular flight condition and this airplane. It should be noted that for the 100 PNdb level, the calculations very closely agree with the measured values.

Figure 25 presents a comparison of measured and calculated noise levels for the Breguet 941 as measured from a side-line position during a takeoff ground roll. Two microphones were used. One was 70 feet to the side of the centerline of the runway and the other 370 feet to the side of the runway centerline as shown on Figure 25. The calculated values are compared with measured values that were made during four different takeoff runs. In general, the calculations for microphone number 1 position are higher than the measured values - by as much as 5 decibels for one frequency range. For the microphone location number 2, the calculations are much more accurate; but in the higher frequency bands, one position was found to be calculating excessive noise by nearly 9 decibels.

Figures 24 and 25 show that the existing prediction methods can make reasonably close estimates of noise in general; but these figures also illustrate that the existing calculation methods are totally inadequate for making accurate estimates of noise for a wide variety of conditions and at all octave bands. It should be kept in mind that an error of five to ten decibels out of 115 seems like a very small percentage, but an increase of six decibels at any level means that the noise for the higher decibel level is twice as loud as for the lower level. Additional improvement is needed on noise estimating methods for V/STOL aircraft that utilize propellers. It is also expected that improvements will be required on noise estimating methods for jet powered V/STOL aircraft.

SUMMARY

As a result of the additional examinations and perturbations made on the designs developed in response to Reference 2 and reported in Reference 1, the following conclusions are drawn:

1. A V/STOL short-haul transport airplane should have serious consideration given in the selection of its design characteristics to the possibility that this airplane may have to operate at nonoptimum cruise conditions. Such considerations would probably result in redesigning the aircraft of Reference 1 which were optimized for a 500-mile stage length. This redesign would permit the aircraft to operate at higher equivalent air speeds than would be required if the airplane were at optimum cruise conditions.

2. If space is available for fuel, V/STOL aircraft can use slightly increased takeoff distance and obtain a large increase in the maximum operational stage length.

3. The design of V/STOL aircraft is very sensitive to the design stage length, and the choice of the best V/STOL arrangement may vary as the design stage length is varied.

4. Proper matching of the propeller takeoff RPM and the engine takeoff RPM for turboprop V/STOL aircraft designs can provide DOC benefits and reductions in the far field noise characteristics of these airplanes. These changes did not reduce the takeoff performance of the turboprop STOL airplanes, but they did give increased cruise speed. For the turboprop VTOL airplanes, the reduced propeller takeoff tip speed and the increased engine takeoff RPM reduced the hover performance, and, hence, it was necessary to increase the engine size.

5. In general, as the aircraft size increases, the perceived noise level characteristics in takeoff of the V/STOL airplanes increase.

6. The existing noise prediction methods are inadequate to make accurate predictions of the noise of propeller-driven aircraft.

REFERENCES

1. Marsh, K. R., "Study on the Feasibility of V/STOL Concepts for Short-Haul Transport Aircraft," NASA CR-670, January 1967

2. Contract NAS2-3036, "Study on the Feasibility of V/STOL Concepts for Short-Haul Transport Aircraft"

TABLE I

V/STOL SHORT-HAUL TRANSPORTS

DESIGN GROUND RULES

- Passenger plus baggage weight is 200 pounds per passenger
- Revenue cargo is 10% of the design passenger weight
- The perceived noise level in the cargo compartment shall not exceed 75 decibels in takeoff or 70 decibels in cruise
- The landing gear is designed for a 12 fps rate of sink
- The airplane structural design criteria is that defined by Federal Aviation Regulations, Part 25, Airworthiness Standard: Transport Category Airplanes
- Takeoff and landing performance is based on sea level, 86°F day
- Special VTOL design criteria:

  T/W = 1.15, all engines operating, no control input
  T/W = 1.05, all engines operating, 50% of the maximum control about the critical axis plus 20% about the other two axes
  T/W = 1.05, the critical engine inoperative, no control input
  T/W = 1.0, the critical engine inoperative, 50% of the maximum control about the critical axis plus 20% about the other two axes

- Special STOL design criteria:

  Takeoff field length is calculated assuming a critical engine is failed

  Landing field length required is the calculated required landing distance divided by 0.60

  The rate of descent shall not exceed 800 fpm during the landing approach

  The maximum deceleration roll during the landing ground roll shall not exceed 0.5 g's

TABLE 2

COMPARISON OF AIRPLANES DESIGNED FOR 300- AND 500-MILE STATUTE MILE STAGE LENGTHS

Item	Turboprop	VTOL	Fan-in-Wing	V/STOL
Design Stage Length, S.Mi.	500	300	500	300
Gross Weight, lb.	62,300	55,950	79,587	63,300
Design VTOL Weight, lb.	62,300	52,320	72,827	56,555
Fuel Load, lb.	6,407	3,835	17,190	7,210
SHP or Thrust per Engine	5,960	5,080	6,400	5,160
Propeller or Wing Fan Diameter	18.3 Ft.	16.1 Ft.	87 In.	79 In.
Optimum Cruise Altitude, Ft.	35,000	25,000	35,000	35,000
Optimum Cruise Speed, Knots	350	395	460	460

TABLE 3

ESTIMATED WEIGHT BREAKDOWN

60-PASSENGER PROPULSIVE WING V/STOL AIRPLANE

Component	Weight, Pounds
Wing Group	4,966
Tail Group	1,559
Body Group	7,445
Alighting Gear	2,743
Flight Controls Group	3,596
Nacelle Group	2,238
Engines	4,760
Exhaust System	134
Lubricating System	140
Fuel System	785
Engine Controls	128
Starting System	200
Fan System	6,127
Hot Gas Ducting System (including diverter values)	1,052
Instrument Group	383
Hydraulic and Pneumatic Group	338
Electrical Group	1,336
Electronics Group	691
Furnishing Group	5,391
Air-Conditioning Group and Anti-Icing	1,423
Auxiliary Gear Group	40
TOTAL EMPTY WEIGHT	45,475
Water, Food, Beverage, etc.	633
Crew Plus Baggage	520
Passengers Plus Baggage	12,000
Cargo	1,200
Fuel (including unusable fuel)	13,222
Oil	250
TOTAL USEFUL LOAD	27,825
TAKEOFF GROSS WEIGHT	73,300

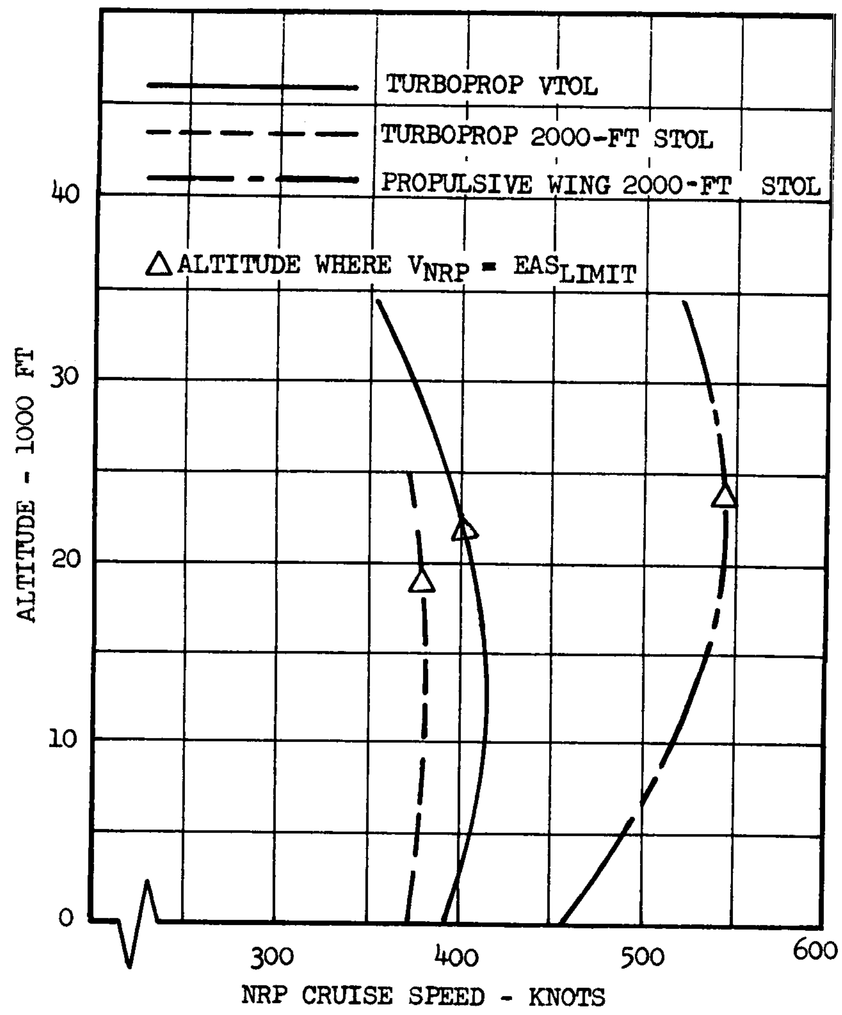


Figure 1. Effect of Altitude on NRP Cruise Speed

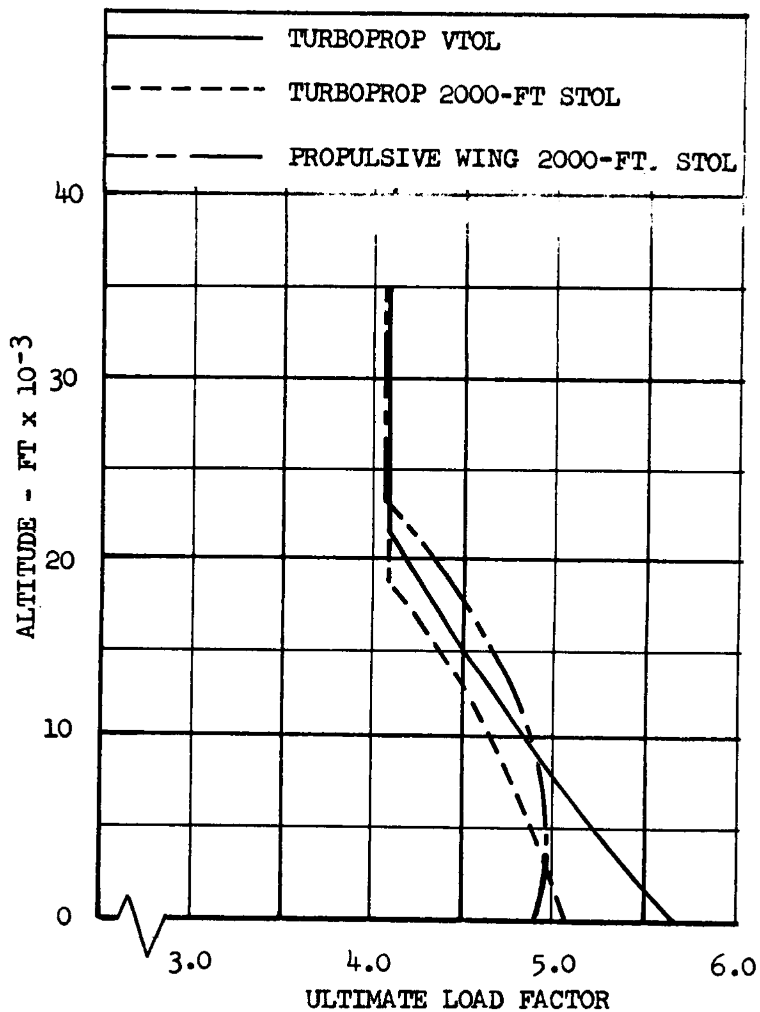


Figure 1a. Effect of NRP Cruise on the Required Ultimate Load Factor

60-PASSENGER TURBOPROP VTOL

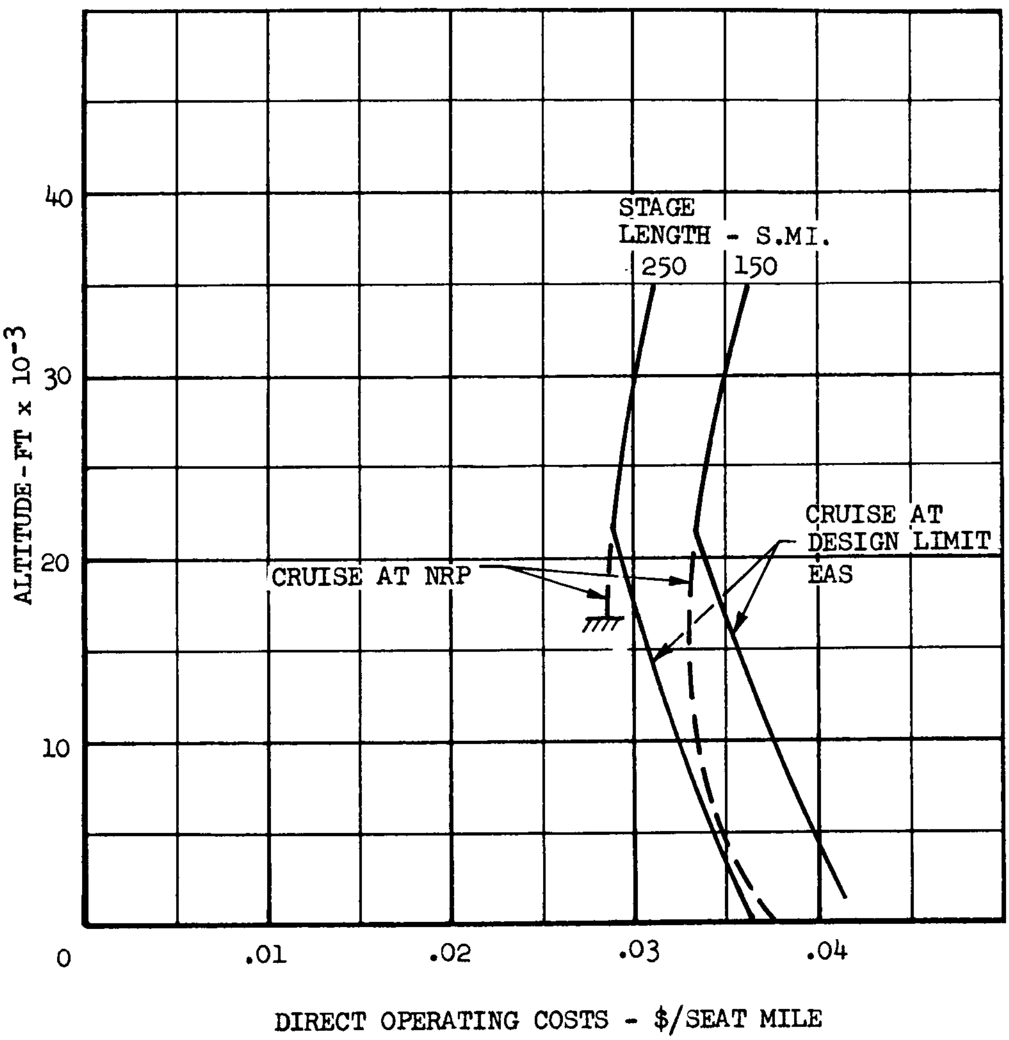


Figure 2. D.O.C. Versus Cruise Altitude

60-PASSENGER TURBOPROP 2000-FT STOL

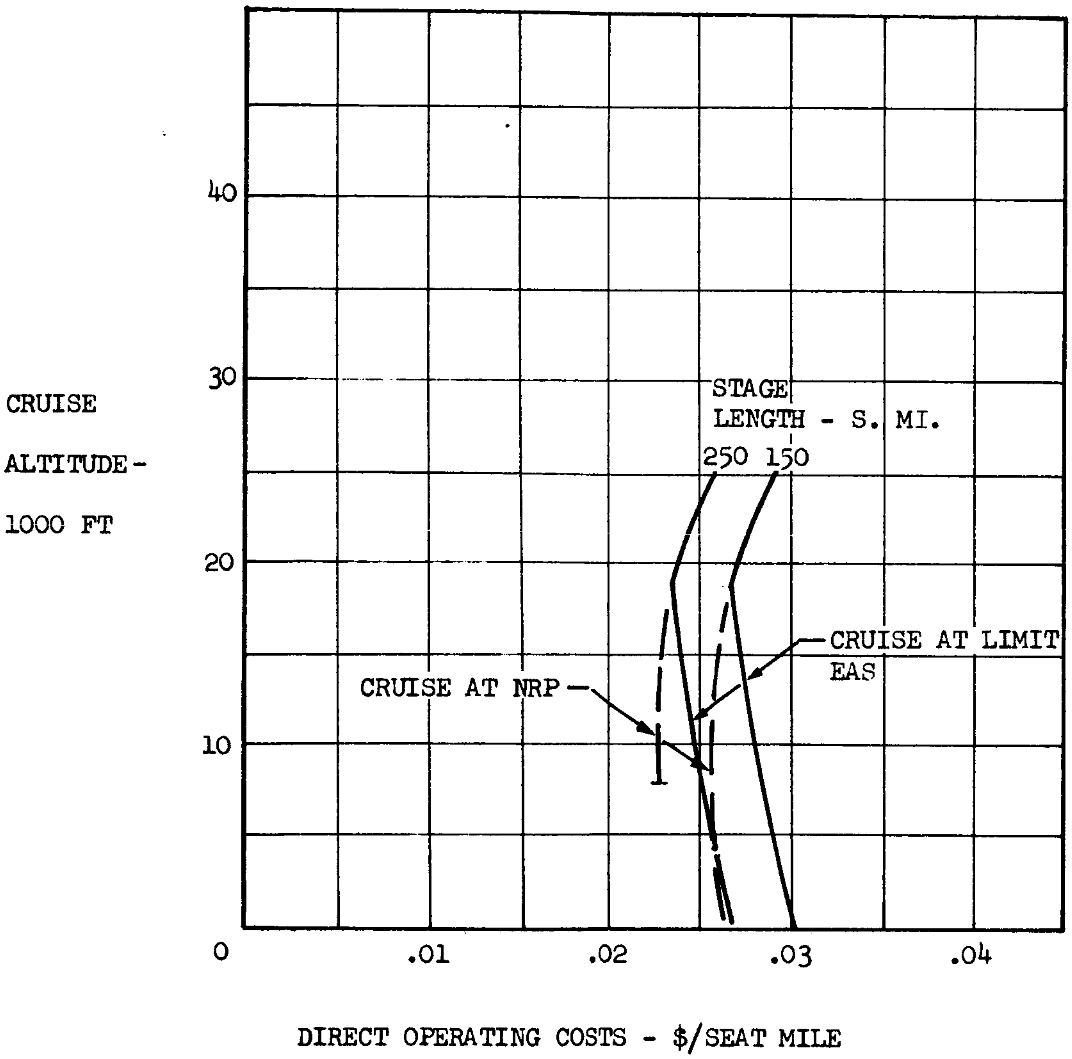


Figure 3. D.O.C. Versus Cruise Altitude

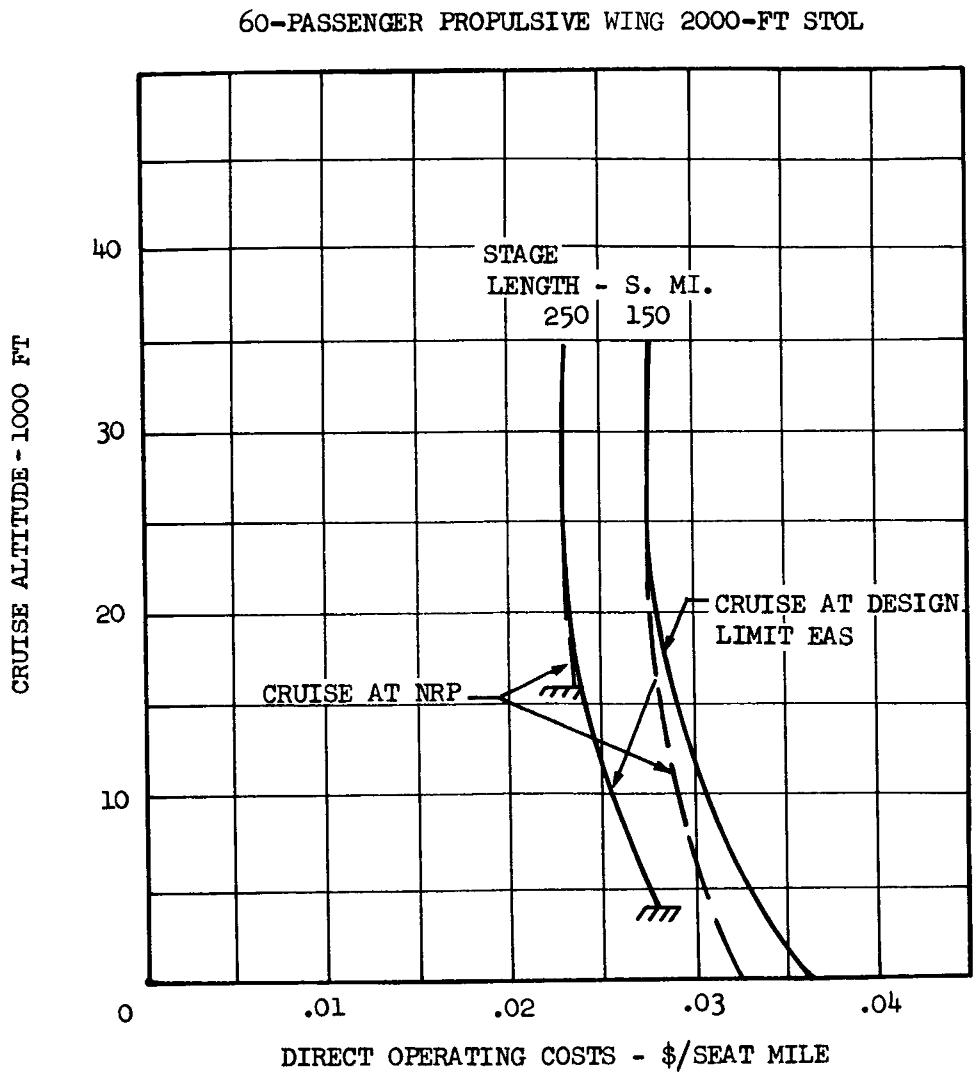


Figure 4. D.O.C. Versus Cruise Altitude

TURBOPROP VTOL

Total Distance to Clear a 50-Ft
Obstacle
SEA LEVEL
86°F
ONE ENGINE FAILED

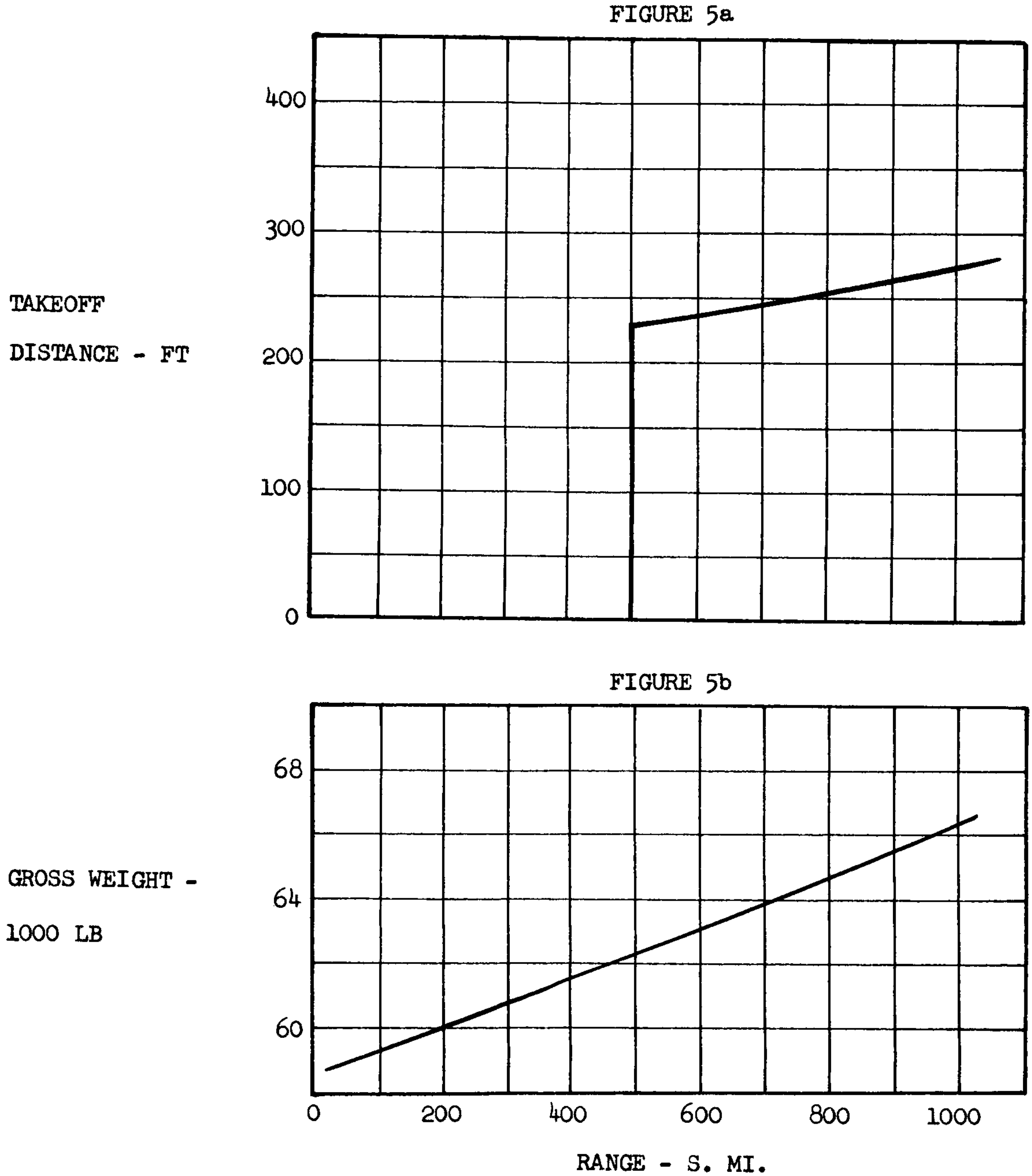


Figure 5. Effect of Operational Range on Takeoff Distance

TURBOPROP 1000-FT STOL

Total Distance to Clear a 50-Ft Obstacle

SEA LEVEL

86°F

ONE ENGINE FAILED

FIGURE 6a

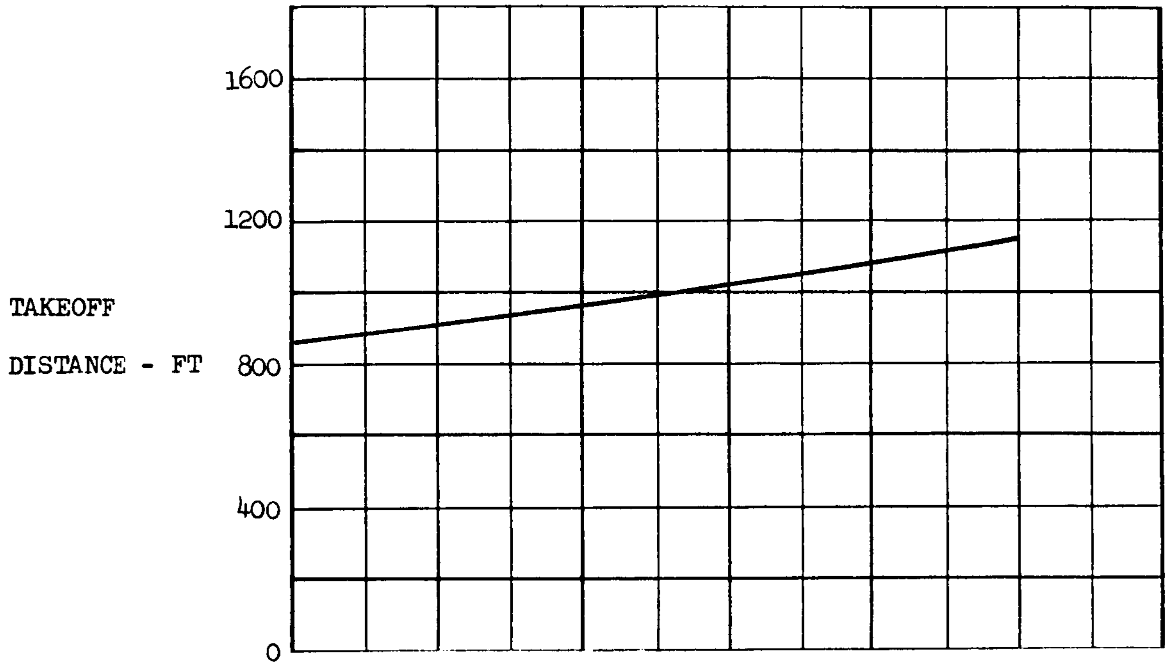


FIGURE 6b

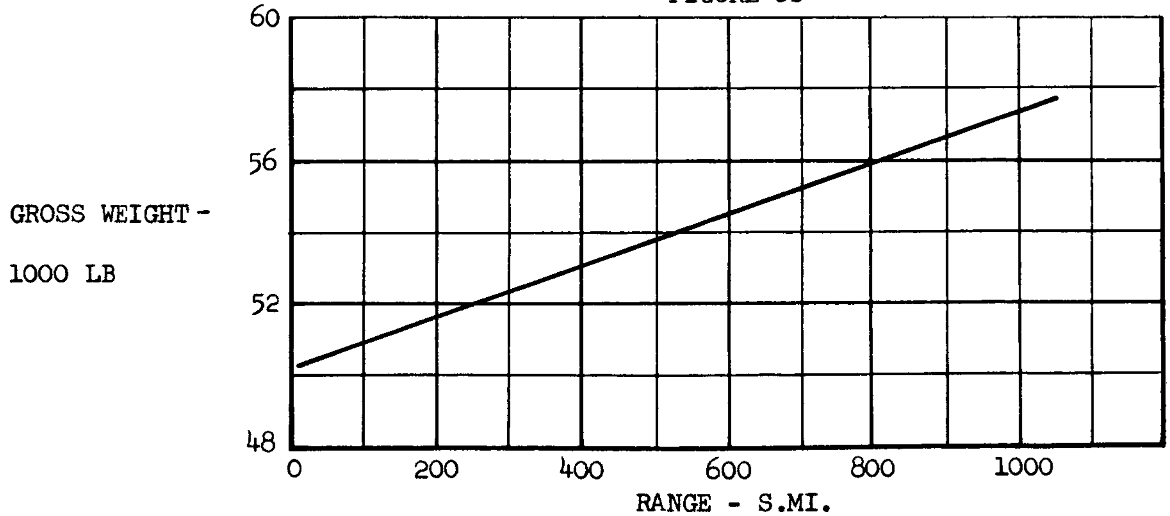


Figure 6. Effect of Operational Range on Takeoff Distance

FAN IN WING V/STOL
Total Distance to Clear a 50-Ft. Obstacle
SEA LEVEL
86°F
ONE ENGINE FAILED

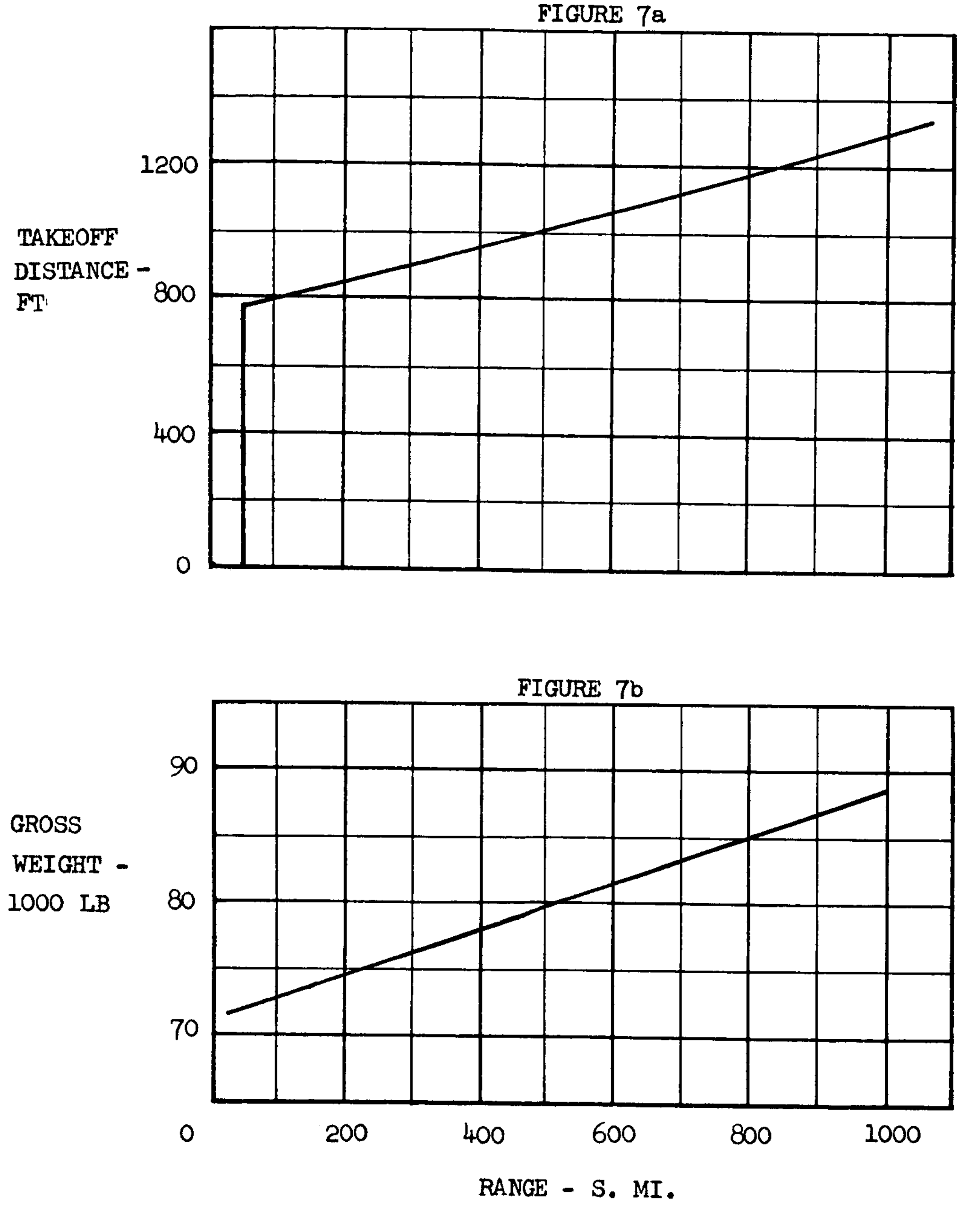


Figure 7. Effect of Operational Range on Takeoff Distance

PROPULSIVE WING 1000-FT STOL
Total Distance to Clear a 50-Ft Obstacle
SEA LEVEL
86°F
ONE ENGINE FAILED

FIGURE 8a

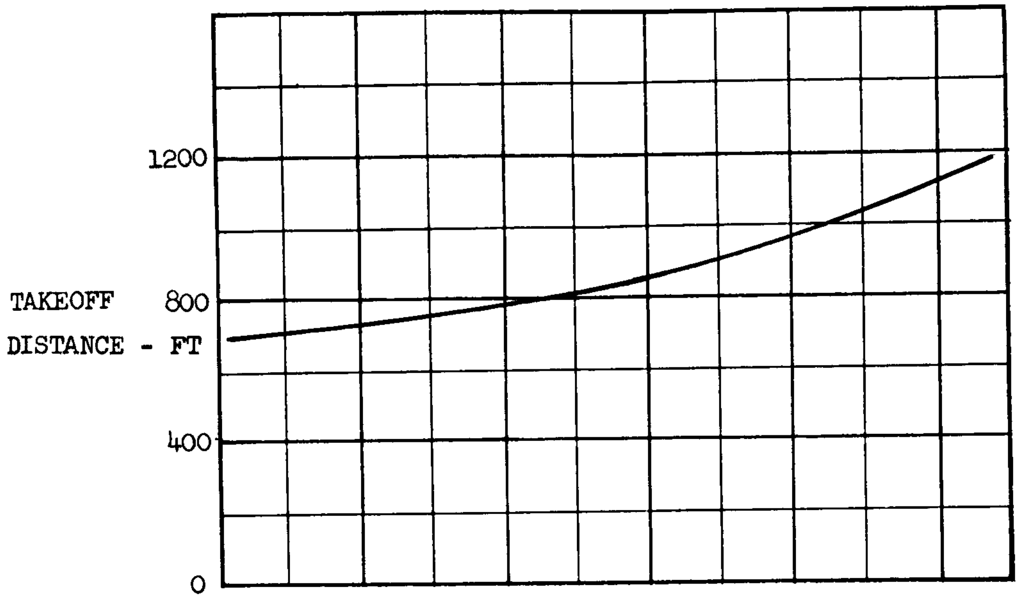


FIGURE 8b

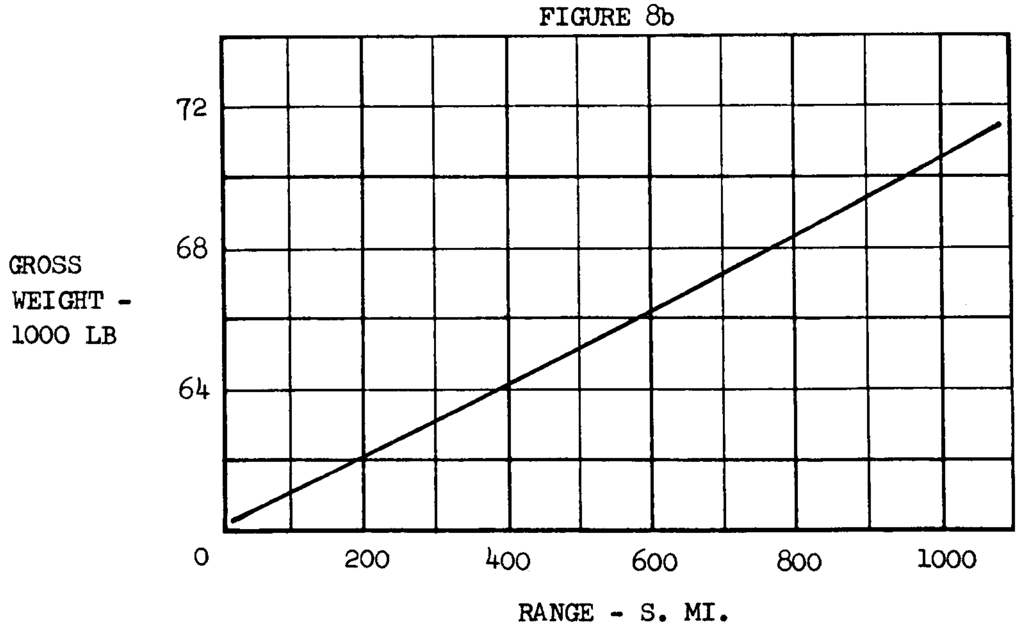


Figure 8. Effect of Operational Range on Takeoff Distance

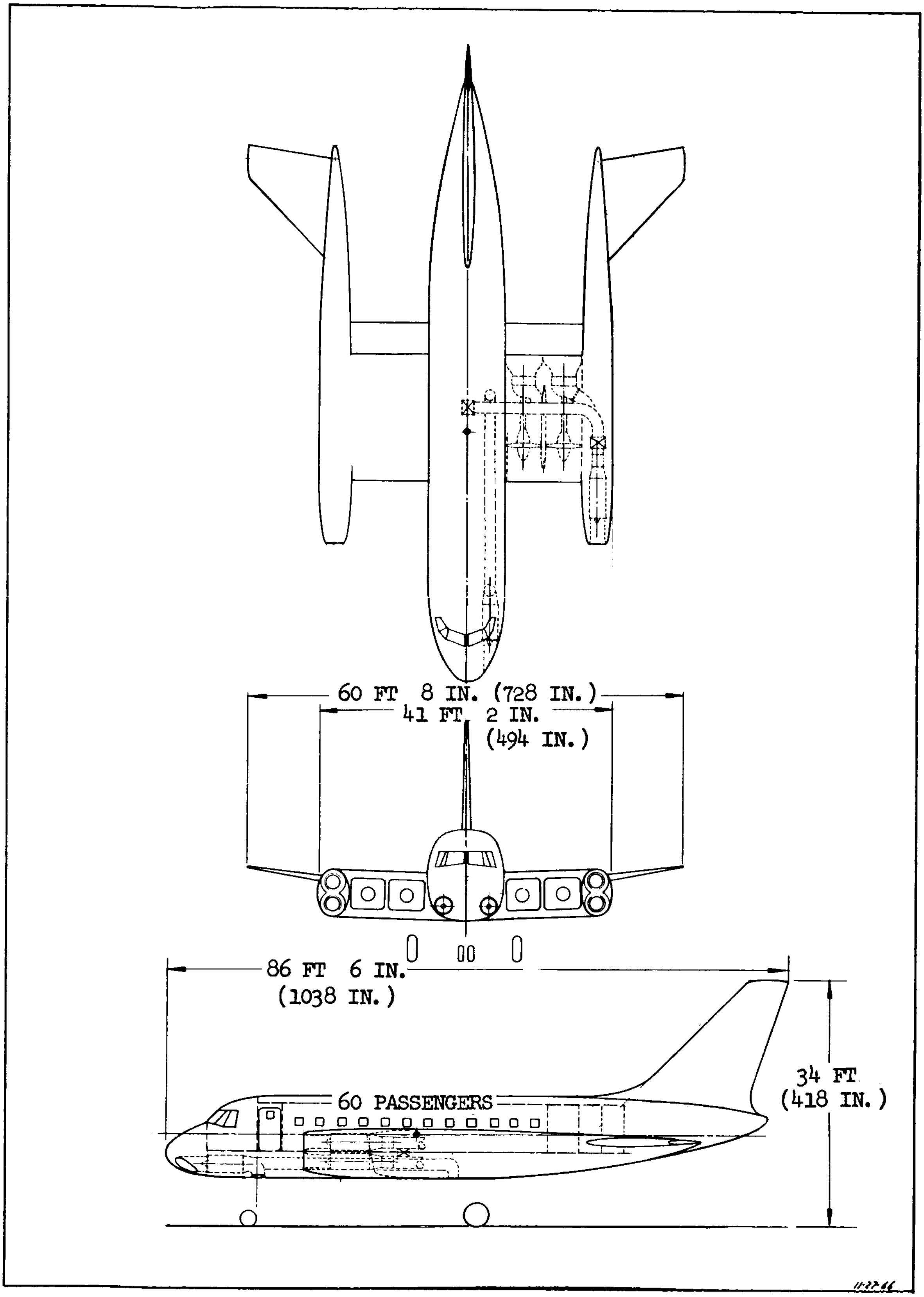


Figure 9. Propulsive Wing V/STOL Airplane

BASE AIRPLANE: 60-PASSENGER TURBOPROP VTOL DESIGNED
FOR A 500 STA MI STAGE LENGTH

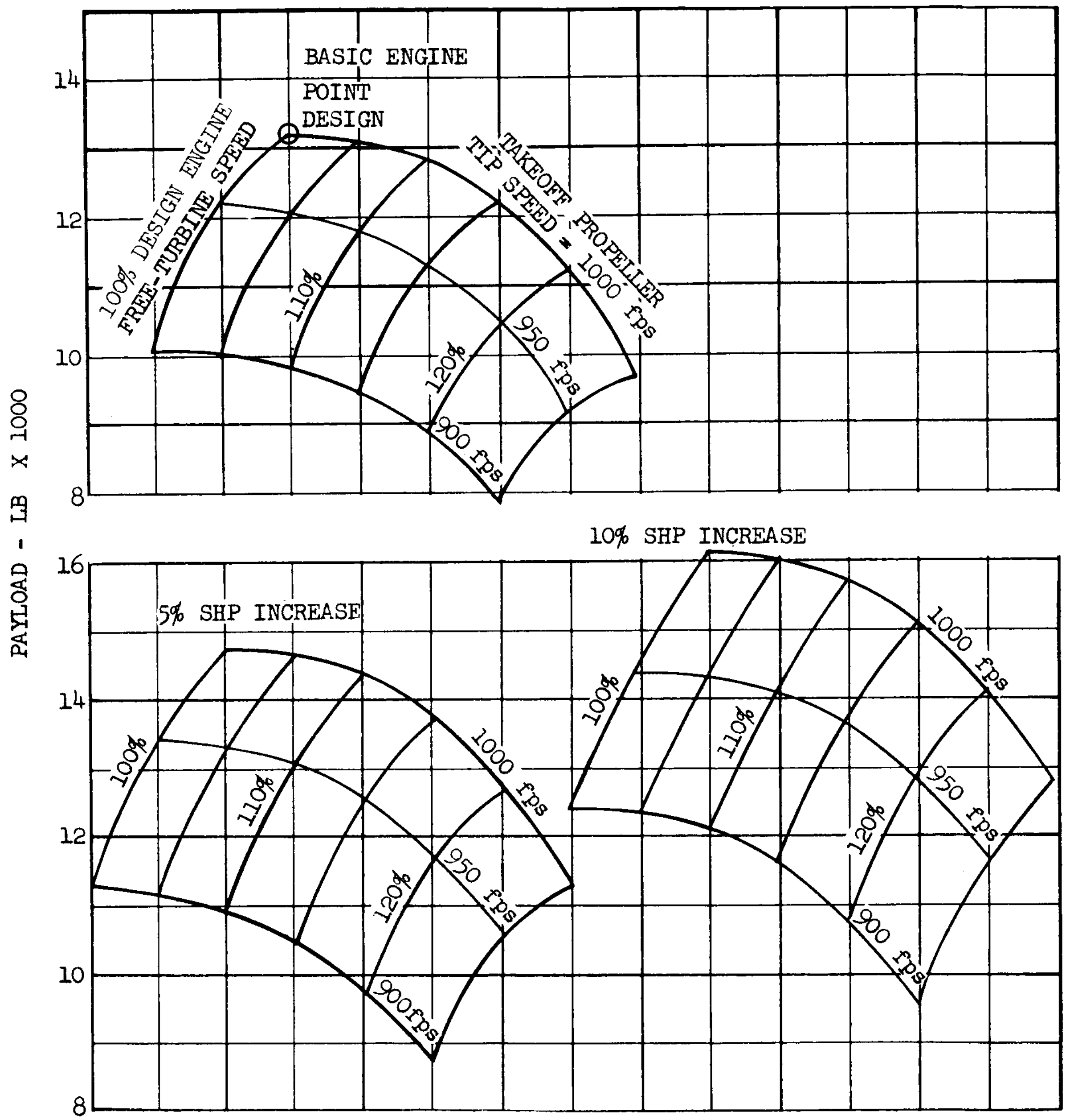


Figure 10. Effect of Takeoff Propeller Tip Speed, Engine Overspeeding, and SHP on Payload

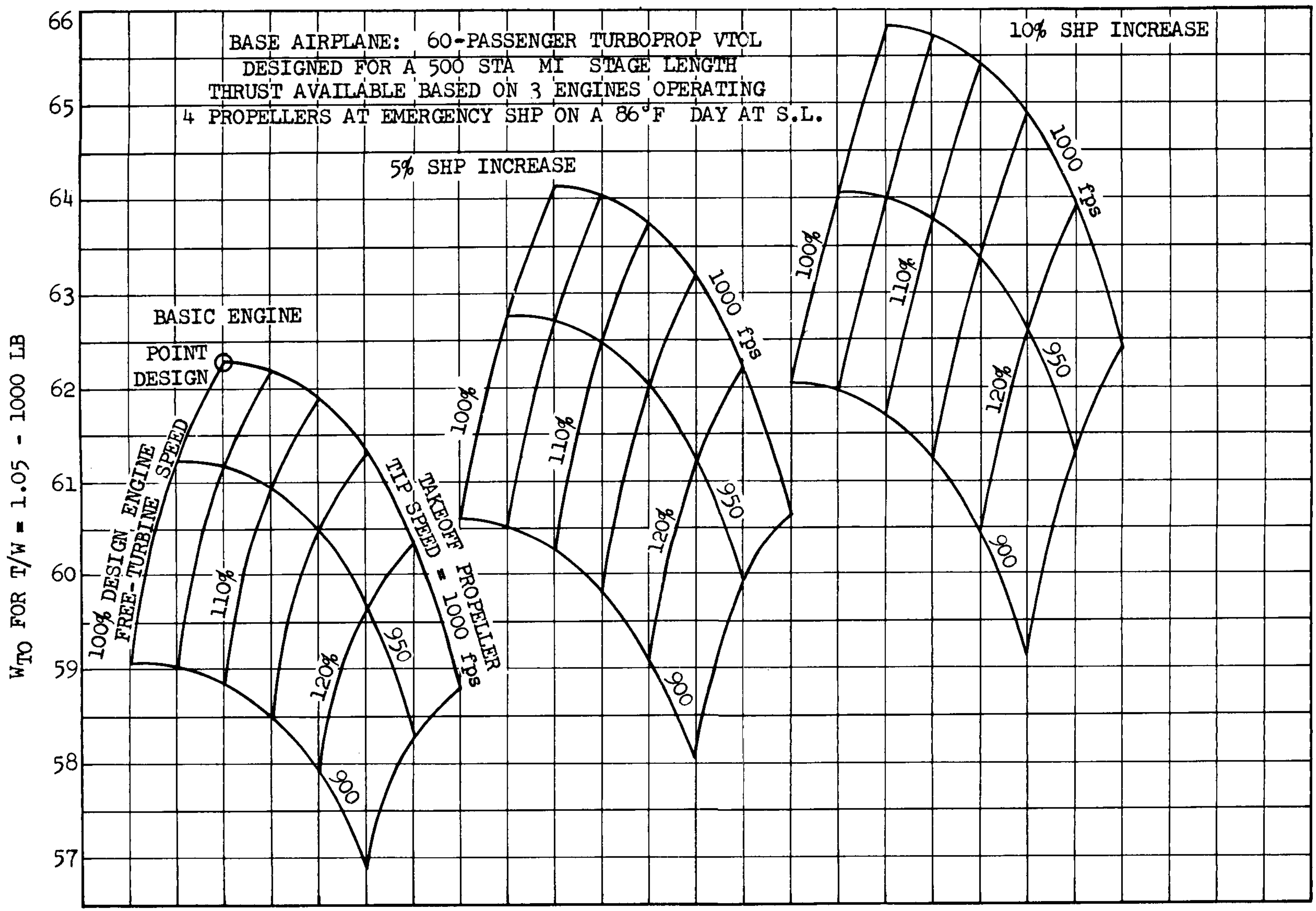


Figure 11. Effect of Takeoff Propeller Tip speed, Engine Overspeeding, and SHP on Takeoff Weight

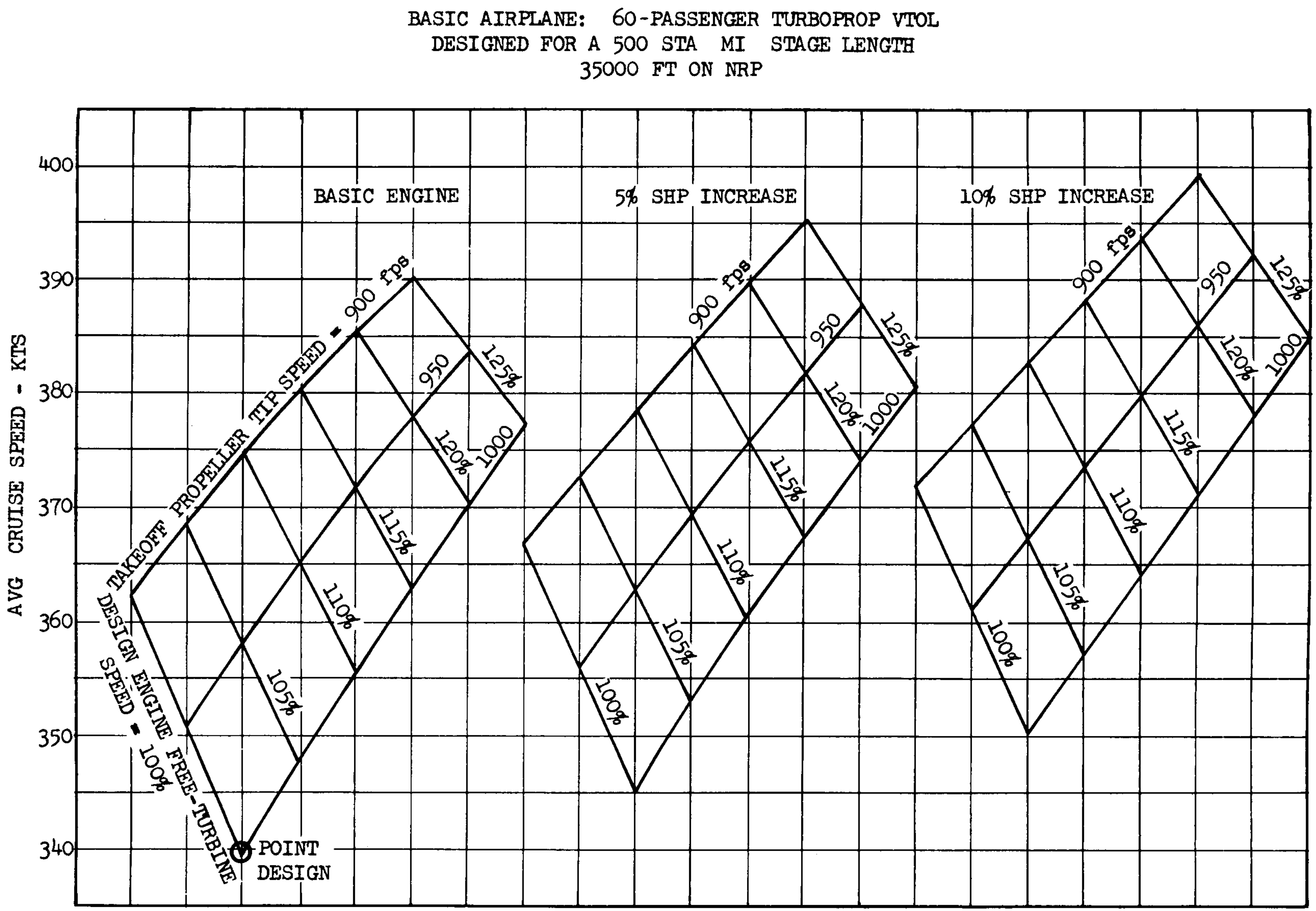


Figure 12. Effect of Takeoff Propeller Tip Speed, Engine Overspeeding, and SHP on Average Cruise Speed

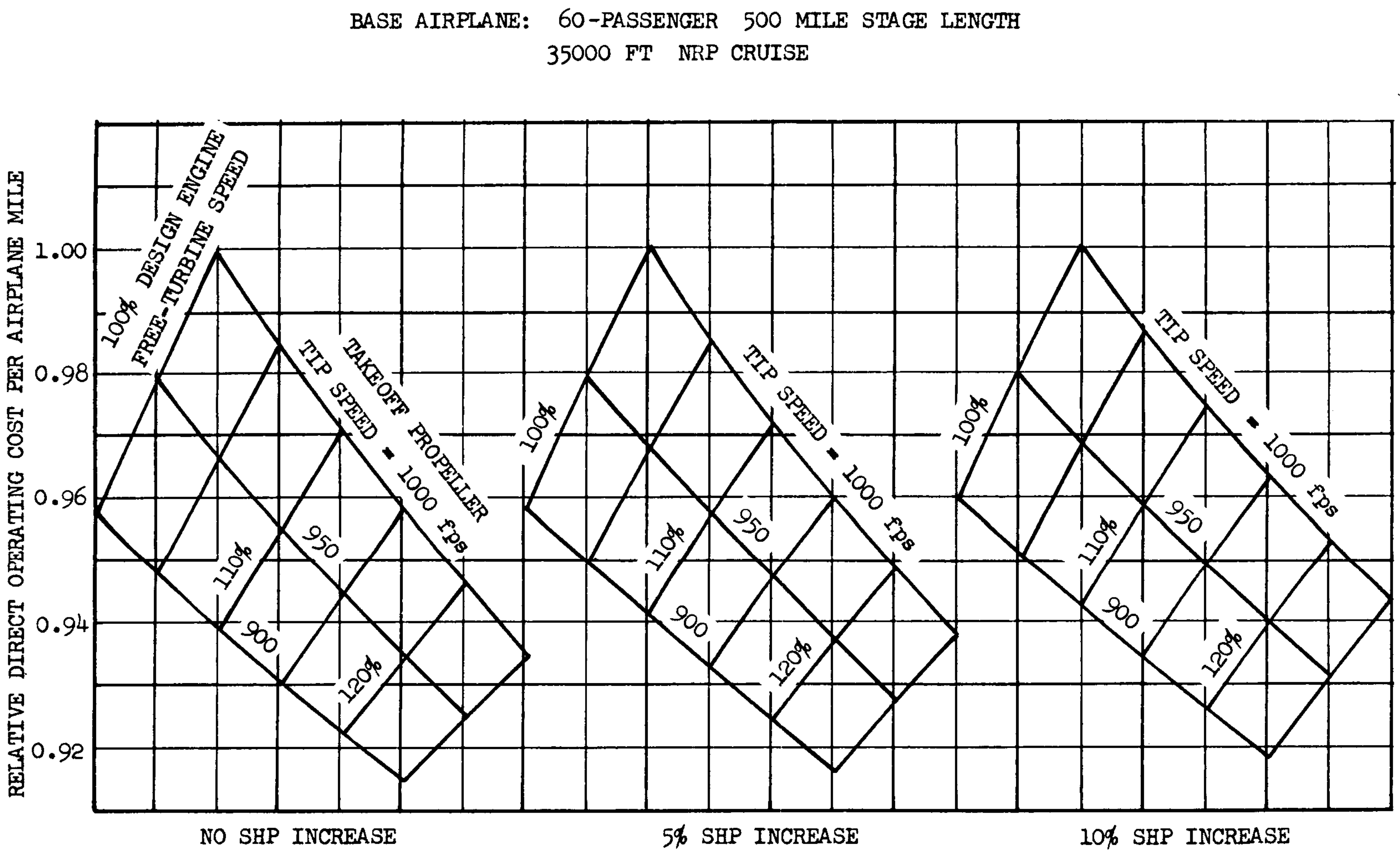
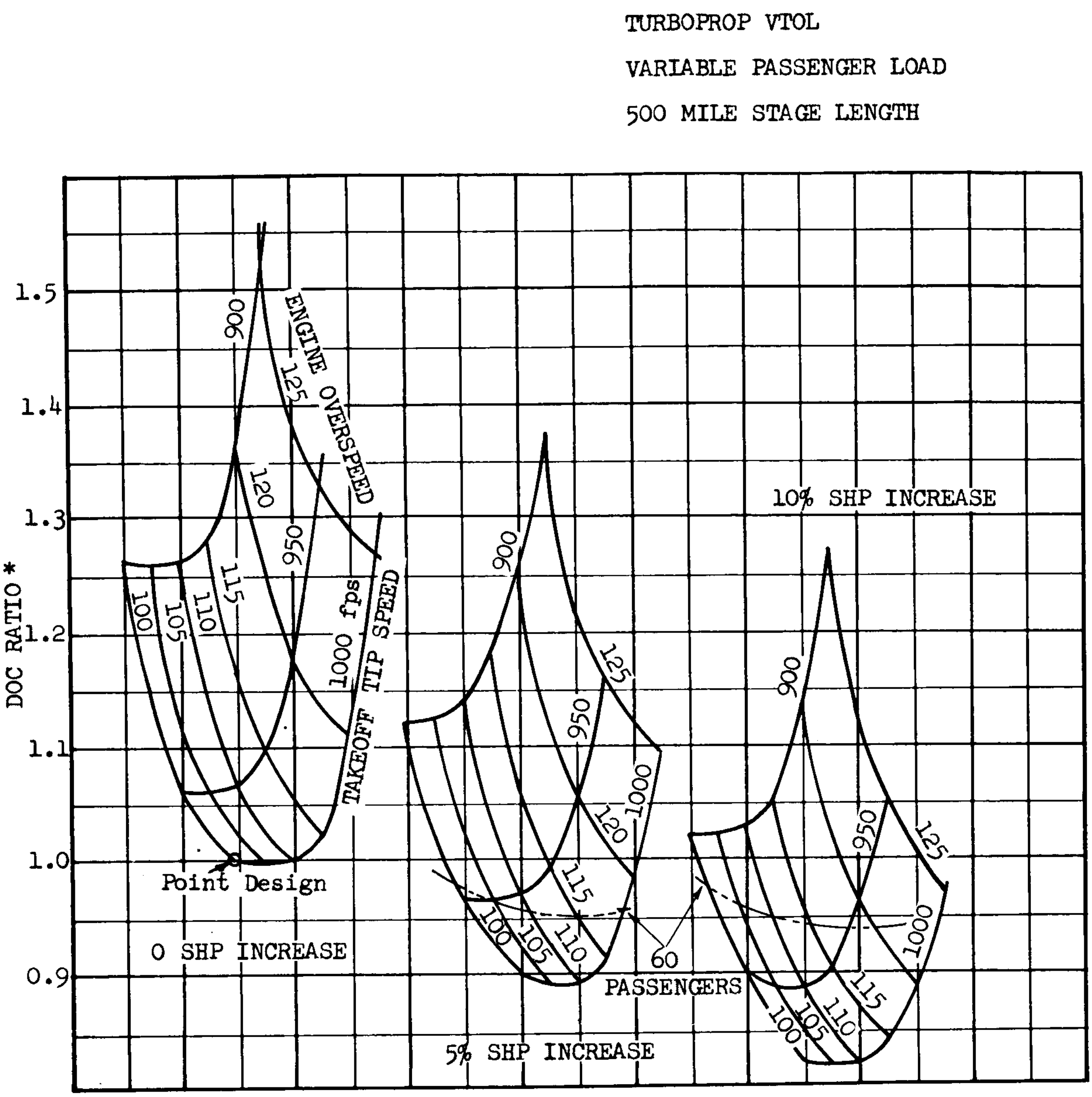


Figure 13. Turboprop VTOL Airplane Relative Direct Operating Cost



* Ratio of alternate airplane D.O.C. to basic airplane D.O.C.

Figure 14. Relative D.O.C. for Tip Speed, Engine Overspeed and Horsepower Variations

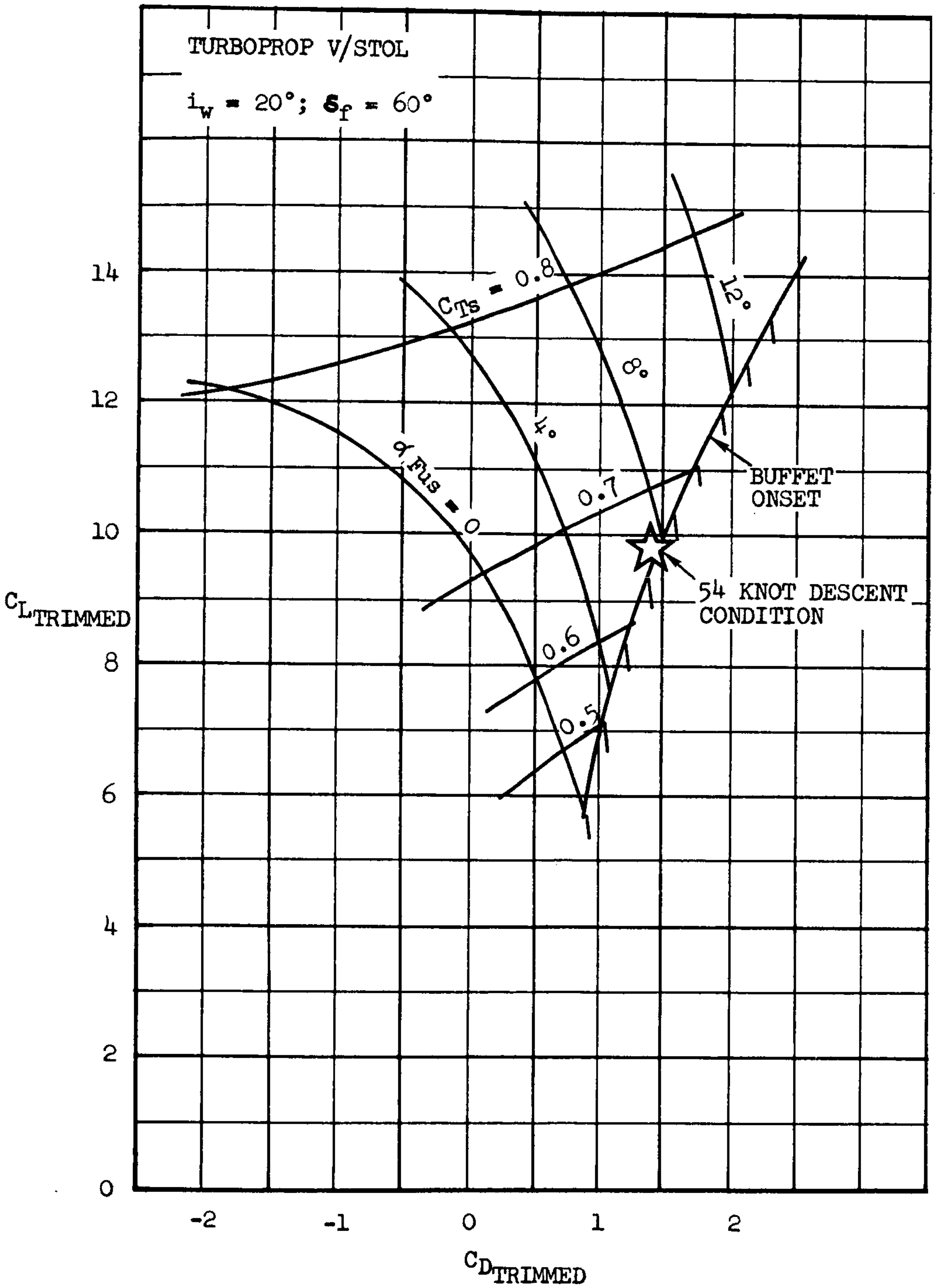


Figure 15. Landing Drag Polar

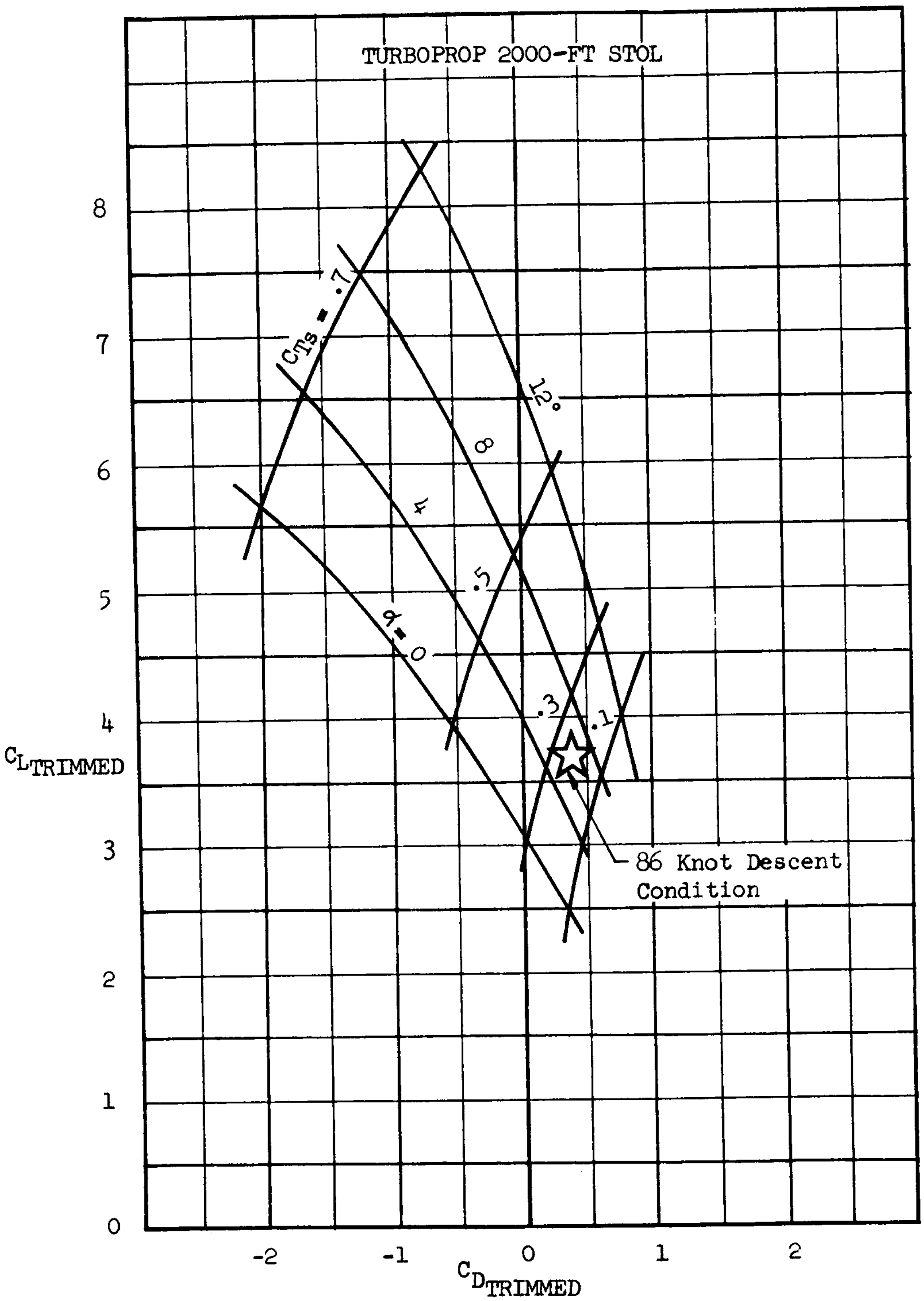


Figure 16. Landing Drag Polar

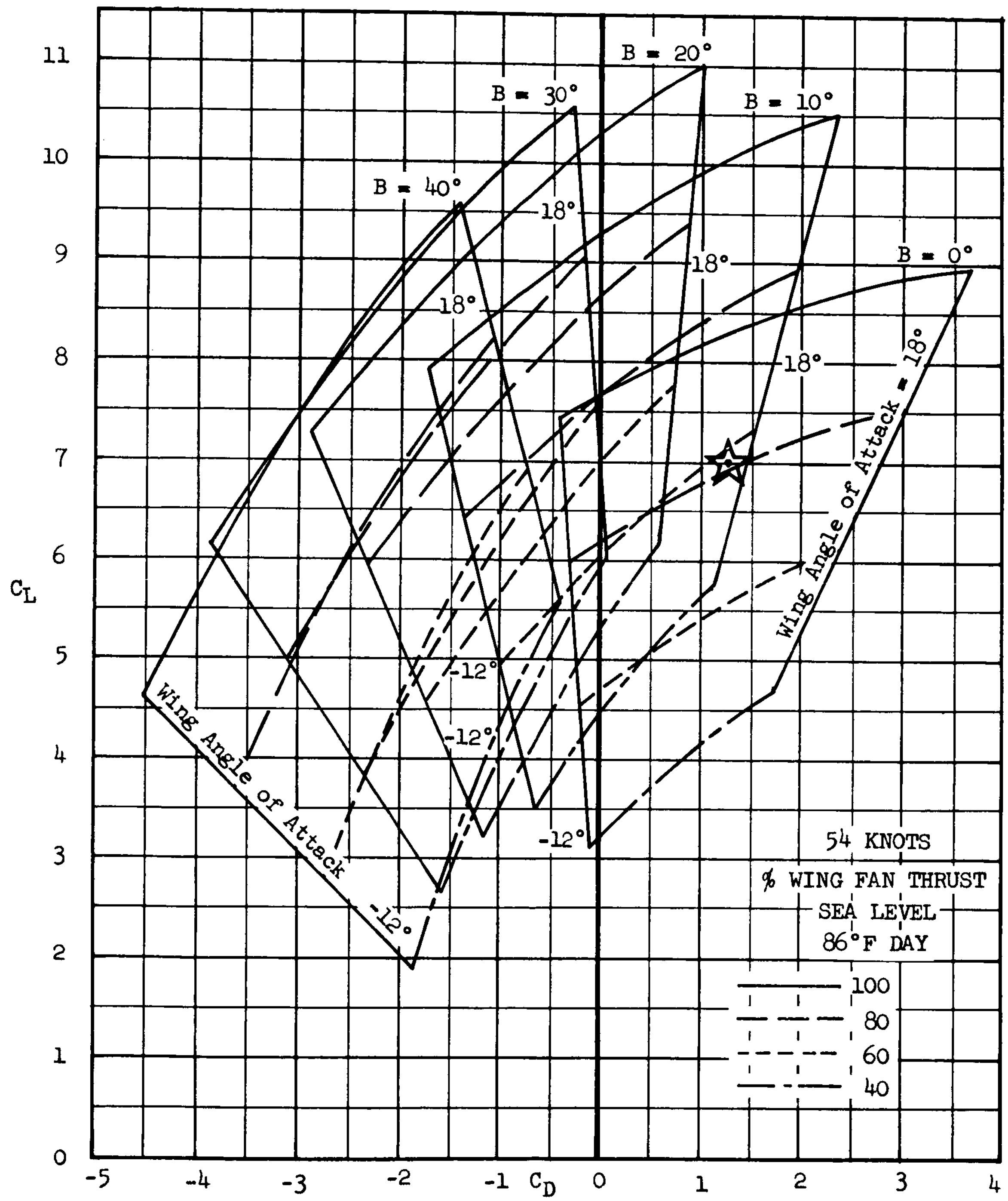


Figure 17. Tail-Off, Nose Fan Inoperative, Power-on Polar for the 60-Passenger Fan-in-Wing V/STOL

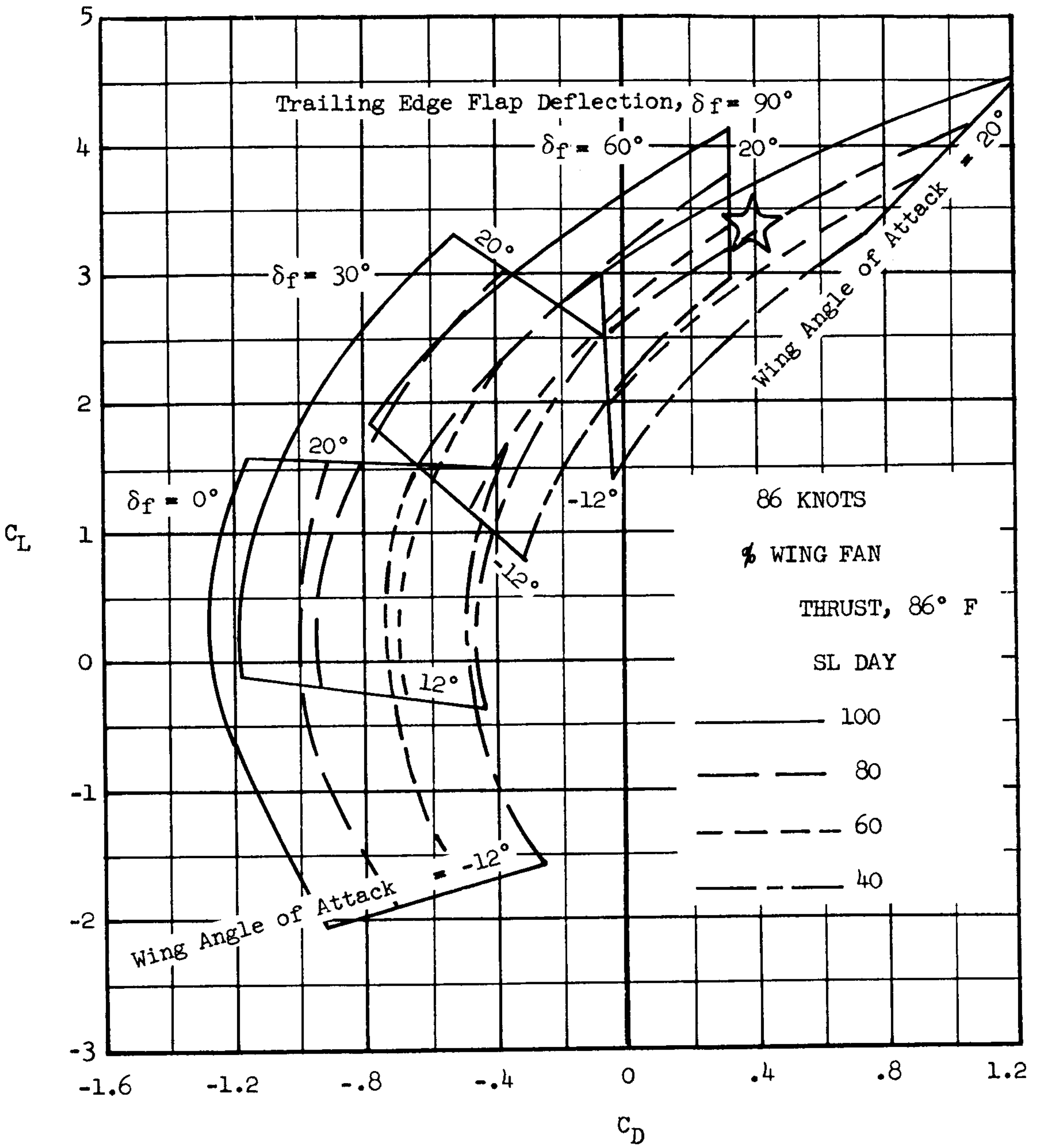


Figure 18. Tail-Off, Nose Fan Inoperative, Power-on Polar for the 60-Passenger Propulsive Wing 2000-Ft STOL

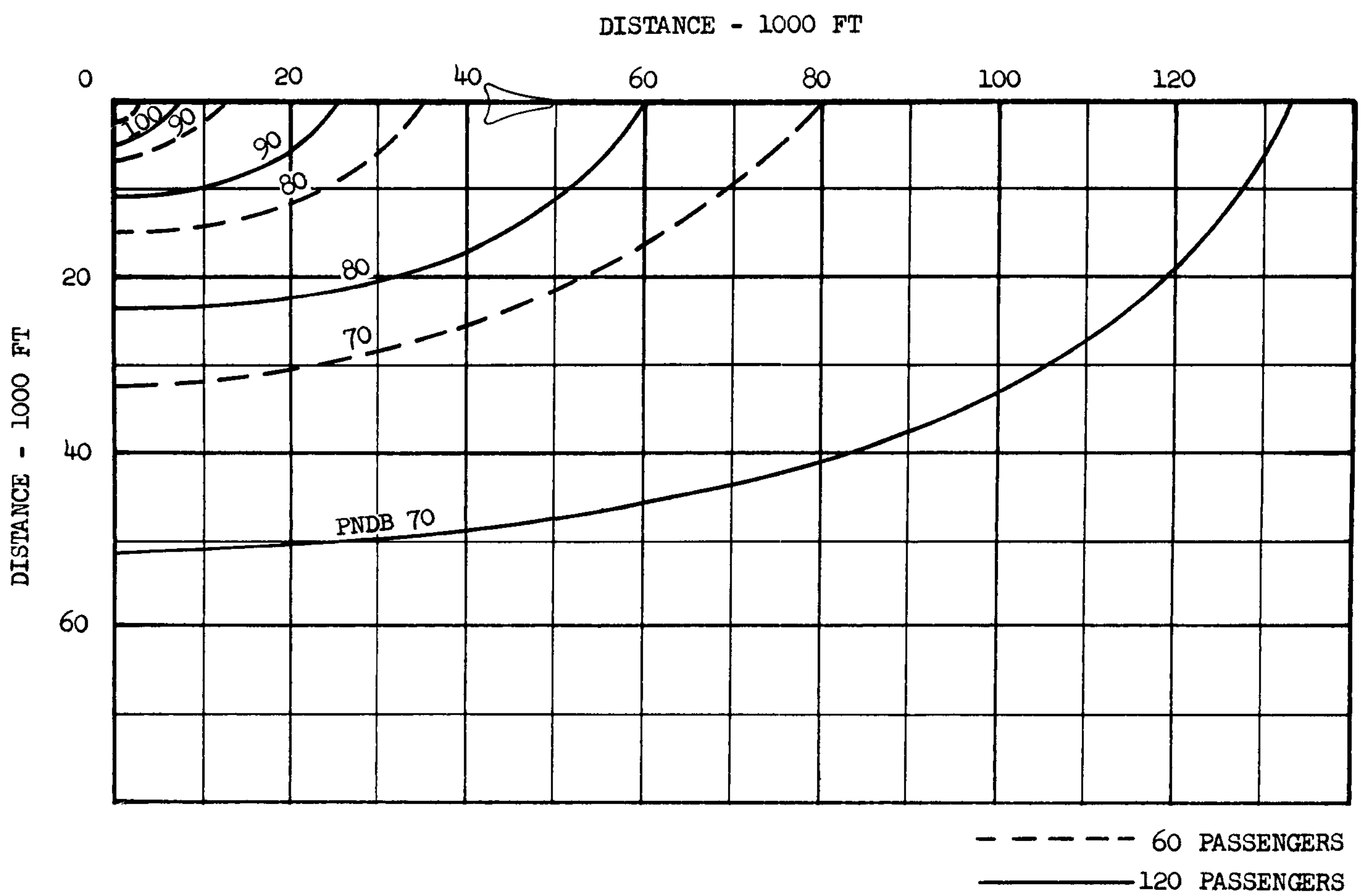


Figure 19. Effects of Size on Perceived Noise Level, Turboprop VTOL

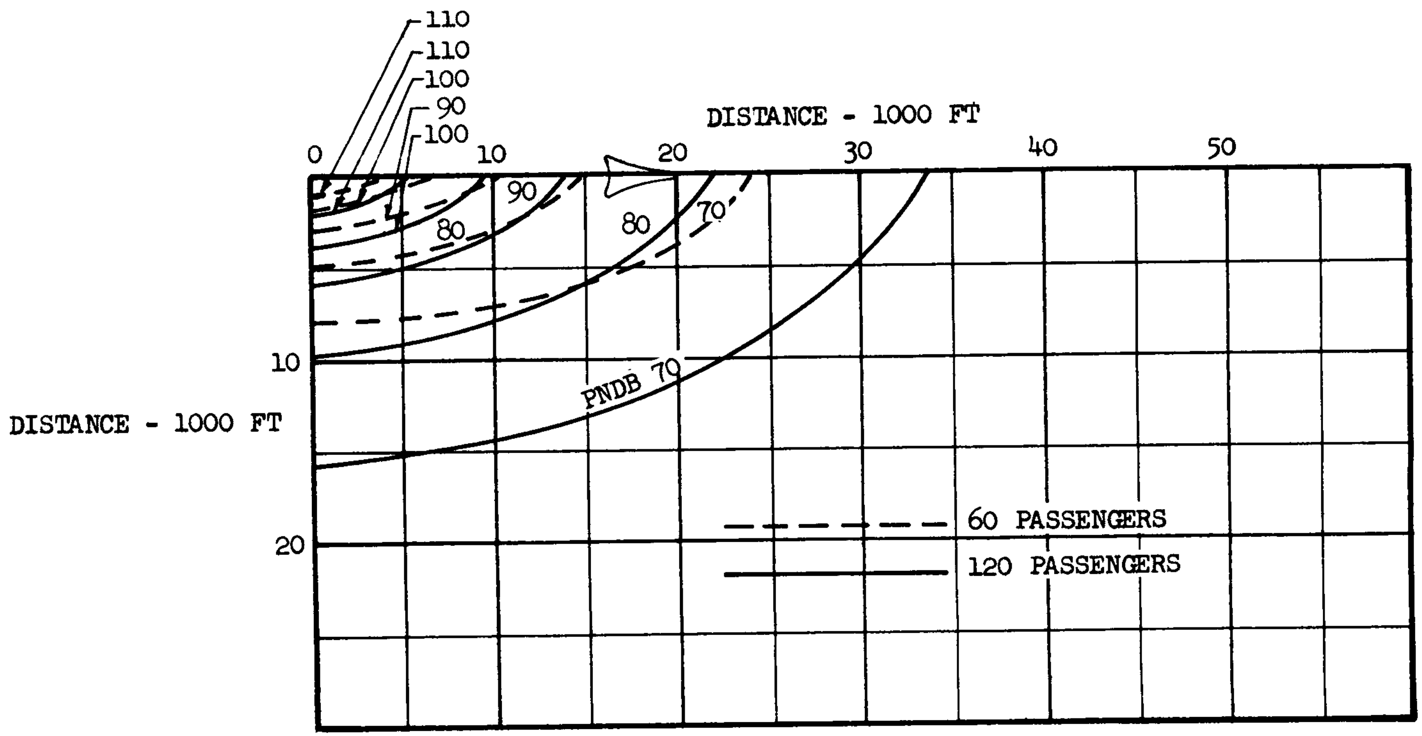


Figure 20. Effects of Size on Perceived Noise Level, Fan-in-Wing V/STOL, Takeoff

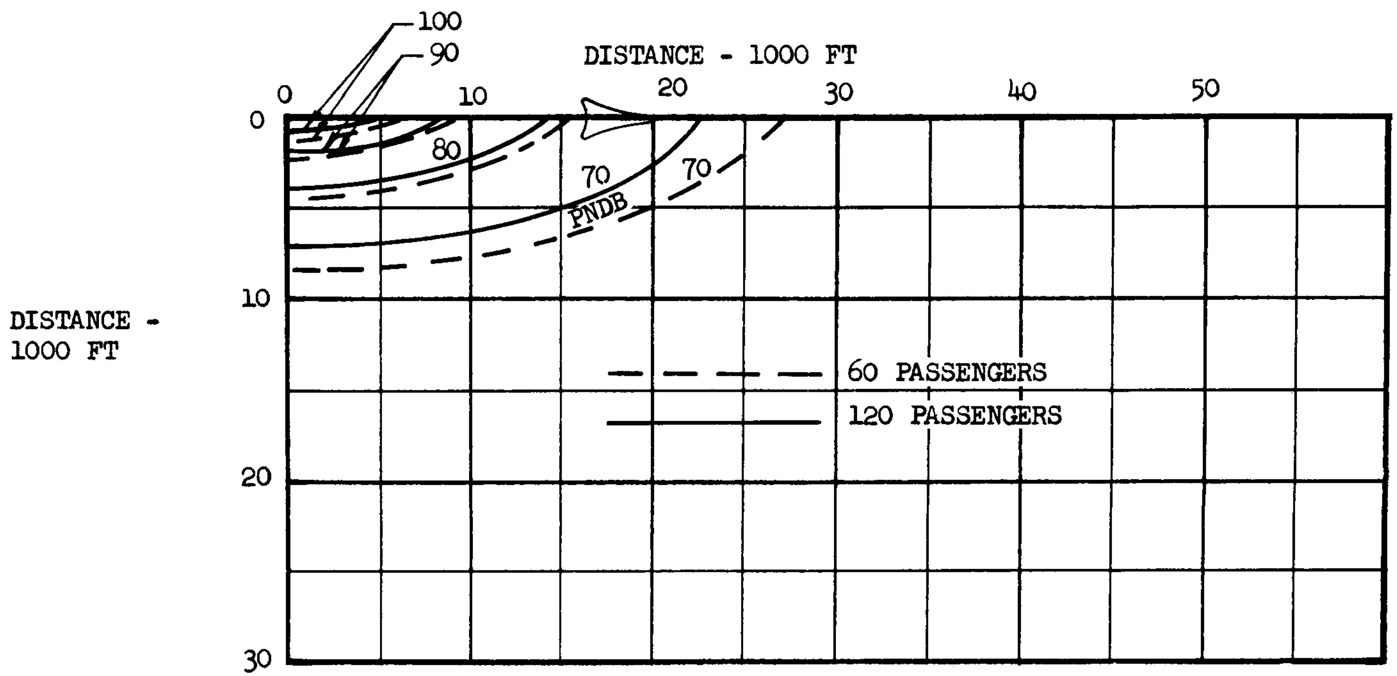


Figure 21. Effects of Size on Perceived Noise Level, Propulsive Wing 2000-Ft STOL, Takeoff

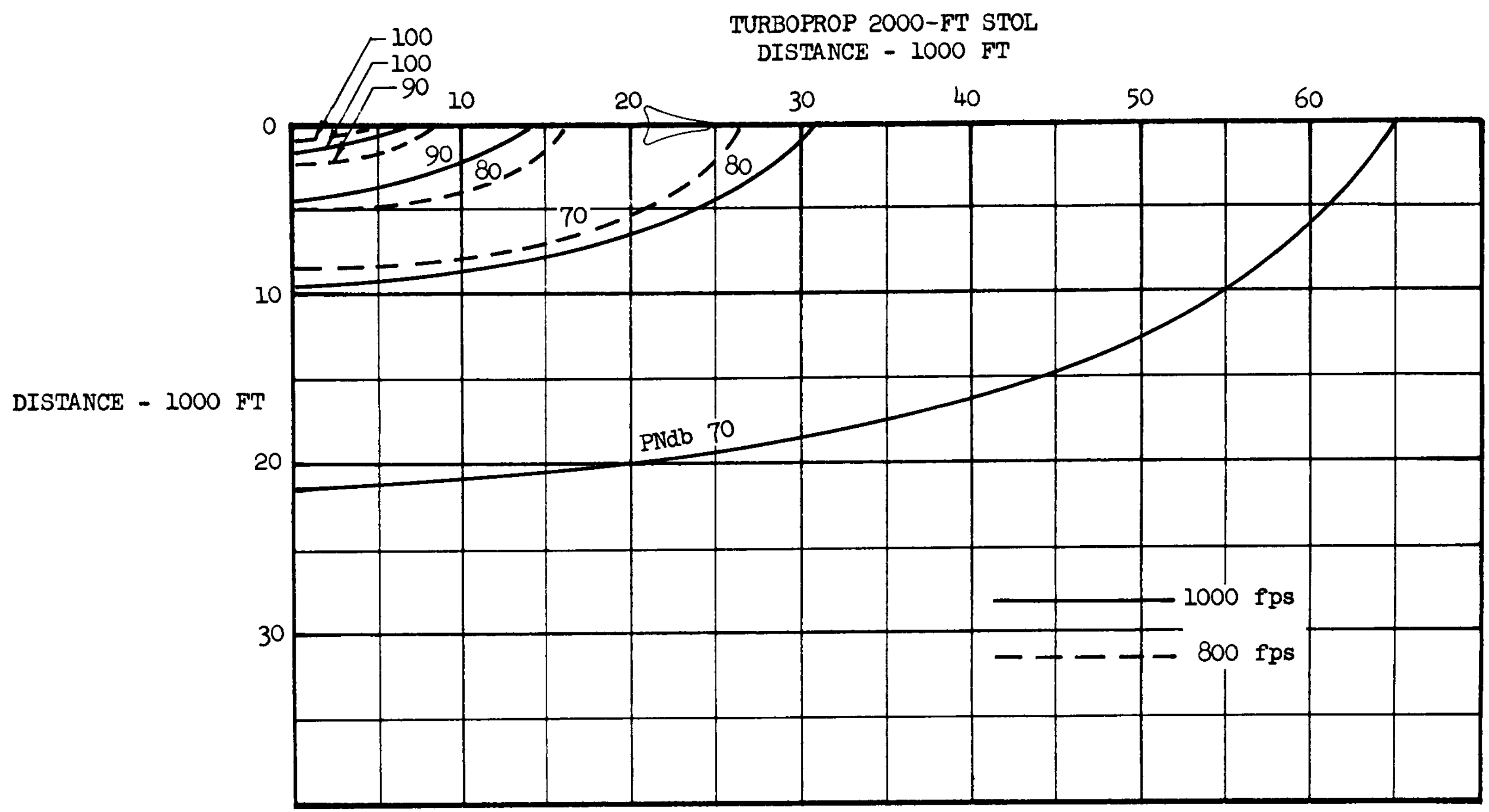
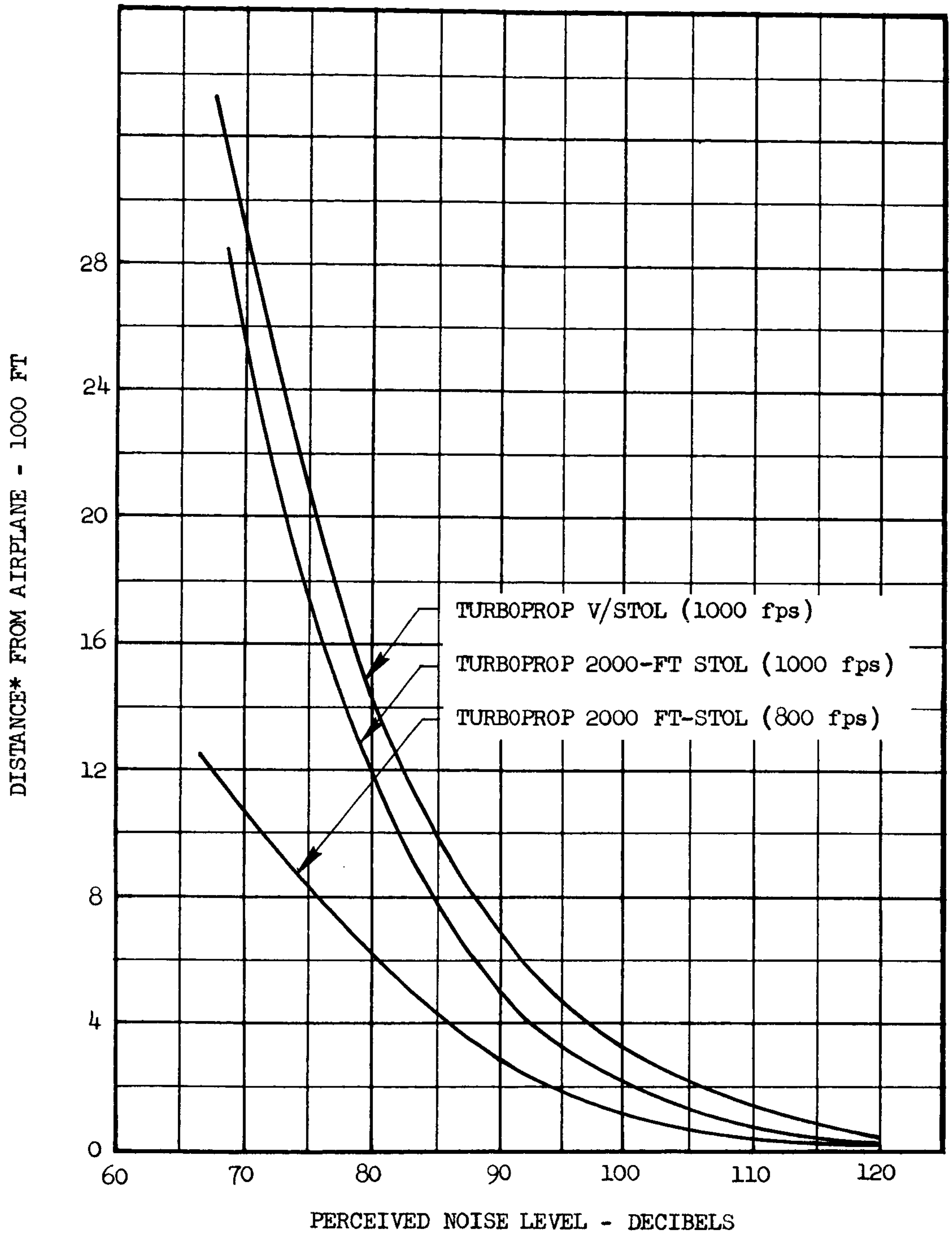


Figure 22. Effects of Propeller Tip Speed on Perceived Noise Level



* Distance is the maximum radial distance from the airplane at which the PNdb is at the level indicated.

Figure 23. Effects of Power and Propeller Tip Speed on Noise, Takeoff

XC-142A AIRPLANE IN HOVER

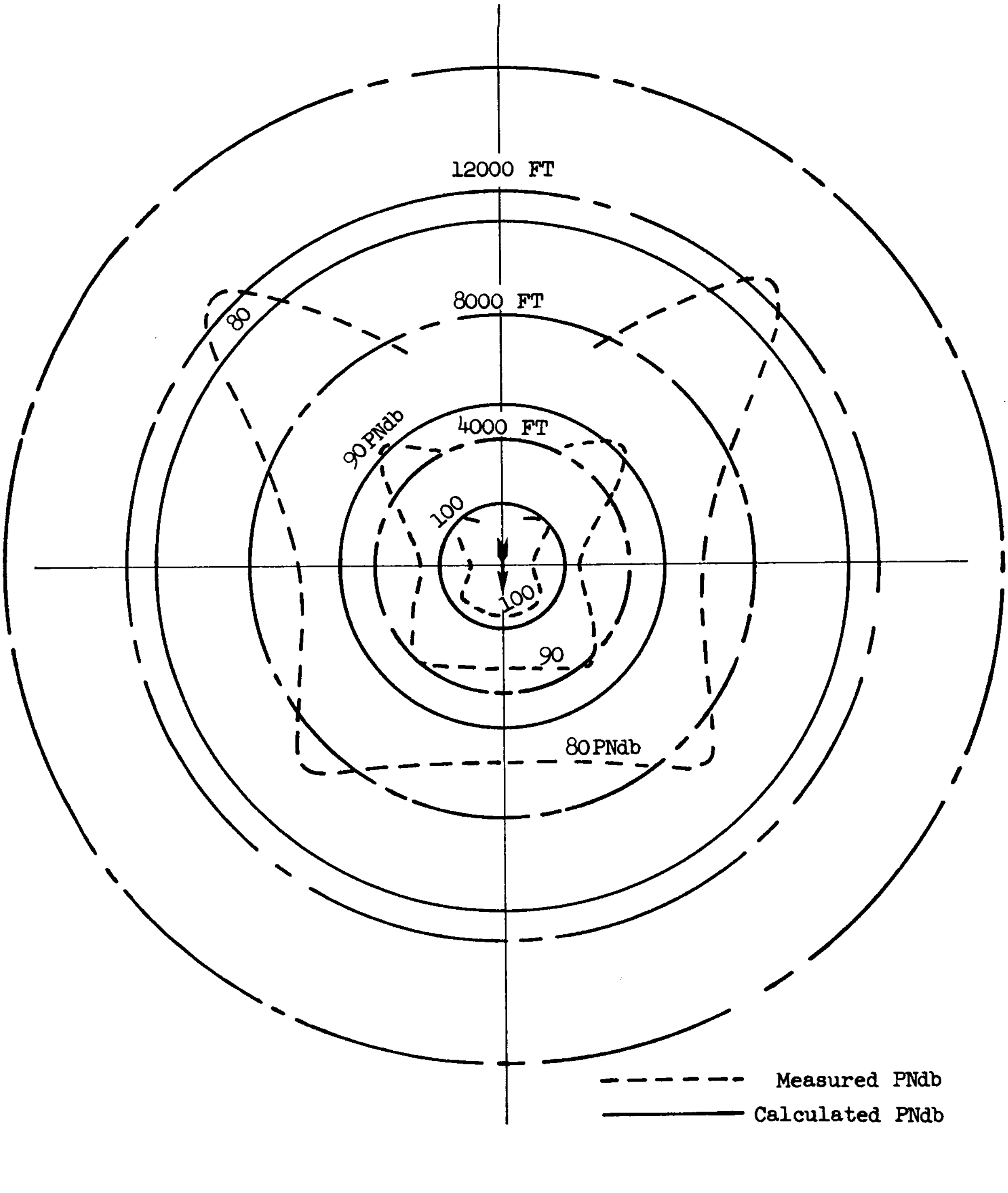


Figure 24. Comparison of Measured and Calculated Perceived Noise

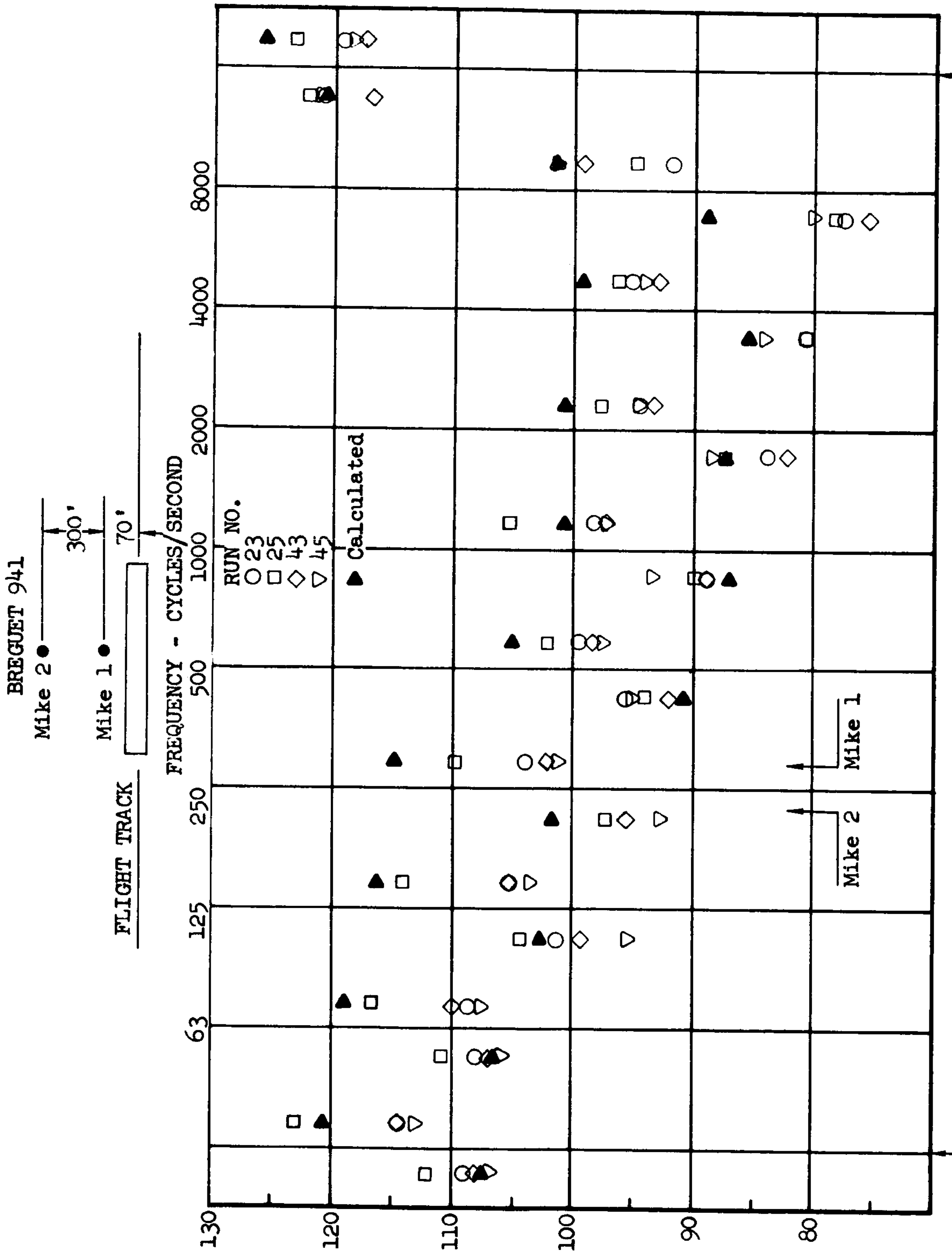


Figure 25. Sideline Takeoff Ground Roll Noise Levels