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

by K. R. Marsh

Prepared by
LING-TEMCO-VOUGHT, INC.
Dallas, Texas
for

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SUMMARY

The technical feasibility of many V/STOL concepts has been proven by wind tunnel tests and flying prototypes. With this proven technical capability and in anticipation of projected population movements, it is now considered appropriate to study the applicability of V/STOL airplanes to short-haul transport requirements.

A feasibility study has been performed in which eighteen airplanes have been developed around three V/STOL propulsion concepts, four V/STOL operational capabilities and three passenger-load capabilities. Each of the airplanes developed has been optimized to give a near minimum direct operating cost on the design stage length of 500 miles within the constraints of its selected V/STOL propulsion system, V/STOL operational capability and passenger-load capability.

This study has found the turboprop V/STOL airplanes to have only modest cruise speed capabilities, relatively low direct operating costs, and comparatively light weights; and there are considerable data to guide the designer of turboprop V/STOL aircraft. The fan-in-wing V/STOL airplanes have a relatively high cruise speed, high direct operating costs, and high propulsion system plus fuel weights and hence gross weights; there are considerable data available to the designer of fan-in-wing airplanes though not as voluminous or complete as for the turboprop. The propulsive wing V/STOL airplanes have high subsonic cruise speed capabilities, low direct operating costs, and relatively light weights; but there are only limited data to guide the designer of such aircraft.

More research data on the V/STOL concepts evaluated in this study will permit better design optimization and reduce the technical risks associated with the development of these aircraft. A set of Federal Aviation Airworthiness Standards, applicable to the novel flight capabilities of V/STOL aircraft, should be developed.

INTRODUCTION

Purpose

The bulk of the population gain expected by 1980 will be in urban areas. At least three super-metropolitan areas - the northeast corridor, the Great Lakes area, and along the California-Pacific Coast - will exist by 1980. They will each extend approximately 400 miles, and they will contain approximately 50 percent of the country's population.

The airports which will serve these super-metropolitan areas will be forced to increase in size and move further from the population centers to find adequate space for servicing the long distance travelers and to avoid problems associated with community acceptance. As a result of this and the increasing congestion on urban highways, the short-haul traveler will be faced with a dilemma - the lack of a rapid, short-haul transport system.

V/STOL short-haul transport aircraft systems with aircraft capable of operating out of very small airports are considered to be one method of solving this dilemma of the short-haul traveler. The technical feasibility of many V/STOL concepts has been proven by wind tunnel tests and flying prototypes; but data were not available to establish the economic feasibility of various V/STOL concepts for short-haul air transport applications. Consequently, LTV Aerospace Corporation under contract (Reference 1) to NASA, Ames Research Center, has conducted an extensive analysis of turboprop, fan-in-wing and propulsive wing V/STOL propulsion system concepts to power short-haul transport aircraft.[1] Aircraft were designed around these three propulsion system concepts, and their operation and costs were evaluated. The basic aircraft were capable of carrying 60 passengers, and several 90 and 120 passenger aircraft were also developed and evaluated.

In addition to evaluating the economic feasibility of various V/STOL short-haul aircraft designs, an examination has been made of the research work required to develop these short-haul aircraft into successful commercial air transports, and an examination has been made of the ability of the existing airworthiness requirements to cope with the novel flight capabilities of V/STOL aircraft.

Concepts Studied

Three different V/STOL propulsion system concepts were studied -- turboprops, fan-in-wings, and propulsive wings (Figure 1). The turboprop airplanes used the washed wing principle with wing tilt applied as

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1 Additional concepts were studied by Boeing and Lockheed Companies under contract to NASA. Preliminary results of these three studies are contained in NASA SP-116; Conference on V/STOL and STOL Aircraft, April 4-5, 1966.

required to meet the specific runway length design criteria. The fan-in-wing airplanes used the pure fan-in-wing principle where all of the gas generator hot gas was diverted to drive the wing fans for takeoff and landing, and ducted straight aft in a conventional turbojet manner for cruise. The propulsive wing airplanes, considered for STOL operations only in this study, used a jet flap principle in conjunction with the propulsive wing to develop high induced lift coefficients for slow speed flight, and these airplanes have a high-bypass ratio turbofan propulsion system.

For this study, the term VTOL, when applied to a specific aircraft, implies that the particular aircraft is designed to takeoff vertically, fly its design stage length without refueling, and land vertically with all fuel reserves on board. The term V/STOL, when applied to a specific aircraft, implies that the particular aircraft is designed to takeoff with a short takeoff run, fly its design stage length without refueling, and land either with a short landing or vertically with all fuel reserves on board; but this aircraft also has the capability to takeoff vertically, fly a fixed distance less than the design stage length without refueling, and land vertically with all fuel reserves on board. The term STOL, when applied to a specific aircraft, implies that the particular aircraft is designed to takeoff with a short takeoff run, fly its design stage length without refueling, and land with a short landing run with all fuel reserves on board. The STOL airplane has no vertical takeoff and landing capability. For this study, the design stage length for all airplanes is 500 statute miles, and the design VTOL stage length for the V/STOL airplanes is 50 statute miles.

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 1000 and 2000 foot runways. All airplanes were optimized to give a minimum direct operating cost at the 500 statute mile stage length.

Study Ground Rules

The ground rules used for this study were mutually agreed upon by NASA and LTV, and were determined by associated studies and experience.

NASA study ground rules. - The more important ground rules established by Reference 1 are as follows:

Passenger accommodations. - The passenger plus baggage weight shall be 200 pounds.

Five abreast seating or more shall be used. Thin back seats with 32 inch pitch seat spacing will be used. The seat width will be 20 inches.

Two lavatories, 38 inches by 35 inches, will be provided.

One stewardess will be provided for 60 passenger versions and two stewardesses will be provided for 90 and 120 passenger versions.

The noise level in the passenger compartment shall not exceed 75 decibels or 70 decibels in the speech interference level in takeoff and cruise, respectively.

Airplane design criteria. - All airplanes will be optimized to give near minimum direct operating costs on a 500 mile stage length.

Space will be provided for 20 pounds of revenue cargo per seat.

Self-contained passenger loading stairways, starting systems, and air conditioning will be provided.

Structural design criteria. - Components such as cross shafting and hot gas ducts shall be designed for infinite life.

The airplanes shall meet the structural strength requirements of Reference 2.

The landing gear will be designed for a limit sink speed of 12 feet per second.

Special slow speed flight control criteria. - The special slow speed flight control power requirements are presented in Table 1. If the desired values of control power impose a severe penalty on an airplane, the acceptable values may be used. These slow speed control requirements are in addition to the trim requirements.

Performance design criteria. - The take-off and landing performance of all aircraft will be based on the assumed atmospheric conditions of an 86°F day at sea level.

All cruise flight performance is calculated assuming standard day atmospheric conditions.

Special VTOL design criteria. - With all engines operating and the aircraft trimmed, the thrust-to-weight ratio shall be equal to or greater than 1.15 with no control input or 1.05 with 50% of the maximum control capability about any one axis and 20% of the maximum control capability about the other two axes. The control system must be able to give 100% of the maximum control moment required about any one axis while it is providing 50% of the maximum control required about the other two axes (no thrust-to-weight ratio specified).

With the critical engine inoperative and the aircraft trimmed, the thrust-to-weight ratio must be equal to or greater than 1.05 with no control input or 1.0 with 50% of the control required about any one axis and 20% of the control required about the other two axes.

Special STOL design criteria. - With the critical engine failed, the airplane must be able to attain a flight path angle of zero in the final approach configuration without a speed change.

The landing field length required will be the calculated total landing distance from a 50 foot height during the landing approach to the end of the landing roll-out times a factor of 1.67.

During the landing approach, the rate of descent shall not exceed 800 feet per minute at a height of less than 50 feet.

The maximum deceleration rate during a landing roll will be 0.5 g's. (It is to be noted that these last three ground rules limit the maximum approach speed to 54 knots for 1000 foot STOL airplanes and to 86 knots for the 2000 foot STOL airplane.)

The takeoff field length required will be the calculated distance from the start of the takeoff ground roll to the point where the airplane reaches a height of 35 feet, assuming that a critical engine is failed.

Special approach design criteria (VTOL and STOL). - At the design approach speed and with all engines operating, the airplane must be able to increase its normal load factor by 0.3 by changing angle of attack or power.

At the design approach speed and with the critical engine failed, the airplane shall be able to encounter a ten-knot, sharp-edged, vertical gust or a ten-knot, horizontal speed change without encountering excessive buffeting.

At the design approach speed and with the critical engine failed, the airplane must be able to increase its normal load factor by 0.1 by changing angle of attack or power without encountering excessive buffeting.

LTV study ground rules. - During this study, LTV has adopted the following ground rules because of limitations considered to exist for the 1970 time period specified for this study.

Propeller diameters are limited to twenty feet.

Tip-turbine-driven-fan pressure ratios are limited to 1.3.

Where engines are interconnected by a hot exhaust interconnecting duct, no more than two engines can be exhausted into a common duct.

STUDY METHODOLOGY

Two general methods of study have been used in this program (Figure 2). First, a series of parametric studies were used to select the characteristics of airplanes that would perform the design mission within the constraints of the study ground rules and the FAR airworthiness requirements. These airplanes were then analyzed to determine their direct operating costs (DOC) on the design stage length of 500 statute miles. That combination of characteristics which resulted in a near minimum DOC for each set of field length and passenger load criteria was then selected as optimum. Numerous simplifying steps were taken during the parametric study. These simplifications were checked to insure that they did not impair the integrity of the study; and hence the data generated by these studies are considered adequate for comparing one airplane against another, providing both airplanes use the same V/STOL propulsion system concept and design criteria.

The parametric studies were followed by a detailed design, operational and economic analysis of each of the optimum aircraft. From these analyses, the fan-in-wing V/STOL, turboprop VTOL, turboprop 2000 foot STOL and propulsive wing 2000 foot STOL airplanes were selected to warrant additional study. Additional analyses of these airplanes included the development of 90 and 120 passenger versions, studies of sensitivity of selected airplanes to the variation of selected variables, and extended economic analyses.

Performance Estimates

The cruise performance estimates for this study have been made at two levels of accountability. For the parametric studies, generalized performance estimation procedures, based on gross geometric and flight characteristics, have been used. These parametric studies provided the data from which the characteristics of the optimum airplanes were selected. Detail estimates were then made of the installed propulsion system performance and drag characteristics for each optimum airplane; and these data were used in comparing the optimum airplanes with each other.

Parametric study methodology - cruise performance. - For the parametric cruise performance studies, generalized drag estimation procedures have been used. Skin friction drag was assumed to vary with the three major aircraft components: (1) fuselage frontal area; (2) engine nacelle frontal area; and (3) wing plus tail surface areas. Empirical equations, found to give reasonable results for parametric studies, were used to predict the skin friction drag for the various combinations of parametric variables. To get approximate sizes for tail configurations for the parametric designs, a survey was made of the tail volume coefficients of flying VTOL and STOL aircraft. This survey showed that these coefficients were reasonably constant; therefore, representative values of tail volume coefficient were combined with the tail arms determined from preliminary layouts to get the tail areas for the parametric analyses.

The drag rise due to compressibility was predicted by the method of Reference 3 for both the parametric and detailed analyses. The predicted drag rise of the turboprop airplanes started at a Mach number of approximately 0.7. The drag rise of the fan-in-wing airplanes was predicted to occur at a Mach number of approximately 0.8. Drag rise prediction techniques are not applicable to prediction of drag rise characteristics of the propulsive wing configurations; therefore, LTV has conducted high speed wind tunnel tests of a propulsive wing configuration. These test data have shown the drag rise Mach number of this configuration to be 0.9; therefore, this drag rise Mach number was used for all propulsive wing configurations evaluated in this study.

The drag due to lift was estimated by the method of Reference 4 with a modification applied as a result of LTV flight test experience. This method correlates drag due to lift with the aspect ratio of the wing and it has been used for both the parametric and detailed analyses.

The basic gas generators have been rubberized as turboshaft, turbojet, and turbofan engines. Vendor data have been used to establish the characteristics of these rubberized engines. The rubberized engine performance data were corrected for installation losses, hot duct losses (including leakage), bleed air extraction, and horsepower extraction to drive accessories.

Rubberized fan data have been used for the fan-in-wing and propulsive wing concepts. For the tip-driven-turbine-fans used in the fan-in-wing concepts, a fan pressure ratio of 1.3 has been used. These fans have been so limited by structural characteristics of this fan which must absorb the loads of the powering turbine attached to the fan tip. The fans on the propulsive wing concepts have a fan pressure ratio of 1.35, because related studies have shown this fan pressure ratio to be near optimum for such lift-cruise fans.

For turboprop concepts, the variation of thrust with fuel flow for combinations of the largest and smallest turboshaft engines and propellers considered reasonable for this study was determined. It was found that for the extreme combinations of these parameters (small engine and large propeller, or large engine and small propeller), the variation of fuel flow with thrust fell within a relatively narrow band for a given cruise speed (Figure 3); therefore, an arbitrary line drawn between these extremes was assumed to define the variation of fuel flow with thrust for the speeds evaluated. This method was then used to convert the turboshaft engine-propeller combinations into pseudo-jet engines and thus simplify the analysis procedures for the parametric studies.

Detailed analyses study methodology - cruise performance. - After characteristics of the optimum airplanes were determined from the parametric studies, more exacting performance estimating procedures were used to predict the performance capabilities of each of these optimum designs. Detailed drag estimates, such as shown in Table 2, were made for each optimum airplane. More exacting stability and control analyses were made, and the revised surfaces, sized as a result of these analyses, were used in developing the detailed drag and weight estimates. Table 3 presents a summary of the detailed drag estimates for the ten 60-passenger airplanes developed for this study.

Detailed predictions of the propulsion system installation losses were made for each of the three propulsion system concepts studied. A set of propeller characteristics was selected, and the performance characteristics of this propeller were programmed into the digital computer so that these characteristics could be used in predicting the performance of turboprop designs. These propeller performance characteristics were obtained from Reference 5.

Special slow speed flight performance estimation methods.- The special slow speed flight performance estimation methods described herein have been used for both the parametric and detailed analyses.

The analytical approach of Reference 6 was used to predict the slow speed flight performance characteristics of the turboprop airplanes evaluated in this study. This method assumes that the stream tube influenced by the wing is filled with air moving at the velocity of the stream tubes generated by the propellers. The method uses power-off aerodynamic data, and the aerodynamic forces and moments are calculated by combining these power-off aerodynamic data with the dynamic pressure of the propeller stream tubes, but with a correction factor applied to compensate for the ratio of the actual mass of air activated by the airplane to the assumed mass previously described. LTV Aerospace Corporation flight test evaluations of the XC-142A have shown the slow speed performance capabilities of this airplane to be slightly better than would be predicted using the analytical method of Reference 6; therefore, the slow speed performance estimates developed for this study are considered conservative. (The XC-142A is a turboprop powered V/STOL transport airplane which uses the tilt-wing concept to get its VTOL capabilities, and its geometric characteristics are described in Reference 7.) The aerodynamic characteristics of a 48% chord, full span double-slotted flap system have been used in predicting the slow speed performance characteristics of the turboprop designs evaluated in this study.

The analytical method of Reference 8 has been used to estimate induced effects for fan-in-wing configurations. This method predicts the induced aerodynamic forces for fan-in-wing airplanes as functions of the fan geometry and performance characteristics, the wing geometry, and the position of the fan in the wing. Comparisons of the results obtained using the method of Reference 8 with wind tunnel data show the method to predict the induced aerodynamic effects of fan-in-wing airplanes sufficiently accurate for feasibility studies.

As a result of the lack of aerodynamic data on propulsive wing configurations, LTV has used aerodynamic force and moment coefficients from tests of a non-optimum configuration (Reference 9). These coefficients were corrected for aspect ratio differences between the model tested and the designs evaluated, and these corrected coefficients are considered sufficiently accurate for a feasibility study. Optimization of the flap arrangement and configuration may allow better slow speed performance than has been predicted for the propulsive wing airplanes evaluated in this study.

Weight Estimates

The weight estimates used in this study were developed using statistical analyses, and they were used in both the parametric and detailed studies. The weight estimation method consists of using statistical weight equations which have been shown to predict the weights of components of contemporary aircraft as functions of geometric and performance characteristics of the aircraft. These equations were derived using a digital computer routine which determines the best fit for a given set of statistical weight data. This routine develops best fit weight equations as functions of geometric and performance variables; and it also develops additional best fit equations by dropping one variable at a time and performing a least square analysis using the remaining variables. In this manner, the simplest equation yielding the highest degree of statistical accuracy is determined. Modifying factors, developed analytically, for special features or design complexities of V/STOL aircraft, not accounted for in the existing statistical data, have been applied to the results of these statistical equations.

The same weight estimation equations for given components have been used, as appropriate, for all airplanes evaluated during this study, thus preventing inadvertent advantage being given to one concept as compared to another.

For situations where statistical weight estimating equations were not available or are otherwise inappropriate; vendor data, scaling curves or specified calculations, based on preliminary structural analyses, were used to arrive at the estimated weights of components. Parametric structural loads and component sizing analyses have been performed as a part of this study to support the substantiation of the estimated weights.

Costs

This study has used direct operating costs (DOC) as the optimization criteria for the airplanes developed. The direct operating costs are those costs which accrue when an airplane is operating, and they consist of the depreciation of flight equipment, direct maintenance costs, and the cost of the flight operations. Direct operating costs for parametric studies have been estimated using LTV developed statistical DOC equations. These equations estimate DOC as functions of selected airplane geometric parameters and performance characteristics, and they have been shown to be sufficiently accurate for assessing the effects of changes in design parameters on DOC for parametric studies.

Direct operating costs for the optimum airplanes have been estimated using the method of Reference 10 with some minor modifications. This method involves a relatively complex cost estimating procedure, and it is expected to give cost data adequate for comparing one optimum airplane with another.

Depreciation-flight equipment. - The major factor in the depreciation of flight equipment is the initial cost of the airplane. A traditional, detailed costing procedure has been used to estimate the initial airplane cost. This method predicts the cost of major airplane components using statistical cost data from conventional airplane designs. For the V/STOL airplanes of this study, correction factors have been applied to compensate for the additional complexity of components that are different for V/STOL concepts. NASA specified that the depreciation periods and residual values specified in Reference 10 be used. The spares cost ratios were specified to be those of Reference 10 except that an avionics spares cost ratio of 50% was to be used, and a spare parts price factor of 1.3 was to be used.

Direct maintenance costs. - In estimating the direct maintenance costs, a deviation was taken to the method of Reference 10. It was considered desirable to take advantage of recent experience available on turbine powered aircraft, and to account for the additional complexity of V/STOL aircraft. A compilation of maintenance experience of various transport airplane operators on all types of turbine powered aircraft was made for each of the major systems of the airplane, with a breakdown of the major systems made in accord with the Air Transport Association Specification 100. Plots were then prepared, for each of these airplane systems, of maintenance manhours per flight hour versus the system weight. Technical judgment was used to adjust these resulting curves for the increased maintenance complexity of the same systems in V/STOL aircraft. These adjusted curves were then used to build the maintenance manhour per flight hour estimates for the designs developed in this study. The estimated weights of the designs developed were broken down in accord with the Air Transport Association Specification 100 format in order that these developed maintenance curves could be used.

Flight operation costs. - The flight operation costs include the fuel and oil costs, crew costs, and insurance. NASA specified that the method of Reference 10 would be followed except crew costs were increased by 22% to represent 1965 costs. Only a pilot and copilot were assumed to be required for the airplanes developed in this study.

Optimum Design Selection Process

For airplanes having a vertical takeoff capability, the combination of parametric variables having a near minimum direct operating cost were selected as the characteristics of the optimum design. It was found that the vertical takeoff conditions were critical in sizing the propulsion system; therefore, each of the candidate combinations of parametric variables for the VTOL airplanes had propulsion systems sized to meet these critical vertical takeoff conditions and the required mission performance. Combinations of parametric variables were selected for cruise at altitudes of 25,000 and 35,000 feet. The primary parametric variables for these airplanes were aspect ratio and wing loading. Checks were made to assure that additional power above that required for VTOL would not lower the DOC of these airplanes.

For the STOL airplanes, the thrust-to-weight ratio was an added primary parametric variable. It was not known whether the takeoff and/or landing or cruise thrust-to-weight ratio requirements would predominate; therefore, the thrust-to-weight ratio was varied for each of these airplanes. For each STOL propulsion system concept, propulsion systems were sized to give three selected thrust-to-weight ratios, and the accompanying combinations of parametric variables that would meet the design missions were identified. Again, combinations of parametric variables were selected for cruise altitudes of 25,000 and 35,000 feet.

Figure 4 presents an example of a typical optimum airplane selection process. Curves of this type were prepared for thrust-to-weight ratios of 0.6, 0.8 and 1.0, and the optimum combinations of wing loading and aspect ratio were selected for each of these three thrust-to-weight ratios. This plot then represents a plot of the optimum wing loadings and aspect ratios for one cruise altitude with the thrust-to-weight ratio as the primary variable; and it can be seen that the minimum direct operating cost occurs at a thrust-to-weight ratio of approximately 0.9. Hence, a thrust-to-weight ratio of 0.9 would be optimum for this propulsion system concept, unless the takeoff and/or landing thrust-to-weight ratio requirements demand a higher thrust-to-weight ratio.

The propulsive wing concept is unique since its wing geometry is dictated by the propulsion system arrangement; therefore, instead of varying wing loading, aspect ratio and thrust-to-weight ratio for this concept, the number of wing fans and thrust-to-weight ratio are the primary parametric variables. The thrust-to-weight ratio and number of wing fans indirectly specify a wing area and aspect ratio for this concept.

STUDY RESULTS

Configuration Design

The aircraft designer is faced with a new challenge in his endeavor to successfully integrate all the requirements of V/STOL, and to a lesser degree STOL, aircraft into a useful vehicle. Unique propulsion system arrangements, sophisticated avionics equipments, and complex control systems must be integrated into an airframe which also contains the complexities of conventional aircraft; and this must be done at an acceptable cost and for a minimum weight. The V/STOL aircraft is a closely integrated package in which no single system or component can be changed without affecting another. The efficiency of a V/STOL aircraft is a direct function of the degree of integration of its systems. A good V/STOL airplane cannot be obtained by simply combining an optimum propulsion system with an optimum complement of avionics equipment and an optimum control system, etc., but rather its success depends on how well all the systems are integrated to function as a unit - not how well each subsystem operates independently.

General component considerations. - Certain components of the V/STOL aircraft developed for this study were selected after special side studies were made. These components were the powerplants, the avionics equipments, and the control systems.

Powerplants. - In projecting the commercial engine state-of-the-art into the 1970 time period for airplane operation with commercially certificated engines by 1973, it has been necessary to use propulsion hardware and performance which are now considered to be at military development levels. The components of the primary propulsion system used in this study have been chosen at the secondary level of military development; i.e., the equipment would no longer be considered for an advanced military aircraft design. It was considered that this "derating" of military equipment establishes propulsion system component performance suitable for commercial operation in 1973 with acceptable levels of reliability and maintainability.

It was assumed that a production version of a lightweight turbojet engine would be available for 1973 and that this engine would be acceptable as a pitch engine. For this role, the turbine inlet temperature was reduced from 2200°F to 1645°F to provide a performance margin for reliability and maintainability and to assure safe operations, since these engines also double as auxiliary powerplants.

A number of candidate primary engines were examined and the General Electric GE1 gas generator technology was considered representative of the engine technology that would be commercially acceptable for 1973. Some general characteristics of this gas generator technology are presented in Table 4.

Avionics equipments. - A survey of the electronic equipment manufacturing industry revealed that much of the airborne avionics hardware required for V/STOL aircraft is available today. Except for the all-weather takeoff and landing system and possibly the terminal area navigation system, the avionic equipment used for V/STOL aircraft will be essentially the same as for conventional aircraft. A communication and navigation equipment list was derived from XC-142A, commercial helicopter, and conventional commercial transport aircraft equipment lists. The FAA certification requirements were used as a guideline for selecting the minimum equipment complement. The equipment used as a basis for determining weight and cost estimates is of recent design, and the specific equipment items are listed in Table 5.

Control systems. - The control systems for all airplanes developed in the study were designed to be capable of providing the "desired" levels of control power as specified by Reference 1 and presented in Table 1. It was found that for all airplanes, the use of "acceptable" levels of control power instead of "desirable" levels had only minor effects on the airplane designs because the furnishing of the "desired" levels of control power was not critical in sizing any propulsion system components.

Limited analyses were made to select the characteristics of stability augmentation systems. For this process, the airplanes have been broken into categories of airplanes having a hover capability, airplanes designed to operate from 1000 foot fields and airplanes designed to operate from 2000 foot fields. The airplanes having a hover capability were determined to need dual rate plus displacement augmentation channels in pitch and roll, and a single rate channel in yaw. The airplanes operating from 1000 foot fields were determined to require single channel yaw and roll dampers. The airplanes operating from 2000 foot fields were determined to require only a single channel yaw damper for their stabilization systems. Although extensive analyses and simulation studies would be required to confirm the results of these limited analyses, the results thus obtained are considered sufficiently accurate for a feasibility study.

Configuration descriptions. - As mentioned previously, the configurations developed for this study utilize three propulsion system concepts (1) the turboprop (2) the fan-in-wing and (3) the propulsive wing.

Turboprop powered concepts. - A typical 60-passenger turboprop airplane is shown in Figure 5. The turboprop airplanes have high wing arrangements and are powered by four turboshaft engines driving four propellers. The wing is provided with leading-edge slats and full-span, 48% chord, double slotted trailing-edge flaps to give a high maximum lift capability and thus compensate for the high wing loading which is desirable for minimum direct operating costs. A unit horizontal tail is mounted on the vertical tail, which consists of a conventional fin and rudder arrangement.

The fuselage has an oval cross-section and its length is established by the combined requirements for cockpit space, passenger cabin and its facilities, and low drag. Two doors are provided for access to the fuselage, and escape hatches are located on each side of the fuselage in the passenger cabin.

Two cubic feet of carry-on-baggage space per passenger are provided in the passenger cabin. Cargo and stowed baggage compartment access doors are located at a convenient height on the lower side of the fuselage. Space is provided for 1200 pounds of revenue cargo at a density of ten pounds per cubic

foot, and stowed baggage space is provided assuming each passenger carries the limits allowable without excess baggage charges.

The unique characteristics of the V/STOL turboprop airplanes are the tilting wing, the use of jet engines for longitudinal control augmentation in all but the 2000 foot STOL, and a transmission system interconnecting all engines.

The general turboprop VTOL design philosophy used by LTV is similar to that used in the development of the XC-142A with one major exception, which is the use of jet engines for pitch control in place of the tail rotor. Two main reasons for this arrangement are the added safety margin provided by the redundant pitch systems; and, at the cruise condition, the drag is reduced by eliminating the tail rotor.

The engines are mounted directly aft of the propellers (Figure 6) keeping the cross-shafting unloaded except when an engine is out or unsymmetrical thrust is desired for control. The wing has no geometric dihedral and the leading edge beam from which the cross-shafting is supported is straight, thus eliminating the need for a gearbox between the left- and right-hand sets of engines.

For cruise flight, the turboprop airplane uses conventional ailerons, rudder, and a unit horizontal tail for control about the lateral, yaw and pitch axes, respectively. For hover, pitch control is obtained from the pitch engines, yaw control is obtained from differential deflection of the ailerons, and lateral control is provided by getting differential thrust from the propellers. During slow speed flight with the wing at incidence angles other than 0° or 90°, a mechanical integrator is provided to combine the outputs of these control producing devices in such a manner that the pilot always gets the roll, yaw and/or pitch moments that he has commanded.

Fan-in-wing concepts. - For this study, NASA restricted LTV to the study of "pure" fan-in-wing airplanes in which all the gas generator power is diverted to drive the lift fans for hover and slow speed flight conditions. Numerous fan-in-wing arrangements were studied and certain fundamental characteristics of these airplanes were learned.

Discussions with powerplant manufacturers led to the conclusion that for the 1970-1975 time period, it would not be possible to connect more than two gas generators into one exhaust manifold system. It was also found that the DOC for the fan-in-wing airplanes reduced as the wing loadings increased, and/or the aspect ratios decreased; therefore, considerable effort was expended in selecting propulsion system arrangements which would aid in minimizing aspect ratio and maximizing wing loading. The ability to duct more than two gas generators to a common manifold or to deflect a portion of the primary gas generator thrust vertically and hence reduce the required fan sizes would probably have made the design integration problems less difficult. It is also possible that the use of turbofan engines for cruise thrust, instead of the turbojet engine that is considered a part of the "pure" fan-in-wing principle, could have lowered the fuel requirements for these designs to levels that would permit considerably smaller airplanes. Since these innovations were not studied, they can only be pointed out as possible areas to improve the capabilities of the fan-in-wing airplanes.

A typical fan-in-wing airplane is shown in Figure 7. It is a high wing airplane powered by six wing-mounted turbojet engines driving four tip-turbine fans installed in the wing and one tip-turbine fan installed in the fuselage nose. The wing has trailing edge flaps on the inboard section and combination trailing edge flap/ailerons on the outboard section. The unit horizontal tail (UHT) is mounted on the top of the vertical fin in order to keep the UHT away from the exhaust of the inboard engines.

The fuselage, except for the differences necessitated by the installations of the nose fan, is similar to the fuselage of the turboprop-powered airplanes, as are the crew and passenger accommodations.

The unique characteristics of the fan-in-wing airplanes are the tip-driven fans mounted in the wing and in the nose of the fuselage. These fans govern the configuration geometry. Several constraints dictated the wing planform which has an essentially constant chord. The first constraint was the minimum fan/turbine diameter. Another constraint was the routing of the fairly large diameter ducts for the hot gas in the wing. After analyzing many options, including routing in front of and in back of the wing beam, it was determined that the best possible routing was to keep the hot gas ducts between the front and rear box beams, thereby keeping the wing depth, the wing chord, and structural box beam weight to a minimum. It is to be noted that the XV-5A uses this approach, but it has single fans per wing making the problem simpler. The chord of a minimum chord wing is then simply the fan diameter plus the front and rear box beam and the length of flap. To provide a taper would require adding area since the wing chord is already a minimum at each fan. Wing sweep back is used to keep the thrust axes of the wing fans in harmony with the wing aerodynamic center.

The engine nacelles are located so that the hot engine exhaust gases are directed to the fan between the wing leading edge and trailing edge box beams. This is in accord with keeping the hot gas ducts from cutting through the beams. The outboard engines are mounted in the conventional "under slung" nacelle below the wing. The proximity to the fuselage requires the inboard nacelles to be located above the wing. Several low wing designs of fan-in-wing airplanes were studied and these were found to have good features, such as more direct ducting paths for the hot gas which drives the nose fan. From further study of these low wing arrangements, it was concluded that the basic gas generators would have their performance severely penalized during hover due to the reingestion of the heated exhaust gases; therefore, the low wing arrangement was selected for the STOL airplanes only, with the high wing arrangement used for the airplanes required to operate VTOL.

For this study, the fan-in-wing airplanes having a VTOL capability were fitted with 15 percent chord flaps, and the designs having only a STOL capability were fitted with 25 percent chord flaps.

The front and rear box beams are designed to provide the same strength and stiffness as a conventional single box wing. This increases the weight of the box approximately 30 percent, which corresponds to a 15 percent increase in wing weight. Figure 8 is a schematic drawing of the hot gas ducting and engine locations. As can be seen, with all engines operating, the hot gas from each engine is divided so that each wing fan absorbs the hot gas output of 1-1/3 engines and the nose fan absorbs the hot gas of approximately 2/3 of one engine. The engine sizes are established by the requirement to provide a thrust/weight ratio of 1.15 with the airplane trimmed and no maneuvering control input on an 86°F day at sea level.

Figure 9 illustrates an engine-out condition (the outboard engine-out is used since it requires the most corrective action to meet the roll trim and control requirements). For this condition, all the hot gas of the operating outboard engine adjacent to the failed engine is directed to the outboard fan. The two inboard fans are powered to their maximum capability. The nose fan is limited to the amount necessary to provide the required 20 percent of the pitching-acceleration. The remainder of the hot gas is then ducted to the outboard fan on the side opposite the failed engine.

With one engine out, the remaining 5 engines are operated at an emergency rating of 110 percent of the gas generator gas horsepower takeoff rating.

An important feature of the fan-in-wing propulsion system is the variable inlet turbine which is designed to operate through a range of hot gas flow of approximately plus or minus 47 percent from the nominal gas flow rate. This propulsion system feature is known as "gas power exchange" or "power transfer." The principle involved is to have one gas generator supply hot gas to more than one power turbine. Each power turbine is mounted on the tip of a fan. Varying the turbine inlet area differentially from one power turbine to another and holding total turbine inlet area constant makes more hot gas flow through one turbine than the other, thereby changing the fan speed and hence providing differential fan thrust.

Each engine is provided with a diverter valve so that its hot gas can be diverted from the fan/turbine to a straight-through nozzle providing conventional jet thrust for cruise flight.

During cruising flight, pitch control is provided by the unit horizontal tail. During slow speed flight operations, pitch control is provided by differential thrust between the nose and wing fans. During cruise, directional control is provided by the rudder, and lateral control is provided by the ailerons. During slow speed flight operations, directional control is provided by differential movement of the vanes which direct the exhaust of each of the wing fans. Lateral control is provided by the gas power exchange system previously described, which gives differential thrust between the wing fans.

Propulsive wing concepts. - A typical propulsive wing airplane is shown in Figure 10. The low wing STOL airplane is powered by six turbojets driving eight wing-mounted turbines which are shaft connected to eight wing fans and two fuselage mounted turbines which are shaft connected to two nose fans. The relatively low aspect ratio wing is fixed at a 5° incidence. A 20 percent chord fan air deflection flap is located at the wing trailing edge. Unit horizontal tails are located on the wing booms.

A conventional fin and rudder vertical tail is located on the fuselage. The crew and passenger accommodations are essentially the same as for the other concepts evaluated in this study.

Some of the unique features of the propulsive wing concept include:

- Twin forward-facing nose fans, located in the forward section of the fuselage, which operate in the cruise as well as the STOL mode.
- Outboard tails mounted on wing booms
- Efficient jet flaps
- Efficient propulsion system for a wide range of conditions
- High cruise Mach number (0.90)

The gas generators are mounted one in each boom and two on each side of the fuselage (Figure 11). The wing turbines are sized and arranged so that each absorbs one half of the gas generated by one engine; therefore, four engines drive the eight wing fans. The fuselage turbines are sized and arranged so that each absorbs all the gas power from one engine; therefore, each inboard engine drives a nose turbine/fan combination.

Each engine is connected to the corresponding engine on the opposite side by a hot gas duct with a shutoff valve. During engine starts, the shutoff valves are closed, permitting each engine to be started in turn. After the engines are started, the shutoff valves are opened to maintain complete thrust symmetry in the event of an engine failure. The propulsive wing concept also uses the "gas power exchange" system. The total thrust loss due to a failed engine is quite small, in the order of 8 to 10 percent with one engine out and the other five engines operated at 110 percent of the takeoff rating.

Figure 12 shows a section through one of the wing fans. The propulsive wing consists of fans mounted vertically within the upper and lower surfaces of the wing, behind the leading edge inlet air duct. Each fan is driven directly by a turbine mounted in the aft section of the wing. The straight-through fan air flow duct exits through a variable area nozzle to ensure efficient fan operation under a wide range of power settings.

The installation of the fuselage nose fans is similar in concept to the wing fans. The turbines driving the nose fans are mounted in the mid-section of the fuselage and connected to these fans by long shafts, thus eliminating the routing of hot gas ducts the entire distance from the gas generators forward to the nose of the airplane.

The wing structure is greatly influenced by the propulsive wing concept and represents a departure from conventional wing design. The main wing torque box is comprised of front and rear truss beams plus upper and lower stiffened and stressed skin panels. The beams occupy the full depth of the physically thick propulsive wing, providing a stiff structure. The wing torque box is located well forward of all the hot gas ducting; and a gas leak, should one occur, would not impair the integrity of primary structure.

In cruising flight, longitudinal control is provided by the two fully-powered unit horizontal tail surfaces. During slow speed flight, pitch control is augmented by differential thrust between the nose and wing fans. In cruising flight, lateral and directional control are provided by the flap/ailerons and the rudder, respectively. During slow speed flight, lateral and directional control are augmented by differential deflection of the wing thrust vector as well as by differentially varying the magnitude of the thrust vector using gas power exchange.

Sixty passenger optimum airplanes. - Drawings of the sixty passenger optimum airplanes developed for this study are presented in Figures 13 through 17. The critical design conditions for these ten 60-passenger aircraft are shown in Table 6. It can be seen that takeoff requirements predominate in sizing propulsion systems of aircraft having a VTOL capability, mainly because of VTOL thrust-to-weight ratio requirements. Cruise speeds for minimum DOC and landing conditions primarily influence STOL propulsion system sizing. The optimum cruise Mach number of the turboprops is approximately 0.6. Fan-in-wing configurations are limited to 0.8 cruise Mach number, and propulsive wing configurations to 0.9. High-speed wind-tunnel tests have substantiated the ability of the propulsive wing concept to cruise at a 0.9 Mach number.

Turboprop airplanes. - Drawings of the sixty-passenger turboprop airplanes are presented in Figures 13 and 14. The geometric similarity of the airplanes is evident. The wings on the VTOL and V/STOL airplanes tilt through 100°, and they are fitted with dual pitch engines in the rear. The 1000 foot STOL airplane has a wing that tilts to an angle of 20° for landing, and the airplane is equipped with one pitch augmentation engine. The 2000-foot STOL airplane does not have a tilting wing or any pitch augmentation engines.

The propulsion systems of the VTOL and V/STOL airplanes were sized by the requirement for a thrust-to-weight ratio of 1.05 on an 86°F day at sea level with the critical engine failed and the airplane at the design VTOL weight. The combinations of wing loading and aspect ratio were selected to give a near minimum direct operating cost on the design stage length. A higher wing loading would give slightly lower direct operating costs, but then the transition stall margins would become critical.

The propulsion systems of the two turboprop STOL airplanes were sized by cruise conditions which required high thrust-to-weight ratios to give the relatively high cruise speeds for minimum direct operating costs. Twenty degrees of wing tilt were used on the 1000 foot STOL airplane to permit it to meet its landing performance requirements. Only one pitch engine is required on the 1000-foot STOL airplane since its horizontal tail has sufficient control power to meet the reduced pitch control requirements with a critical (in this case, the pitch engine) engine failed.

The propeller characteristics of the turboprop airplanes were optimized for takeoff performance, a ground rule used by LTV for this study. As a result, 140 activity factor, 0.5 integrated design lift coefficient blades, and a takeoff tip speed of 1000 feet-per-second were used for all 60-passenger turboprop airplanes. During the optimization process for the turboprop designs, these propeller characteristics were not varied; but the engine-propeller combination was run at the optimum rpm in cruise. It was found that this optimum cruise rpm was about 75 percent of the takeoff rpm. After it was determined that for the turboprop STOL airplanes, cruise performance was critical for sizing the propulsion system rather than takeoff performance, it was considered appropriate to see if better propeller characteristics could be selected since the characteristics of the selected turboshaft engine show a rapid drop in available power as the cruise engine rpm is reduced. The effects of propeller tip speed, coupled with the 100 percent free turbine tip speed, activity factor, and design integrated lift coefficient on cruise speed, were investigated.

Figure 18 shows the variation in cruise speed as a function of propeller geometric and operating characteristics. A change of approximately 45 knots can be realized by changing the maximum design tip speed from 1000 to 700 feet-per-second, the activity factor from 140 to 100, and the integrated design lift coefficient from 0.5 to 0.3.

The effect of varying power and the maximum propeller tip speed on takeoff performance of the 2000-foot design is shown in Figure 19 for various flap settings. It can be seen that the takeoff performance can be considerably better than the design landing distance. Decreasing the maximum tip speed has little effect on takeoff distance for these airplanes.

It was also desired to determine the necessity of cross-shafting for the turboprop 2000-foot STOL airplane. The sensitivities of the roll and yaw requirements to true airspeed for this configuration were studied to determine the approximate speed where cross-shafting would no longer be needed. Figure 20 presents the net rolling moment available from a spoiler roll control system versus true airspeed. The effectiveness of six percent chord spoilers is shown for trim angles of attack of 5, 10, and 15 degrees. For any speed above 65 knots, the maneuvering roll control requirement can be met at reasonable angles of attack and with a 6 percent chord spoiler system. However, Figure 21 shows that the yaw control requirement is more critical than the roll control requirement. These yaw control requirements have been developed from test data on a two-engine configuration as reported in Reference 10. The yawing moments available from a plain flap rudder with boundary layer control and a double hinged rudder are shown as functions of true airspeed. With the required spoiler control input to trim out the resulting rolling moment at a trim angle of attack of 10° and with the number one engine out and the propeller feathered, the resulting yawing moments at maximum power show a relatively large vertical tail area or a sophisticated rudder system was required to eliminate cross-shafting below approximately 75 knots.

Since the yaw control available was considered marginal in the operational speed regime of the 2000-foot STOL design, cross-shafting was used on all turboprop configurations.

Fan-in-wing airplanes. - Figures 15 and 16 show drawings of the sixty-passenger fan-in-wing airplanes. These airplanes are equipped with six gas generators, four wing fans and a fuselage nose fan. The airplanes having a VTOL capability have high wing arrangements and a "tee-tail;" whereas the STOL airplanes have low wings and more conventional tail configurations.

The gas generators of the VTOL and V/STOL airplanes were sized at the design VTOL weights jointly by (1) the requirement for a thrust-to-weight ratio of 1.0 on an 86°F day at sea level with the most critical engine inoperative and the reduced simultaneous control inputs required being developed, and (2) the requirement for a thrust-to-weight ratio of 1.15 on an 86°F day at sea level with all engines operating and no control input other than that required for trim. The fans were sized by the requirement for a thrust-to-weight ratio of 1.15 on an 86°F day at sea level. The wing loading and the aspect ratio are the maximum and minimum, respectively, that can be obtained with sufficient structure and space in the wing for the propulsion system components. Even higher wing loadings and lower aspect ratios, if they were possible, would give lower direct operating costs.

The propulsion system of the fan-in-wing 1000-foot STOL airplane was sized to give the thrust-to-weight ratio required to permit flight at the design landing speed, including the specified margins for control and stall with the critical engine failed. The propulsion system of the fan-in-wing 2000-foot STOL airplane was sized to give a minimum direct operating cost with the takeoff performance requirements being almost as critical as the cruise requirements. The direct operating costs of the fan-in-wing STOL airplanes would be lower if their wing loadings could be increased or their aspect ratios decreased.

The fuel weight of the fan-in-wing airplanes was found to be one of the factors causing the weight of these airplanes to be relatively large. Since the fuel reserves required by V/STOL short-haul transport airplanes have not been firmly established, it was considered desirable to determine the influence this factor could have on the size of the fan-in-wing V/STOL airplane. The reserve fuel for this airplane is 33 percent of the total fuel weight, and approximately 7 percent of the gross weight of the airplane. Figure 22 shows the sensitivity of the fan-in-wing V/STOL airplane empty weight and gross weight to change in reserve fuel requirements. This figure shows a 20 percent change in the reserve fuel will change the takeoff and empty weight by approximately 3.5 percent.

Propulsive wing airplanes. - The propulsive wing airplanes, shown in Figure 17, are geometrically similar, differing only in size because the 1000-foot STOL airplane has a higher design thrust-to-weight ratio. The propulsion system of the propulsive wing 1000-foot STOL airplane was sized to give the thrust-to-weight ratio required to permit flight at the design landing speed, including the specified margins for control and stall with the critical engine failed. The propulsion system of the propulsive wing 2000-foot STOL airplane was sized by cruise conditions which give a minimum direct operating cost on the design stage length. The number of wing fans used on the propulsive wing airplanes were optimized to give a near minimum direct operating cost.

Since only limited data were available to support the design of the propulsive wing airplanes, it was considered appropriate to evaluate the sensitivity of the propulsive wing 2000-foot STOL airplane to changes in skin friction and propulsion system efficiency. Figure 23 shows the variation in the design takeoff weight with changes in the skin friction drag and the propulsion system efficiency for the propulsive wing 2000-foot STOL airplane, and it shows a 10 percent increase in the skin friction coefficient causes a 3.5 percent change in takeoff weight, and a 10 percent change in propulsion efficiency causes a change of approximately 5 percent in the takeoff weight.

Configuration design summary. - Table 7 summarizes some of the more important physical characteristics of the ten 60-passenger optimum airplanes developed during this study. Reference to this table shows that the gross weights of these airplanes vary from approximately 53,000 pounds for the turboprop 2000-foot STOL airplane to over 95,000 pounds for the fan-in-wing VTOL airplane. A breakdown of gross weights into the five major categories of structure, propulsion, fixed equipment, fuel, and useful load less fuel (Figure 24) shows that all designs have comparable structural weight ratios which vary from 27 percent to 29 percent of the gross weight. The actual weights of fixed equipment and useful load less fuel were almost the same for all designs; therefore, the percentage of gross weight assigned to these items varies inversely with the airplane's gross weight. The predominant factors in establishing the gross weight were then the sum of the propulsion system and the fuel weights. These factors varied from 23 percent for the turboprop 2000-foot STOL airplane to 40 percent for the fan-in-wing VTOL airplane. Table 8 presents a detailed estimated weight breakdown for each of the 60-passenger airplanes.

The powerplant sizes required by these designs are considered reasonable for the 1970 time period.

Economic Analyses

For the 60-passenger airplanes, the direct operating costs per passenger seat-statute mile were predicted as a function of stage length. A 2000-hour per year utilization and a non-productive time of 10.25 minutes were assumed, in accordance with Reference 1. Figure 25 is a plot of these direct operating costs for each of the 60-passenger airplanes. These costs were predicted using the method described in Reference 10 with the modifications specified by NASA in Reference 1. For the turboprop airplanes, the direct operating costs (DOC) vary from approximately 2.2 cents per seat-mile for the 2000-foot STOL to approximately 2.7 cents per seat-mile for the VTOL at a 500-mile stage length. As the operating stage length is reduced to 100 miles, the DOC vary from 3.4 cents per seat-mile for the 2000-foot STOL to 4.1 cents per seat-mile for the VTOL. In general, the DOC of the VTOL airplane are approximately 23 percent greater, the V/STOL airplane DOC are approximately 15 percent greater, and the 1000-foot STOL airplane DOC are approximately 9 percent greater than the DOC of 2000-foot STOL airplane. (It should be noted that these cost data were generated assuming that all designs were fitted with propellers optimized for the takeoff performance condition.)

For the fan-in-wing airplanes, the DOC vary from 2.8 cents per seat-mile for the 2000-foot STOL airplane to approximately 3.6 cents per seat-mile for the VTOL airplane at a 500-mile stage length. When the operating stage length is reduced to 100 miles, the DOC of the 2000-foot STOL airplane increase to over 5 cents per seat-mile and the DOC of the VTOL airplane increases to approximately 5.8 cents per seat-mile. The seat-mile costs of the 1000-foot STOL airplane and the V/STOL airplane are approximately 7 percent greater than the seat-mile costs for the 2000-foot STOL airplane.

For the propulsive wing airplanes, the DOC vary from 1.9 cents per seat-mile for the 2000-foot STOL airplane to 2.3 cents per seat-mile for the 1000-foot STOL airplane on a 500-mile stage length. At a 100-mile operating stage length, the DOC of the 2000-foot STOL airplane are approximately 3.4 cents per seat-mile and the DOC of the 1000-foot STOL airplane are 4.2 cents per seat-mile. At all stage lengths, the DOC of the 1000-foot STOL airplane are approximately 25 percent greater than for the 2000-foot STOL airplane.

The initial airplane costs used in predicting the DOC are presented in Figure 26. These costs were predicted to vary from 2.17 million dollars for the turboprop 2000-foot airplane to 4.63 million dollars for the fan-in-wing VTOL airplane. The fan-in-wing and propulsive wing airplanes were predicted to cost approximately 80 dollars per pound of empty weight. The turboprop VTOL and V/STOL airplanes were predicted to cost approximately 74 dollars per pound of empty weight, and the turboprop STOL airplanes were predicted to cost approximately 66 dollars per pound of empty weight. These initial airplane costs were based on a quantity of 300 airplanes being bought with no research and development work being required to extend the technical state-of-the-art.

In developing the direct operating costs, the maintenance manhours per flight hour used for each of the 60-passenger airplanes are presented in Figure 27. It can be seen from this bar chart that the airframe maintenance was predicted to be approximately the same for all designs, varying from about 8 maintenance manhours per flight hour for the propulsive wing 2000-foot STOL airplane to almost 10 maintenance manhours per flight hour for the turboprop VTOL airplane. The major differences in total maintenance manhours per flight hour between one airplane and another were due to the propulsion system maintenance requirements. The major factors causing the propulsion system maintenance requirements to vary were the number and size of gas generators. The propulsion system maintenance manhours per flight hour varied from approximately 5 for the turboprop 2000-foot STOL airplane to nearly 15 for the fan-in-wing VTOL airplane.

Figure 28 and Table 9 show the breakdown of direct operating costs into the components of depreciation of flight equipment, direct maintenance, and flight operations. The depreciation costs per seat-mile were the least for the propulsive wing 2000-foot STOL airplane. This occurs because of its nominal initial cost and its very high cruise speed (Mach Number 0.9). The fan-in-wing VTOL airplane has the highest depreciation, primarily due to its high, initial cost. The cruise speed of this airplane (Mach Number 0.8) was unable to compensate for its high initial cost. The direct maintenance and flight operations costs were lowest for the propulsive wing 2000-foot STOL airplane and highest for the fan-in-wing VTOL airplane. The high speed of the propulsive wing 2000-foot airplane combined with its relatively low maintenance requirements and nominal fuel consumption kept these components of seat-mile costs to a minimum. The size of the fan-in-wing VTOL airplane was sufficient to keep these major components of seat-mile costs to a maximum. Turboprop designs have relatively low to modest initial costs, direct maintenance manhour requirements and fuel costs; but the modest cruise speed of these designs counteracts these ingredients of seat-mile costs. Rematching of the propeller and engine operational rpm range, which has previously been shown to increase the cruise speed of the turboprop STOL airplanes by approximately 45 knots, can reduce the DOC by approximately 10 percent for a 500-mile stage length.

Operations Analyses

For this study, operations analyses have included the determination of the far field noise characteristics of each of the 60-passenger airplanes, a determination of V/STOL air traffic control problems, and a determination of some of the requirements of an all-weather takeoff and landing system for V/STOL aircraft.

Far field noise environment. - The noise generated by V/STOL aircraft looms as one of the major stumbling blocks to community acceptance of V/STOL short-haul transport systems. As a result, the far field noise characteristics of the ten 60-passenger airplanes have been estimated.

Typical perceived noise level directivity contours are presented in Figures 29 to 32. These contours were predicted assuming the airplanes were developing maximum power from all engines while static at ground level. In the development of these contours, it has also been assumed that there are no wind effects, the air is dry and there are no terrain features which would affect noise transmission characteristics. Figure 33 shows the variation in the maximum perceived noise level with distance from the airplane, as measured along the radial line at which the distance is the maximum for a given PNdb. It may be noted that the PNdb for all aircraft at a distance of 1000 feet are approximately 112, the maximum level considered acceptable adjacent to airports. At distances greater than 2/3 of a mile, the turboprop airplanes have noticeably higher noise levels than the fan-in-wing and propulsive wing airplanes. The turboprop 2000-foot STOL airplane has no jet engines to augment longitudinal control during slow speed flight; therefore, it has much lower noise characteristics than the turboprop V/STOL airplane. Analyses have shown that these jet (pitch control) engines make large contributions to noise in the 300 to 600 cycles per second octave band and are primary contributors to noise in octave bands above 600 cycles per second. High frequency noise attenuates with distance at a higher rate than does low frequency noise; thus the noise differences between the turboprop 2000-foot STOL and the turboprop V/STOL airplanes at distances greater than one mile are evidence of the propulsion system power output differences for these two airplanes; but the noise differences between these two airplanes at distances of less than one mile, are evidence of the high-frequency noise generated by the pitch engine on the turboprop V/STOL airplane.

Perceived noise level contours for takeoff and landing are presented in Figure 34 for the turboprop V/STOL, in Figure 35 for the turboprop 2000-foot STOL, in Figure 36 for the fan-in-wing V/STOL, and in Figure 37 for the propulsive wing 2000-foot STOL. These contours represent the noise levels that would be detected on the ground along the airplane flight path; and it has been assumed that during takeoff, takeoff power is applied on all engines and the airplane makes a climbout at a 20° flight path angle. During landing, it is assumed that the airplane approaches at a 10° descent angle with the required approach power.

Propeller noise estimates have been developed using the methods of references 12 and 13 with a delta correction factor applied. The delta correction factor was the difference between the measured and estimated noise characteristics of the XC-142A using these same estimating methods. Gas generator intake noise was estimated using the method of Reference 14 and the spectrum distribution described by Reference 15; and the noise characteristics of the turboprop and pitch engine exhausts were estimated using the method of References 13 and 16 with a correction factor applied to account for the different exhaust velocities. The noise generated in fan intakes was estimated using the methods of References 14 and 17, and the noise generated by the fan exhaust was estimated by the method of Reference 13. The fan exhaust noise of the propulsive wing airplanes was increased three decibels to account for the additional noise generated due to the flap being deflected in the exhaust slipstream.

Air traffic control. - Traditionally, new aircraft have been required to fit the air traffic control system rather than modifying the air traffic control system to fit the new aircraft. During the enroute mode of flight, a V/STOL airplane will be similar to conventional aircraft; and conventional enroute navigation aids and air traffic control systems should suffice. However, terminal air traffic control modifications should be considered for a V/STOL short-haul transport system.

Metropolitan complexes, with many airports for conventional air traffic, will find their conventional air traffic control systems unable to properly cope with novel flight capabilities and requirements of a V/STOL short-haul air transport system. A V/STOL short-haul transport airplane will not be able to economically tolerate lengthy air traffic control flight delays, and an attempt to mix V/STOL traffic with conventional air traffic could impose severe economic problems on the conventional air transport system as well. The V/STOL airplane will go in and out of airports using very steep ascent angles, because, economically, the V/STOL airplane should climb to relatively high cruise altitudes even for short flights in order to minimize DOC. As an example, this study has found that V/STOL airplanes should cruise at their design cruise altitudes (25,000 to 35,000 feet) if the range is greater than 150 miles, and the optimum cruise altitude drops to approximately 11,000 feet if the range is reduced to 50 miles. It is projected that movements of V/STOL aircraft in congested terminal areas, which would include these large and rapid altitude changes, would severely tax the capabilities of conventional air traffic control systems; therefore, the capability to effectively handle V/STOL air traffic movements should be developed.

All-weather takeoff and landing system. - One of many requirements for general public acceptance of a V/STOL short-haul air transport system will probably be that it be able to maintain regular and dependable schedules under all-weather conditions. V/STOL aircraft, as a result of their lower operational speed capabilities in the terminal area, will have a potential for operating safely to lower weather minimums than conventional aircraft; but this potential will be maximized only if a suitable V/STOL all-weather takeoff and landing system is available. DOC benefits will also accrue to a V/STOL short-haul transport system that has an all-weather takeoff and landing system that can handle V/STOL traffic effectively because such a system would be expected to reduce the non-productive times associated with takeoff and landing functions.

Tasks that a V/STOL all-weather takeoff and landing system will probably have to perform include providing obstacle clearance, keeping air traffic flowing smoothly while maintaining safe flight margins for all aircraft, and minimizing ground noise generated by the V/STOL aircraft during takeoff and landing. Many advances are being made in conventional all-weather takeoff and landing systems, and these advances will have increasing applicability to STOL aircraft at the longer STOL design field lengths. These conventional all-weather takeoff and landing systems will probably not suffice for airplanes having a VTOL or a short design field length capability because it is expected that the operator of such aircraft will want the system to permit multiple, simultaneous approaches from any direction and at varying glide slope angles - a capability not being designed into the conventional system.

Using helicopter flight operations, fixed based V/STOL aircraft simulator studies and flight experience on the XC-142A, LTV has predicted that the following information should be displayed to the V/STOL aircraft pilot and/or fed into the autopilot during an all-weather takeoff or landing.

a. Angular position with respect to the takeoff or landing point.

b. Absolute altitude above the takeoff or landing point.

c. Distance from the takeoff or landing point.

d. Velocity with respect to the takeoff or landing point.

e. Angular rates

f. Attitude, airspeed, and heading.

An all-weather takeoff and landing system having these capabilities includes not only the ground based ILS equipment, but also the as-yet-undefined airborne sensors and instrumentation and the aircraft control and stabilization systems. Providing provisions for the airborne components of an all-weather takeoff and landing system and integrating these components into the aircraft may have a strong influence on the design of V/STOL aircraft, but the extent of this impact can not be predicted until detailed characteristics of the system are known. It also can not be predicted whether any one V/STOL concept can perform all-weather takeoffs and landing maneuvers better than any other concept, and this determination can only be established with extensive operational tests.

Operational analyses conclusions. - Noise looms as a potential community acceptance problem for V/STOL short-haul transport airplane systems. V/STOL short-haul transport aircraft will be able to use existing enroute air traffic control systems; but new terminal air traffic control systems will probably be required if V/STOL systems are to have practical economic characteristics. Special all-weather takeoff and landing systems will probably be required to take the maximum advantage of the potentials offered by V/STOL aircraft. The operational analyses made in this study show that considerable additional research is required, but no one V/STOL concept appears to have an operational advantage over any other concept.

Additional Study of Selected Designs

As a result of the economic analyses, operations analyses, and technical judgement, four of the ten 60-passenger airplanes were considered to warrant additional study. The four considered to warrant additional study were the propulsive wing 2000-foot STOL airplane, the turboprop 2000-foot STOL airplane, the turboprop VTOL airplane and fan-in-wing V/STOL airplane.

The propulsive wing 2000-foot STOL airplane was selected for additional study because it had the lowest direct operating cost of any of the airplanes studied. Since the propulsive wing concepts are supported by very little test data and their technical feasibility has not been proven by flying aircraft, the turboprop 2000-foot STOL airplane was also selected since its direct operating costs were the second best. The technical feasibility of this concept has been proven by flying aircraft.

The turboprop VTOL airplane was selected for further study because of, (1) the apparent military interest in VTOL aircraft, (2) only a slight weight and cost penalty when compared to V/STOL, and (3) the mass of data available to support the design of such an aircraft. The fan-in-wing V/STOL airplane was selected for further study for reasons similar to those used in selecting the turboprop VTOL with the exception that the V/STOL airplane was chosen rather than the fan-in-wing VTOL airplane because the VTOL was so large that it was not considered compatible with the other designs being given additional study.

Extended economic analyses were made of each of these airplanes, and 90- and 120-passenger versions were designed.

Extended economic analyses. - The extended economic analyses made of these four designs included evaluations of the influences of non-productive time, annual utilization, a combined military and civil buy, and gas generator costs on direct operating costs.

Non-productive time. - For this study, the block time is measured from the time the airplane starts its taxi from the passenger loading ramp at the point of origin until it stops at the passenger unloading ramp at the airplane's destination. The non-productive time or fixed time is the time lost in making air maneuvers plus the time spent for ground taxi, waiting for air traffic control clearances, etc. The major effect of non-productive time is to reduce the block speed and hence increase the direct operating costs. The following equation illustrates the influence of the non-productive time on the block speed:

$$V_b = \frac{R}{t_o + t_f}$$

Where: V_b = block speed in miles per hour

R = range in miles

t_o = the time to fly the route, with no non-productive time, in hours

t_f = the non-productive time in hours

The time to fly the route, t_o, can be approximated by the equation

$$t_o = \frac{R}{V_{cr}}$$

Where V_{cr} = the cruise speed in miles per hour

Thus the equation for V_b can be approximated:

$$V = \frac{R}{R + V_{cr}t_f} Vcr$$

As the fixed time approaches zero, the block speed approaches the cruise speed, or when the range is large compared to the product of cruise speed and fixed time, the block speed approaches the cruise speed. By contrast, as the range decreases, and for a non-productive time not equal to zero, the block speed is considerably less than the cruise speed. As an example, for a cruise speed of 500 mph, a range of 50 miles and a fixed time of 10-1/4 minutes, the block speed is only 37 percent of the cruise speed. If the range were 500 miles instead of 50 miles, then the block speed would increase to over 85 percent of the cruise speed.

Figures 38 through 41 show the variation of DOC with stage length for non-productive times varying from 4 minutes to 15 minutes for each of the four airplanes considered to warrant additional study. These curves are for a utilization of 2000 hours per year. At the design stage length of 500 miles, the DOC for a 4-minute non-productive time is approximately 93 percent of the DOC with a 10-1/4 minute non-productive time for each of these four airplanes. At a 50-mile stage length, the DOC for a 4-minute non-productive time is approximately 75 percent of the DOC for a 10-1/4-minute non-productive time for each of these airplanes. The variation of non-productive time has an increasingly important effect on DOC as the design stage length is reduced, but no one airplane is appreciably more sensitive than any other to the variation of non-productive time.

Annual utilization. - For all curves presented in this report, the annual utilization is 2000 hours per year, unless otherwise stated. Figures 42 through 45 show the variation of DOC with annual utilization for each of the four airplanes considered to warrant additional study. In general, it can be concluded that increasing the annual utilization from 2000 hours per year to 4000 hours per year, reduces the DOC to approximately 80 percent of the DOC for 2000 hours annual utilization at all stage lengths; and the variation of annual utilization does not show advantages for any one airplane.

Combined civil-military buy. - In making an assessment of a combined civil-military buy on DOC, Reference 1 directed that the civil buy alone would be for 300 airplanes, but the combined buy would include 600 airplanes. It was assumed, based on limited side studies, that the civil airplanes could utilize 75 percent of the non-recurring design, development, and testing performed on the military airplane when there was a combined buy. Figure 46 presents the influence of the combined civil-military buy as compared to the civil - only buy on DOC for the four airplanes considered to warrant additional study. It can be seen that the combined buy reduces DOC approximately 15 percent for each of these airplanes with no one airplane having a decisive advantage over any other.

Insofar as the probability of a military buy is concerned, the following points should be considered. The military has shown a reluctance to buy STOL airplanes capable of operating from 2000-foot airfields. The military services have conducted experiments on modifying existing airplanes to develop such performance capabilities. These operational capabilities have been demonstrated in spite of some undesirable flying qualities; but there has been no apparent move by any of the services to remedy these minor deficiencies and procure such vehicles.

The XV-5A and the XC-142A airplanes have been bought by the military services in order to gain operational experience with vehicles having a VTOL capability. The military is trying to determine just how such vehicles might better improve the operational effectiveness of military units. There is little question about the military being able to gain effectiveness by using V/STOL vehicles, but the question that remains is, "Will the increased effectiveness justify the increased costs of such vehicles?" Costs (i.e., total system costs) will be so critical to this decision that it is predicted that the military will be unwilling to compromise a first generation V/STOL vehicle design for a potential joint civil-military buy. The operational costs for a civil version are also expected to be so critical to the success of a commercial V/STOL transport that the civil operator cannot afford a compromise in his vehicle in order to get a combined buy, and it is not considered likely that the design conditions for a military V/STOL airplane would result in an airplane that would have operational costs on commercial routes that could be competitive even though lower initial costs would result from a joint buy. Thus, it is concluded that a combined civil-military buy will be doubtful for any first generation V/STOL aircraft, but it is expected that this pattern will change with subsequent generation aircraft.

Influence of gas generator costs. - Since the propulsion system is so critical to the successful design of a V/STOL aircraft, a study was made of increasing the costs of gas generators by 100 percent and reducing the gas generator costs by 50 percent for the four airplanes considered to warrant additional study. Figure 47 presents the variation of DOC with these gas generator costs. Increasing the gas generator costs 100 percent causes the DOC for all airplanes to increase approximately 13 percent. Reducing the gas generator costs by 50 percent reduces the DOC by approximately 6 percent. The influence of the propulsion system costs on DOC are not as severe for the propulsive wing 2000-foot STOL airplane, but this slight advantage is not sufficient to be decisive in favor of this airplane as compared to the other airplanes.

Hypothetical route analysis. - In order to evaluate the airplanes considered to warrant additional study in an operational environment, NASA specified a hypothetical route (Figure 48) for which the performance and DOC characteristics of these airplanes were to be calculated. Two assignments of non-productive time were made for this study. One was a non-productive time assignment of 10-1/4 minutes for all route segments (as specified in Reference 1). The other, dependent upon the field length performance of the aircraft, was as follows:

1. For a short takeoff, three minutes were used - two minutes for taxi from the passenger loading area to the end of the runway and one minute for the takeoff and acceleration to the climb speed.

2. For a vertical takeoff, two minutes were used - one minute for taxi from the passenger loading area to the takeoff area, and one minute for the takeoff and acceleration to the climb speed.

3. For a short landing, 7-1/4 minutes were used - four and one-fourth minutes for getting into the traffic pattern and getting aligned with the runway, one minute for the landing itself, and two minutes for taxi from the runway to the passenger loading area.

4. For a vertical landing, two minutes were used - one minute to descend and decelerate from the let-down speed at an altitude of 1000 feet to the landing touchdown (this is performed as a straight-in approach), and one minute for taxi from the touchdown point to the passenger loading area.

For the variable non-productive time analysis, the V/STOL airplane is operated with a short takeoff and a vertical landing on segments A-B and D-E, VTOL on segments B-C, E-F, and F-A, and STOL on segment C-D of the route shown in Figure 48. The VTOL and STOL airplanes are operated with vertical and short takeoff and landings, respectively, on all route segments. Figure 49 shows the power of non-productive time on the route block time when non-productive time has been computed as described. As an example, this analysis shows that, with a four minute non-productive time, the turboprop tilt-wing VTOL airplane cruising at 350 knots has a route block speed almost equal to that of the propulsive wing 2000-foot STOL airplane cruising at approximately 520 knots with a 10-1/4-minute non-productive time. If the propulsive wing airplane could reduce its non-productive time to four minutes, its route block speed would increase from 313 miles per hour to 390 miles per hour. Only a 6 percent improvement in route block speed, from 350 to 370 miles per hour, can be realized by giving the fan-in-wing V/STOL airplane a VTOL non-productive time.

The DOC for flying the complete route are presented in Figure 50. For this chart, the variable non-productive time schedule assumes 10.25 minutes for all except the VTOL segments, and 4 minutes for the VTOL segments. The most notable point shown on this chart is that the DOC of the turboprop VTOL and propulsive wing 2000-foot STOL airplanes are approximately equal for the variable non-productive time assumptions used. The DOC for the turboprop powered 2000-foot STOL airplane are approximately 6 percent lower than those of propulsive wing 2000-foot STOL airplane and the turboprop VTOL airplane when the variable non-productive time schedule is used.

90- and 120-passenger versions. - 90- and 120-passenger versions of these four airplanes were developed to determine the effects of size changes. The physical characteristics of these designs are presented in Table 10. The major changes resulting from those increased passenger loads are the increase in the number of engines and propellers from four to six as the design passenger load is increased to 90 on the turboprop VTOL airplane, and the increase in the number of fans from ten to twelve as the design passenger load is increased to 120 on the propulsive wing 2000-foot STOL airplane.

Figure 51 shows the ratio of the gross weight of airplanes designed for other passenger loads to the gross weight of the airplane designed for 60 passengers. This figure shows that as the passenger load is doubled for the fan-in-wing V/STOL airplane, the design gross weight increased by approximately 65 percent. For the turboprop VTOL airplane, the design gross weight increases by 45 percent as its passenger load is increased by 50 percent; and as the passenger capacity is doubled, the design gross weight increase is 80 percent. This change in slope occurs because a transition is made from four to six propellers in going from 60 to 90 passenger design loads; but the six propeller arrangement is still adequate for the 120-passenger design load. The propulsive wing 2000-foot STOL airplane gross weight increases approximately 65 percent as the passenger load is doubled; and the turboprop 2000-foot STOL airplane gross weight increases approximately 60 percent as the design passenger load is doubled. Thus it is seen that the growth characteristics of these four airplanes are comparable except for the turboprop tilt-wing VTOL which has a noticeably higher growth factor caused by increasing the number of propellers and engines. The detailed estimated weights for these 90- and 120-passenger airplanes are presented in Table 11.

Figure 52 presents the direct operating costs on the design stage length for the 60-, 90-, and 120-passenger versions of these four airplanes. This chart shows that increasing the design passenger load from 60 to 120 passengers decreases the DOC to approximately 66 percent for the fan-in-wing V/STOL airplane. For the turboprop VTOL airplane, the DOC of the 120-passenger version is 76 percent of the DOC of the 60-passenger version. For the propulsive wing 2000-foot STOL airplane, the DOC of the 120-passenger version is 57 percent of the DOC of the 60-passenger version; and for the turboprop 2000-foot STOL point airplane, the DOC of the 120-passenger version is 63 percent of the DOC of the 60-passenger version. Thus, increasing the design passenger load benefits the DOC of the propulsive wing 2000-foot STOL airplane the most, and the turboprop VTOL airplane the least.

From this study it is concluded that the propulsive wing 2000-foot STOL airplanes can best adapt to design passenger loads greater than 60.

Specific Research Requirements

From these design studies, the following specific items of research required to assure the timely development of promising V/STOL short-haul transport airplane concepts are identified; and these research items are divided into two categories. One category includes those items of research that are applicable to specific V/STOL propulsion system concepts, and the other category includes those items of research that are applicable to all V/STOL concepts studied.

Research applicable to specific V/STOL concepts. - The following items of research are applicable to the specific concepts evaluated in this study.

Turboprop V/STOL concepts. - Considerable data are available to guide the designer of turboprop V/STOL concepts, but additional research may permit more nearly optimum designs and thus slightly lower direct operating costs; but it is not anticipated that marked extensions of the technical state-of-the-art could be gleaned from such research. The following are specific areas where research efforts are considered appropriate for turboprop V/STOL short-haul transport aircraft.

- Recent experience at LTV has uncovered the fact that an accurate methodology for predicting the static thrust performance of propellers does not exist. This study has shown the static propeller performance characteristics to be critical to the design of VTOL turboprop aircraft; therefore, data are required which will permit an accurate assessment of the effects of propeller characteristics on static propeller performance.

- The turboprop V/STOL short-haul transport airplanes will have lower DOC if they can cruise at higher speeds; therefore, data are required to accurately define compressibility effects on airplane-propeller interference in cruise flight, thus permitting proper airplane and propeller tailoring for improved flight performance at moderate subsonic cruise speeds.

- Data are required which will accurately define the limits on the propeller-wing relationships for acceptable transition performance of tilt-wing aircraft. Data should be able to answer the questions:

  How far from the fuselage side can a propeller tip be?

  What is the influence of propeller overlap or gap?

  How far beyond the propeller tip can the wing tip extend?

  What are the limits on the longitudinal positioning of the propeller plane with respect to the wing?

Fan-in-wing V/STOL concepts. - Considerable data are available to support the design of fan-in-wing V/STOL short-haul transport aircraft, but additional research may provide means of reducing operating costs by refinements in designs and by extensions of the existing state-of-the-art. The following are specific areas where research efforts are considered appropriate for V/STOL fan-in-wing short-haul transport aircraft.

- Data are required which define changes that must be made to permit tip-driven fans to operate efficiently at higher pressure ratios than the present limit of 1.3. This will permit the design of fan-in-wing aircraft with higher wing loadings and lower aspect ratios, both of which contribute to lower direct operating costs.

- Data are required which will permit design of a producible fan louver system that turns this exhaust air to high angles efficiently. Such a capability will provide better takeoff performance for the STOL fan-in-wing airplanes, and better transition performance for the VTOL and V/STOL fan-in-wing airplanes.

- Data are needed which will guide the design optimization of the gas power exchange system and its control. For this study, it has been assumed that a gas power exchange system will exist, and it has been assumed that all the gas power exchange control devices will have the sensitivity required by a V/STOL lateral control system. The parameters, which these control sensing devices monitor to detect such emergencies as an engine failure, must be determined; the characteristics of the devices they control must be selected; and the required responses and sensitivities of the total system must be obtained. The integration of the gas power exchange control system into the flight control system must also be accomplished; therefore, data are required to guide these design and design integration functions.

- Data are needed which will guide the design of a hot gas interconnect system connecting several gas generators through a common plenum. This will also require research data which will guide the design of a multiple engine control system.

- Data are needed which will guide the design optimization of a hot gas ducting system. In particular, specific research is needed which will guide the design of hot gas ducting joints, expansion provisions, insulation, shielding, support, and flow control devices.

- Data are required which will permit a more accurate assessment of the change in aerodynamic characteristics due to changes in configuration variables. This should include such items as the variation of induced lift when a wing, with more than one fan per wing panel, has these fans operating at different fan pressure ratios for extended time periods. Also, the ability to determine the variation of induced lift with unconventional wing/fan arrangements is considered desirable.

Propulsive wing V/STOL concepts. - Little data are available to support the design of propulsive wing V/STOL concepts. Additional research efforts are required to provide much of the basic data for this concept; and it can be expected that extensions of the present state-of-the-art will develop from active research efforts on this concept. The following are specific areas where research efforts are considered appropriate for propulsive wing V/STOL short-haul transport aircraft.

- Data are required which will guide the design of optimum methods for deflecting the fan thrust downward for slow speed flight. These data should consider both the internal flow characteristics within the duct, and the external flow characteristics around the wing; and they should be concerned with the induced lift characteristics for slow speed flight as well as the cruise flight efficiency of the concept.

- Data are required which will guide the optimization of inlet designs for propulsive wing inlets. These data should permit an assessment of the inlet configuration on propulsion system performance at all flight speeds, induced lift at slow speeds, and the drag rise characteristics of the airplane at high subsonic cruise Mach numbers.

- Data are required to guide the optimization and establishment of design requirements for exhaust systems for propulsive wing concepts. The variations in the slow speed induced lift characteristics as well as the cruise flight characteristics as functions of the propulsive wing exhaust configuration must be known.

- Data are needed to guide the design optimization of a gas power exchange system, a common interconnecting plenum, and a hot gas ducting system as has been mentioned for the fan-in-wing concept.

- Data are required to permit accurate assessment of the change in aerodynamic characteristics due to change in configuration variables; e.g., data must permit assessment of the induced lift as fan pressure ratio, inlet aspect ratio, exhaust aspect ratio and/or flap deflection vary. A similar assessment capability for the influence of these same parameters on cruise performance is desired.

Research applicable to all V/STOL concepts. - The following are areas of specific research which are required to support the development of any V/STOL short-haul transport concept.

- Data are required which will accurately define the control power requirements for all flight regimes and size aircrafts.

- Data are required which will define the cockpit display requirements for a VTOL, all-weather (zero/zero) landing system. This will include both the readout of data required by the pilot and the data accuracy.

- Data are required to guide the design of foreign object damage (FOD) protection devices on propulsion system installations and the determination of techniques to minimize the reingestion of hot exhaust gases by gas generators for all configurations. An understanding of the complete recirculation fields around all V/STOL aircraft is therefore required.

- Data are required which can be used to establish design criteria for VTOL and STOL airport surfacing.

- Data are required that will permit the noise generated by the propulsion system to be a variable in the analysis process of optimizing a V/STOL propulsion system.

- Data are needed to better define the origin of noise for all V/STOL system concepts. These data should be of such quality that the engineer will know how noise might best be reduced at its source.

- Data are needed to describe the noise attenuation characteristics of various structural fabrication techniques and materials.

- Research data are needed which will guide propulsion system manufacturers in the reduction of weight of propulsion system components and reduction in specific fuel consumption, especially for operations at low power settings.

- Data are required to better define the non-productive times applicable to each of the V/STOL concepts. A minimization of the non-productive time will require an understanding of the operational limitations that contribute to non-productive time for each concept. These include such items as the time to start engines or fans, change configurations, and make instrument approaches to a V/STOL IFR system; and it is anticipated that this item of research will require considerable flight operational experience with many V/STOL aircraft types.

- Reference 1, in harmony with the existing Federal Aviation Regulations, required that the required landing field length be the calculated minimum landing field length divided by 0.6. This factor has been determined to be appropriate for conventional aircraft but research effort should be expended to assure that this is an appropriate field length correction factor for V/STOL aircraft. This is an important parameter in determining the configuration of STOL aircraft and, hence, its magnitude should be established. It is possible that this factor may change with each concept and/or with each design field length.

- Data are required which will permit the engineer to make accurate estimates of the static and rotary stability derivatives for all V/STOL configurations in all flight regimes.

Airworthiness Requirements

In reviewing the capabilities of airworthiness requirements to cope with the novel flight capabilities of V/STOL aircraft, Federal Aviation Regulations Part 25, "Airworthiness Standards: Transport Category Airplanes," and Part 29 "Airworthiness Standards: Transport Category Rotorcraft," have been used. In Part 25, the zero thrust stalling speed of the airplane is considered an operational limit, and many other flight characteristics are based on this speed; e.g., the minimum allowable takeoff and approach speeds are functions of the zero thrust stall speed. Such requirements are not appropriate for V/STOL aircraft because they are designed to operate safely below this speed.

V/STOL aircraft may be influenced by ground effects more than will conventional aircraft, because some V/STOL aircraft are able to fly in air disturbances that they are creating. Hence, Federal Aviation Regulations must take cognizance of this unique flight capability and assure that the V/STOL airplane always operates in a safe flight regime, especially in the ground effect region.

Numerous V/STOL concepts use gas generators to drive thrust producing devices through interconnected transmission systems. The propulsive wing and the fan-in-wing concepts have fans driven through an interconnecting system of hot gas ducts, and the turboprop aircraft have propellers driven by turboshaft engines through an interconnecting system of gear cases and shafting. The existing Federal Aviation Regulations are concerned with engine failures where propellers are connected directly to the engine; hence the Federal Aviation Regulations must be modified to take cognizance of these interconnected transmissions systems and establish regulations which assure safety after failures likely to occur anywhere in the propulsion system.

In addition, design standards for components of the interconnecting transmission system must be established. Special attention must be given to the installation requirements for hot gas ducting systems to protect ducting and surrounding structure from damage due to heat.

Where conventional aircraft can put fuel in their wings and thus keep it away from the passenger compartments, many V/STOL concepts will be prevented from putting fuel tanks in the wings and, hence be forced to put it adjacent to the passenger compartments. The fan-in-wing concept, as an example, has its wing filled with propulsion system components. Federal Aviation Regulations must take cognizance of this potential safety hazard and assure that fuel system design standards will maximize safety where the fuel is located adjacent to passenger compartments.

It is considered appropriate to recommend that a new set of Federal Aviation Regulations be established for V/STOL aircraft.

STUDY CONCLUSIONS

The technical feasibility of VTOL and STOL turboprop airplanes has been proven by several aircraft. Short-haul transport aircraft using turboprop propulsion systems have been shown to be relatively light and to have relatively low initial costs; but the modest cruise speeds of these aircraft reduce their attraction as potential commercial aircraft.

The technical feasibility of fan-in-wing airplanes has been demonstrated by one aircraft, and this study has shown that short-haul transport aircraft of the 1970 time period using the "pure" fan-in-wing principle would be heavy and expensive. The fan-in-wing aircraft do have a good cruise speed capability, and this combined with the external appearance of a modern turbojet airplane would have strong passenger appeal in commercial operations.

The technical feasibility of the propulsive wing airplane has not been established by any flying aircraft, and only limited wind tunnel data are available to substantiate the potential technical feasibility of this concept. The propulsive wing concept has been evaluated only in STOL short-haul transport airplane configurations in this study; and these airplanes have been found to be light, to have low initial and direct operating costs, and to have a high subsonic cruise speed capability. The apparent economy of operation for aircraft using this concept will be attractive to air transport operators; and the unusual, but modern, appearance of aircraft built around this V/STOL concept probably should appeal to passengers.

Additional research could improve the efficiency of aircraft designed around the three V/STOL propulsion concepts evaluated in this study by permitting the design of more nearly optimum configurations. It is anticipated that the fan-in-wing airplanes would be particulary affected by additional research and design studies. It is probable that significant reductions in size, initial costs, and direct operating costs can be obtained by using turbofan engines for cruise, by deflecting a portion of the thrust downward for hover with the remaining thrust diverted to augment fan lift, and by unconventional fan/wing arrangements. It is also considered probable that additional research on the propulsive wing concept would permit some reductions on its already low weight, initial cost and direct operating costs; and it is considered that such data would show a VTOL version using this propulsion system concept to be very competitive with other VTOL short-haul transport airplanes.

The noise generated by V/STOL airplanes is expected to be a major factor in obtaining community acceptance of V/STOL short-haul transport systems. The far field noise characteristics for the airplanes developed in this study are approximately the same at a distance of 1,000 foot from the airplanes with all engines at take-off power. The attenuation characteristics of propeller noise were considerably less than for the fan-in-wing and propulsive wing airplanes; therefore, the noise characteristics of the propeller powered airplanes were noticeably higher at distances greater than 2/3 mile. Additional experimental data and analytical analyses are needed to better define the origin of noise, to determine how to best suppress the noise at its origin, and to permit noise to be a primary design variable.

The non-productive time characteristics of V/STOL aircraft are critical to the economy of operation of these aircraft; therefore, it is important to be able to identify all the factors which contribute to non-productive time. Examples of some of these factors include the time lost in making configuration changes, the time lost in starting or stopping any engines or fans that are used for slow speed operations only, the time lost in accelerating or decelerating through the transition speed regime, the time lost in getting intermeshed with other airport air traffic, the time lost due to flying under instrument flight rules rather than visual flight rules, etc. The nebulous nature of these elements of non-productive time is evident; and it is projected that a considerable number of operational flight tests will be necessary to establish the ranges of magnitude that can be expected for each of these variables. It is also projected that these magnitudes will be different for each V/STOL concept.

The airworthiness standards described by the existing Federal Aviation Regulations are considered inadequate to cope with the novel flight capabilities of V/STOL aircraft; therefore, it is recommended that a new set of airworthiness standards be established specifically for V/STOL aircraft. The airworthiness standards for V/STOL aircraft should establish airworthiness safety objectives and hence be applicable to all V/STOL concepts.

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TABLE 1.- CONTROL POWER REQUIREMENTS

Design Passenger Load	Roll, rad/sec^2		Pitch, rad/sec^2		Yaw, rad/sec^2	
	Desired	Acceptable	Desired	Acceptable	Desired	Acceptable
VTOL						
60	1.20	.60	.60	.30	.50	.25
90	1.08	.54	.54	.27	.45	.22
120	.96	.48	.48	.24	.40	.20
STOL						
60	.45	.22	.40	.20	.20	.10
90	.40	.20	.36	.18	.18	.09
120	.36	.18	.32	.16	.16	.08

TABLE 2. TYPICAL OPTIMUM DESIGN DRAG ESTIMATE

Component	Wetted Area Sq Ft	Characteristic Lgth Ft	F.R. or t/c	R_E* 10^{-6}	Flat Plate C_F	C_{f_o}/C_f	C_{f_o}	Interference or Roughness Factor	C_{f_R}	f=D/q Sq Ft	C_{D_o}
Wing (S = 692 Sq Ft)	1100	8.59	.15	12.5	.0029	1.329	.00385	1.32	.00509	5.60	.00809
Wing Camber	-	-	-	-	-	-	-	-	-	.33	.00048
Vertical Tail	244	9.59	.085	14.0	.00286	1.174	.00336	1.50	.00504	1.23	.00178
Horizontal Tail	300	5.75	.085	8.4	.00309	1.174	.00363	1.50	.00545	1.64	.00236
Nacelles											
Inboard	362	19.20	3.91	28.0	.00257	1.091	.00280	1.60	.00449	1.62	.00234
Outboard	396	19.20	3.91	28.0	.00257	1.091	.00280	1.60	.00449	1.78	.00257
Base	-	-	-	-	-	-	-	-	-	1.58	.00228
Fuselage	2450	81.00	6.90	118.2	.00206	1.200	.00247	1.32	.00326	8.00	.01156
Gear Fairings	59	10.20	5.23	14.8	.00283	1.430	.00405	1.15	.00466	.27	.00039
Misc + Unidentif. Items	-	-	-	-	-	-	-	-	-	2.00	.00289
TOTAL	4911	-	-	-	-	-	-	-	-	24.05	.03474

NOTES: f (Gear Extended) = 12 square feet

C_{f_e} = .00490

* Based on V = 350 knots at 35,000 ft

TABLE 3. ZERO-LIFT ESTIMATED DRAG COEFFICIENTS, 60 PASSENGER DESIGNS

Propulsion System Concept	Design T.O. and Ldg. Capability	Design Field Length-Ft.	Wing Area-Ft^2	Wetted Area-Ft^2	Equivalent Flat Plate Area - ft^2	C_{D_0}	C_{fe}	e
Turboprop	VTOL	-	692	4911	24.05	.0348	.0049	.725
Turboprop	V/STOL	-	676	4882	22.63	.0335	.0046	.736
Turboprop	STOL	1000	610	4589	21.52	.0353	.0047	.74
Turboprop	STOL	2000	610	4589	21.37	.0350	.0047	.74
Fan-in-wing	VTOL	-	1350	7119	30.20	.0224	.0042	.83
Fan-in-wing	V/STOL	-	1000	5912	25.09	.0251	.0042	.84
Fan-in-wing	STOL	1000	1100	6281	26.78	.0244	.0043	.83
Fan-in-wing	STOL	2000	895	5492	23.35	.0261	.0043	.83
Propulsive Wing	STOL	1000	768	5562	22.57	.0294	.0041	.80
Propulsive Wing	STOL	2000	575	4611	18.14	.0315	.0039	.80

TABLE 4.- GE 1 GAS GENERATOR TECHNOLOGY

Turbine Inlet Temperature	2200°F
Compressor Stage Pressure Ratio	1.21
Turbojet Engine Configuration	
Thrust-to-weight ratio	8
Thrust per unit pound of engine air flow	75-85 pounds/pounds/sec
Thrust per unit of engine volume	350 pounds/ft^3
Turboprop Engine Configuration	
SHP to engine weight ratio	7 SHP/pound
SHP per unit pound of engine air flow	140-150 SHP/pound/sec
SHP per unit of engine volume	215 SHP/ft^3

TABLE 5.- AVIONICS EQUIPMENT LIST

Equipment	Quantity	Characteristics
VHF Communications Transceiver	2	Airborne Radio, Inc. (ARINC) Characteristics No. 546
Navigation Receiver	2	ARINC Characteristic No. 547
Marker Beacon Receiver	1	Bendix MKA-28 equivalent
ADF System	1	ARINC Characteristic No. 550
ATC Transponder	1	ARINC Characteristic No. 532D
DME	1	ARINC Characteristic No. 521D
Audio System	3	
Cockpit Voice Recorder	1	ARINC Characteristic No. 557
Flight Data Recorder	1	ARINC Characteristic No. 542
Compass System	2	Collins MC-102 or equivalent
Weather Radar	1	RCA AVQ 50 or equivalent
Terminal Area Navigation System	1	As yet undefined. May be a self-contained or precision NAVAID.
All-Weather Takeoff and Landing System	2	As yet undefined. Will include receivers, sensors, displays, altimeters, and couplers.

TABLE 6. CRITICAL DESIGN CONDITIONS FOR 60 PASSENGER AIRPLANES

Concept	Design Field Length	Cruise Alt. Ft	Cruise Mach No.	Critical Design Criteria
Turboprop	VTOL	35,000	.59	Takeoff VTOL
	V/STOL	25,000	.65	Takeoff As VTOL
	1000 Ft STOL	25,000	.615	Min DOC (Cruise Speed)
	2000 Ft STOL	25,000	.615	Min DOC (Cruise Speed)
Fan-in-Wing	VTOL	35,000	.8	Takeoff VTOL
	V/STOL	35,000	.8	Takeoff as VTOL
	1000 Ft STOL	35,000	.8	Landing
	2000 Ft STOL	35,000	.8	Takeoff (Fan Size)
				Min DOC (Cruise Speed)
Propulsive Wing	1000 Ft STOL	35,000	.9	Landing
	2000 Ft STOL	35,000	.9	Min DOC (Cruise Speed)

TABLE 7. 60 PASSENGER OPTIMUM AIRPLANE PHYSICAL CHARACTERISTICS

CHARACTERISTICS / POINT DESIGNS	W	W_E	W_F	L	b	h	SPEC. RATED T_E OR SHP	$N_{E_{CR}}$	D_P OR D_{FW}	AR	W/S	T/W
TURBOPROP TILTWING VTOL	62,300	41,226	6,407	81 FT	83 FT 4 IN	28 FT 6 IN	5960	4	18 FT 4 IN	10	90	1.20
TURBOPROP TILTWING V/STOL	62,115	39,880	7,557	81 FT	79 FT	28 FT 10 IN	5540	4	17 FT 2 IN	9.23	91.8	1.06
TURBOPROP 1000 FOOT STOL	53,783	33,845	5,282	81 FT	74 FT 2 IN	27 FT 8 IN	3410	4	15 FT 11 IN	9	88.2	.88
TURBOPROP 2000 FOOT STOL	52,758	32,908	5,195	81 FT	74 FT 2 IN	27 FT 3 IN	3410	4	15 FT 11 IN	9	86.6	.88
FAN–IN–WING VTOL	95,327	60,660	19,865	98 FT 6 IN	71 FT	33 FT	7720	6	105 IN	3.73	70.6	1.15
FAN–IN–WING V/STOL	79,587	47,622	17,190	93 FT 7 IN	58 FT 8 IN	29 FT	6400	6	87 IN	3.44	79.6	1.04
FAN–IN–WING 1000 FOOT STOL	78,919	46,861	17,282	90 FT 4 IN	64 FT	35 FT 7 IN	5710	6	80 IN	3.73	71.7	.89
FAN–IN–WING 2000 FOOT STOL	72,110	41,513	15,836	90 FT 4 IN	56 FT 8 IN	35 FT 7 IN	4600	6	71.5 IN	3.60	80.5	.77
ADAM 1000 FOOT STOL	67,451	41,599	11,138	86 FT	74 FT 7 IN	32 FT 1 IN	4700	6	36.1 IN	3.74	87.8	.91
ADAM 2000 FOOT STOL	54,963	32,228	8,051	83 FT 4 IN	62 FT 5 IN	29 FT 1 IN	2540	6	26.6 IN	3.36	95.5	.64

W = DESIGN GROSS WEIGHT, POUNDS
W_E = EMPTY WEIGHT, POUNDS
W_F = FUEL WEIGHT, POUNDS
L = AIRPLANE LENGTH
b = WING SPAN
h = AIRPLANE HEIGHT

SPEC RATED T_E = RATED ENGINE THRUST, POUNDS
SPEC RATED SHP = RATED SHAFT HORSEPOWER

$N_{E_{CR}}$ = NUMBER OF CRUISE ENGINES
D_P = PROP DIAMETER
D_{FW} = DIAMETER OF WING FANS
AR = ASPECT RATIO
W/S = WING LOADING, POUNDS PER SQUARE FOOT
T/W = STATIC THRUST TO WEIGHT RATIO, ALL ENGINES OPERATING, 86 F AT SEA LEVEL

TABLE 8
ESTIMATED WEIGHTS
60 Passenger Airplanes

	Turboprop				Fan-in-Wing				Propulsive Wing	
COMPONENTS	VTOL	V/STOL	1000 FT STOL	2000 FT STOL	VTOL	V/STOL	1000 FT STOL	2000 FT STOL	1000 FT STOL	2000 FT STOL
Wing Group	5159	4856	4376	4350	8884	6544	7159	6204	5363	3893
Tail Group	1084	1087	893	888	2562	1613	2027	1762	1480	1082
Body Group	7466	7376	6852	6461	9096	8130	8046	7571	7165	6699
Alighting Gear	2328	2250	2001	1987	3697	3035	2951	2645	2522	1969
Flight Controls Group	2156	2090	1416	743	4487	2898	2478	1893	3319	1741
Nacelle Group	2027	2020	1901	1894	2630	2385	2335	2156	2127	1886
Engines	2900	2640	1460	1460	6150	4530	4230	3210	3288	1530
Air Induction System	144	144	144	144	144	144	144	144	144	66
Exhaust System	100	100	100	100	252	180	168	144	-	-
Lubricating System	140	140	140	140	140	140	140	140	140	140
Fuel System	384	447	317	312	1192	1031	1037	950	668	483
Engine Controls	128	128	128	128	128	128	128	128	128	128
Starting System	200	200	200	200	200	200	200	200	200	200
Propellers or Fan System	3000	2580	1632	1632	7524	4320	3348	2532	3762	1762
Transmission System *	3598	3457	2302	2302	2696	1824	1892	1406	1647	1241
Auxiliary Power Plant Group	-	-	-	200	200	200	200	200	200	200
Instrument Group	383	383	383	383	383	383	383	383	383	383
Hyd. and Pneumatic Group	305	300	285	280	400	354	350	330	321	282
Electrical Group	1235	1210	1150	1440	1535	1396	1375	1310	1280	1140
Electronics Group	691	691	691	691	691	691	691	691	691	691
Furnishings Group	6176	6176	5906	5906	5919	5976	5919	5919	5267	5267
Air Cond. and Anti Icing	1582	1565	1528	1527	1710	1480	1620	1555	1464	1405
Auxiliary Gear Group	40	40	40	40	40	40	40	40	40	40
TOTAL EMPTY WEIGHT	41226	39880	33845	32908	60660	47622	46861	41513	41599	32228
Water, Food, Beverage, etc.	633	633	633	633	633	633	633	633	633	633
Crew plus baggage	520	520	520	520	520	520	520	520	520	520
Passengers plus baggage	12000	12000	12000	12000	12000	12000	12000	12000	12000	12000
Cargo	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200
Fuel **	6471	7632	5335	5247	20064	17362	17455	15994	11249	8132
Oil	250	250	250	250	250	250	250	250	250	250
TOTAL USEFUL LOAD	21074	22235	19938	19850	34667	31965	32058	30597	25842	27735
TAKE-OFF GROSS WEIGHT	62300	62115	53783	52758	95327	79587	78919	72110	67451	54963

** Includes unusable fuel also * Hot Gas Ducting, diverter valves etc. for fan-in-wing and Propulsive Wing designs.

TABLE 9. DIRECT OPERATING COST BREAKDOWN
60 Passenger Designs
500-Mile Stage Length

Design			Direct Operating Costs			
Propulsion System Concept	T. O. and Ldg. Capability	Design Field Length-Ft	Depreciation	Maintenance	Flight Operations	Total
Turboprop	VTOL	-	.0089	.0088	.0090	.0267
Turboprop	V/STOL	-	.0078	.0078	.0091	.0247
Turboprop	STOL	1000	.0077	.0078	.0083	.0238
Turboprop	STOL	2000	.0068	.0073	.0081	.0222
Fan-in-wing	VTOL	-	.0111	.0098	.0143	.0352
Fan-in-wing	V/STOL	-	.0087	.0084	.0134	.0305
Fan-in-wing	STOL	1000	.0088	.0086	.0127	.0301
Fan-in-wing	STOL	2000	.0080	.0081	.0119	.0280
Propulsive Wing	STOL	1000	.0067	.0070	.0093	.0230
Propulsive Wing	STOL	2000	.054	.055	.0079	.0188

TABLE 10. COMPARISON OF 60, 90 AND 120 PASSENGER AIRPLANE CHARACTERISTICS

	FAN-IN-WING V STOL			TURBOPROP VTOL			PROPULSIVE WING 2000 FT STOL			TURBOPROP 2000 FT STOL*		
CHARACTERISTICS / DESIGN PASSENGER LOAD	60	90	120	60	90	120	60	90	120	60	90	120
DESIGN GROSS WEIGHT – POUNDS	79,587	104,100	133,200	62,300	89,900	111,000	54,963	70,000	86,800	52,758	70,100	86,100
ASPECT RATIO	3.44	3.31	3.22	10	12	12	3.36	3.49	4.08	9	8	8
WING LOADING – POUNDS PER SQUARE FT.	79.6	79.1	81.7	90	80	80	95.5	112.8	112.6	86.6	90	90
NUMBER OF FANS OR PROPELLERS	5	5	5	4	6	6	10	10	12	4	4	4
PROPELLER OR FAN DIAMETER	87 IN	101 IN	114 IN	18 FT 4 IN	17 FT 9 IN	20 FT	26.6 IN	28.1 IN	31.1 IN	15 FT 11 IN	16 FT 9 IN	18 FT 11 IN
NUMBER OF GAS GENERATORS	6	6	6	4	6	6	6	6	6	4	4	4
GAS GENERATOR SIZE-SHP OR THRUST SPEC. RTD.	6,400	8,400	10,750	5,960	5,600	6,760	2,540	2,840	3,480	3,410	4,650	5,250
CRUISE SPEED – KNOTS	460	460	460	350	356	365	520	520	520	370	390	390

* The cruise speed was 330 knots for the 60-passenger airplane when the 100% rpm propeller tip speed was 1000 fps. The speed noted in the table is for a 100% rpm propeller tip speed of 800 fps, but all DOC computations except those shown in Figure 52 have used the lower cruise speed.

TABLE 11
ESTIMATED WEIGHTS

90 and 120 Passenger Airplanes

	Turboprop				Fan-in-Wing		Propulsive Wing	
COMPONENTS	VTOL		2000 FT STOL		V/STOL		2000 FT STOL	
Design Passenger Load	90	120	90	120	90	120	90	120
Wing Group	9689	12531	5444	6996	8402	10756	4225	5410
Tail Group	2177	2818	1500	1930	2091	2725	1314	1650
Body Group	10333	12278	8352	9895	10034	12254	8501	10125
Alighting Gear	3685	4659	2797	3512	4138	5592	2792	3544
Flight Controls Group	2454	2298	752	659	4038	4963	1671	1350
Nacelle Group	2979	3648	1634	1857	2378	2968	2181	2460
Engines	4138	5266	2179	2536	6990	9570	1980	2472
Air Induction System	216	216	144	144	144	144	90	102
Exhaust System	150	150	100	100	240	300		
Lubricating System	210	210	140	140	140	140	140	140
Fuel System	533	630	406	464	1168	1454	560	651
Engine Controls	192	192	128	128	128	128	128	128
Starting System	375	375	250	250	200	200	200	200
Propellers or Fan Systems	4342	5362	2565	3179	7064	9920	2018	3170
Transmission System *	5585	6384	3282	3567	2482	3150	1399	1710
Aux. Power Plant Group	-	-	200	200	200	200	200	200
Instrument Group	383	383	383	383	383	383	383	383
Hydraulic/Pneumatic Group	425	582	367	501	506	700	367	504
Electrical Group	1488	1664	1304	1454	1608	1833	1303	1461
Electronics Group	691	691	691	691	691	691	691	691
Furnishings Group	6665	8139	6665	8139	7523	9181	6665	8139
Air Cond. and Anti-Icing	2501	3249	2233	2914	2167	2830	2044	2695
Auxiliary Gear Group	60	80	60	80	60	80	60	80
TOTAL EMPTY WEIGHT	59271	71805	41576	49719	62775	80162	38912	47265
Water, Food, Beverages, etc.	950	1266	950	1266	950	1266	950	1266
Crew Plus Baggage	660	660	660	660	660	660	660	660
Passengers Plus Baggage	18000	24000	18000	24000	18000	24000	18000	24000
Cargo	1800	2400	1800	2400	1800	2400	1800	2400
Fuel **	8969	10619	6864	7805	20665	24462	9428	10959
Oil	250	250	250	250	250	250	250	250
TOTAL USEFUL LOAD	30629	39195	28524	36381	41325	53038	31088	39535
TAKE-OFF GROSS WEIGHT	89900	111000	70100	86100	104100	133200	70000	86800

** Include unusable fuel also

* Hot gas ducting, diverter valves, etc. for fan-in-wing and propulsive wing designs.

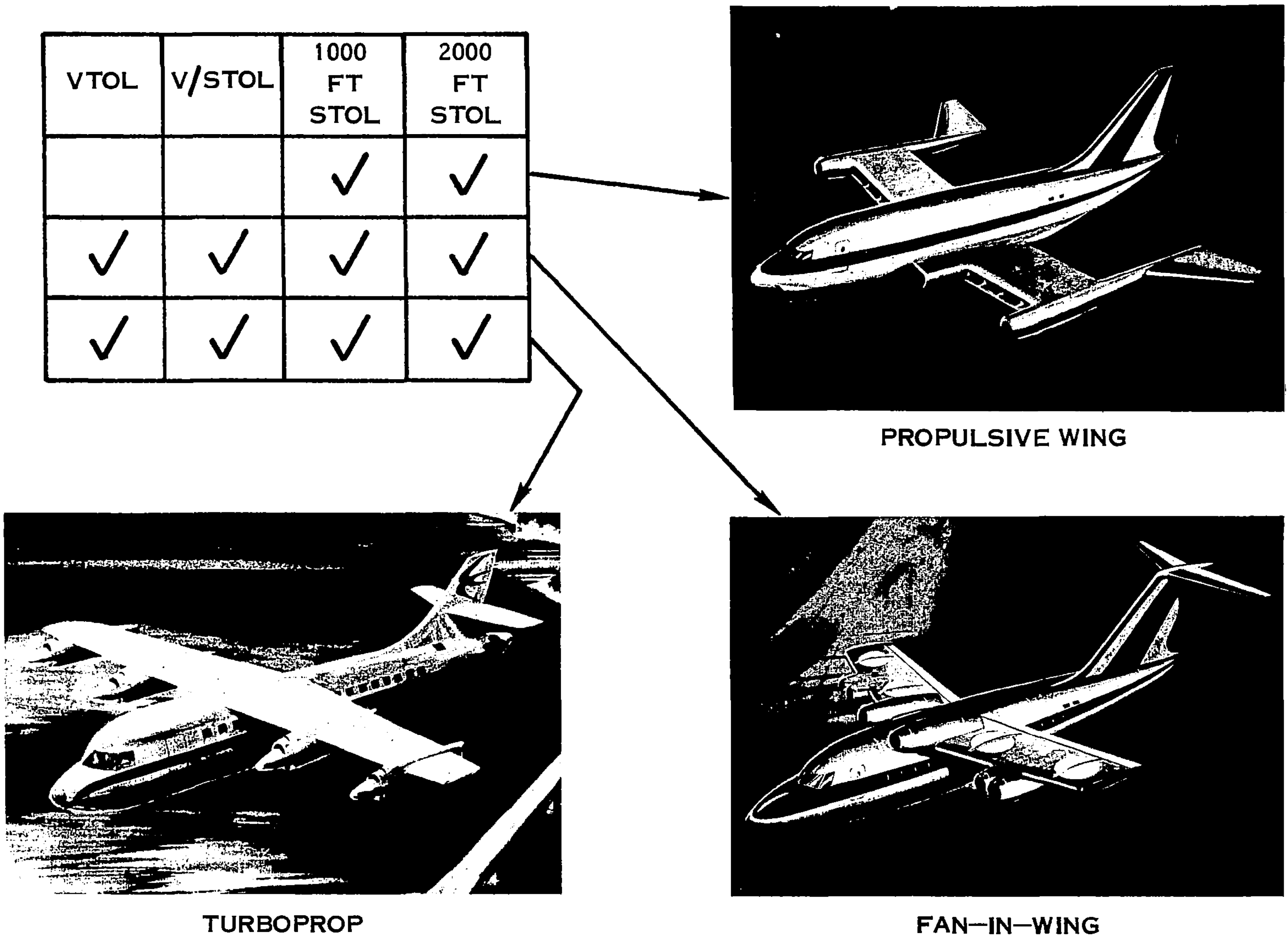


FIGURE 1. AIRPLANES DEVELOPED

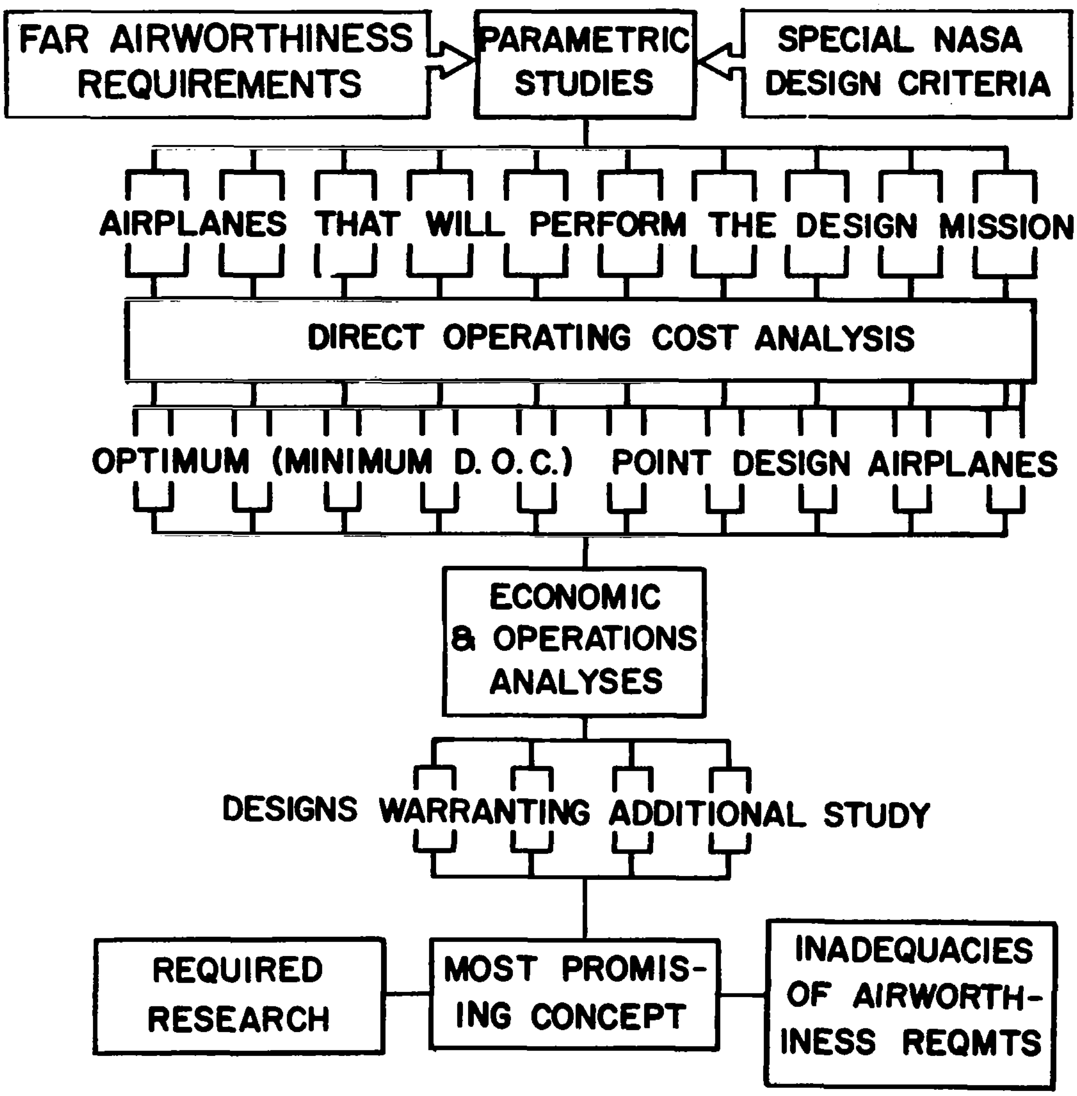


FIGURE 2. - LTV STUDY FLOW BLOCK DIAGRAM

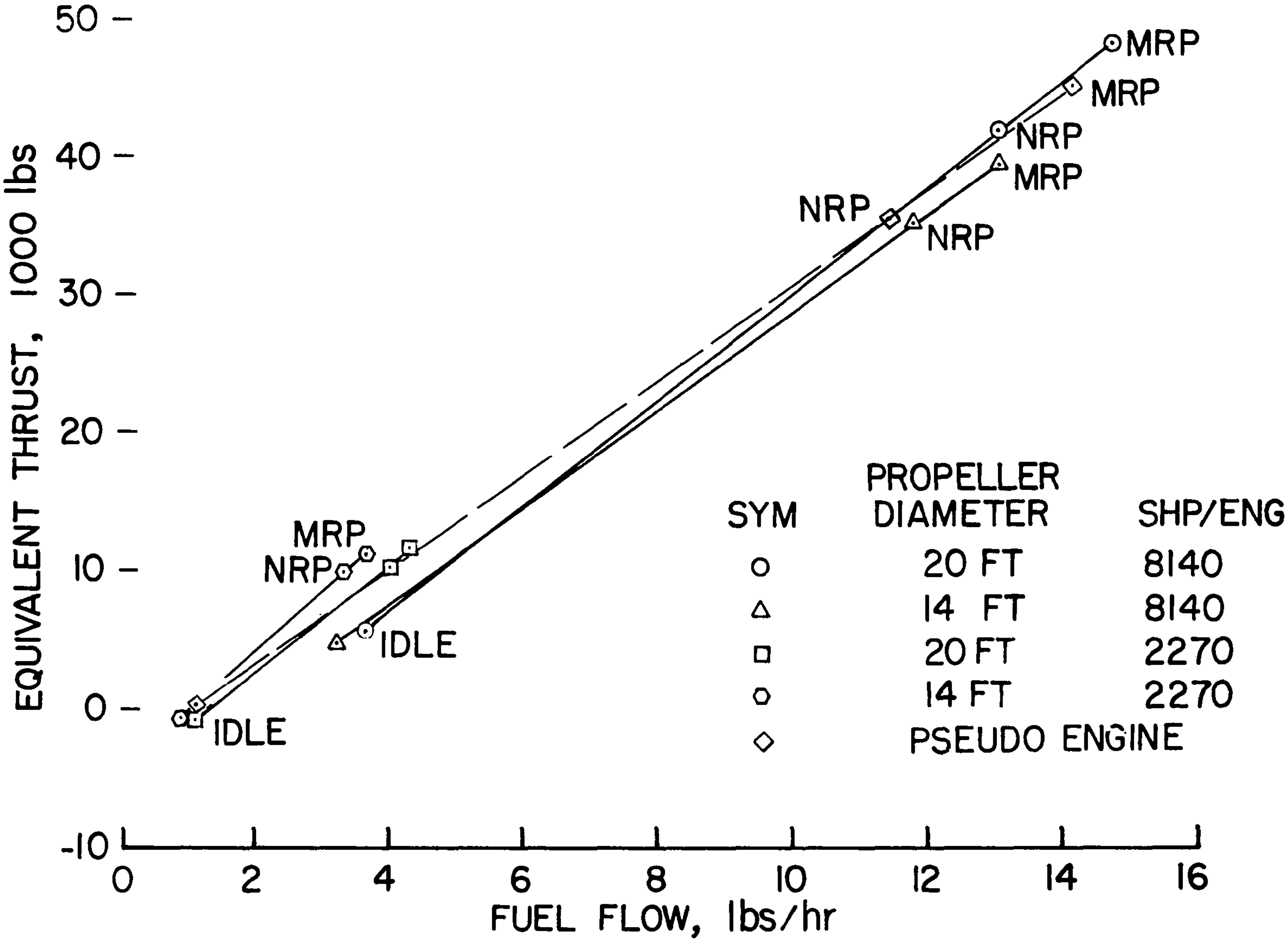


FIGURE 3. - RUBBERIZED PROPELLER - ENGINE PERFORMANCE

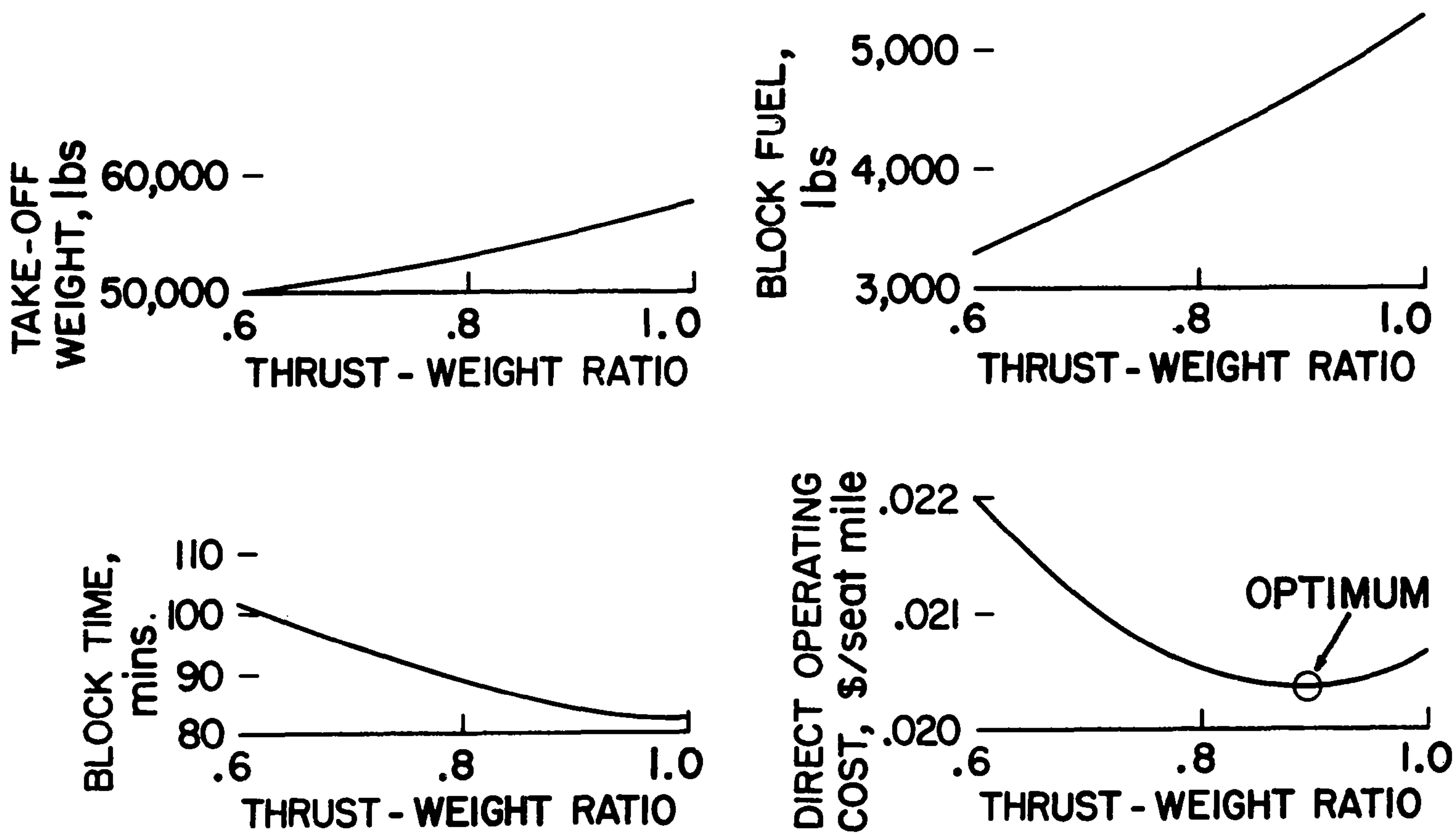


FIGURE 4. - TYPICAL OPTIMUM DESIGN SELECTION PROCESS

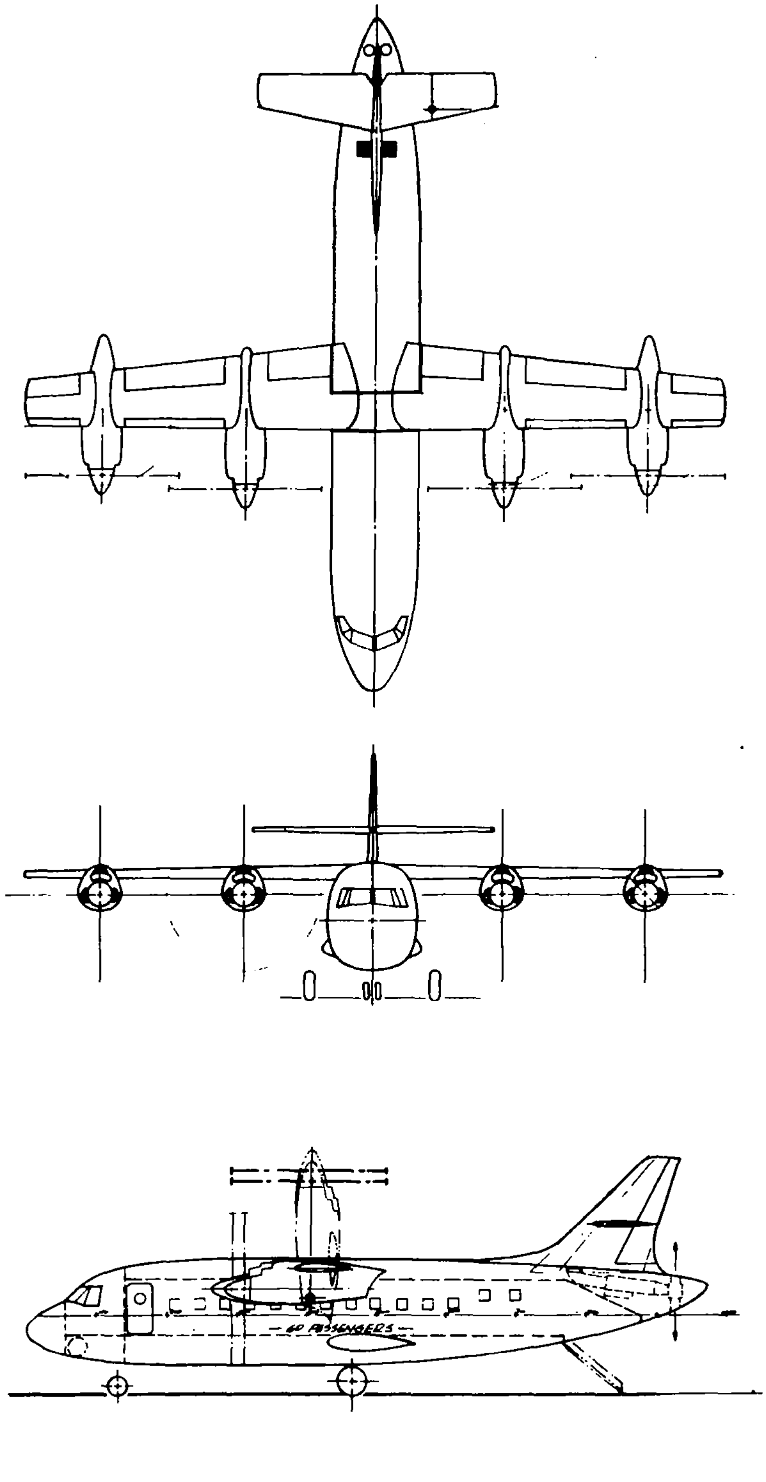


FIGURE 5. - TYPICAL TURBOPROP AIRPLANE

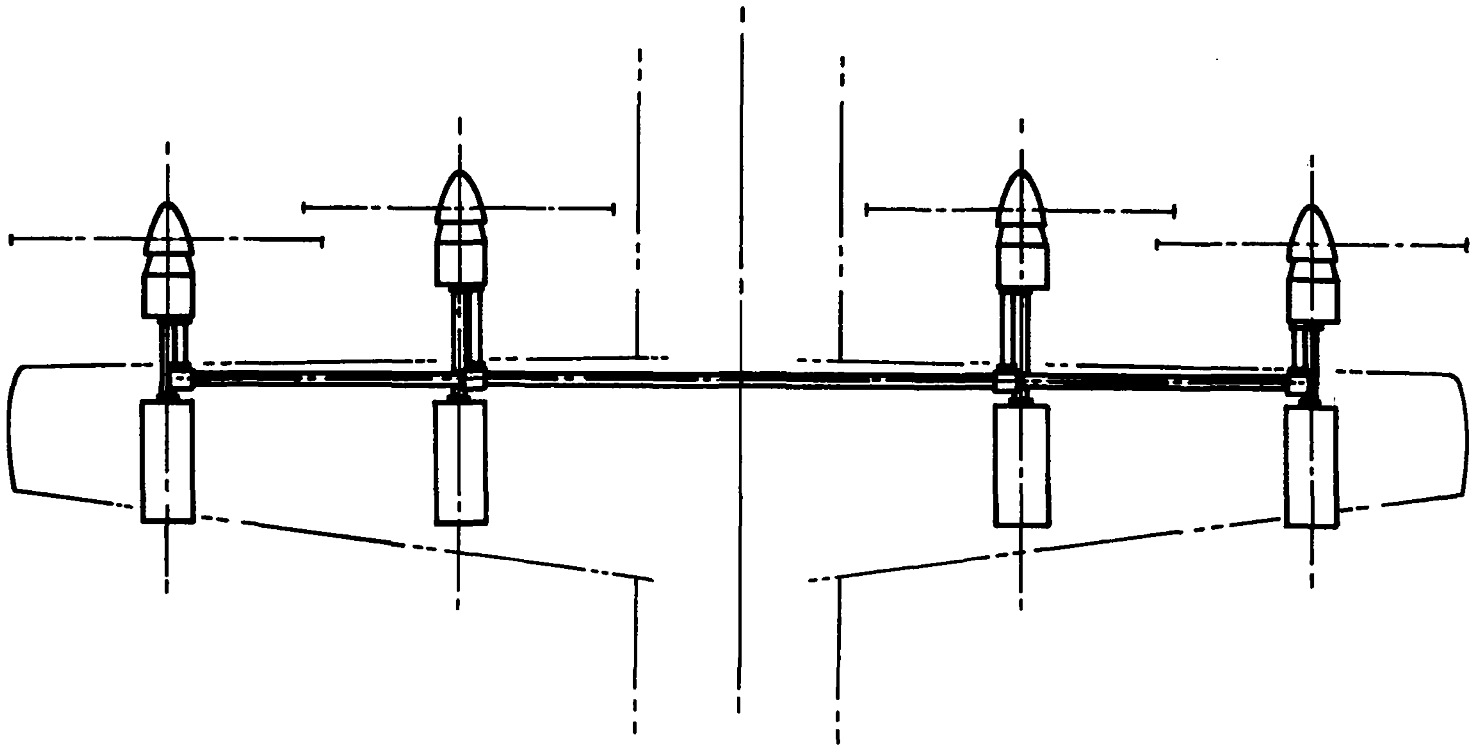


FIGURE 6. - TURBOPROP AIRPLANE TRANSMISSION SYSTEM

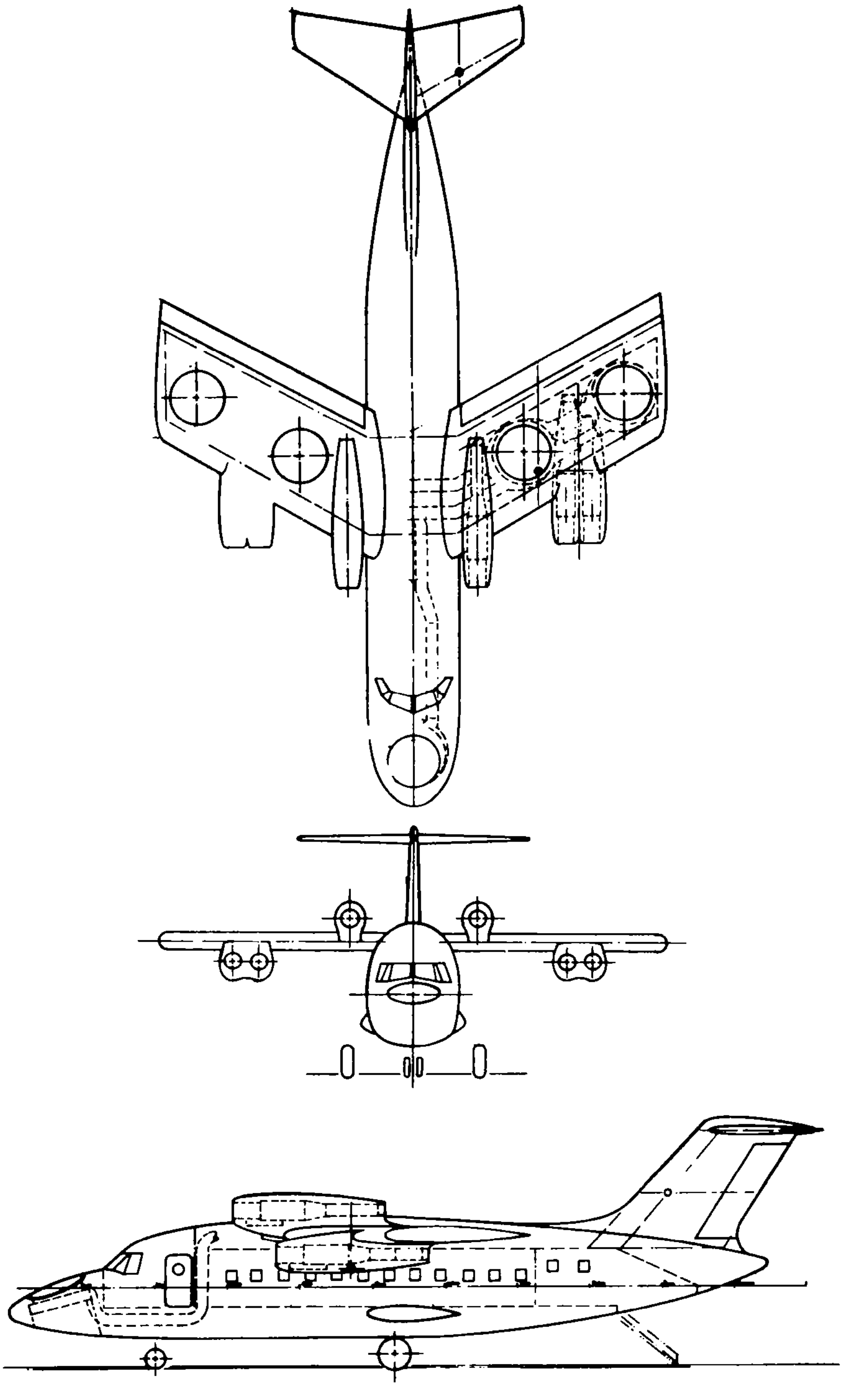


FIGURE 7. - TYPICAL FAN-IN-WING AIRPLANE

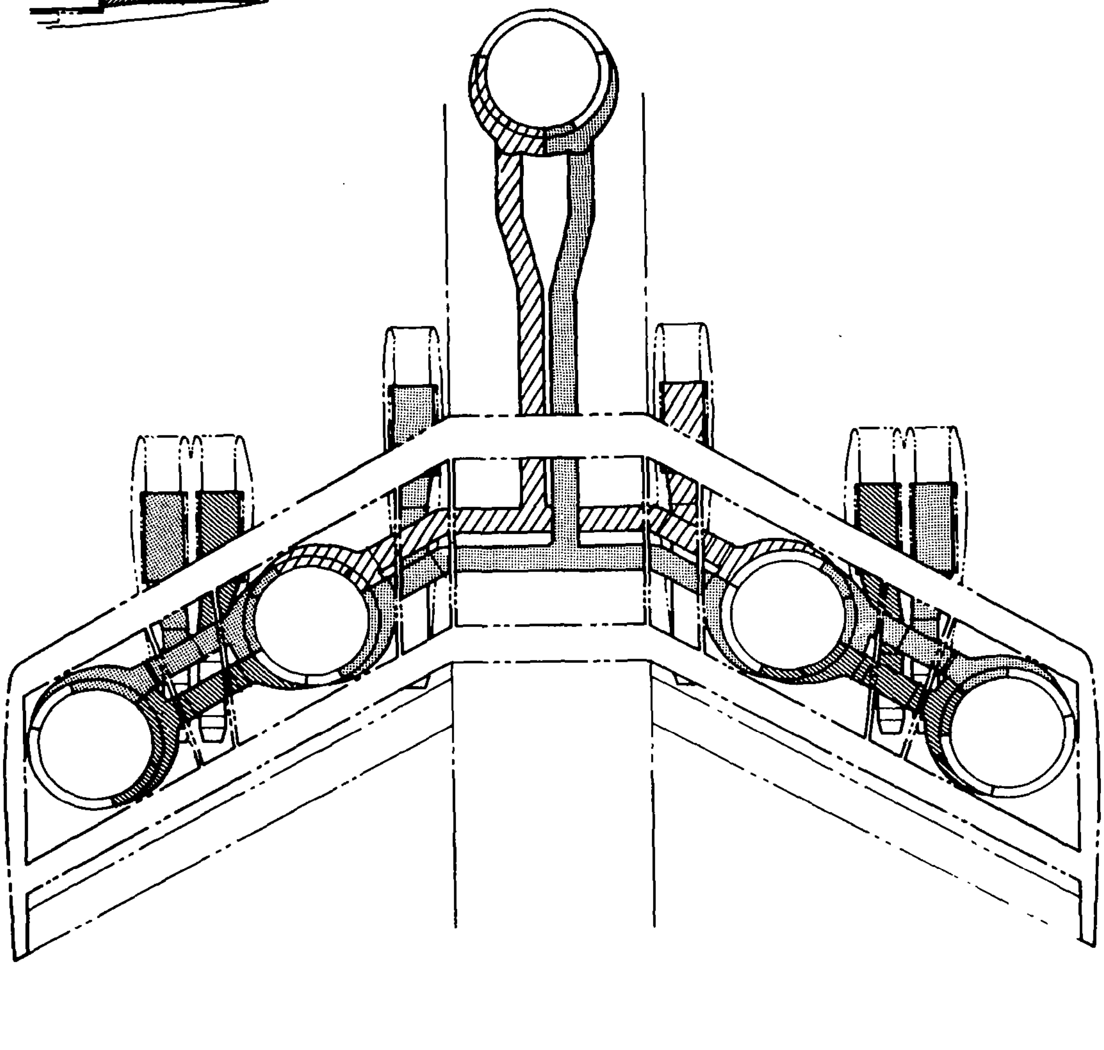


FIGURE 8. - FAN-IN-WING AIRPLANE TRANSMISSION SYSTEM SCHEMATIC - ALL ENGINES OPERATING

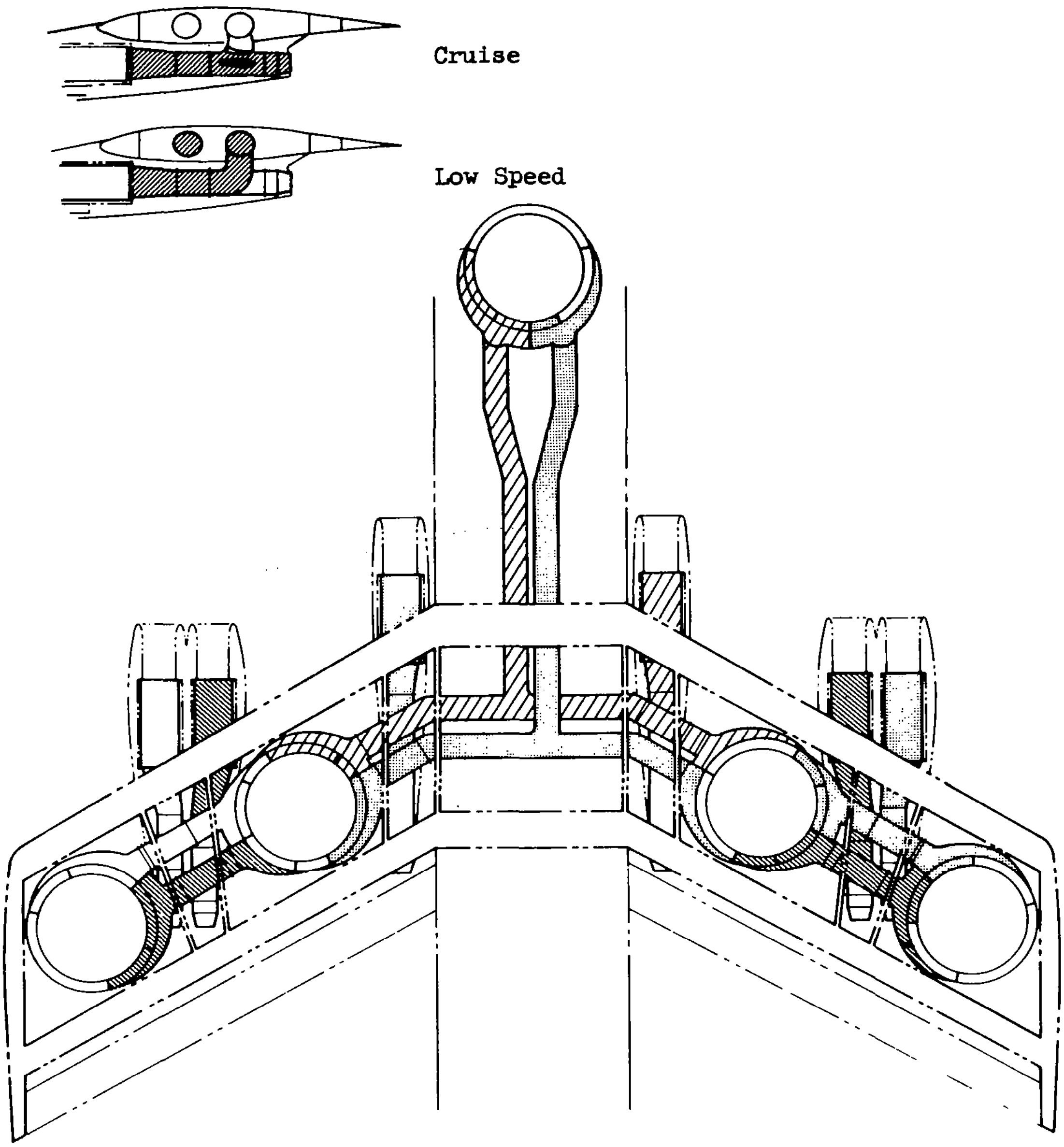


FIGURE 9. - FAN-IN-WING AIRPLANE TRANSMISSION SYSTEM SCHEMATIC - OUTBOARD ENGINE INOPERATIVE

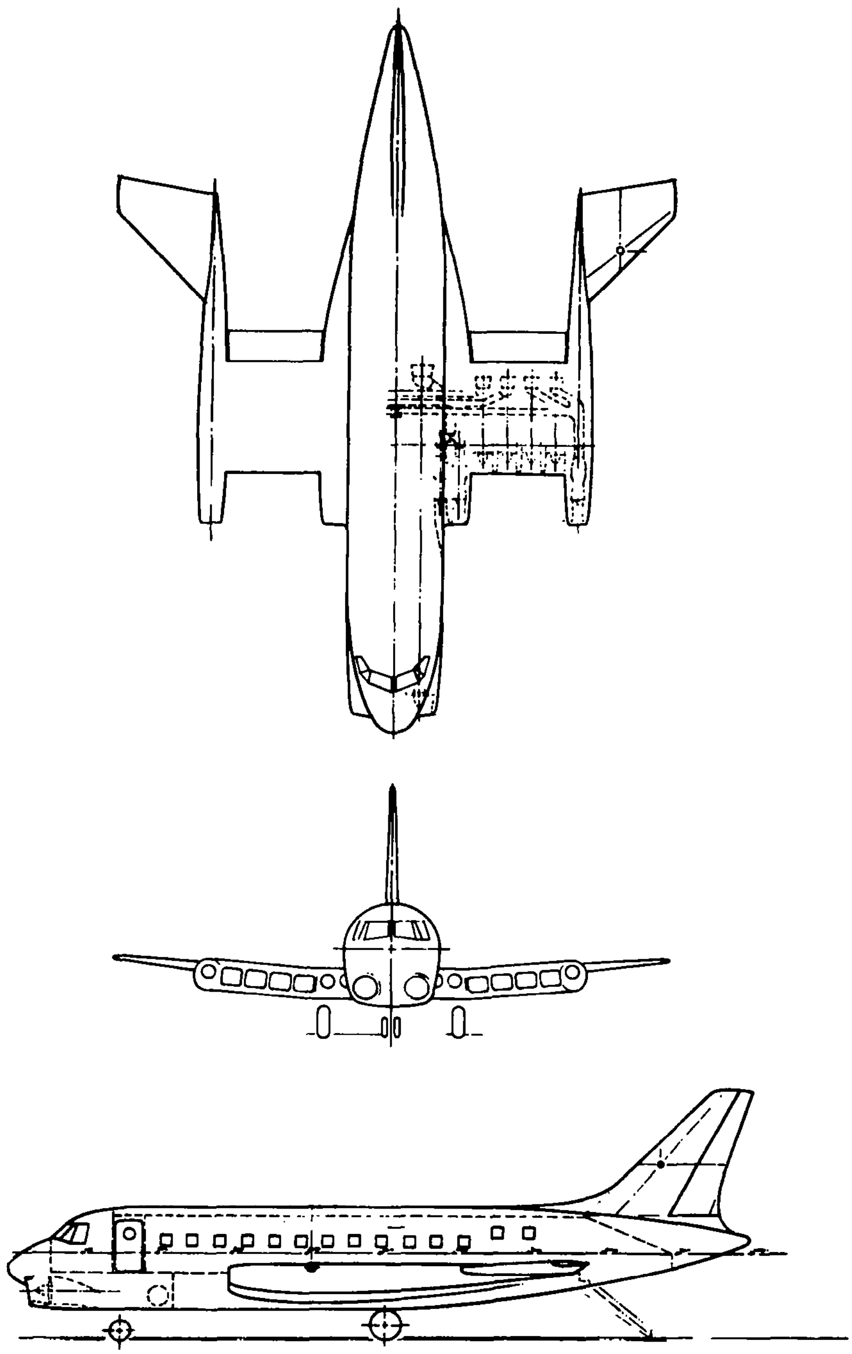


FIGURE 10. - TYPICAL PROPULSIVE WING AIRPLANE

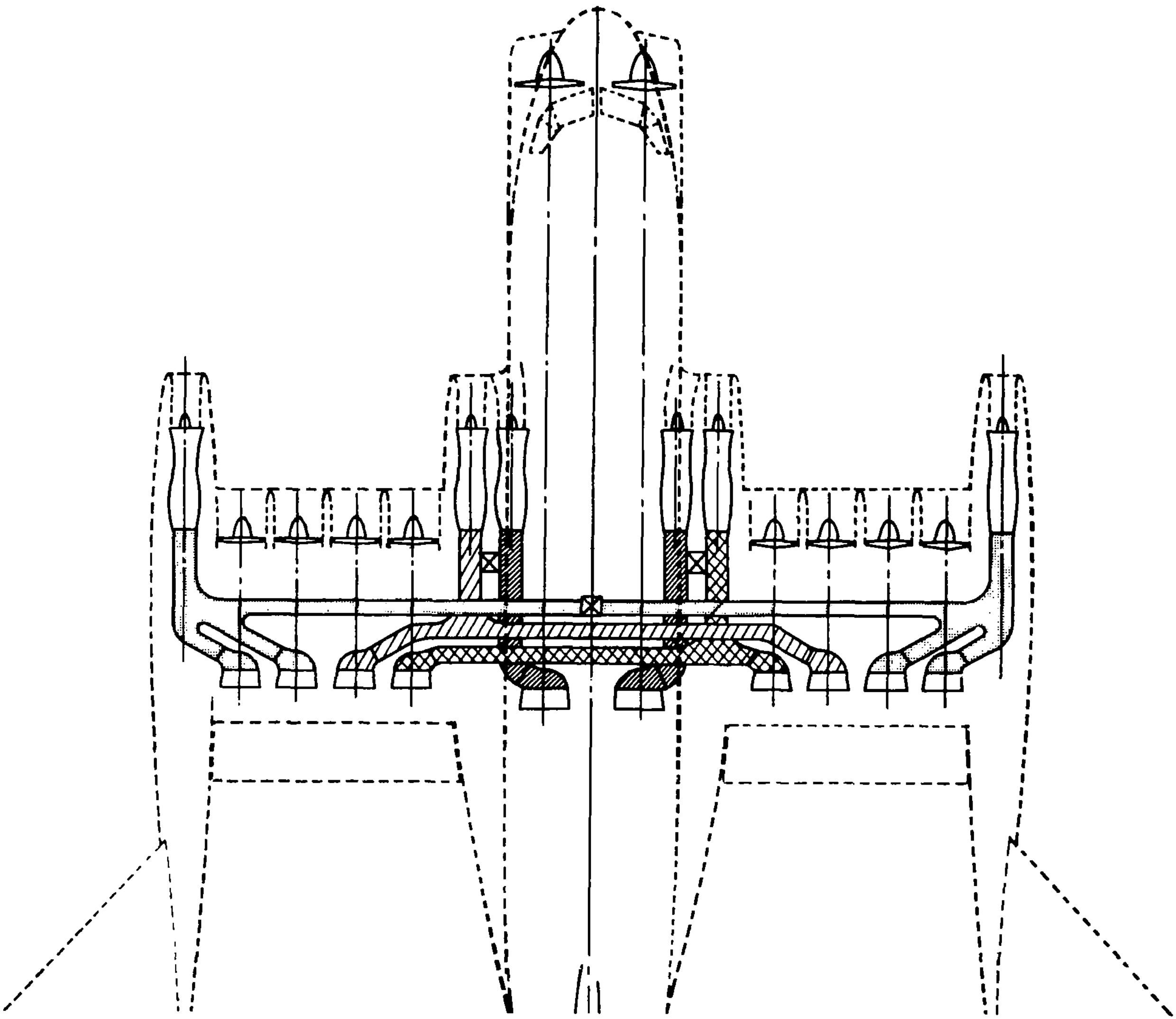


FIGURE 11. - PROPULSIVE WING AIRPLANE TRANSMISSION SYSTEM SCHEMATIC-
ALL ENGINES OPERATING

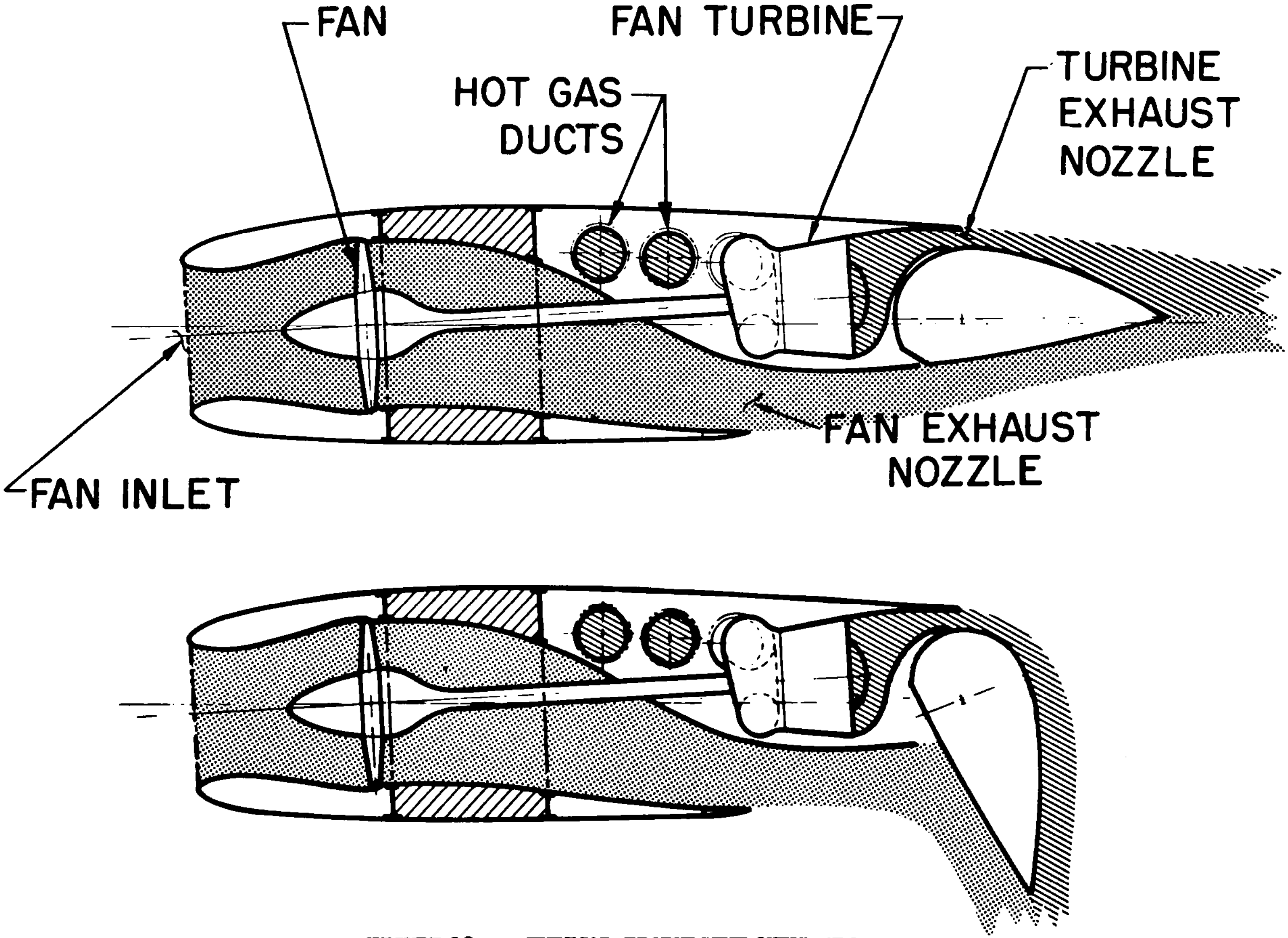


FIGURE 12. - TYPICAL PROPULSIVE WING CROSS SECTION

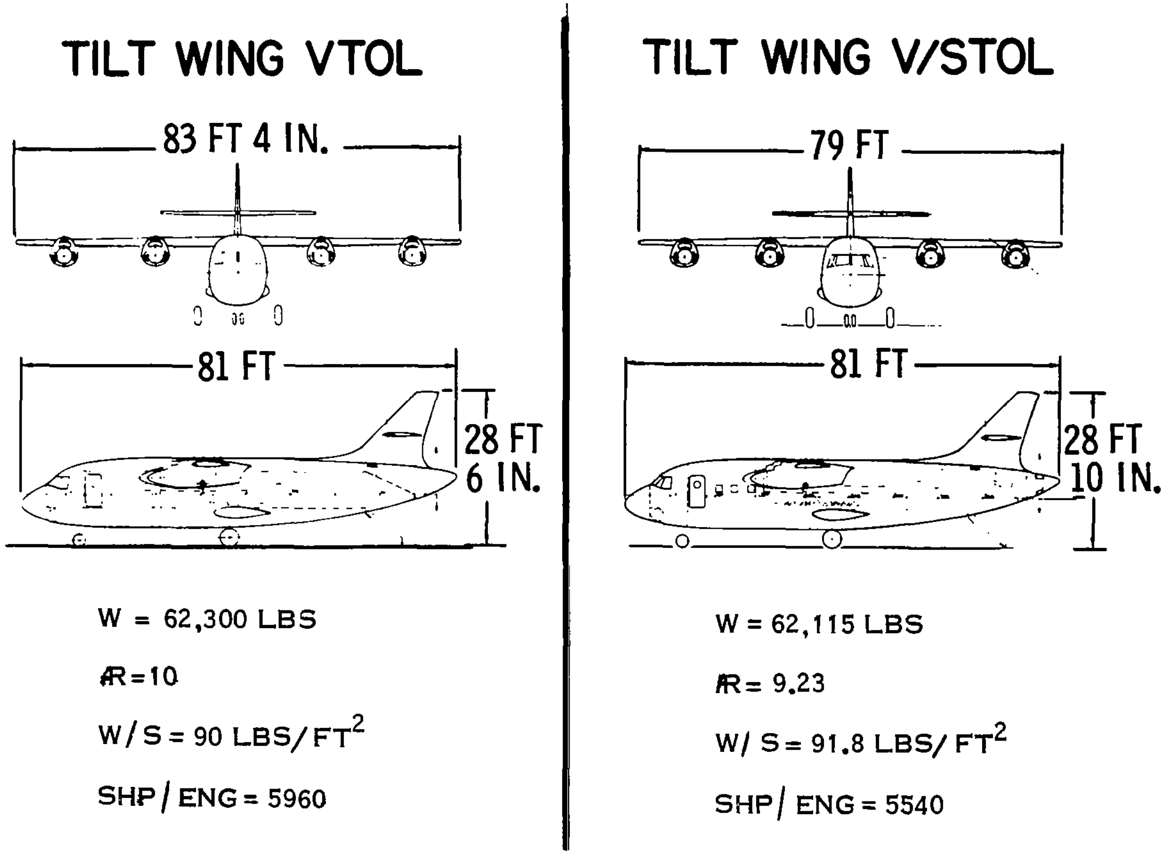
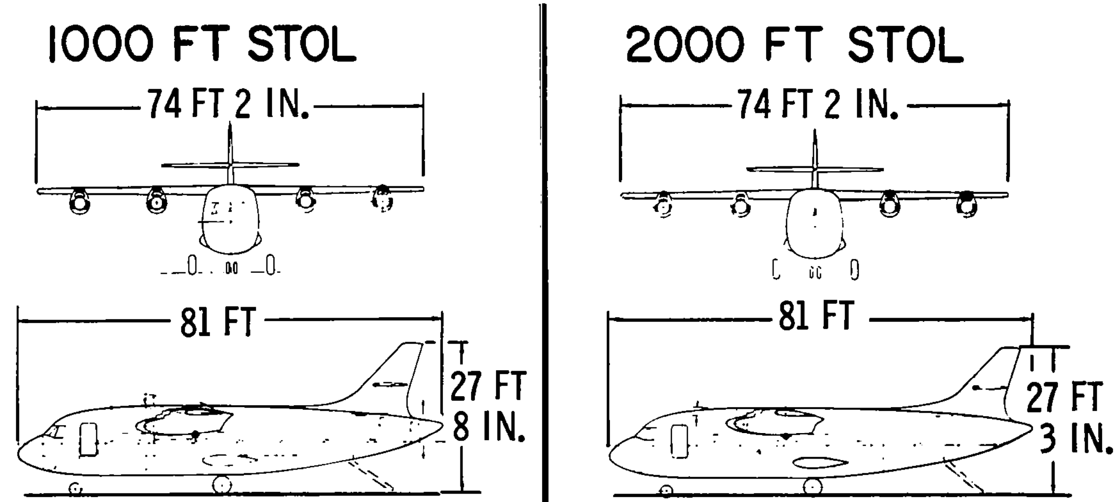


FIGURE 13. - TURBOPROP OPTIMUM VTOL AND V/STOL AIRPLANES



1000 FT STOL

W = 53,783 LBS

$AR = 9$

W S = 88.2 LBS FT^2

SHP/ENG = 3410

2000 FT STOL

W = 52,758 LBS

$AR = 9$

W/S = 86.6 LBS/FT^2

SHP/ENG = 3410

FIGURE 14. - TURBOPROP OPTIMUM STOL AIRPLANES

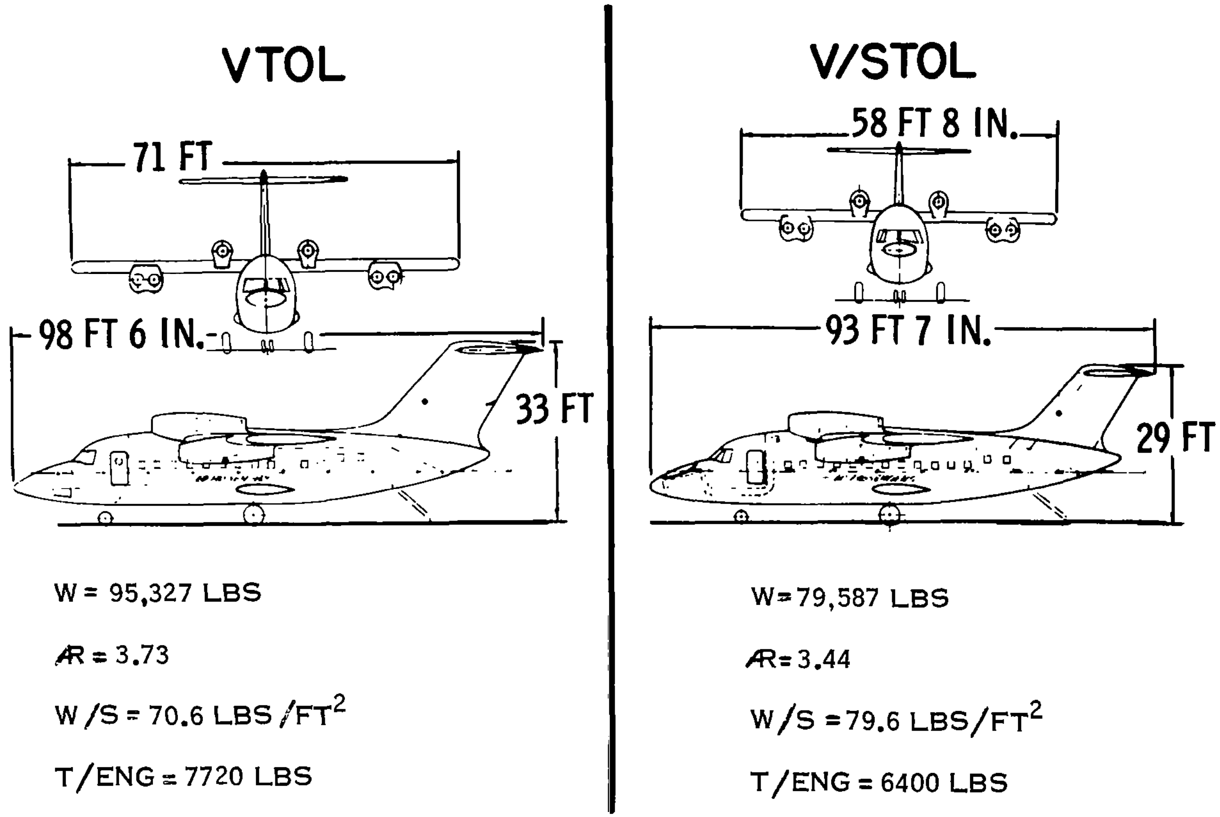


FIGURE 15. - FAN-IN-WING OPTIMUM VTOL AND V/STOL AIRPLANES

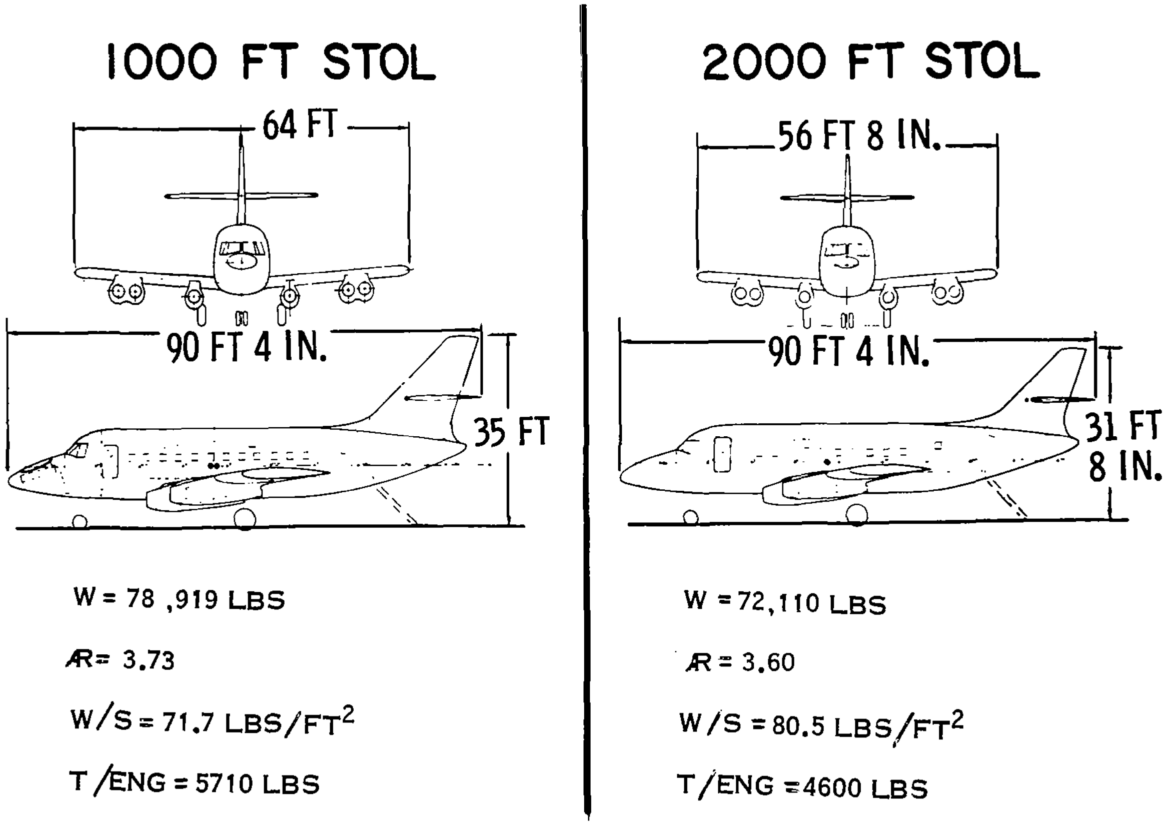


FIGURE 16. - FAN-IN-WING OPTIMUM STOL AIRPLANES

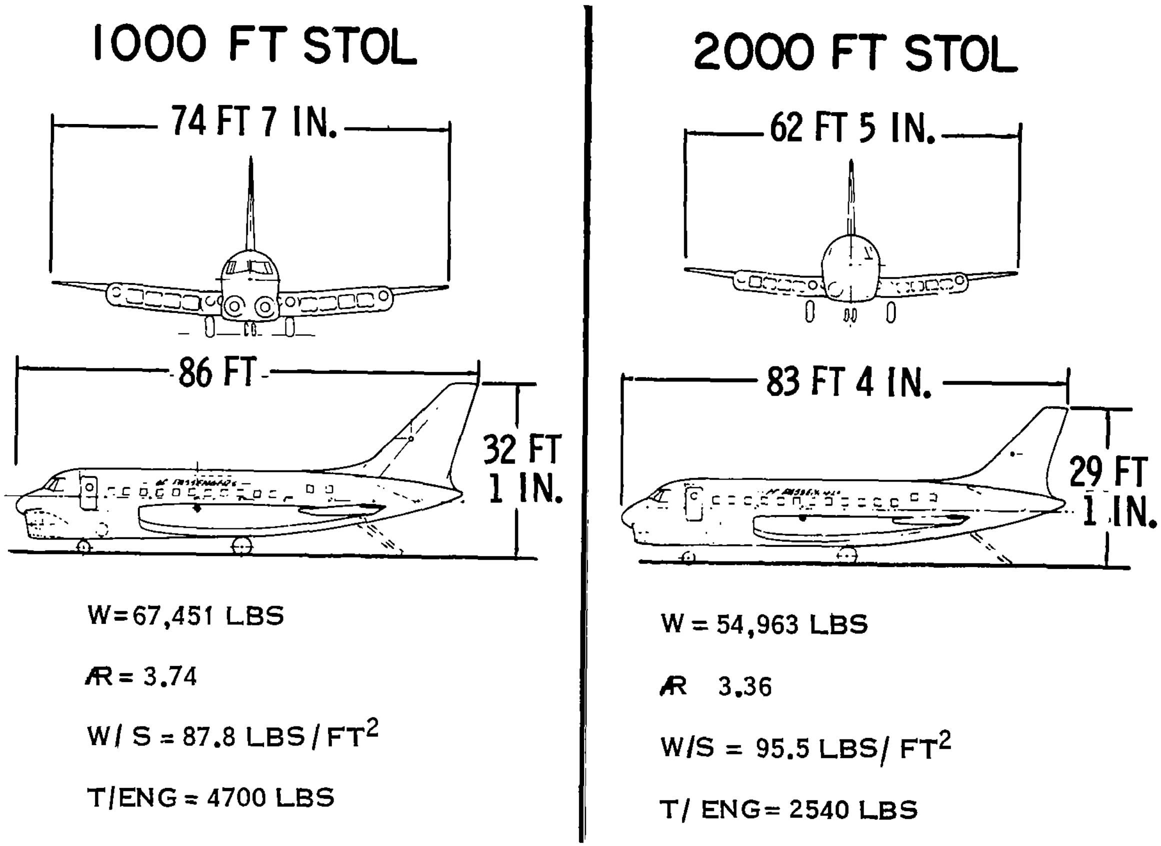


FIGURE 17. - PROPULSIVE WING OPTIMUM STOL AIRPLANES

	TAKEOFF TIP SPEED - fps			
	700	800	900	1000
	APPROXIMATE OPTIMUM CRUISE TIP SPEED - fps			
C_{L_i} = .15	700	800	850	860
C_{L_i} = .3	700	770	810	840
C_{L_i} = .5	670	720	750	780

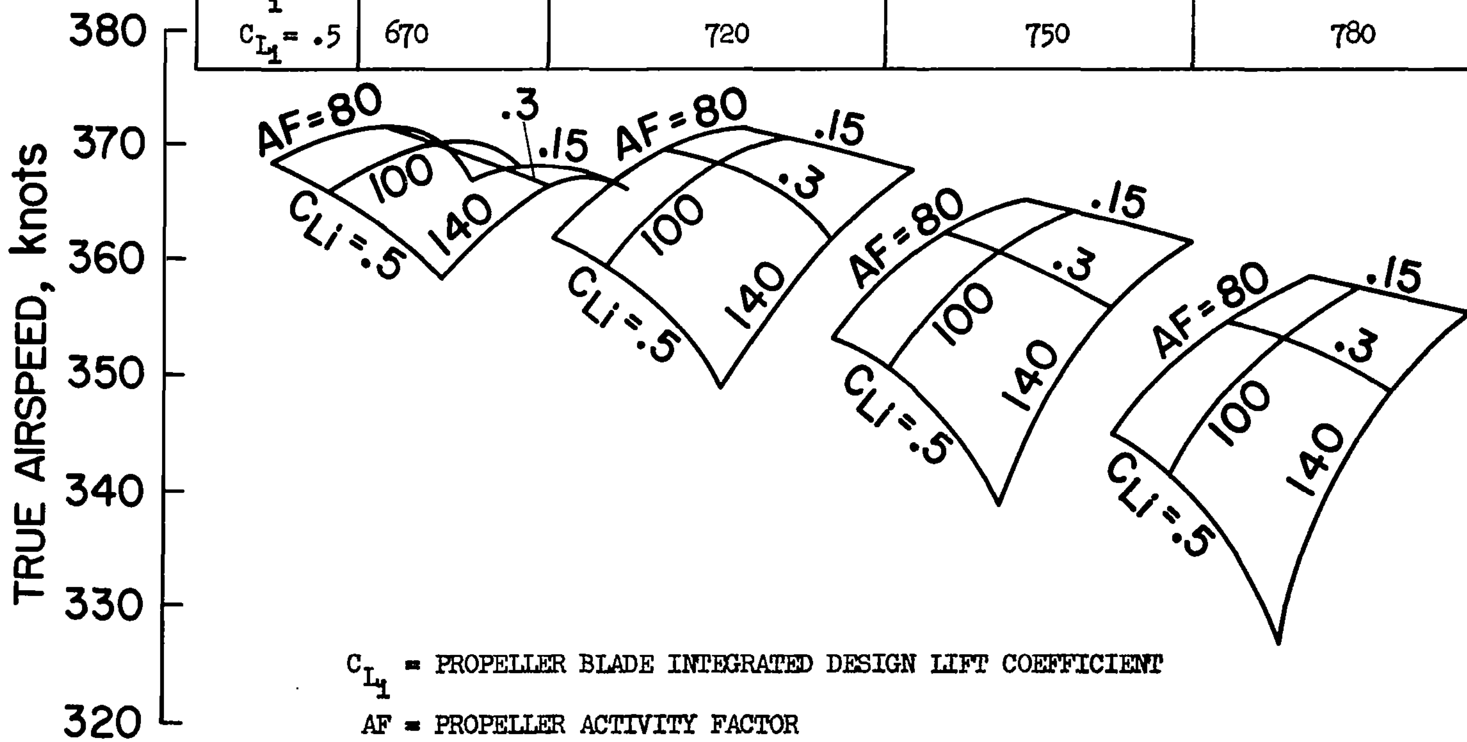


FIGURE 18. - INFLUENCE OF PROPELLER GEOMETRIC AND OPERATING CHARACTERISTICS ON CRUISE SPEED-TURBOPROP STOL AIRPLANE, V_{MAX} ON NRP, ALT = 25,000 FT., D_p = 15.91 FT.

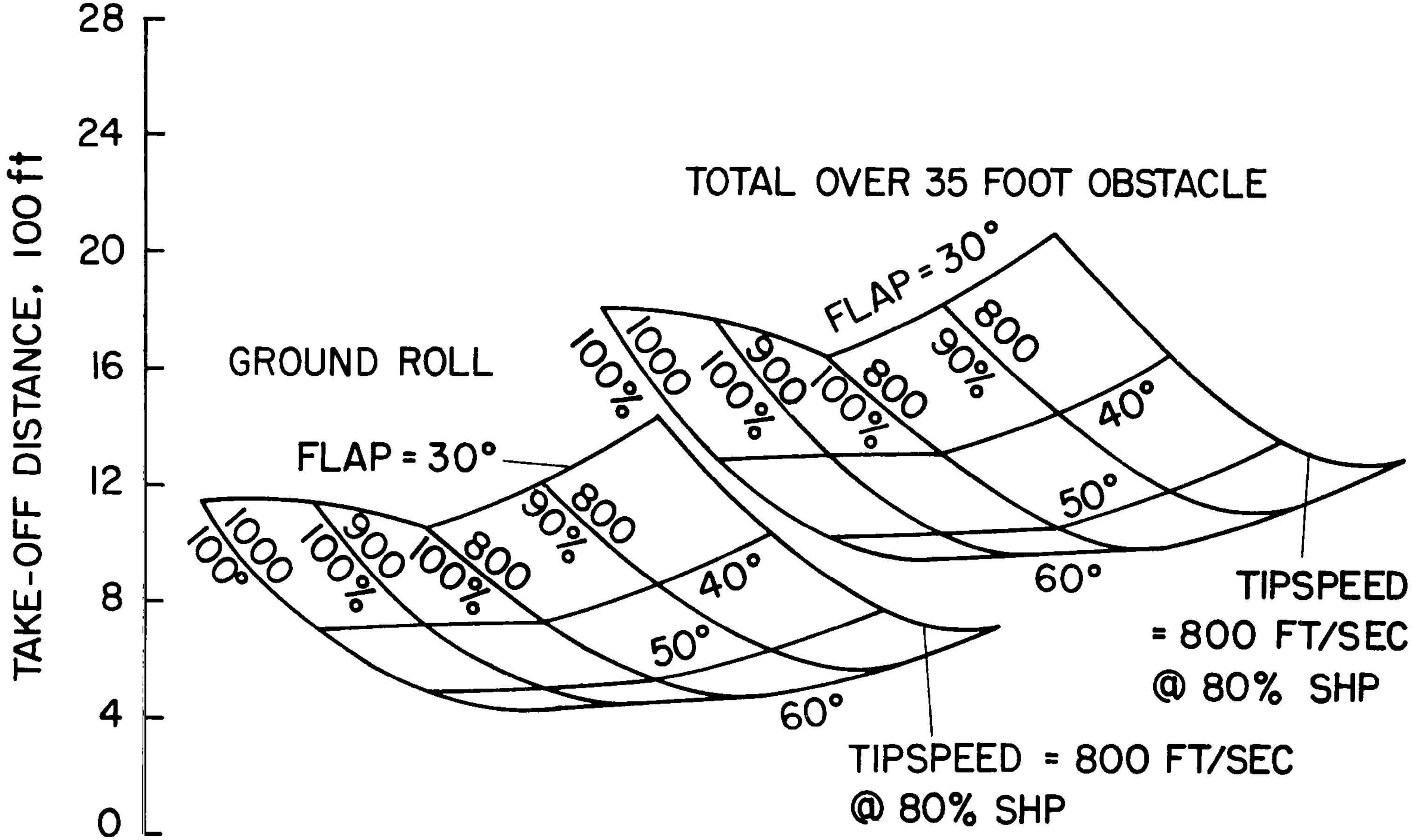


FIGURE 19. - INFLUENCE OF ENGINE-PROPELLER OPERATING CHARACTERISTICS AND THE WING FLAP SETTING ON TAKE-OFF PERFORMANCE - TURBOPROP STOL AIRPLANE, 86°F. DAY, SEA LEVEL

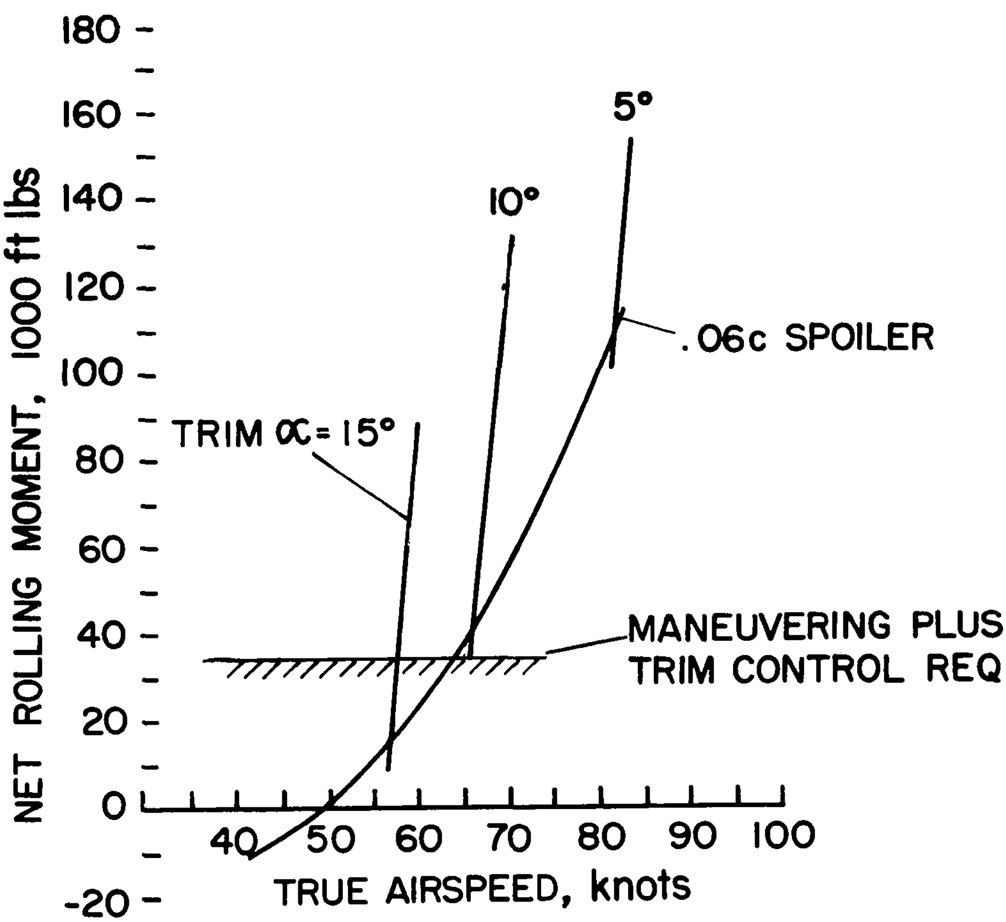


FIGURE 20. - ABILITY OF SPOILERS TO PROVIDE ROLL CONTROL-TURBOPROP 2000 FOOT STOL AIRPLANE, TAKE-OFF POWER WITH OUTBOARD ENGINE FAILED, NO CROSS SHAFTING

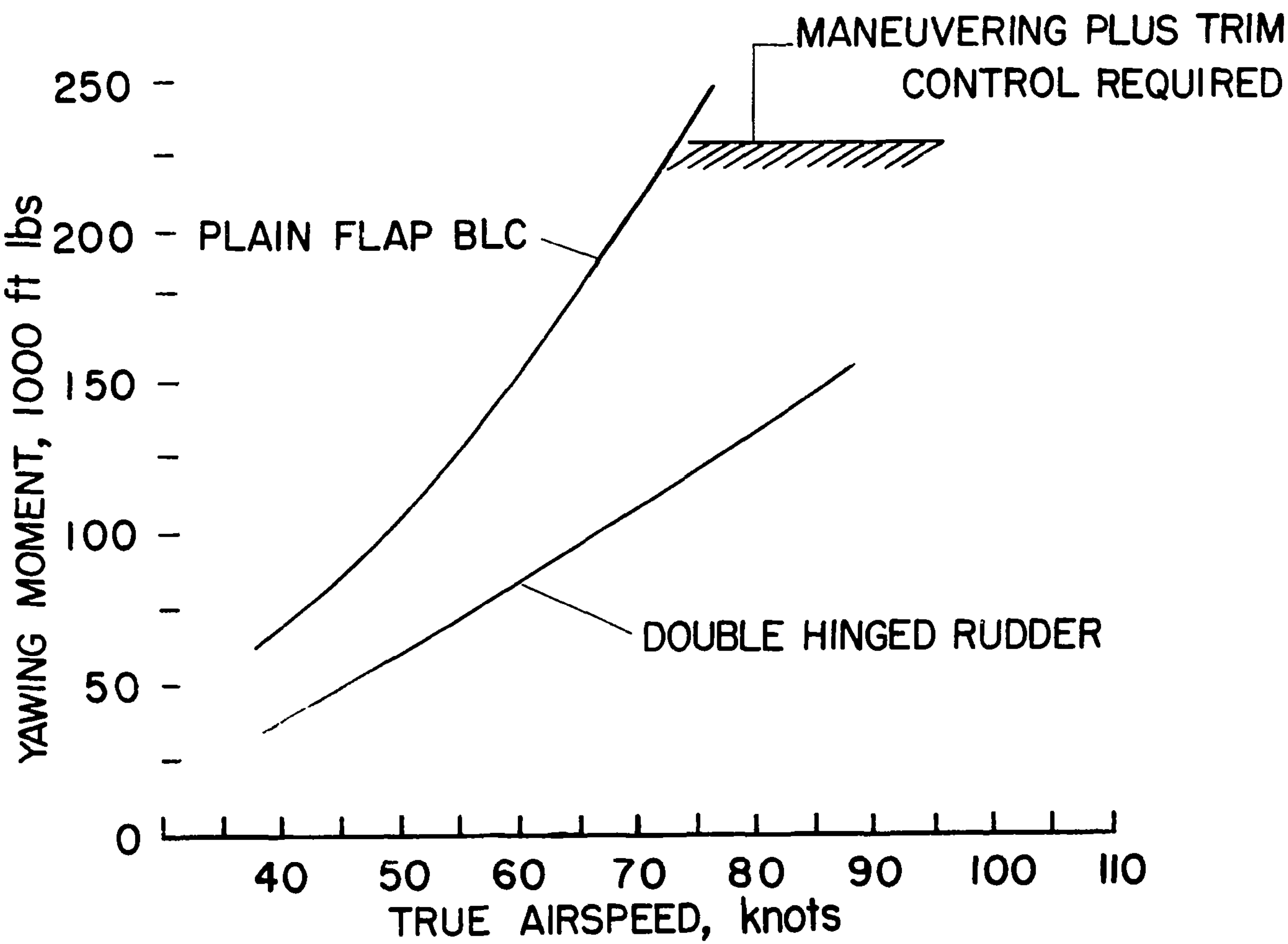


FIGURE 21. - ABILITY OF VERTICAL TAIL TO PROVIDE YAW CONTROL-TURBOPROP 2000 FOOT STOL AIRPLANE, TAKE-OFF POWER WITH OUTBOARD ENGINE FAILED, NO CROSS SHAFTING, TRIM $\alpha = 10^{\circ}$, $\delta_F = 40^{\circ}$

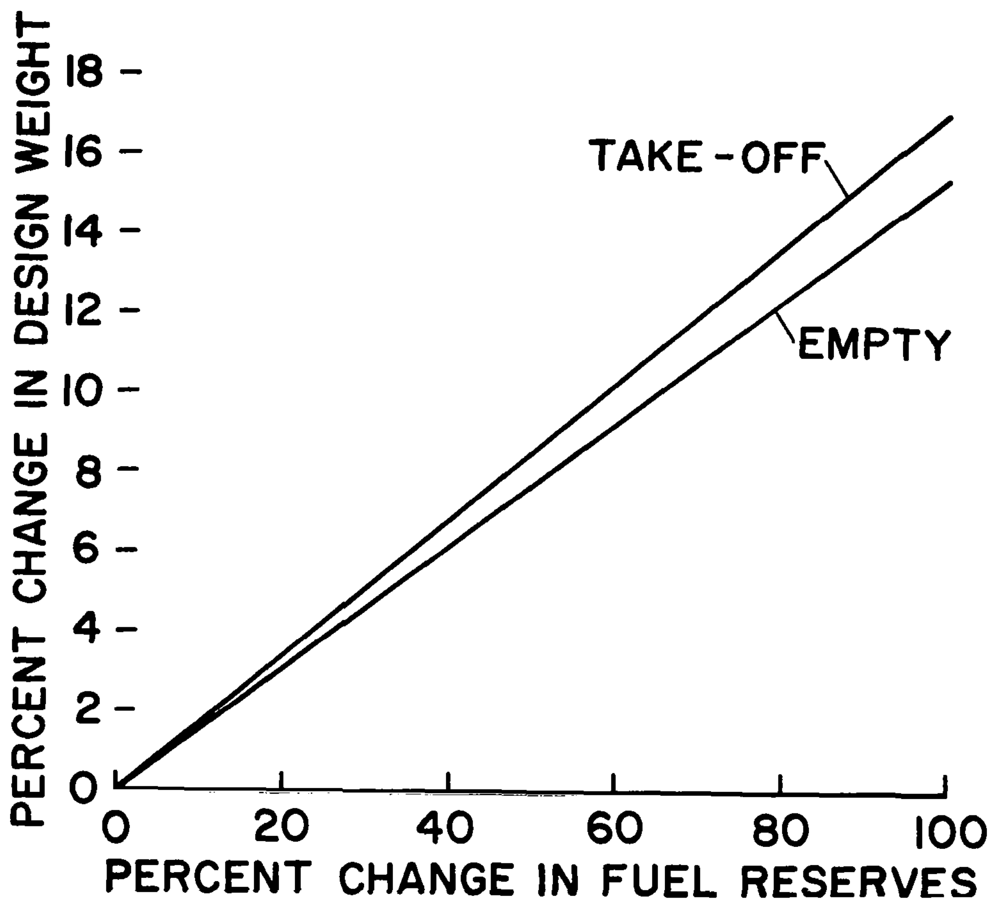


FIGURE 22. - WEIGHT SENSITIVITY TO FUEL RESERVES - FAN-IN-WING V/STOL AIRPLANE, 100% FUEL RESERVE = 33% TOTAL FUEL

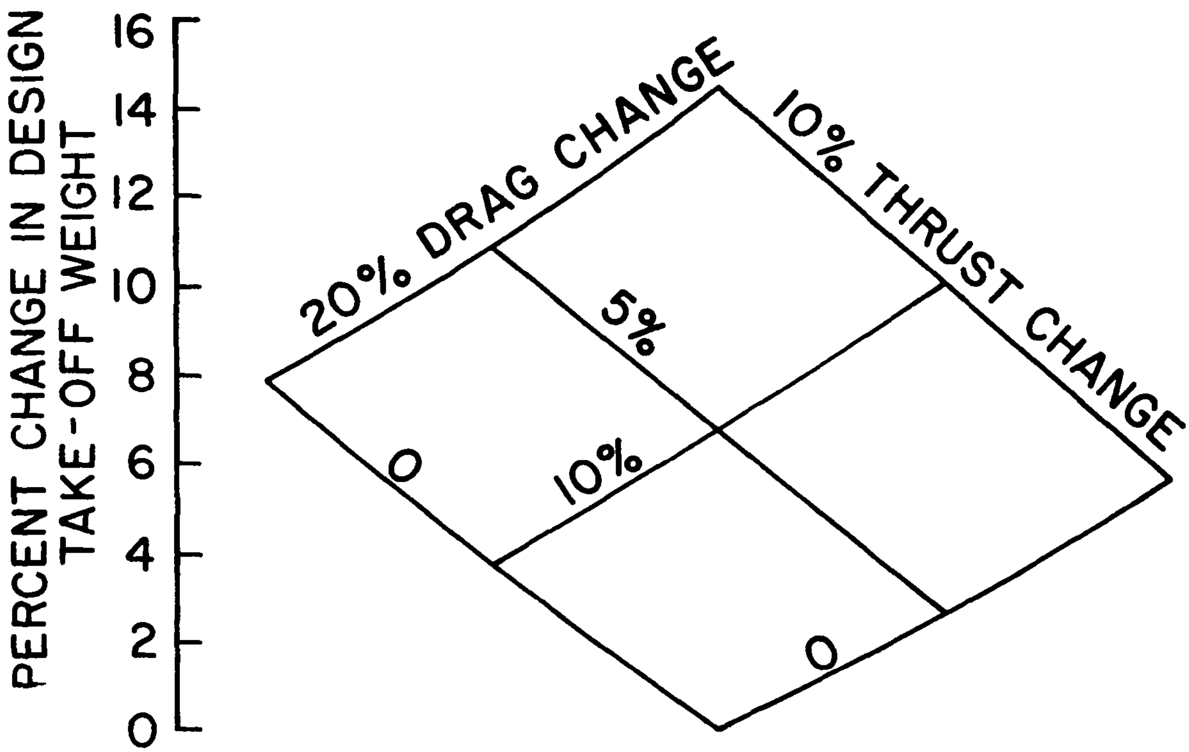


FIGURE 23. - WEIGHT SENSITIVITY TO SKIN FRICTION DRAG AND PROPULSION SYSTEM EFFICIENCY - PROPULSIVE WING 2000 FOOT STOL AIRPLANE

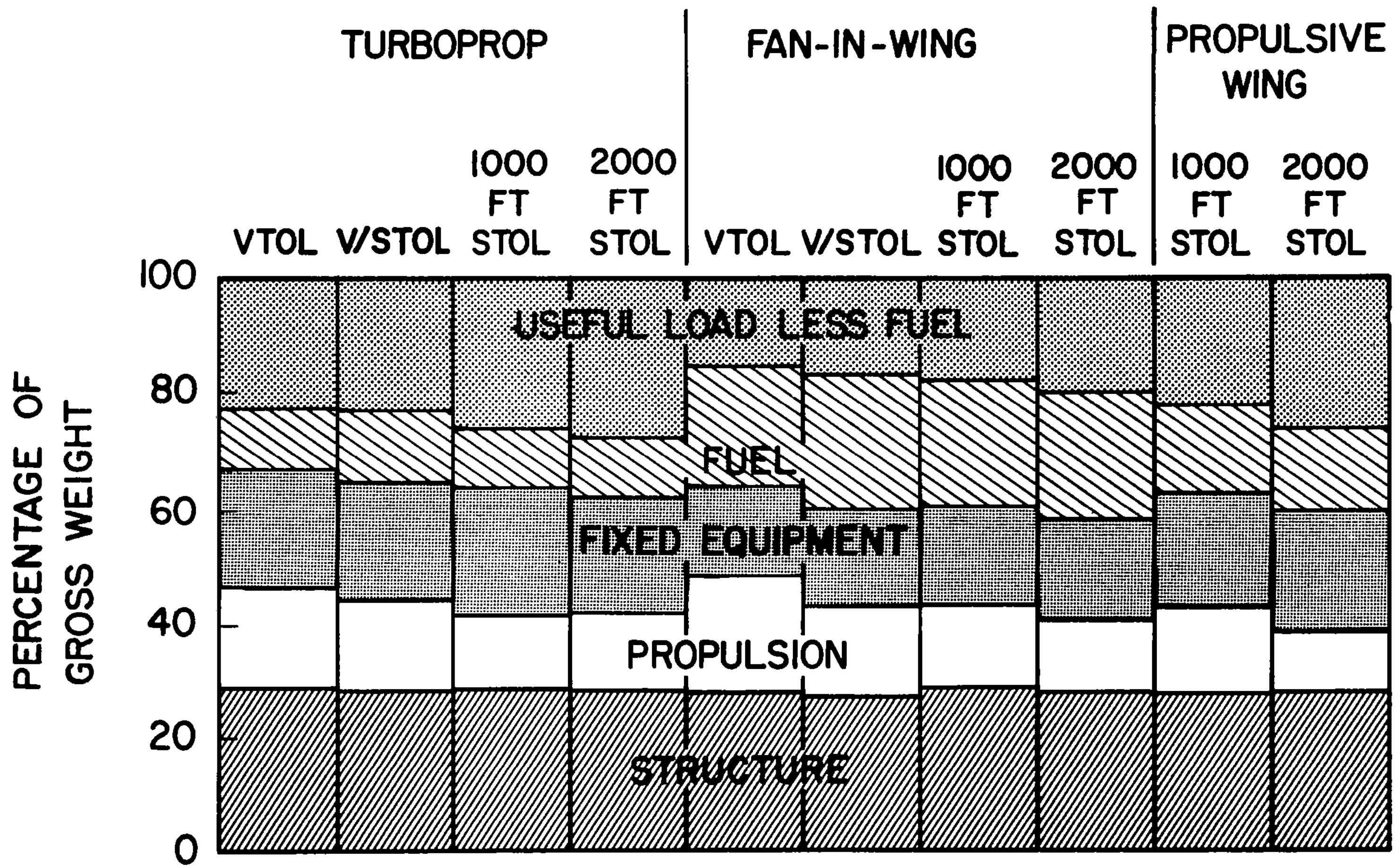


FIGURE 24. - WEIGHT BREAKDOWN COMPARISONS - 60 PASSENGER AIRPLANES

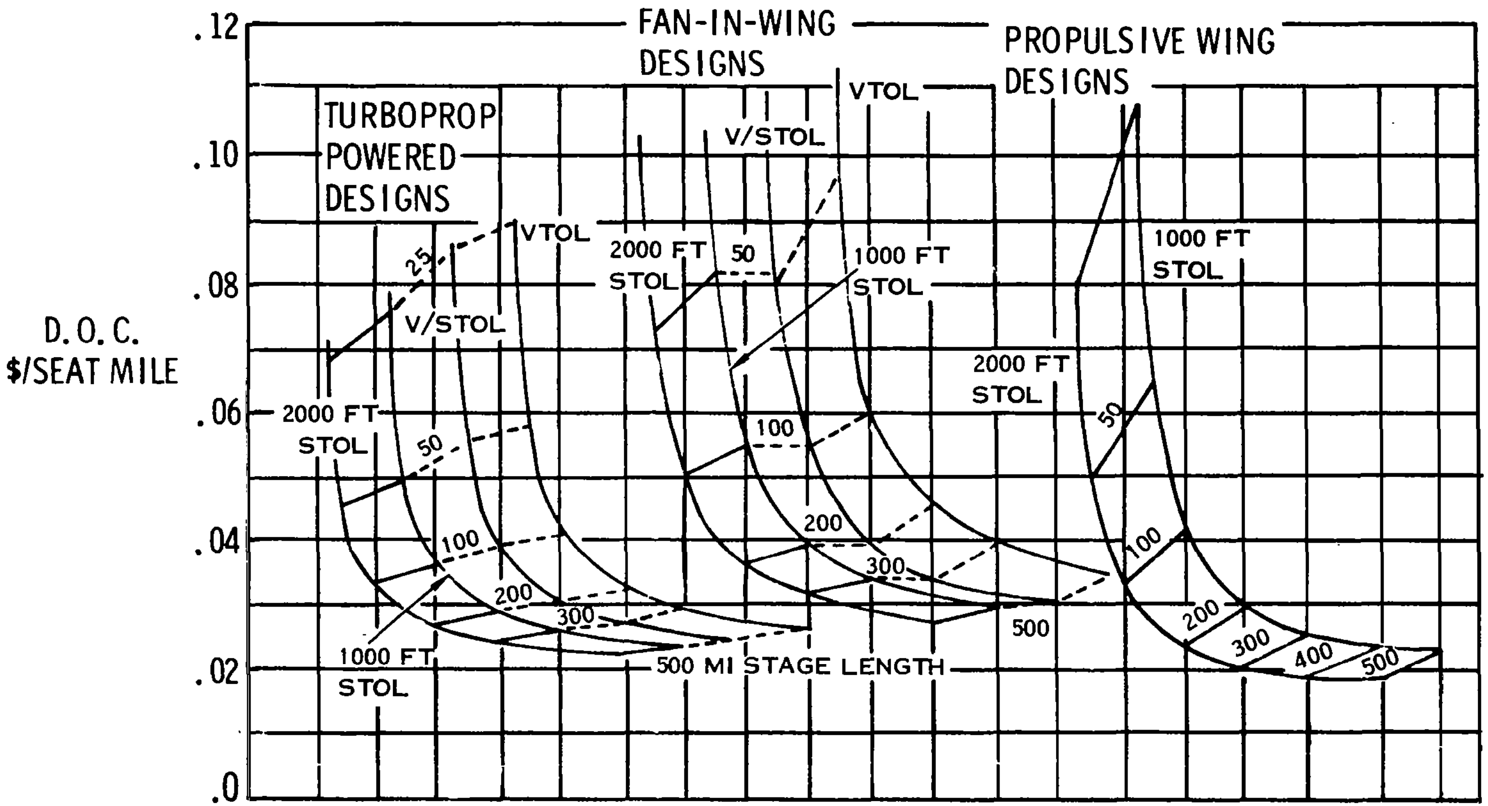
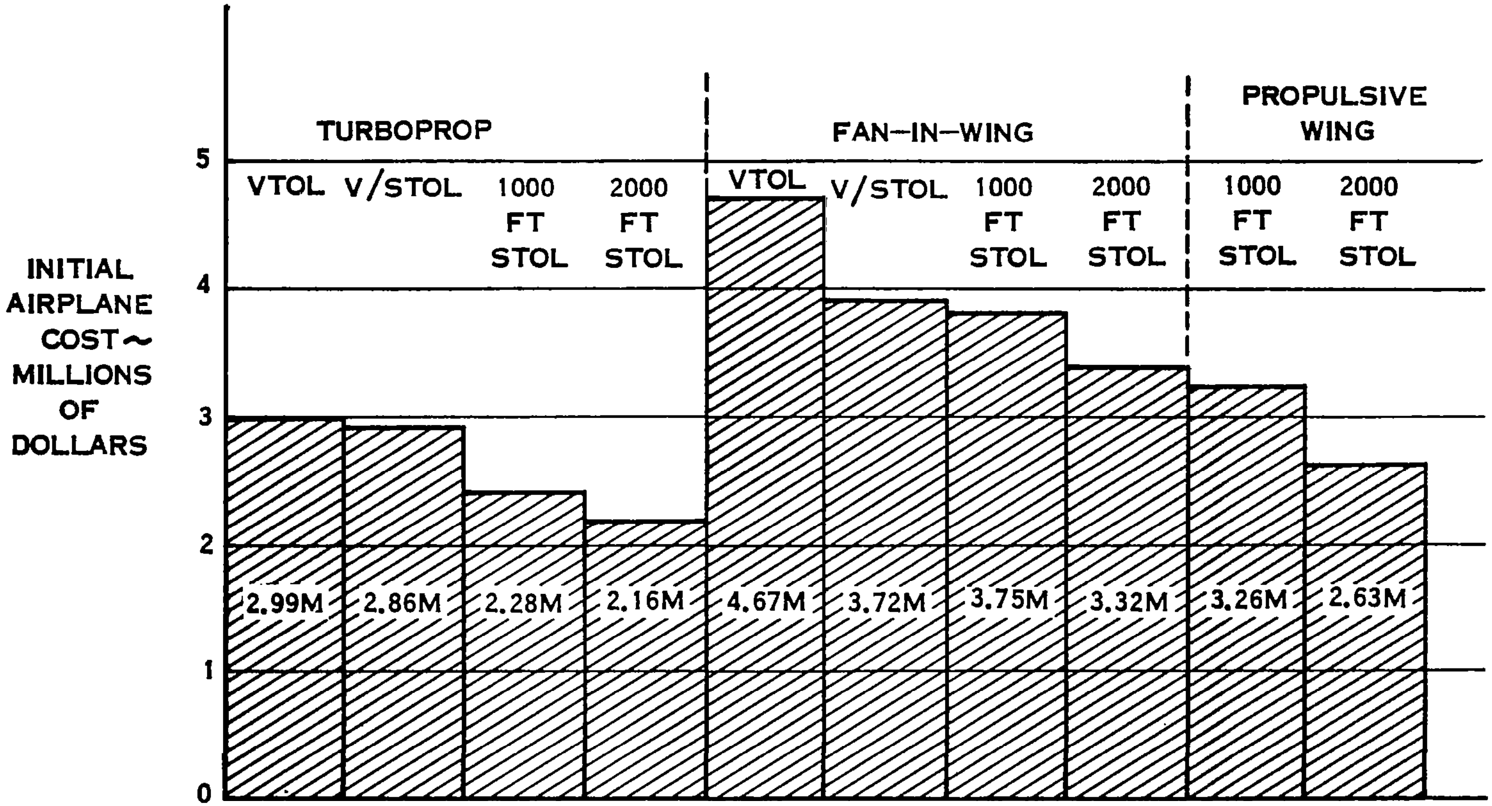


FIGURE 25. - DIRECT OPERATING COSTS - 60 PASSENGER AIRPLANES; NON PRODUCTIVE TIME = 10 1/4 MINUTES, UTILIZATION = 2000 HOURS PER YEAR, PRODUCTION RUN = 300 AIRPLANES.



AVERAGE INITIAL AIRPLANE COSTS ASSUMING 300 AIRPLANES PRODUCED WITH NO RESEARCH AND DEVELOPMENT COSTS INCLUDED

FIGURE 26. INITIAL AIRPLANE COSTS

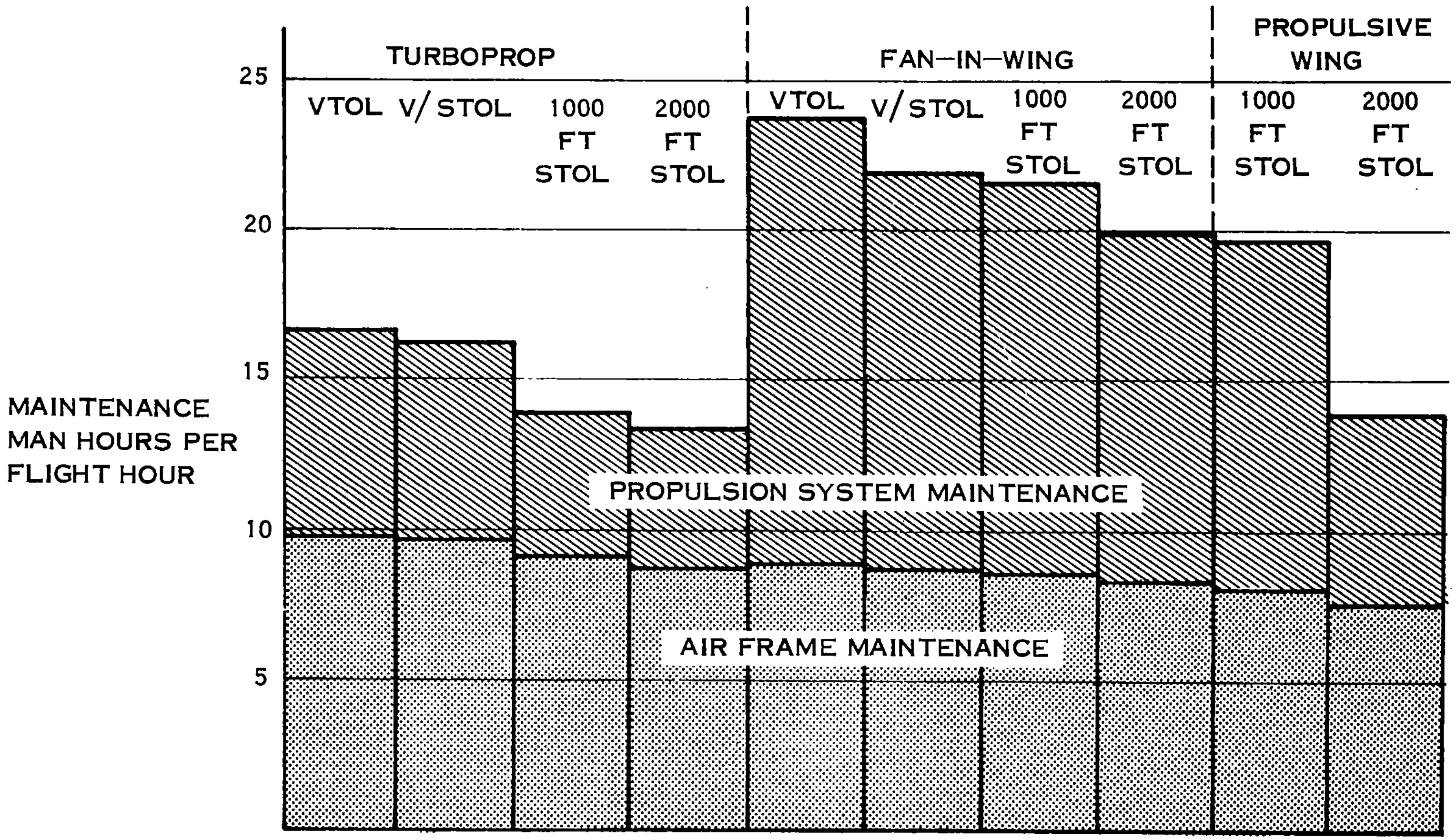


FIGURE 27. - MAINTENANCE REQUIREMENTS

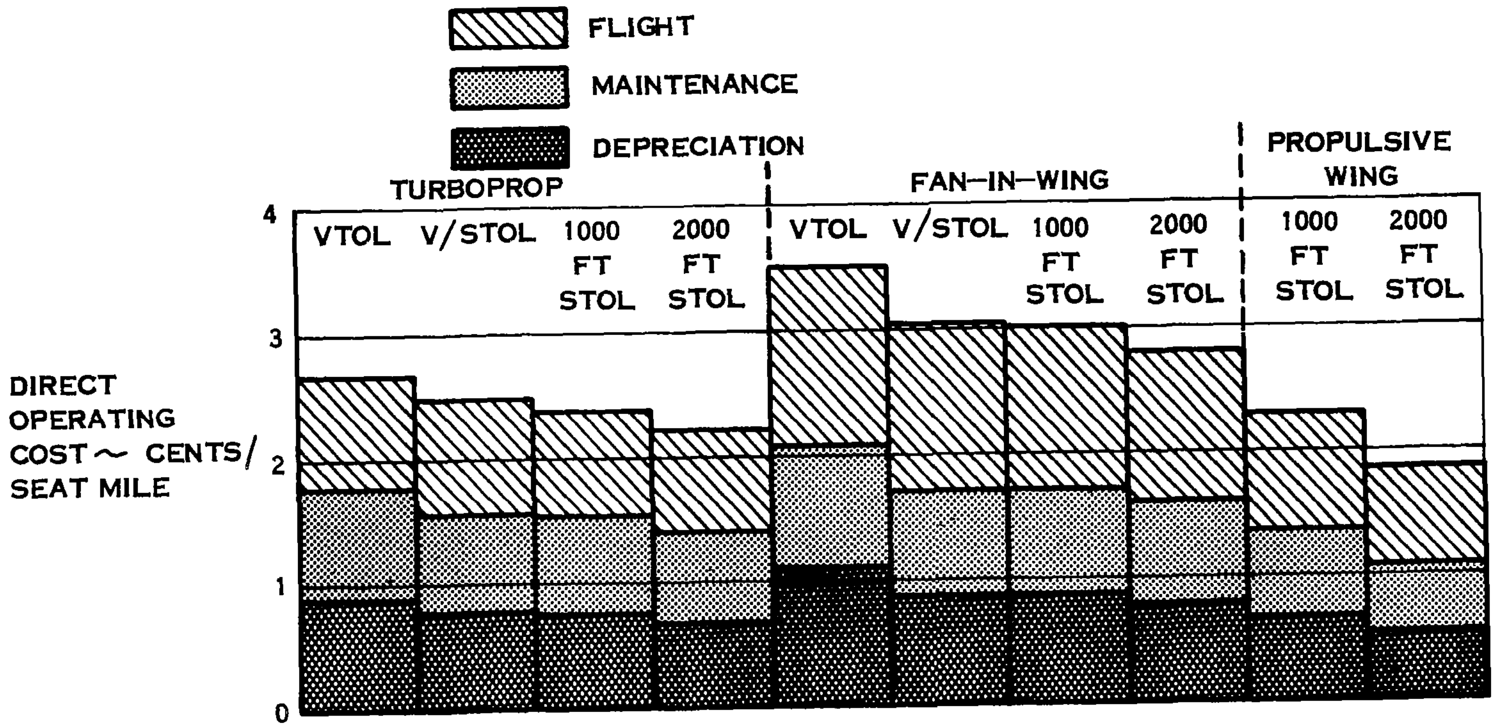


FIGURE 28. - DIRECT OPERATING COST BREAKDOWN - 500 MILE STAGE LENGTH

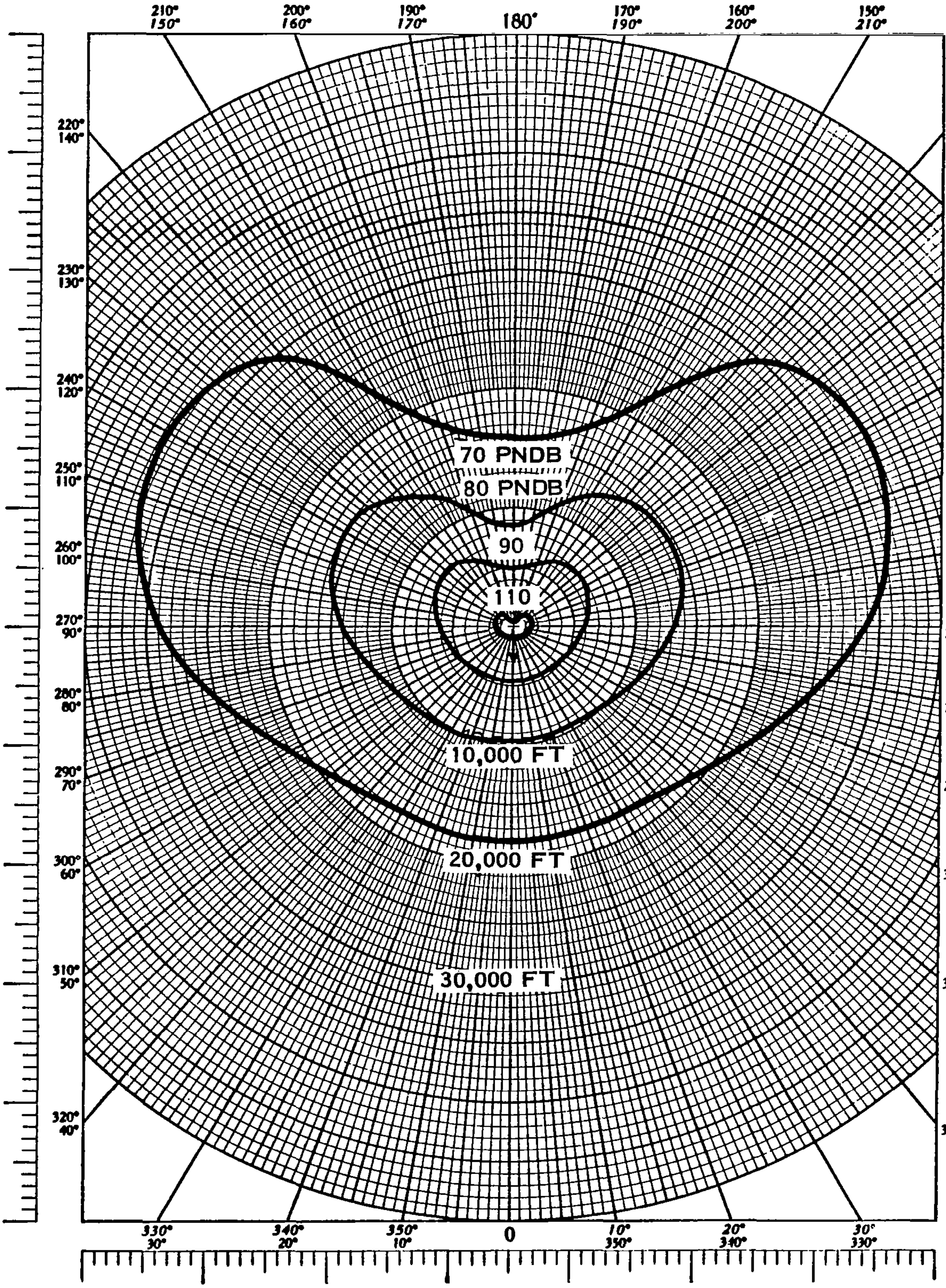


FIGURE 29. - PERCEIVED NOISE LEVEL DIRECTIVITY CONTOURS-
TURBOPROP V/STOL AIRPLANE, 1000 FPS TIP SPEED

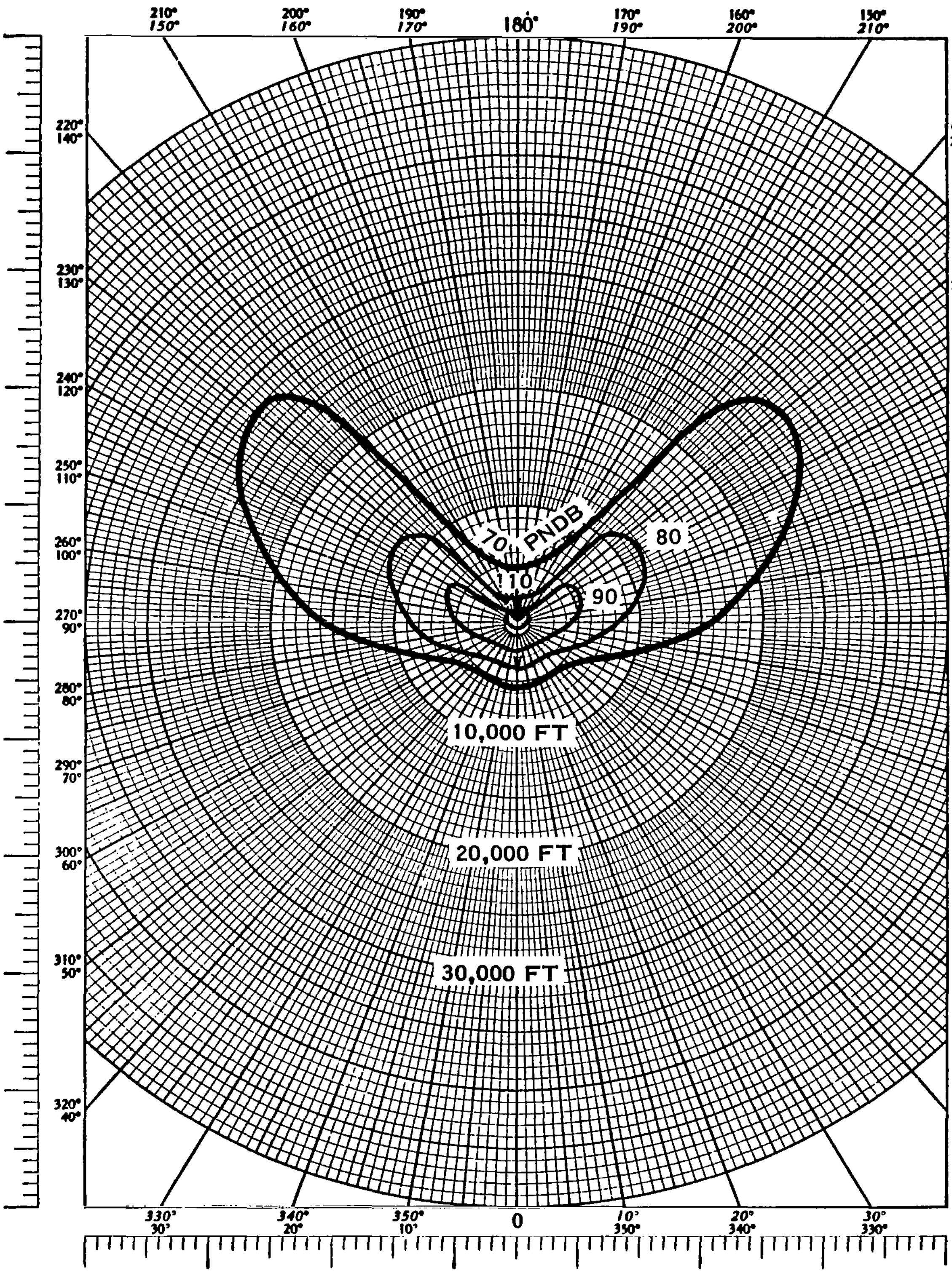


FIGURE 30. - PERCEIVED NOISE LEVEL DIRECTIVITY CONTOURS, TURBOPROP 2000 FOOT STOL, 1000 FPS TIP SPEED

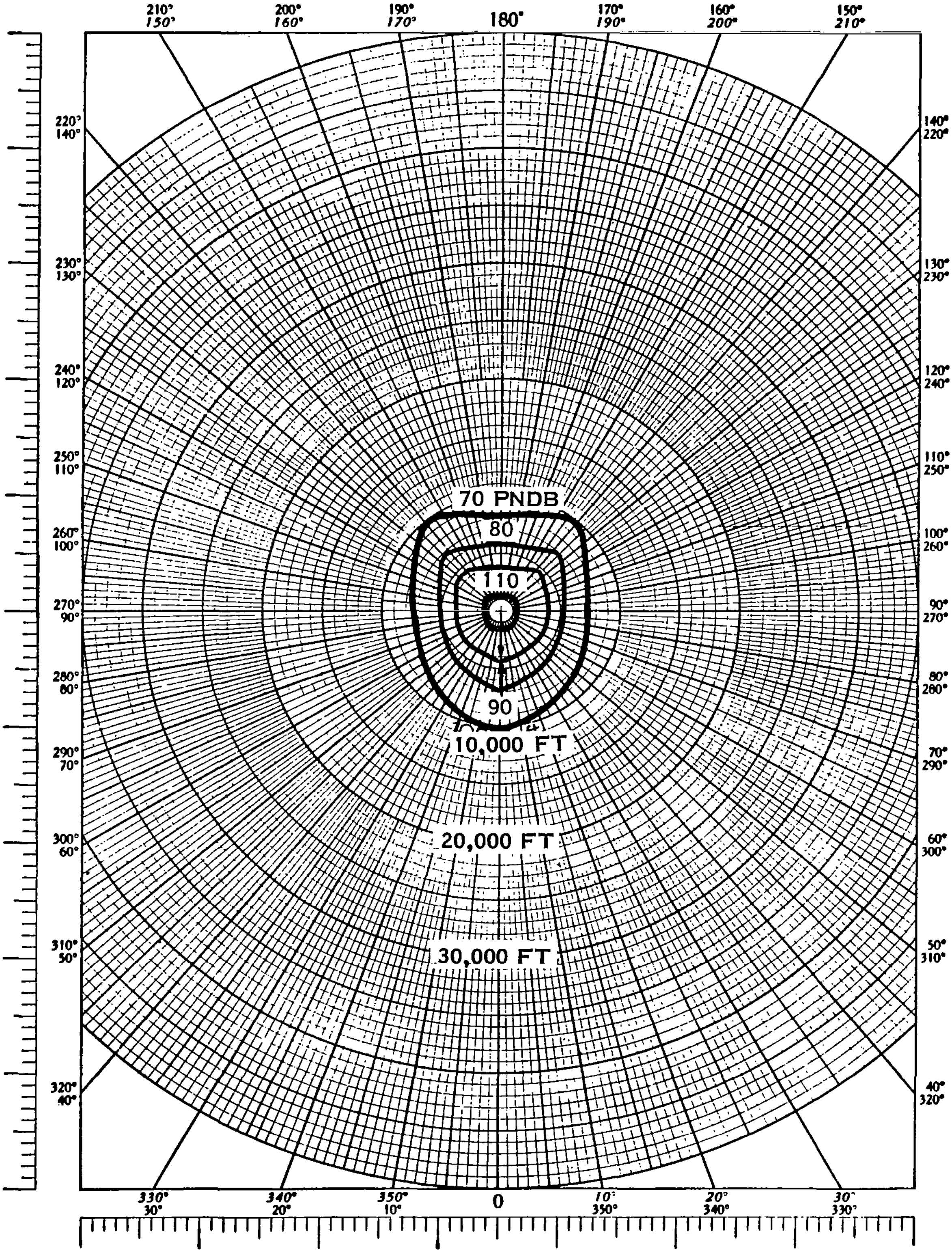


FIGURE 31. - PERCEIVED NOISE LEVEL DIRECTIVITY CONTOURS - FAN-IN-WING V/STOL AIRPLANE

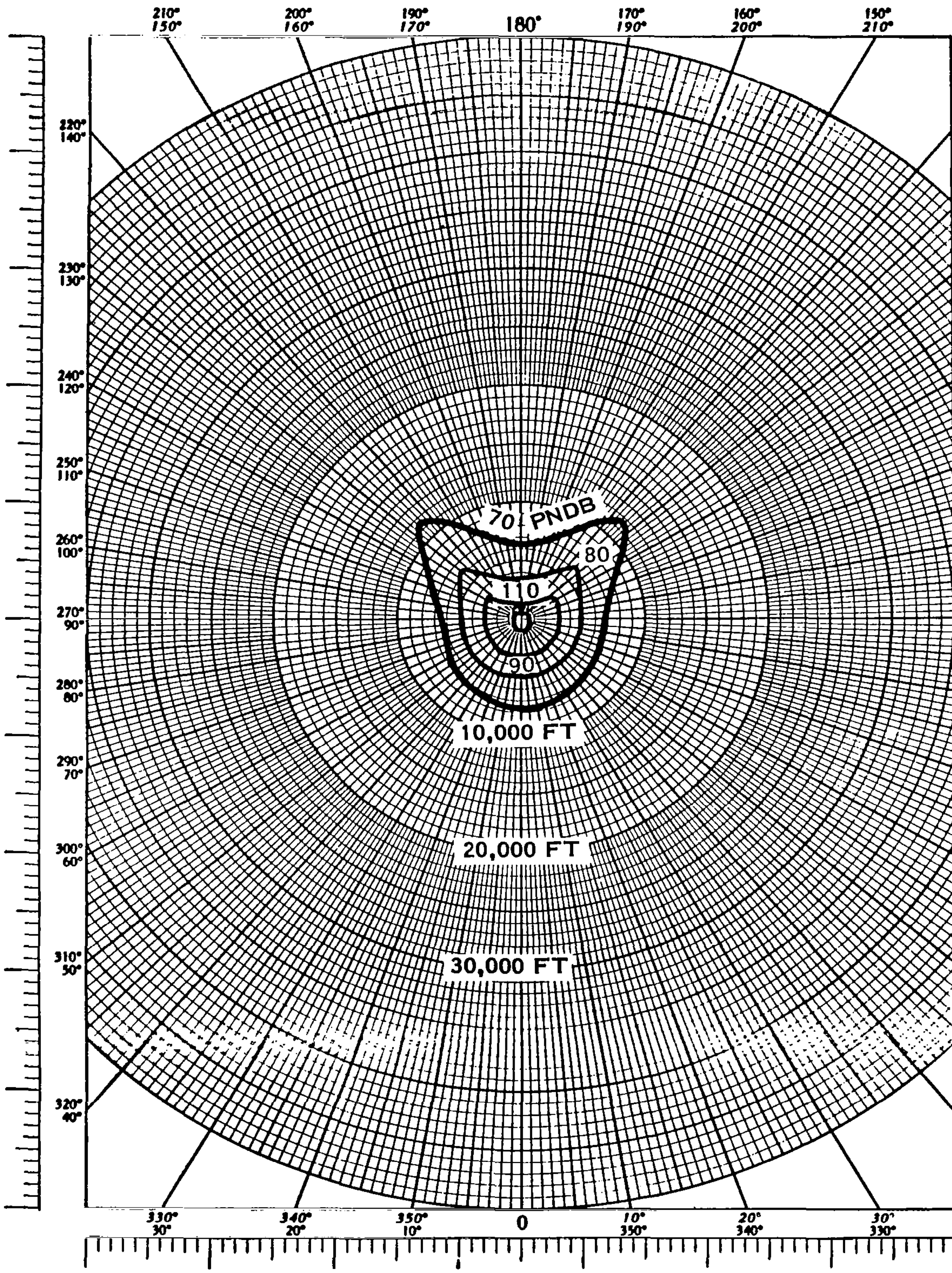
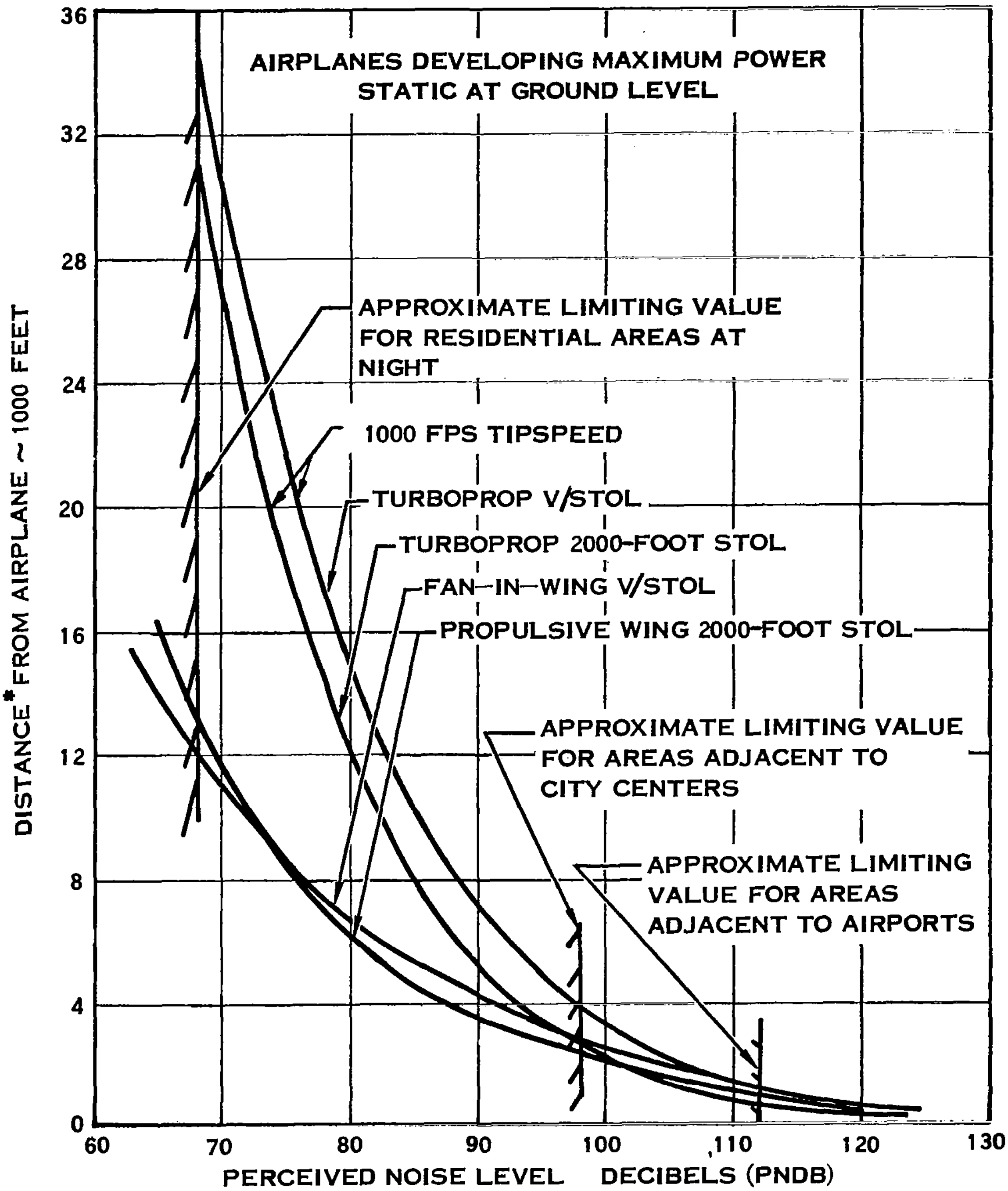


FIGURE 32. - PERCEIVED NOISE LEVEL DIRECTIVITY CONTOURS-
PROPULSIVE WING 2000 FOOT STOL AIRPLANE



*DISTANCE IS MEASURED AT THE ANGLE AT WHICH THE MAXIMUM PNDB' OCCURS, MEASURED RADIALLY FROM THE AIRPLANE.

FIG. 33. PERCEIVED NOISE LEVEL VS DISTANCE*

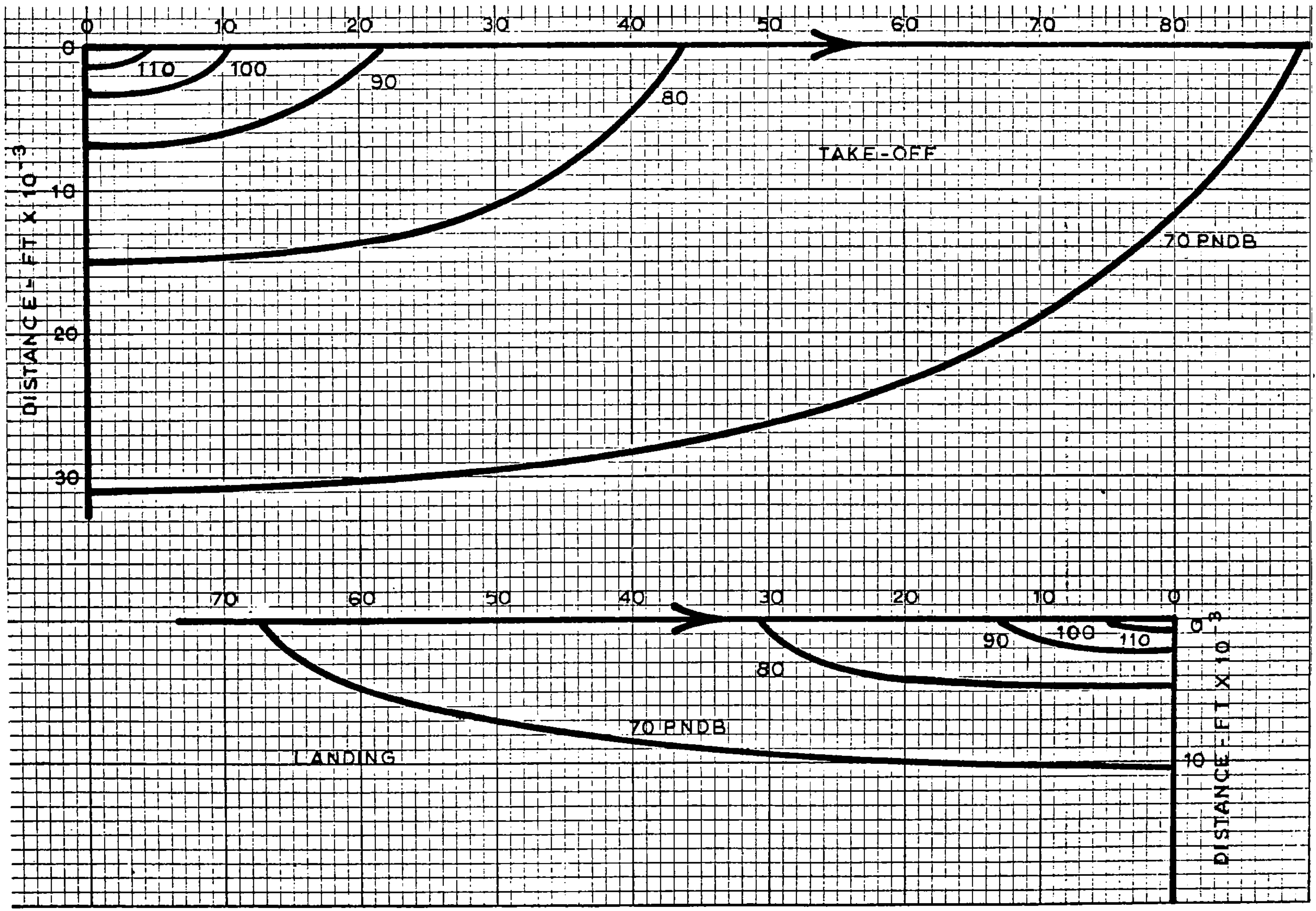


FIGURE 34. - PERCEIVED NOISE LEVEL CONTOURS FOR TAKEOFF AND LANDING, TURBOPROP V/STOL AIRPLANE

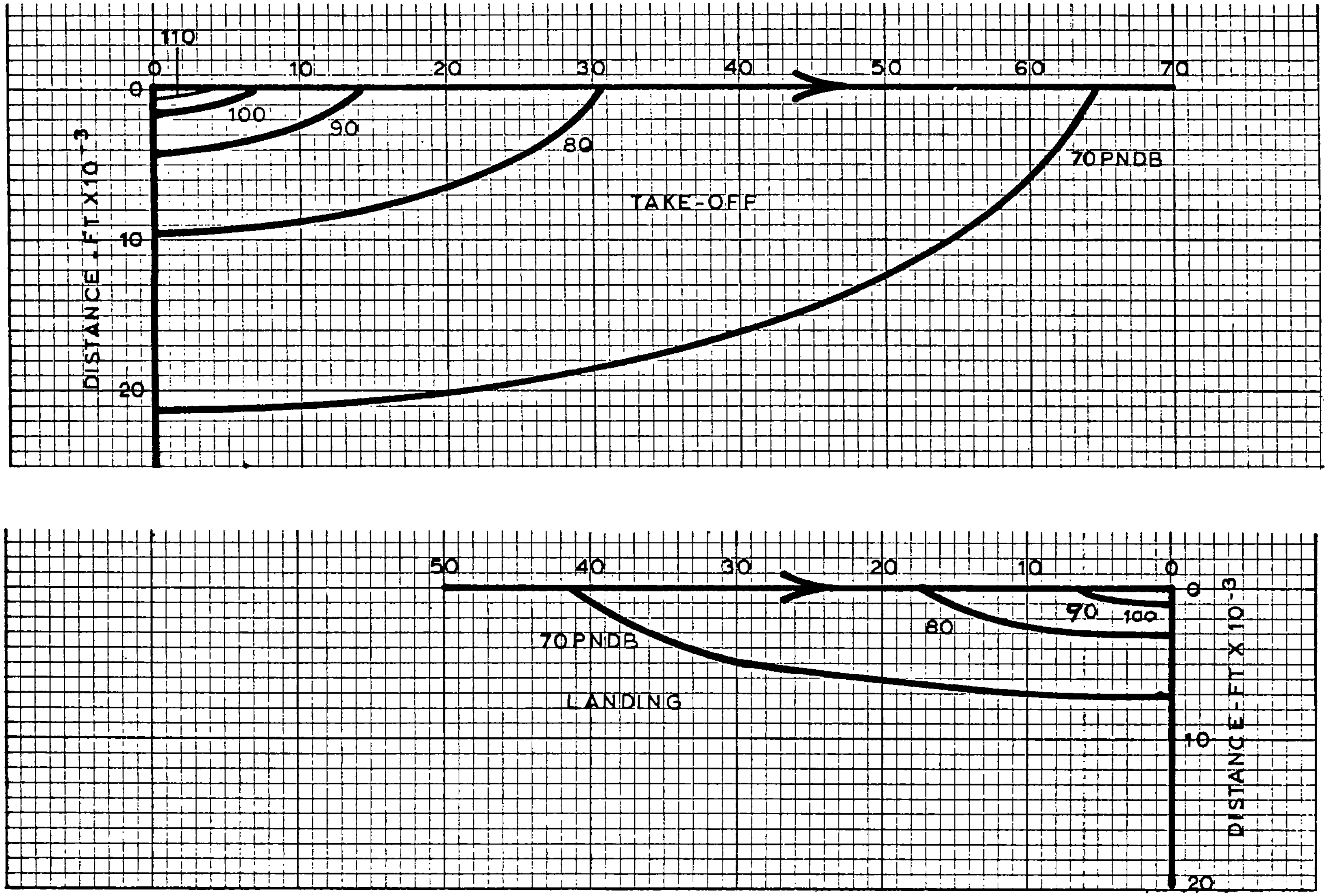


FIGURE 35 - PERCEIVED NOISE LEVEL CONTOURS FOR TAKEOFF AND LANDING-
TURBOPROP 2000 FOOT STOL AIRPLANE

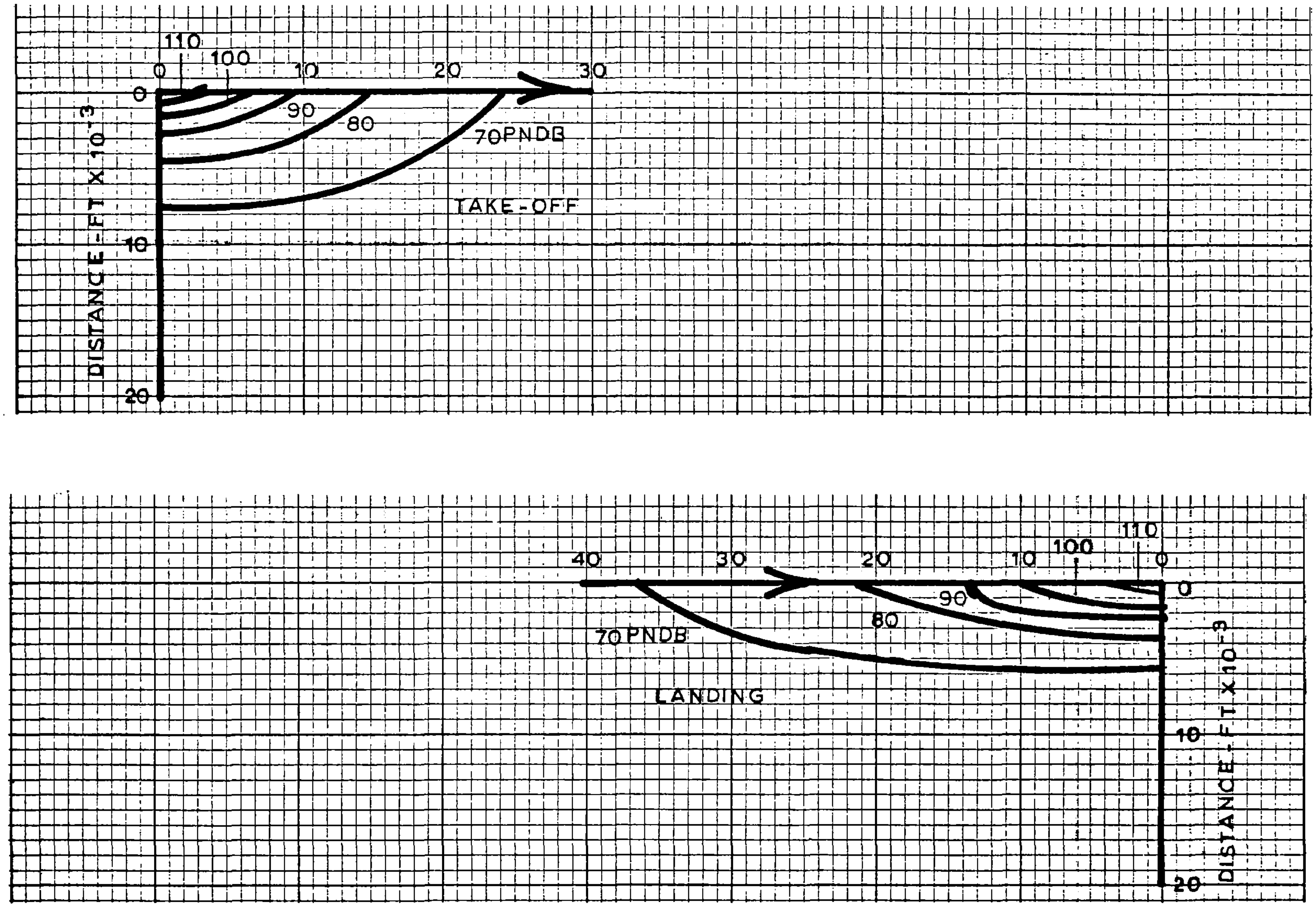


FIGURE 36 - PERCEIVED NOISE LEVEL CONTOURS FOR TAKEOFF AND LANDING,
FAN-IN-WING V/STOL AIRPLANE

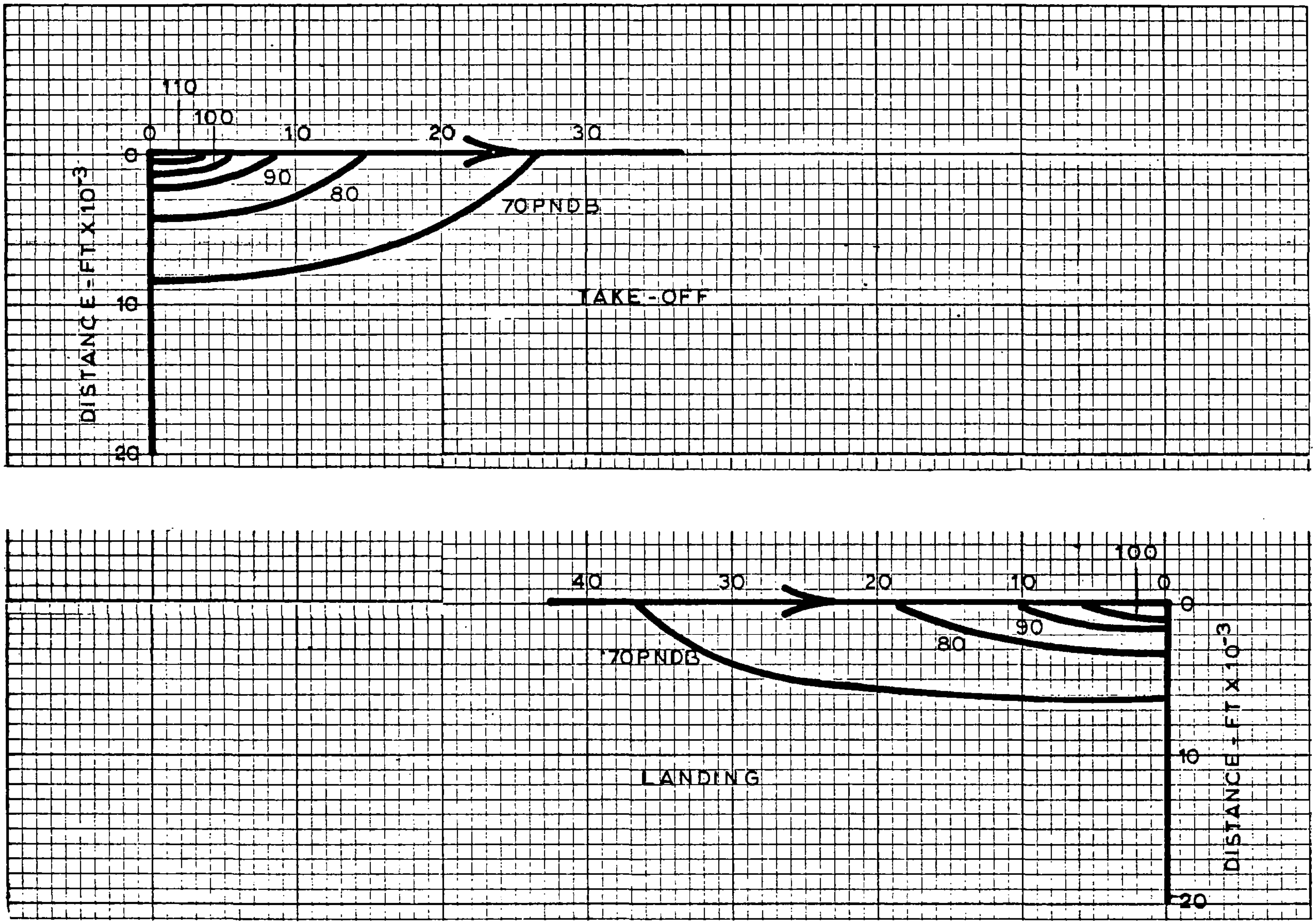


FIGURE 37 - PERCEIVED NOISE LEVEL CONTOURS FOR TAKEOFF AND LANDING, PROPULSIVE WING 2000 FT. STOL AIRPLANE

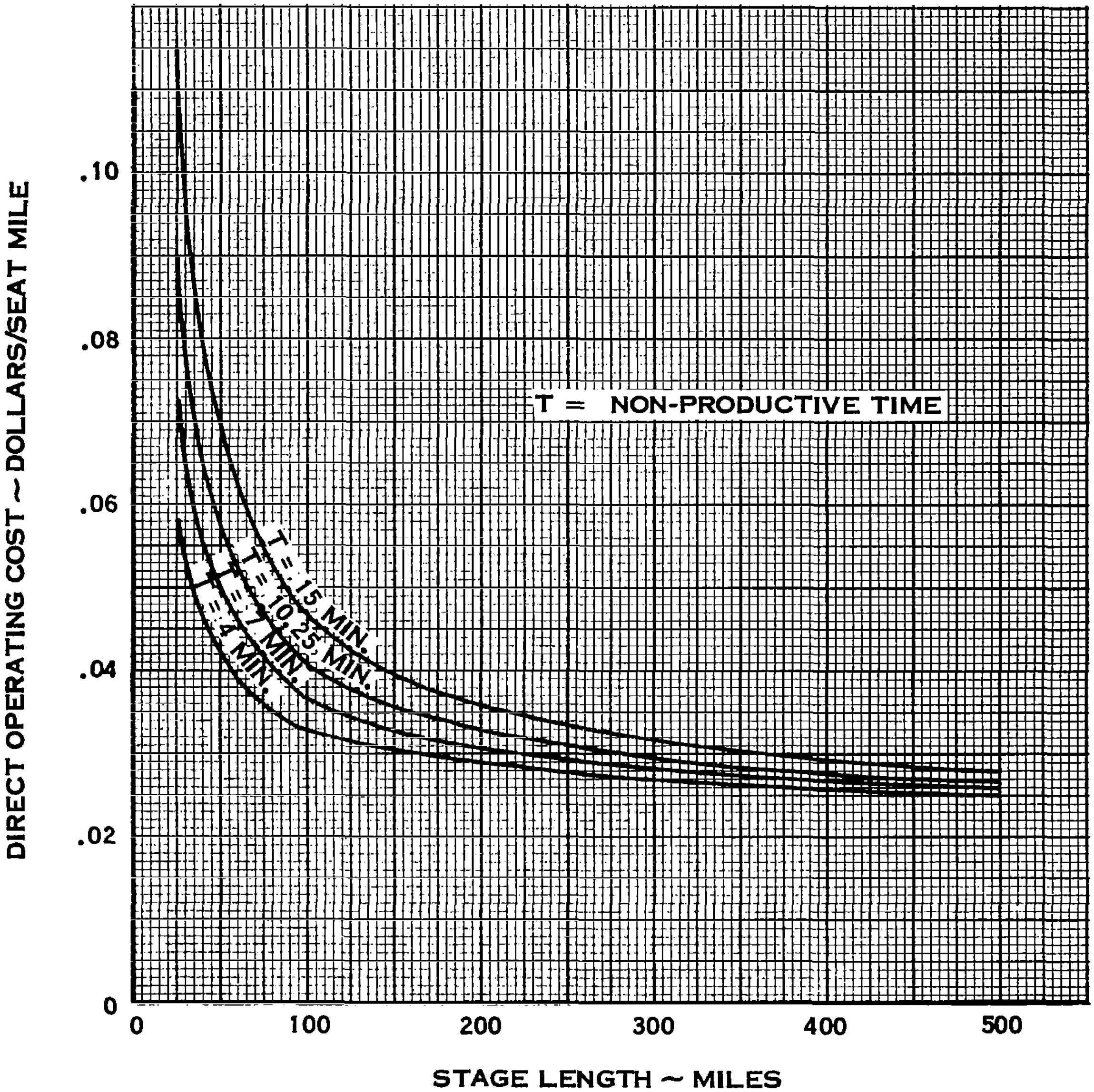


FIGURE 38. - EFFECT OF NON-PRODUCTIVE TIME ON DIRECT OPERATING COSTS-
TURBOPROP VTOL AIRPLANE

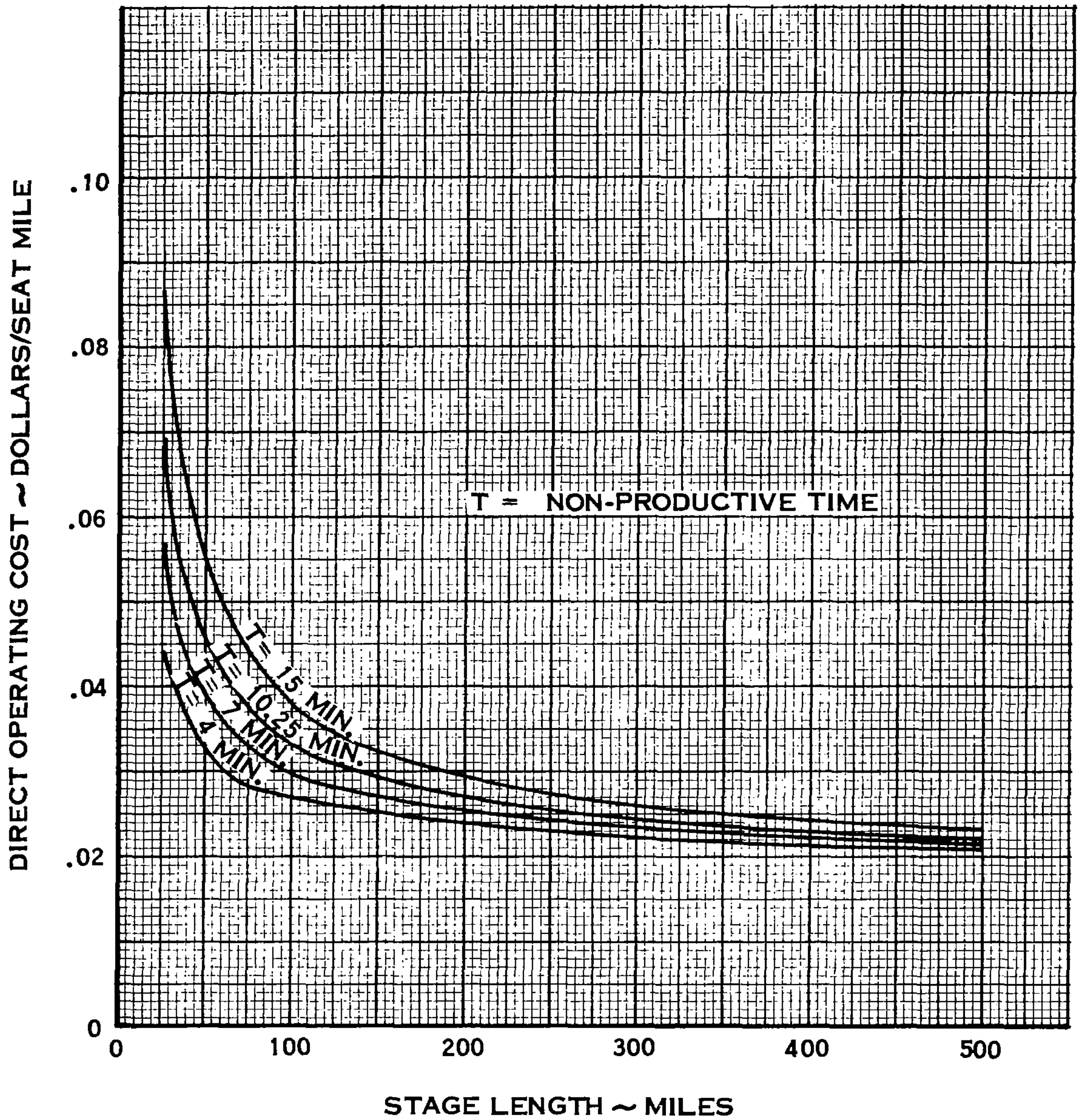


FIGURE 39. - EFFECT OF NON-PRODUCTIVE TIME ON DIRECT OPERATING COSTS - TURBOPROP 2000 FOOT STOL AIRPLANE

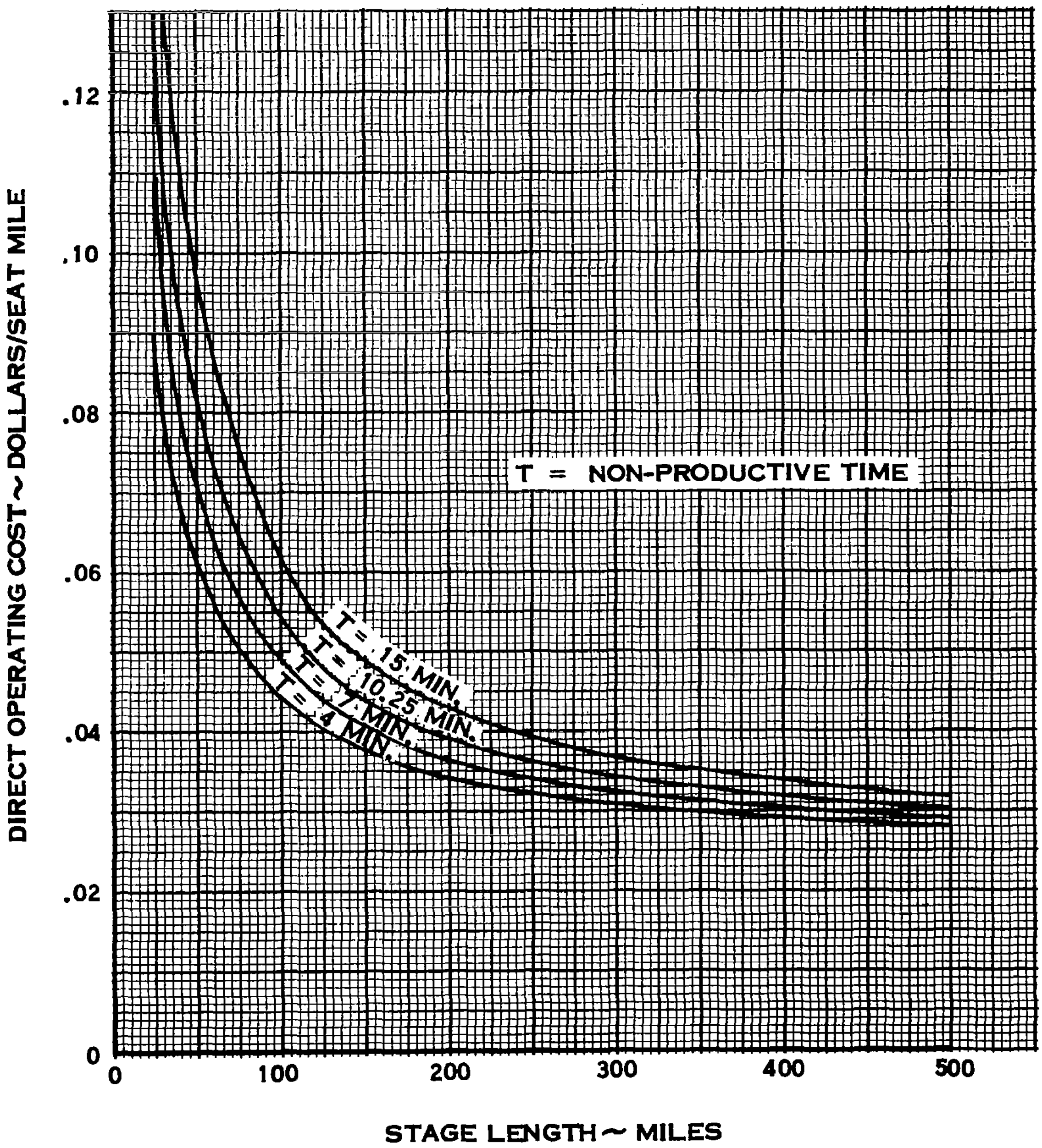


FIGURE 40. - EFFECT OF NON-PRODUCTIVE TIME ON DIRECT OPERATING COSTS-
FAN-IN-WING V/STOL AIRPLANE

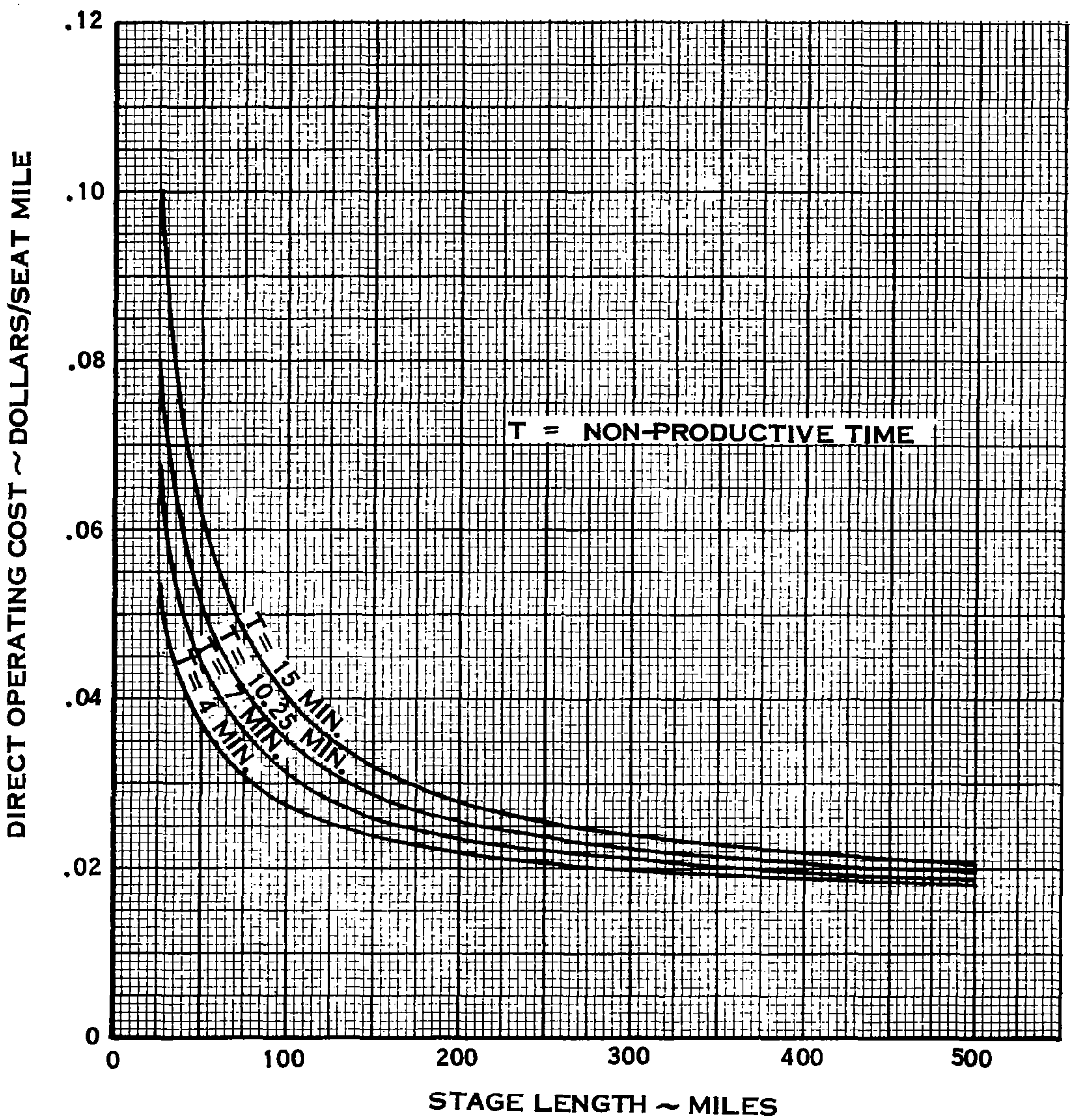


FIGURE 41. - EFFECT OF NON-PRODUCTIVE TIME ON DIRECT OPERATING COSTS-
PROPULSIVE WING 2000 FOOT STOL AIRPLANE

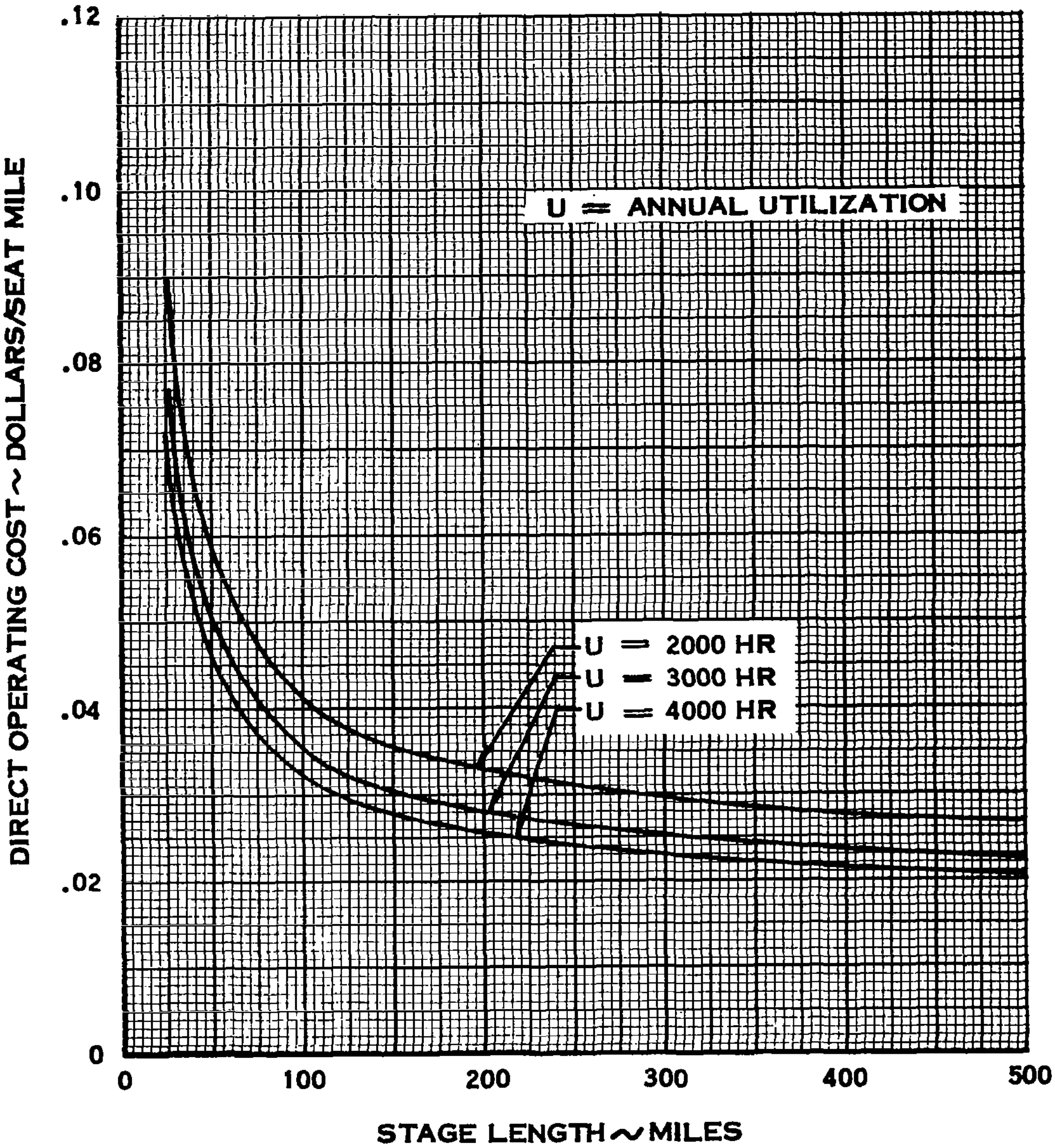


FIGURE 42. - EFFECT OF ANNUAL UTILIZATION ON DIRECT OPERATING COSTS - TURBOPROP VTOL AIRPLANE

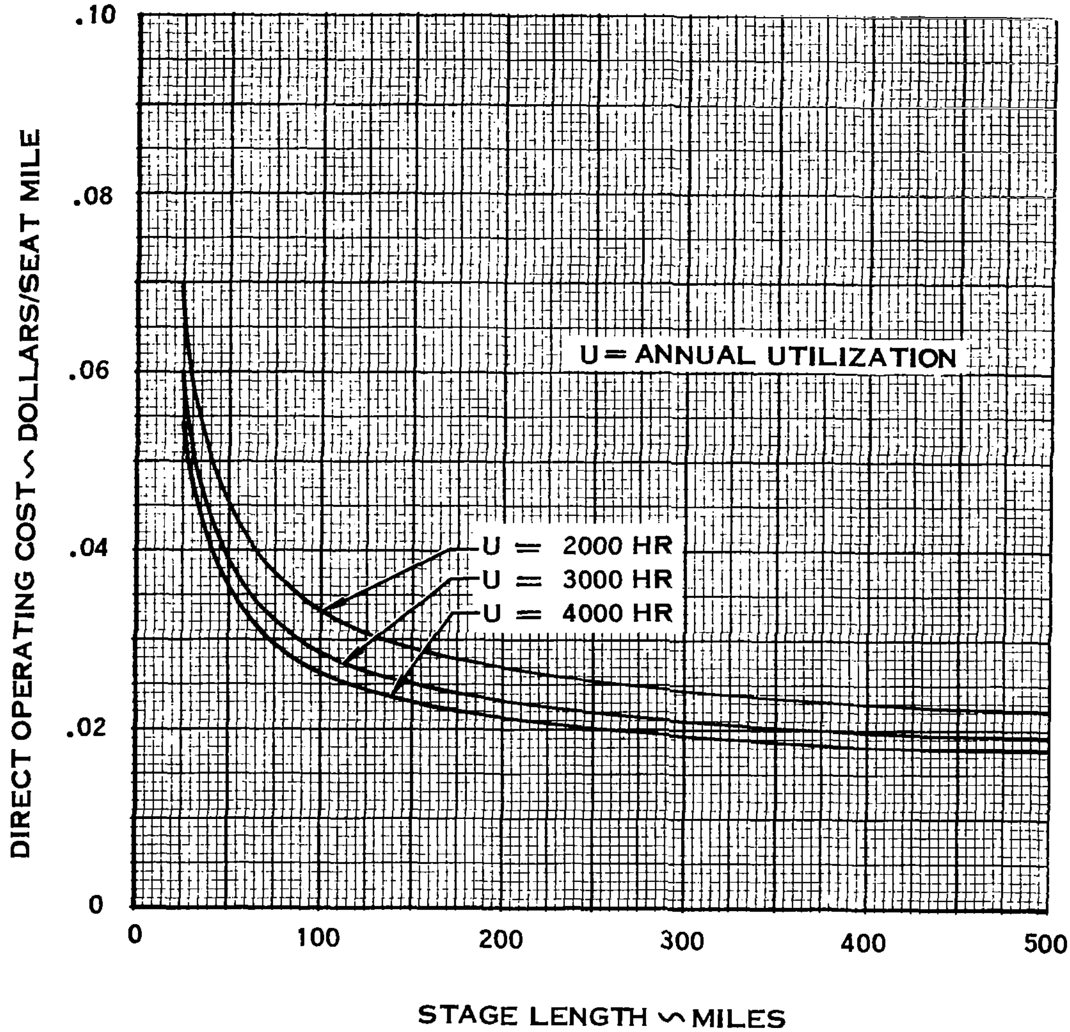


FIGURE 43. - EFFECT OF ANNUAL UTILIZATION ON DIRECT OPERATING COSTS-
TURBOPROP 2000 FOOT STOL AIRPLANE

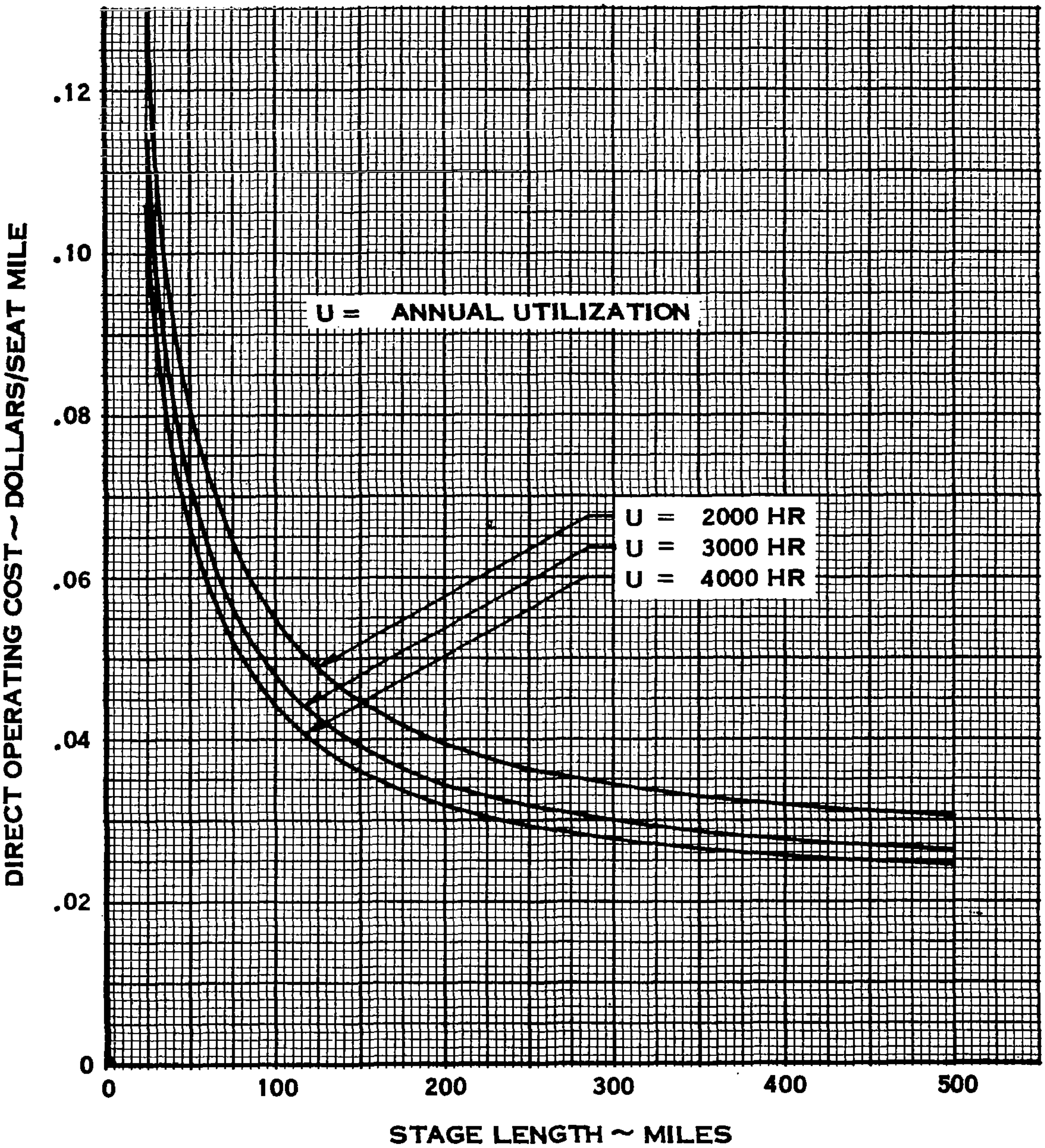


FIGURE 44. - EFFECT OF ANNUAL UTILIZATION ON DIRECT OPERATING COSTS - FAN-IN-WING V/STOL AIRPLANE

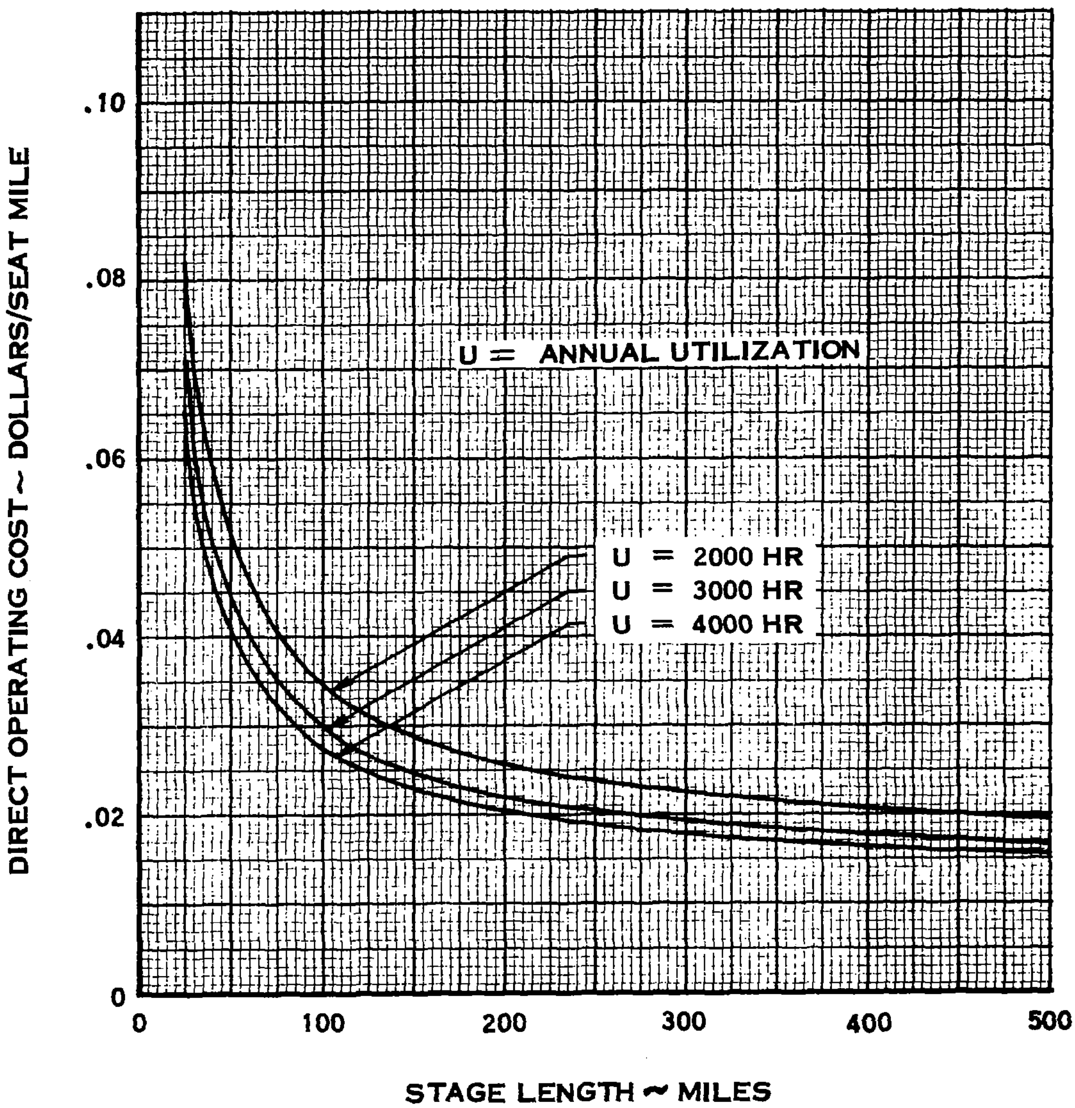


FIGURE 45. - EFFECT OF ANNUAL UTILIZATION ON DIRECT OPERATING COSTS-PROPULSIVE WING 2000 FOOT STOL AIRPLANE

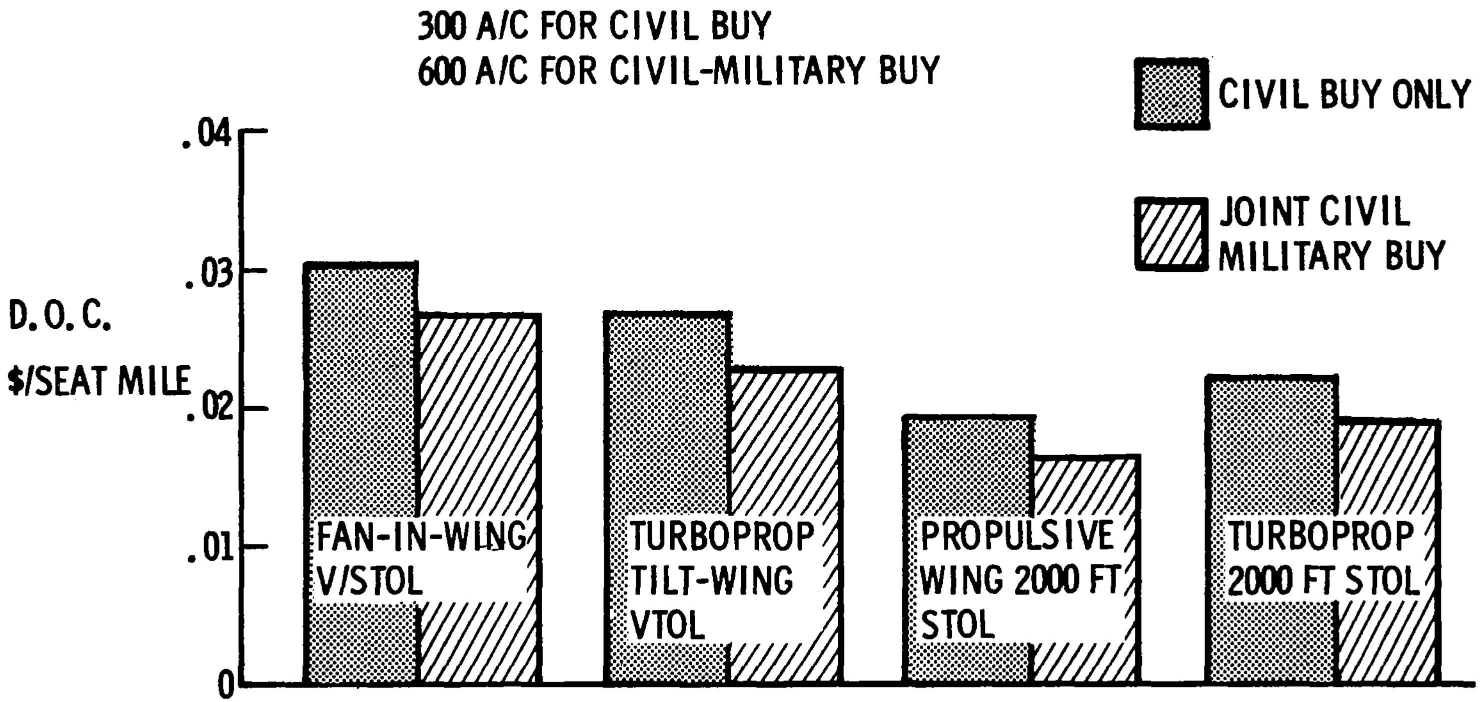


FIGURE 46. - INFLUENCE OF A JOINT CIVIL-MILITARY BUY ON DOC

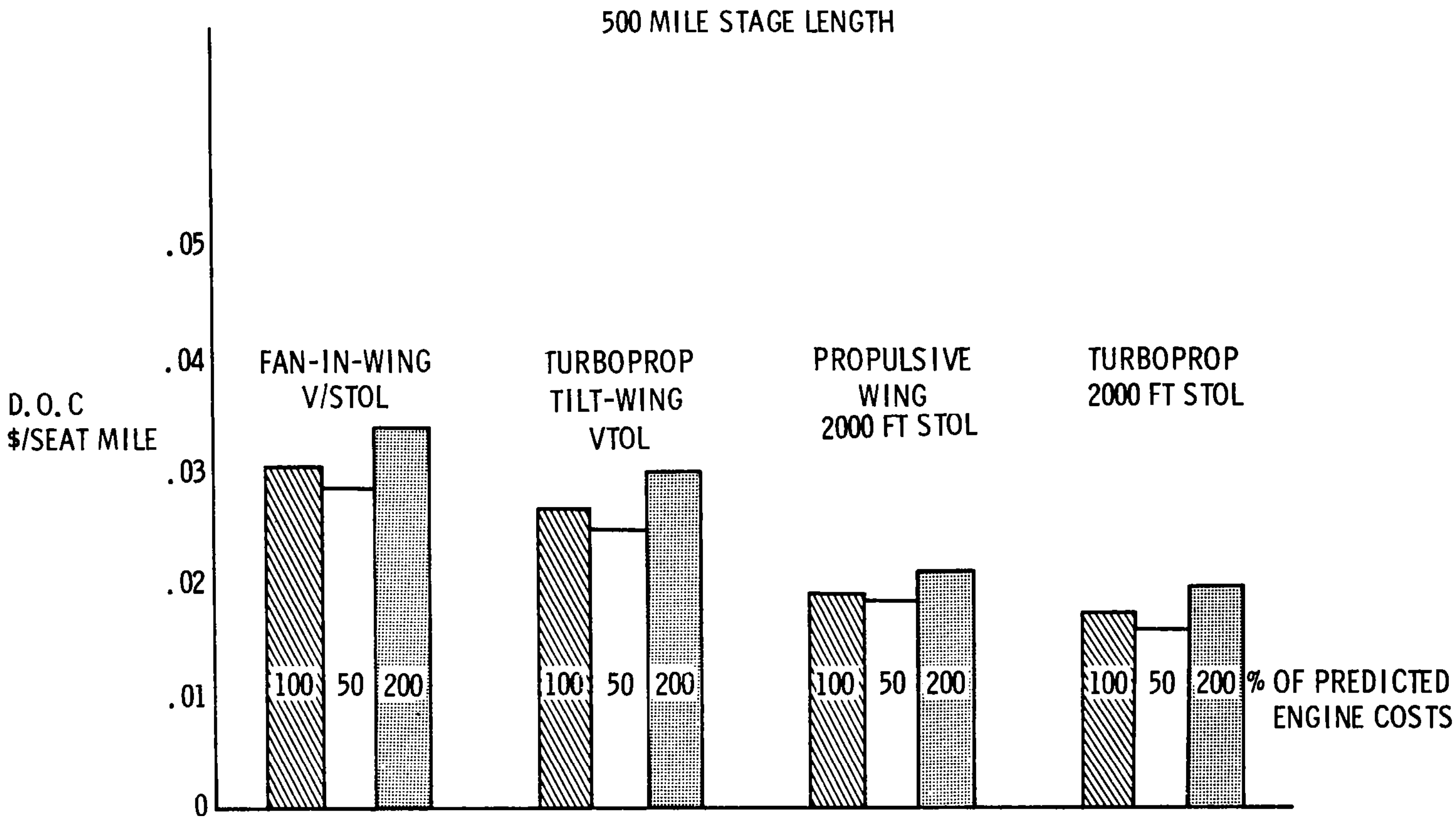
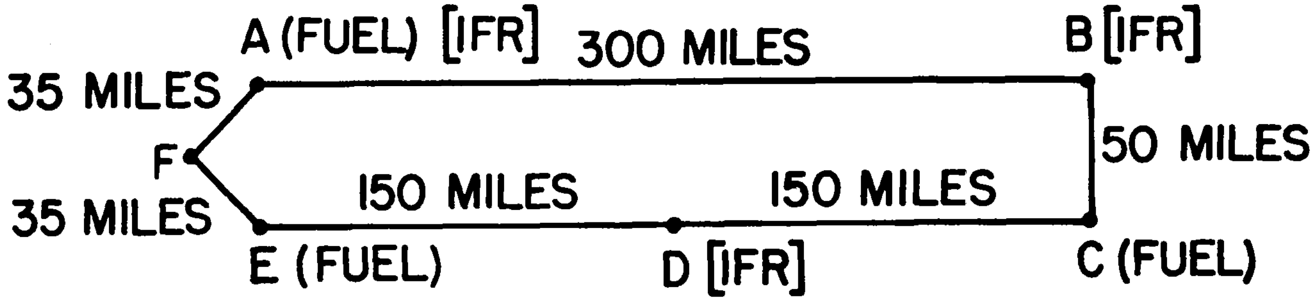


FIGURE 47. - INFLUENCE OF GAS GENERATOR COSTS ON DOC



NON PRODUCTIVE TIME

① 10 1/4 MINUTES

② SHORT TAKEOFF 3 MINUTES
VERTICAL TAKEOFF 2 MINUTES
SHORT LANDING 7 1/4 MINUTES
VERTICAL LANDING 2 MINUTES

FIGURE 48. - HYPOTHETICAL ROUTE

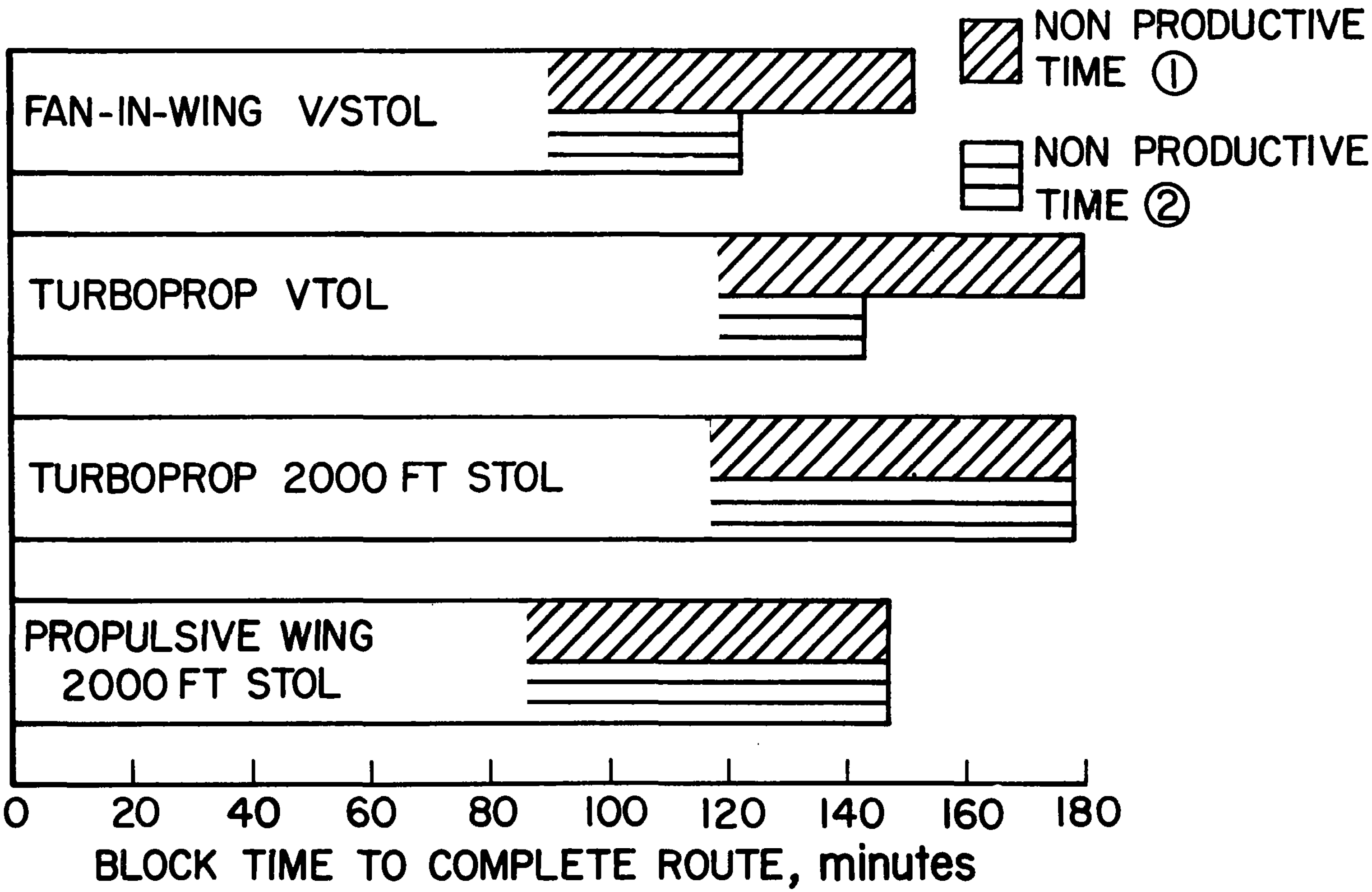


FIGURE 49. - HYPOTHETICAL ROUTE BLOCK TIME

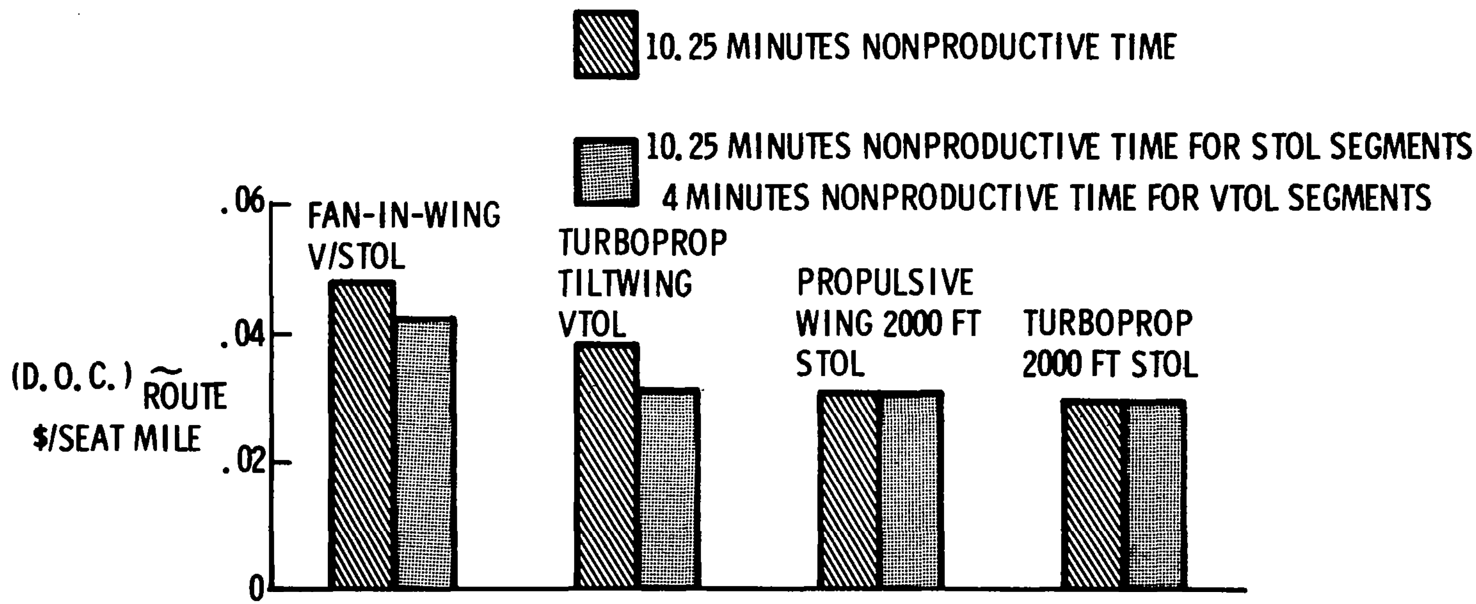
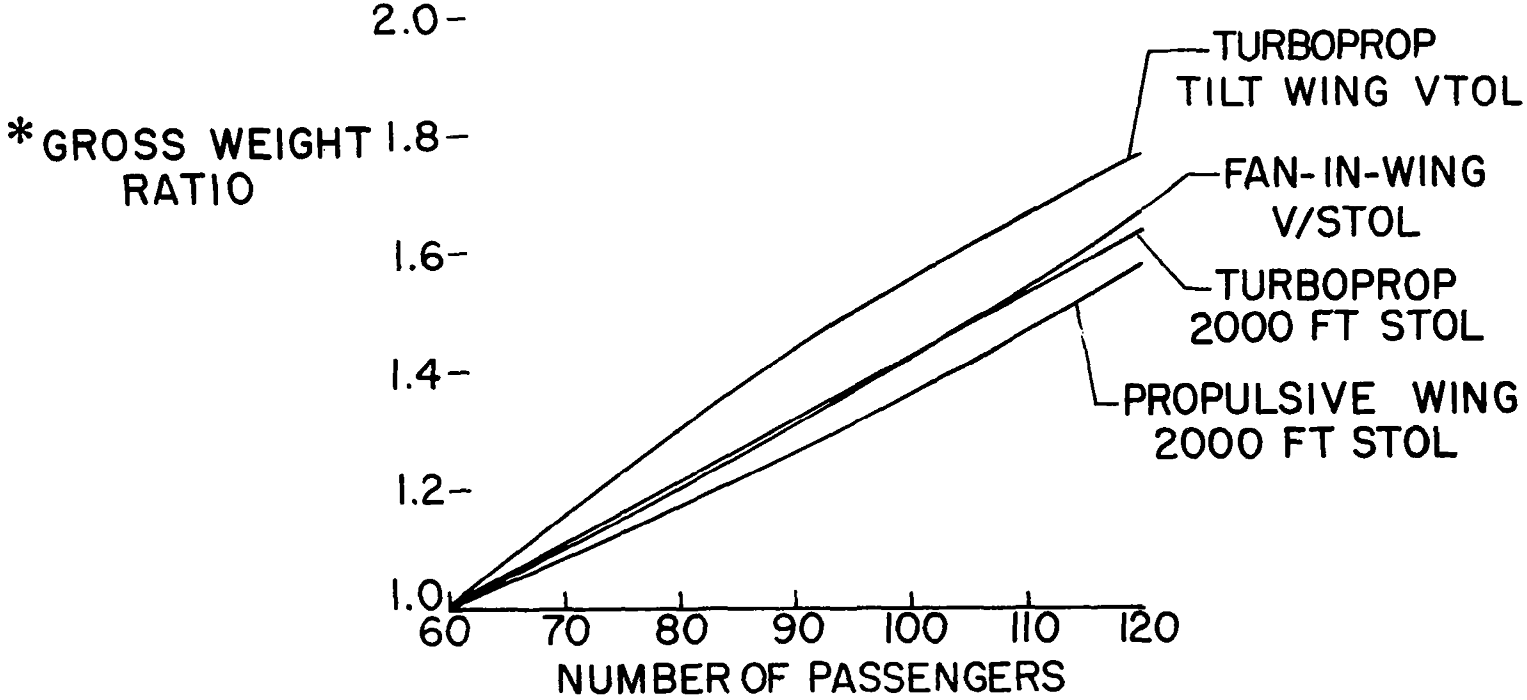


FIGURE 50. - HYPOTHETICAL ROUTE DOC



*THE RATIO OF THE GROSS WEIGHT OF AN AIRPLANE DESIGNED TO A PASSENGER LOAD TO THE GROSS WEIGHT OF AN AIRPLANE DESIGNED TO CARRY 60 PASSENGERS

FIGURE 51. - GROSS WEIGHT VARIATION WITH PASSENGER LOAD

NASA-Langley, 1967

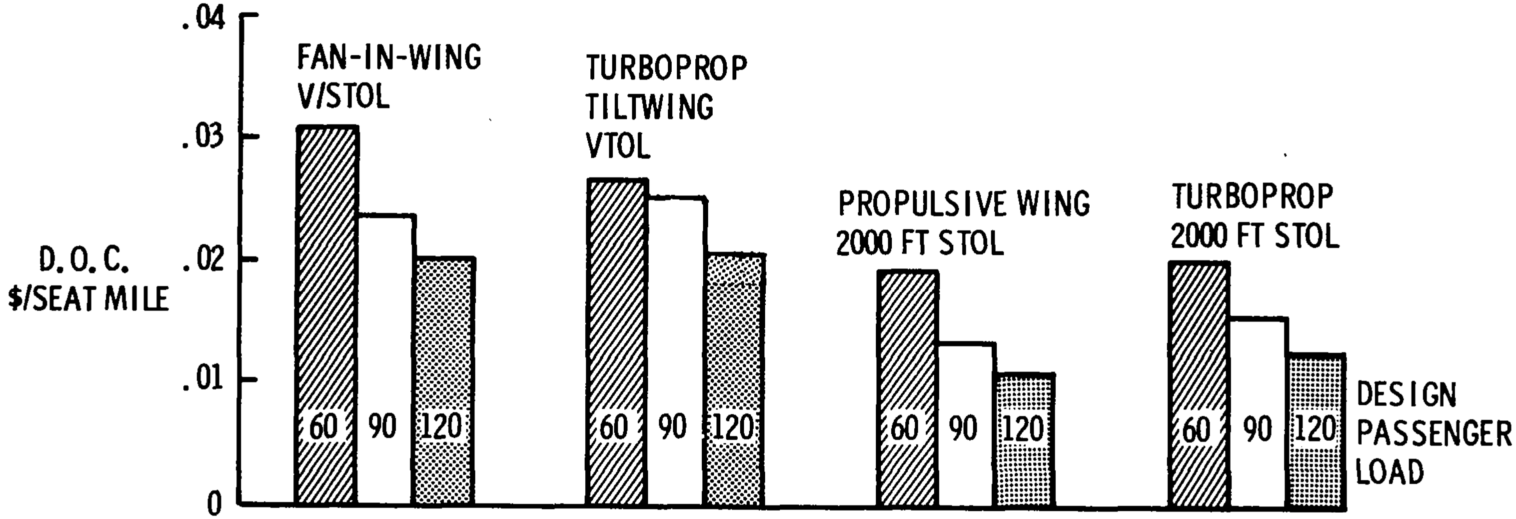


FIGURE 52. - DIRECT OPERATING COSTS VARIATION WITH DESIGN PASSENGER LOAD

NASA CONTRACTOR REPORT

NASA CR-670(01)

NASA CR-670(01)

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

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • DECEMBER 1967

NASA CR-670(01)

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

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Prepared under Contract No. NAS 2-3036 by
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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

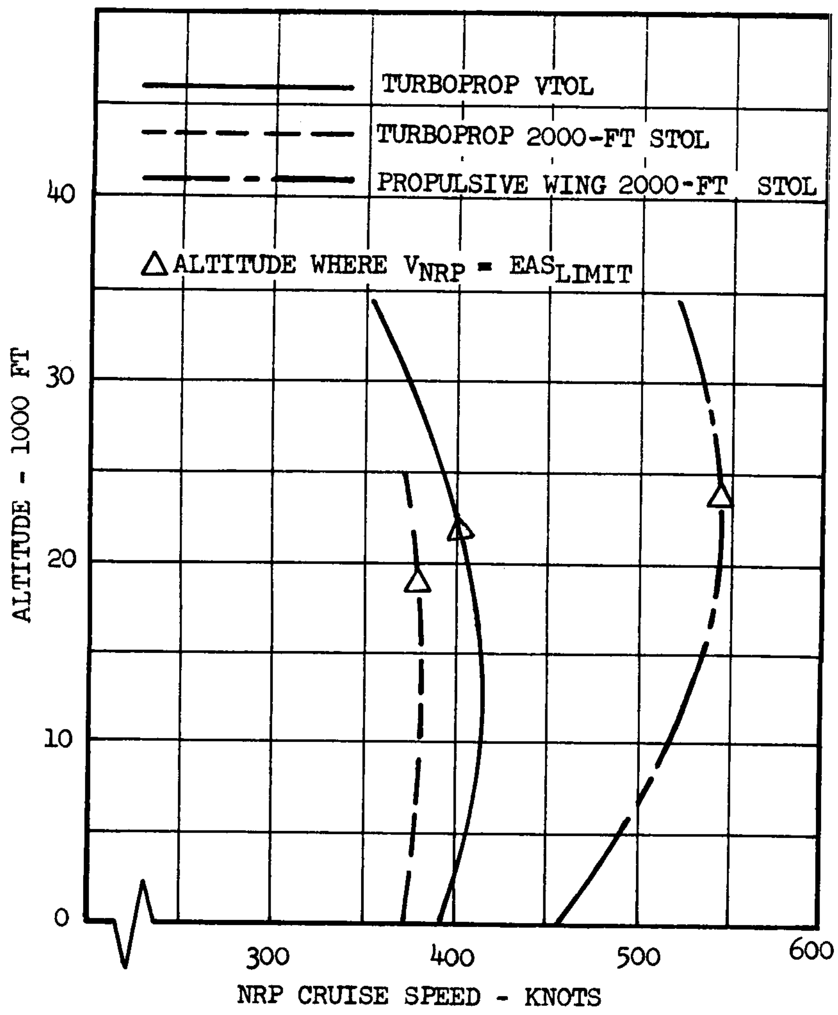


Figure 1. Effect of Altitude on NRP Cruise Speed

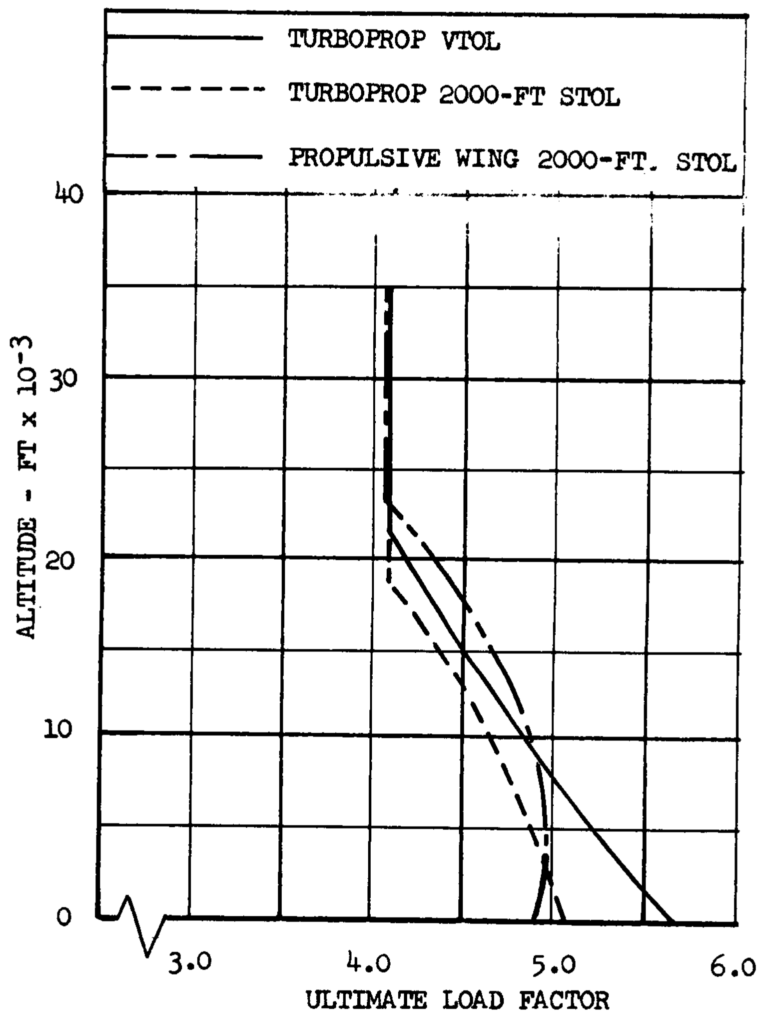


Figure 1a. Effect of NRP Cruise on the Required Ultimate Load Factor

60-PASSENGER TURBOPROP VTOL

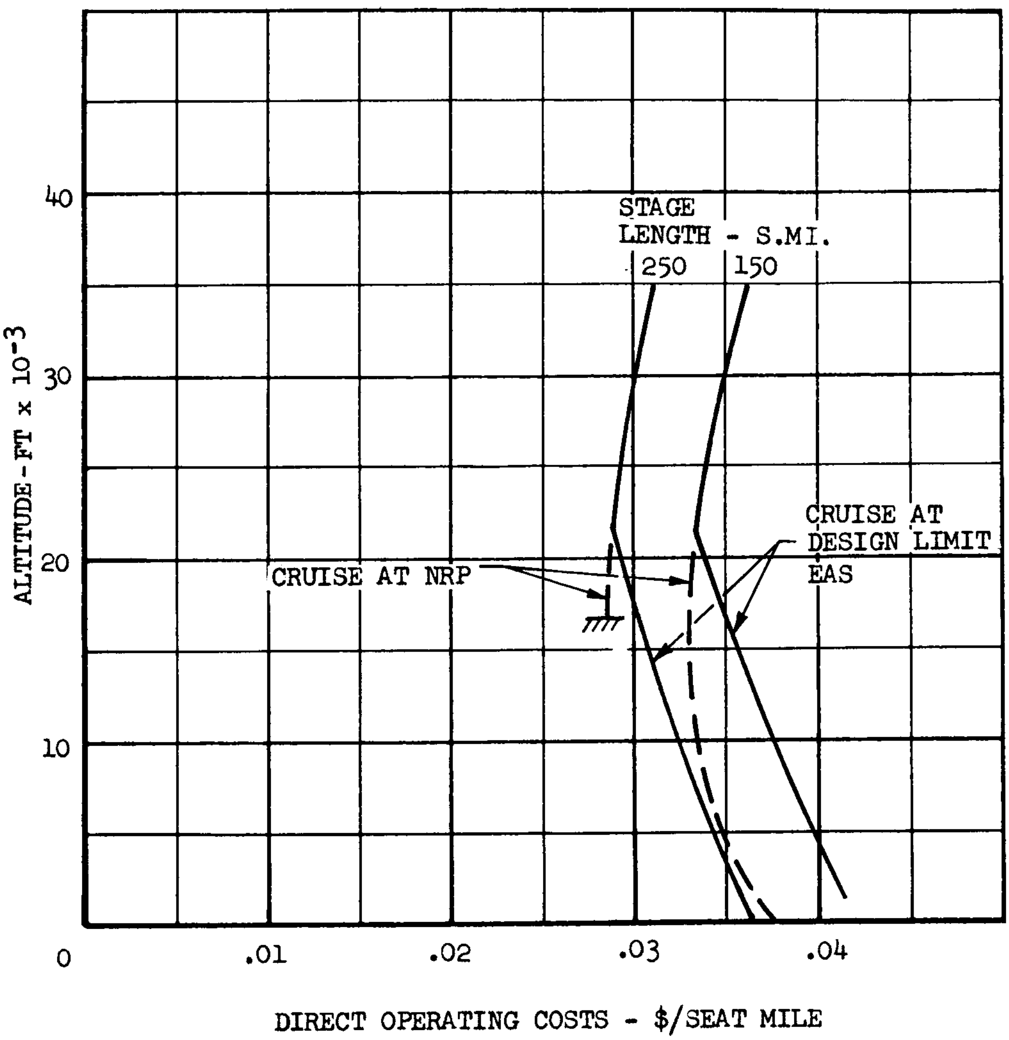


Figure 2. D.O.C. Versus Cruise Altitude

60-PASSENGER TURBOPROP 2000-FT STOL

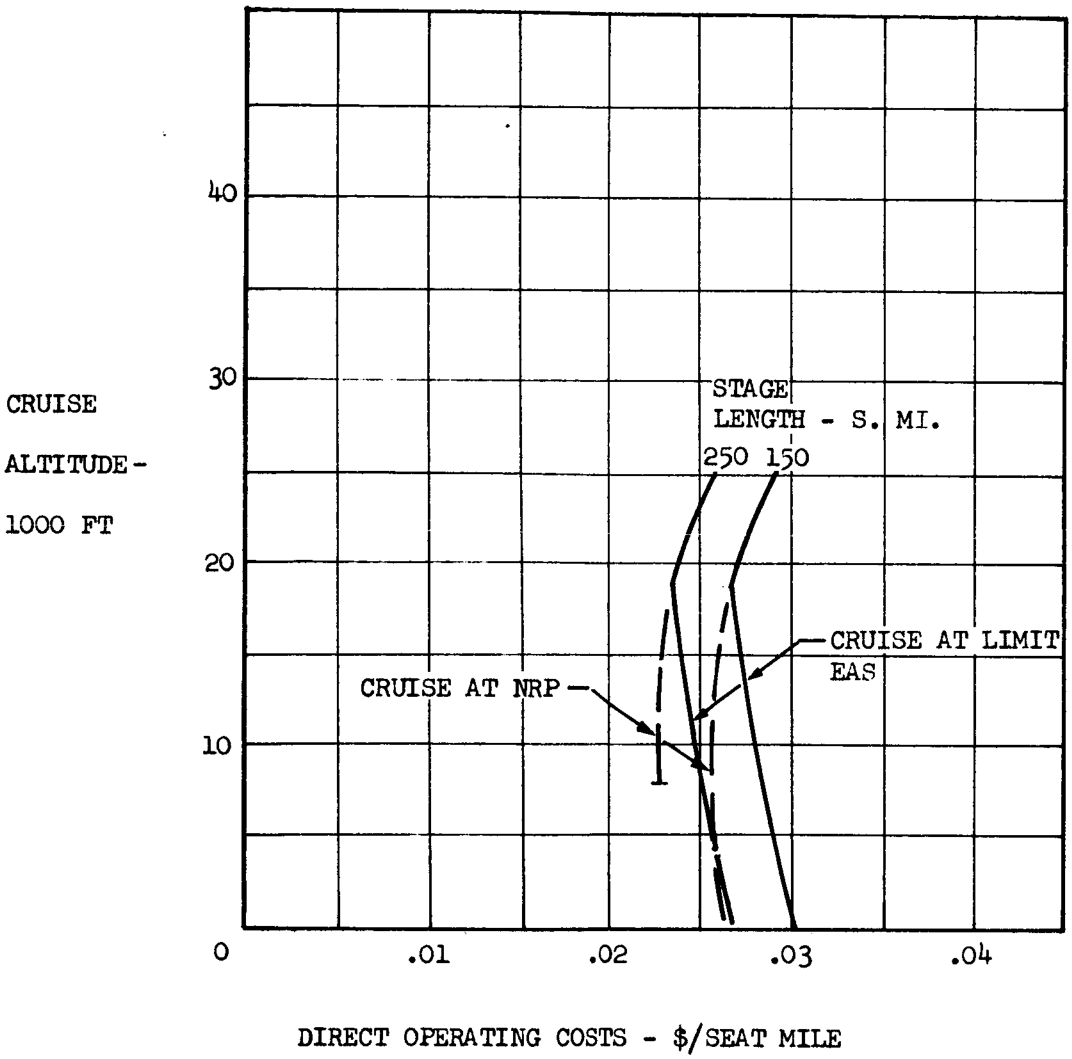


Figure 3. D.O.C. Versus Cruise Altitude

60-PASSENGER PROPULSIVE WING 2000-FT STOL

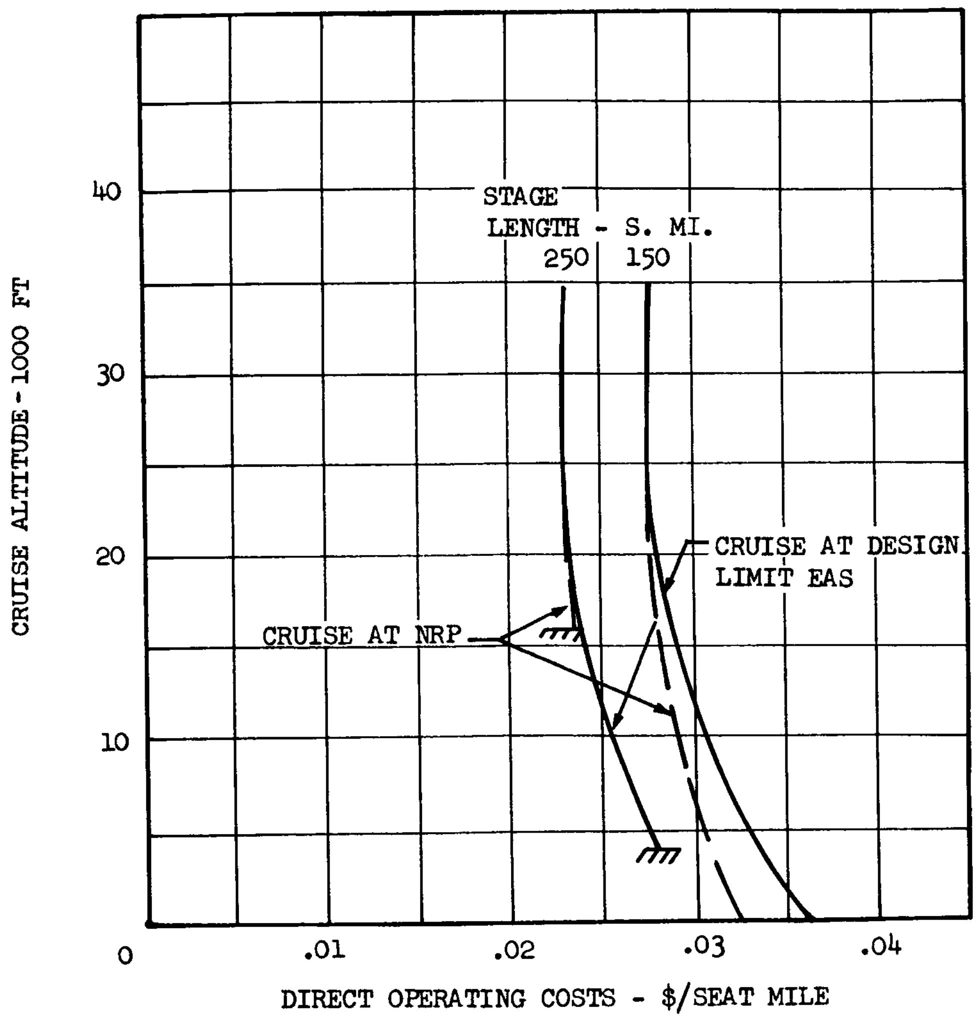


Figure 4. D.O.C. Versus Cruise Altitude

TURBOPROP VTOL

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

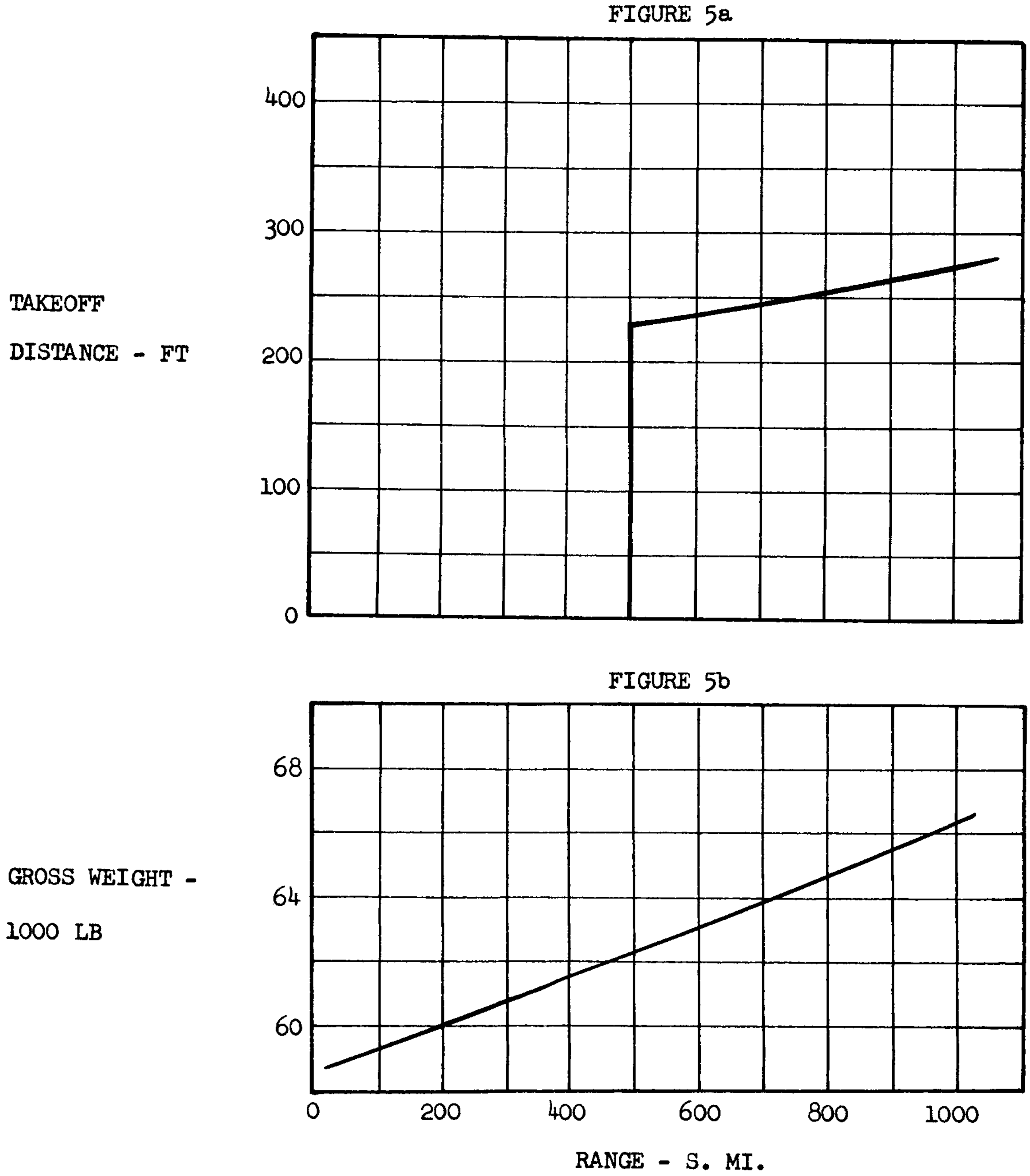


Figure 5. Effect of Operational Range on Takeoff Distance

TURBOPROP 1000-FT STOL

Total Distance to Clear a 50-Ft

Obstacle

SEA LEVEL

86°F

ONE ENGINE FAILED

FIGURE 6a

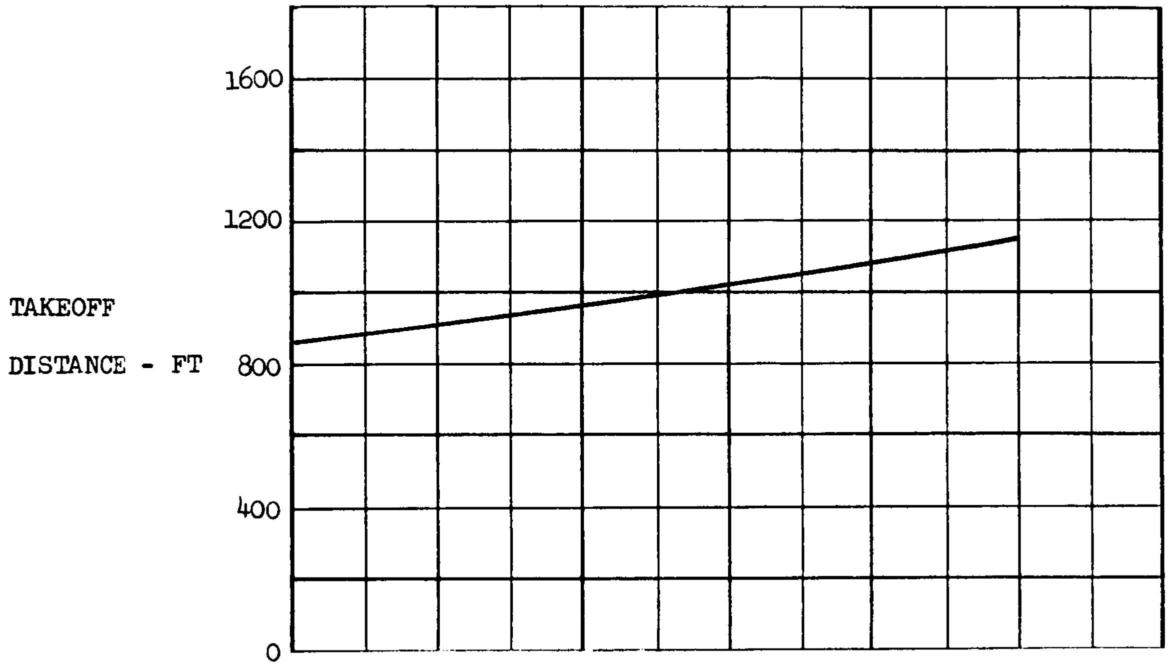


FIGURE 6b

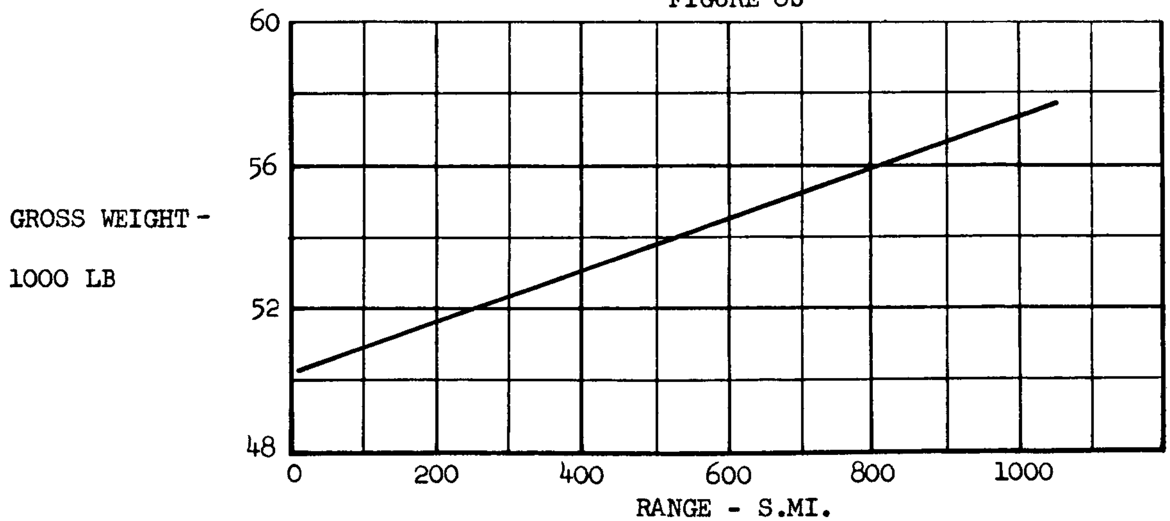


Figure 6. Effect of Operational Range on Takeoff Distance

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

FIGURE 7a

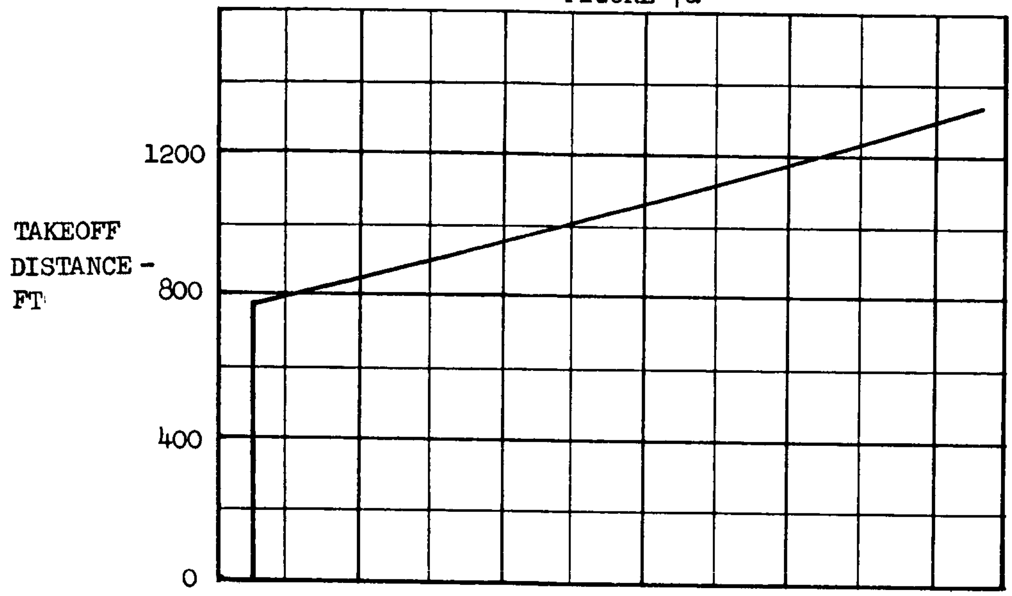


FIGURE 7b

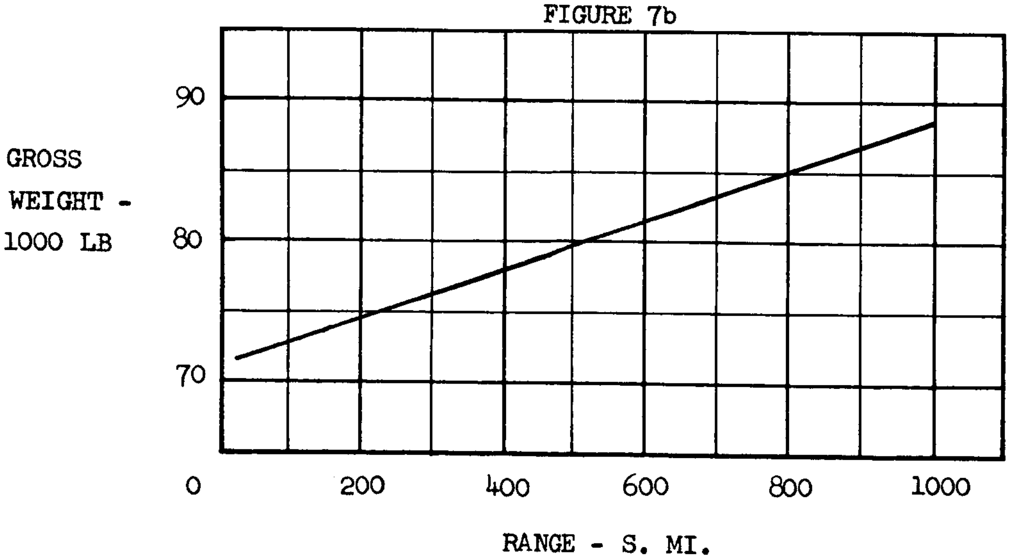


Figure 7. Effect of Operational Range on Takeoff Distance

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

FIGURE 8a

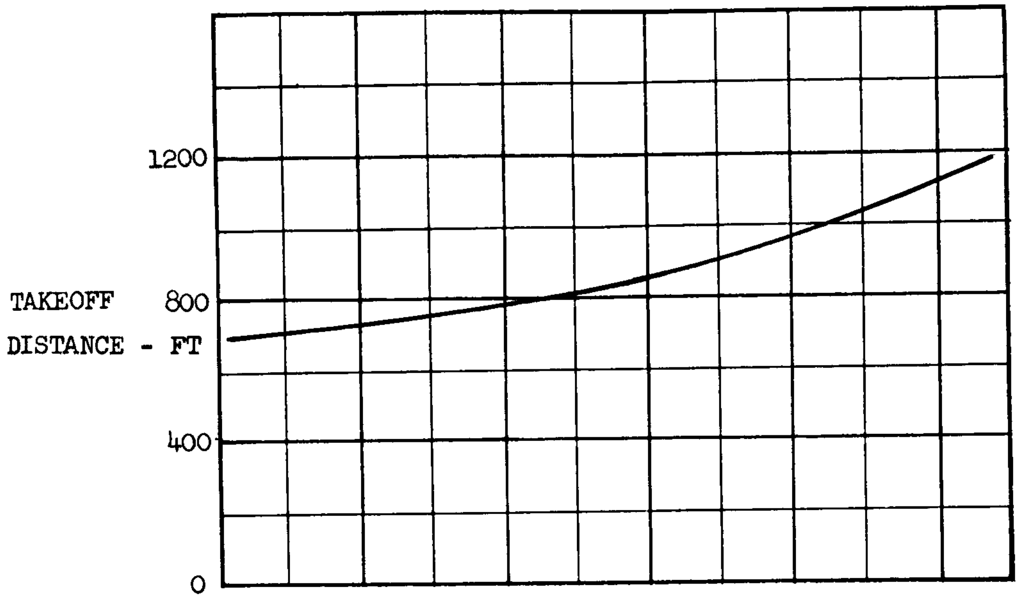


FIGURE 8b

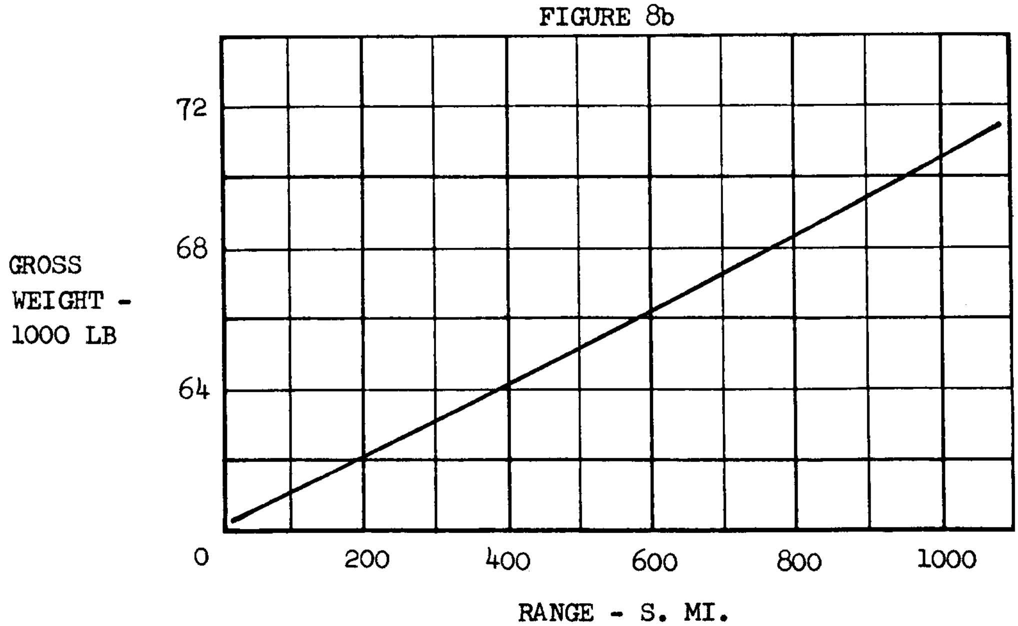


Figure 8. Effect of Operational Range on Takeoff Distance

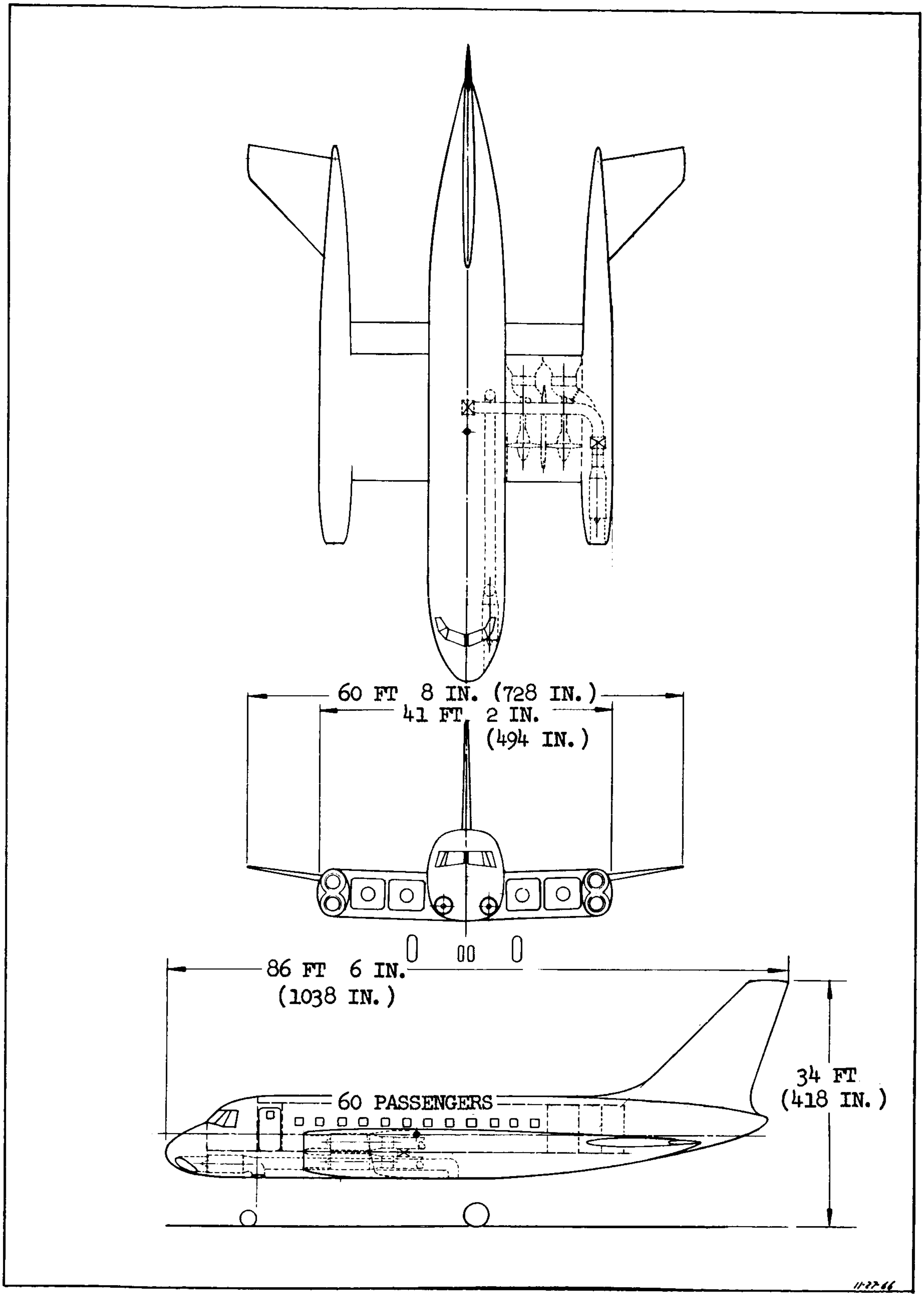


Figure 9. Propulsive Wing V/STOL Airplane

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

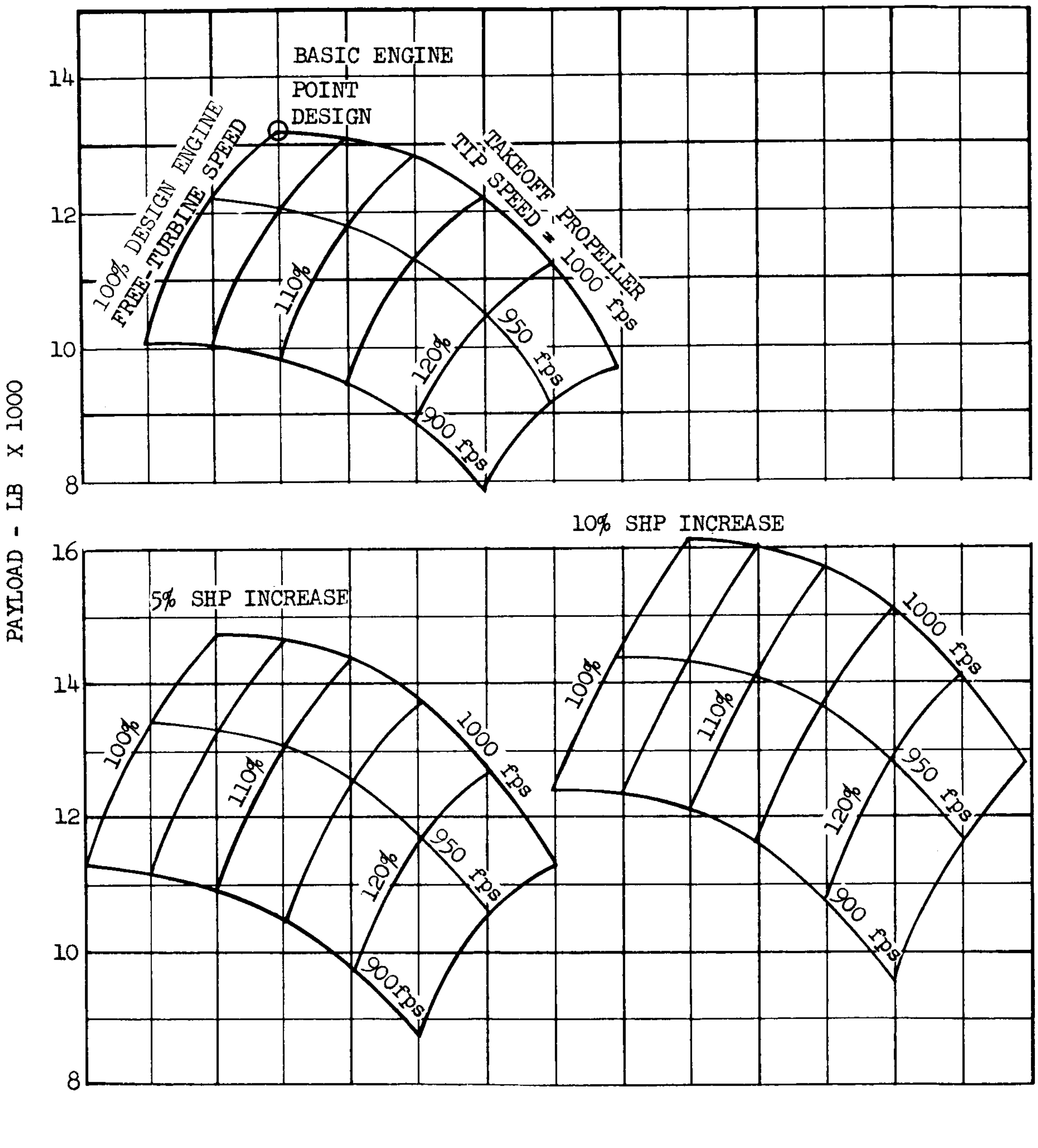


Figure 10. Effect of Takeoff Propeller Tip Speed,
Engine Overspeeding, and SHP on Payload

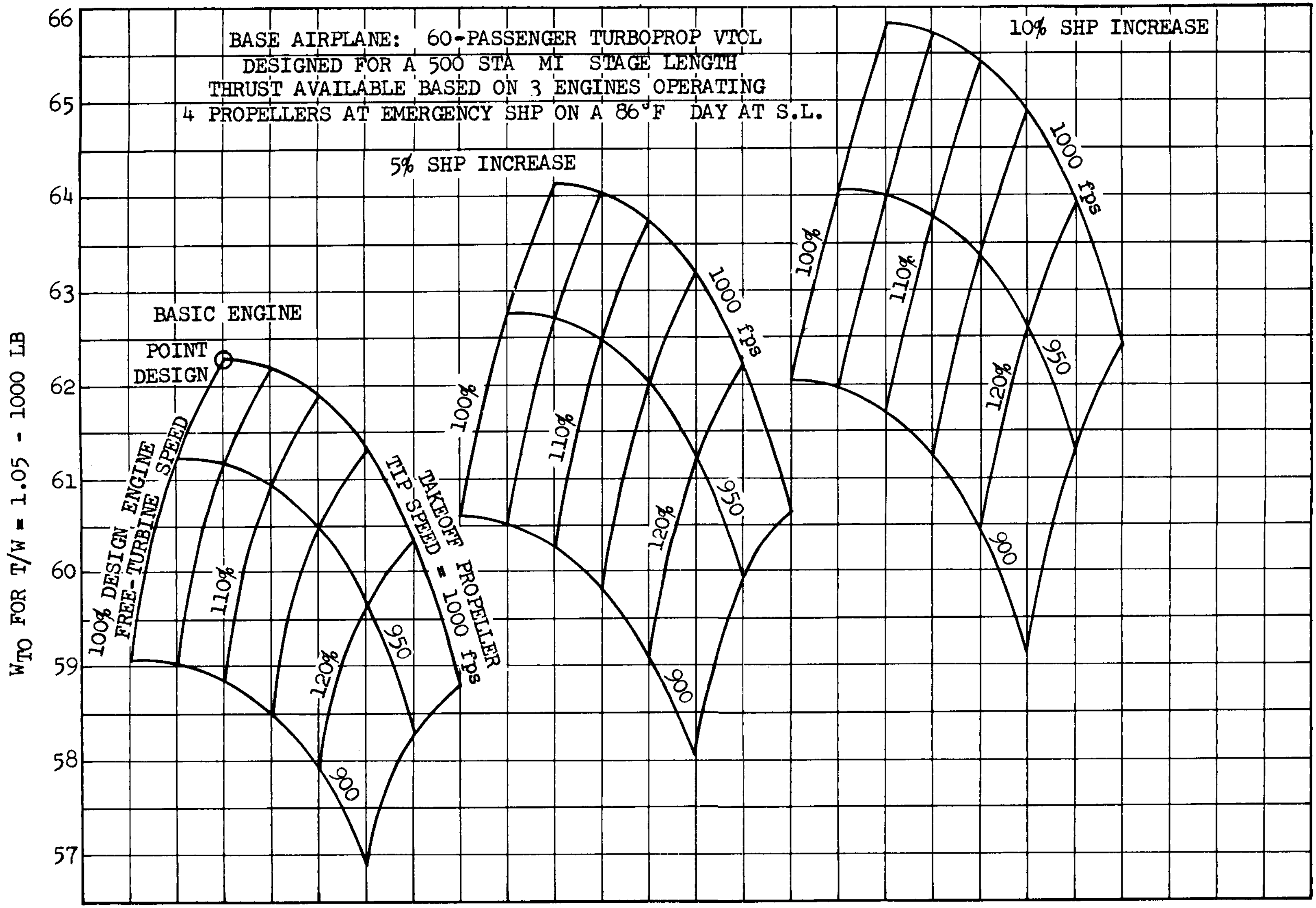


Figure 11. Effect of Takeoff Propeller Tip speed, Engine Overspeeding, and SHP on Takeoff Weight

BASIC AIRPLANE: 60-PASSENGER TURBOPROP VTOL
DESIGNED FOR A 500 STA MI STAGE LENGTH
35000 FT ON NRP

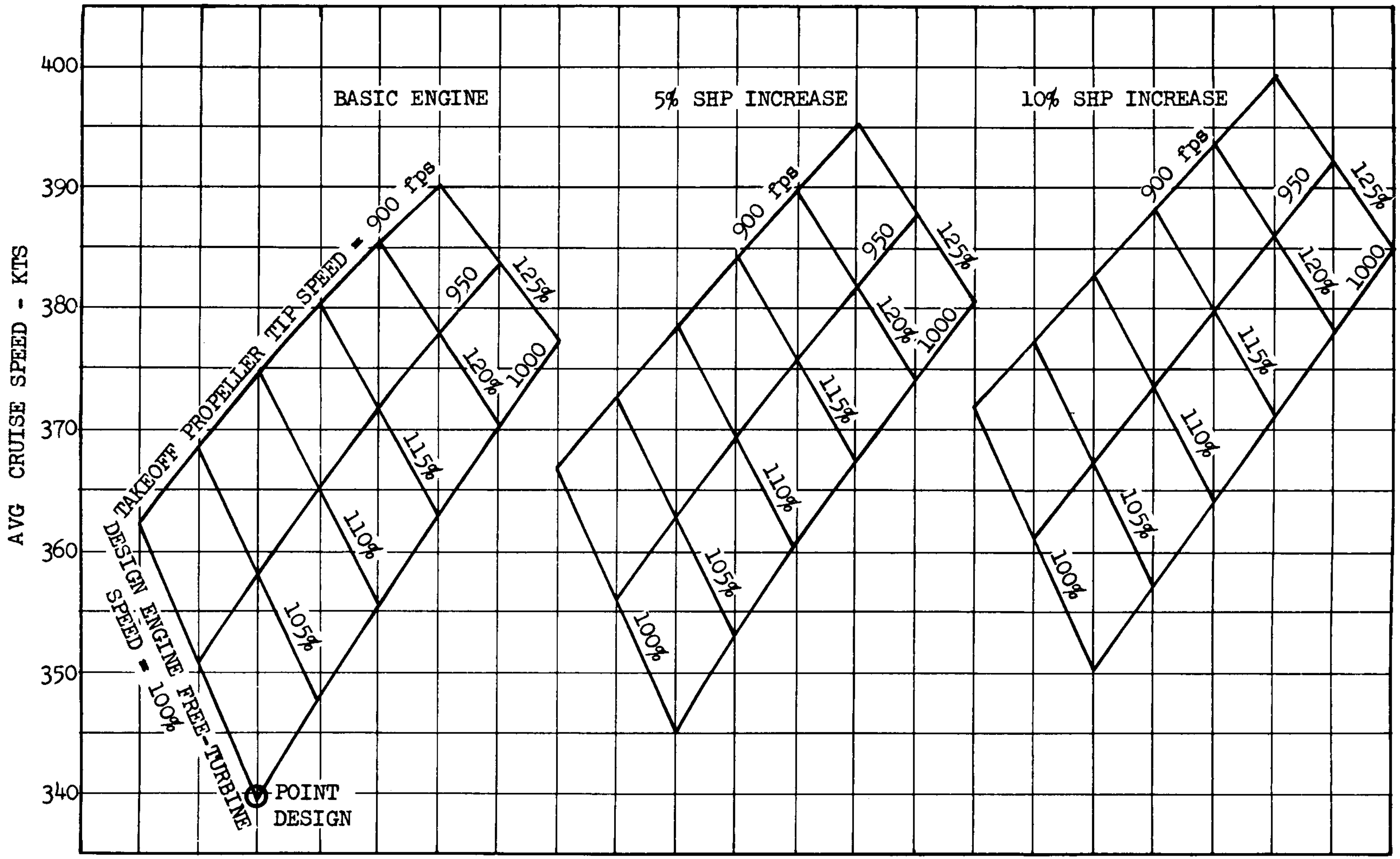


Figure 12. Effect of Takeoff Propeller Tip Speed, Engine Overspeeding, and SHP on Average Cruise Speed

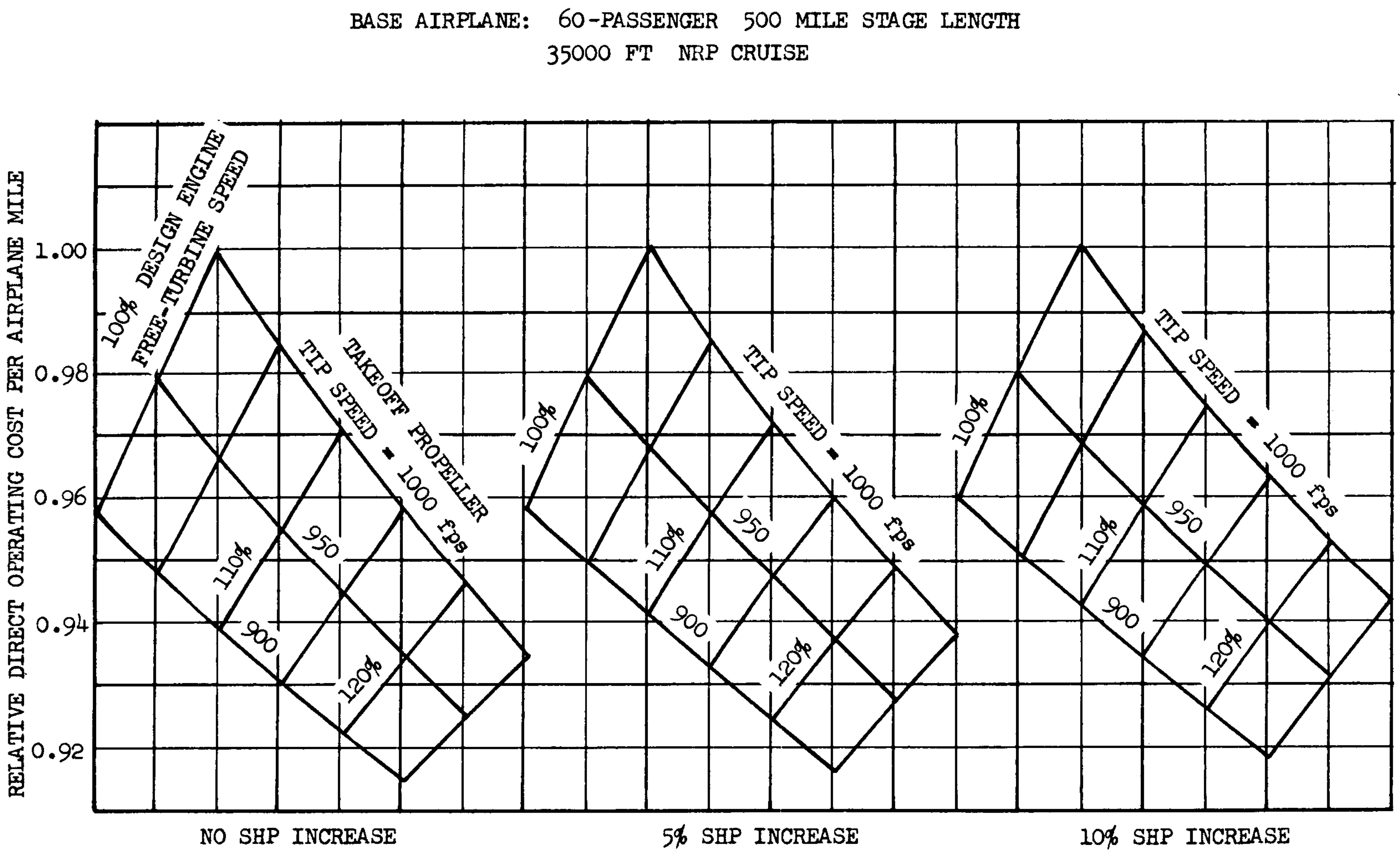
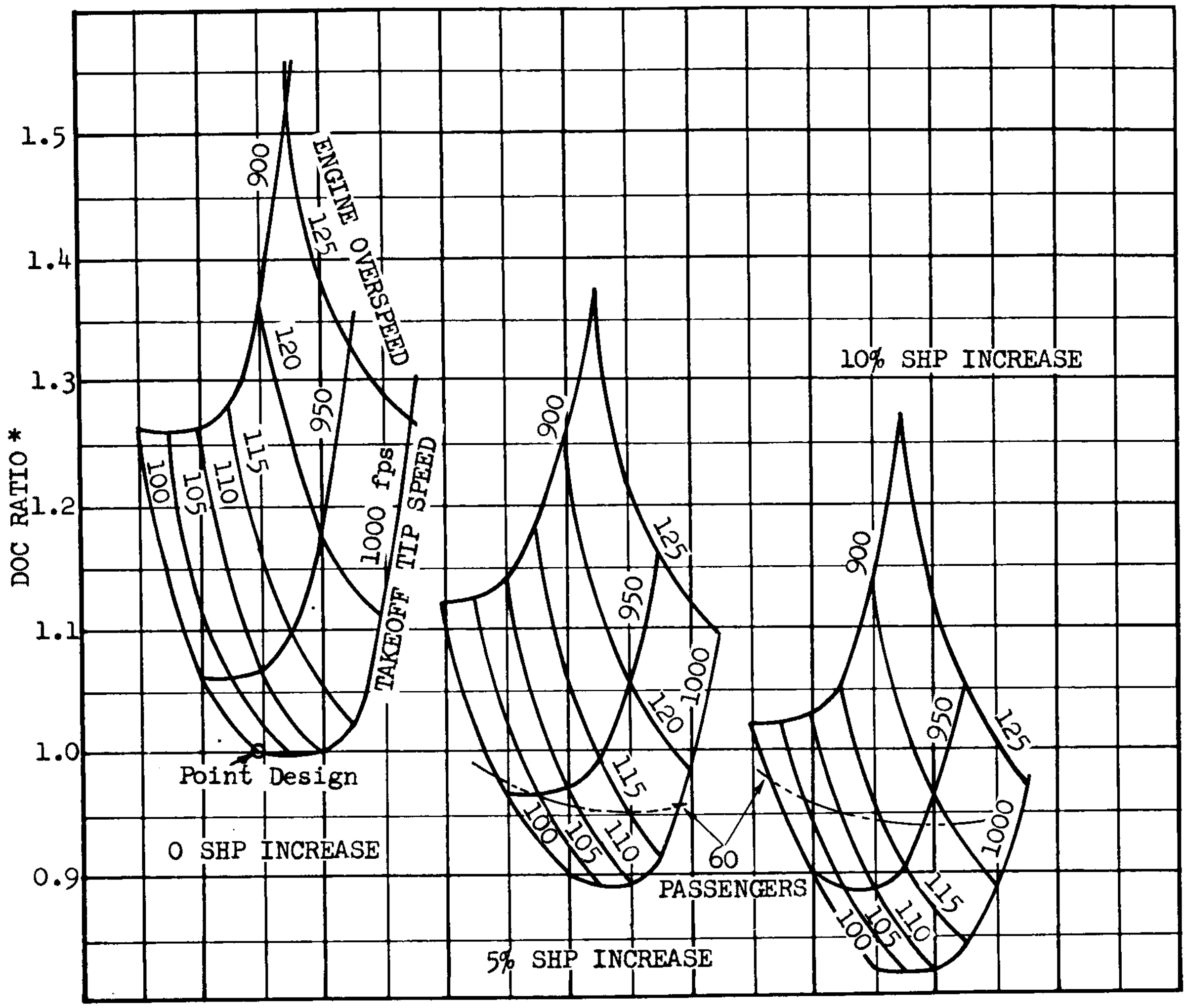


Figure 13. Turboprop VTOL Airplane Relative Direct Operating Cost

TURBOPROP VTOL

VARIABLE PASSENGER LOAD

500 MILE STAGE LENGTH



* 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

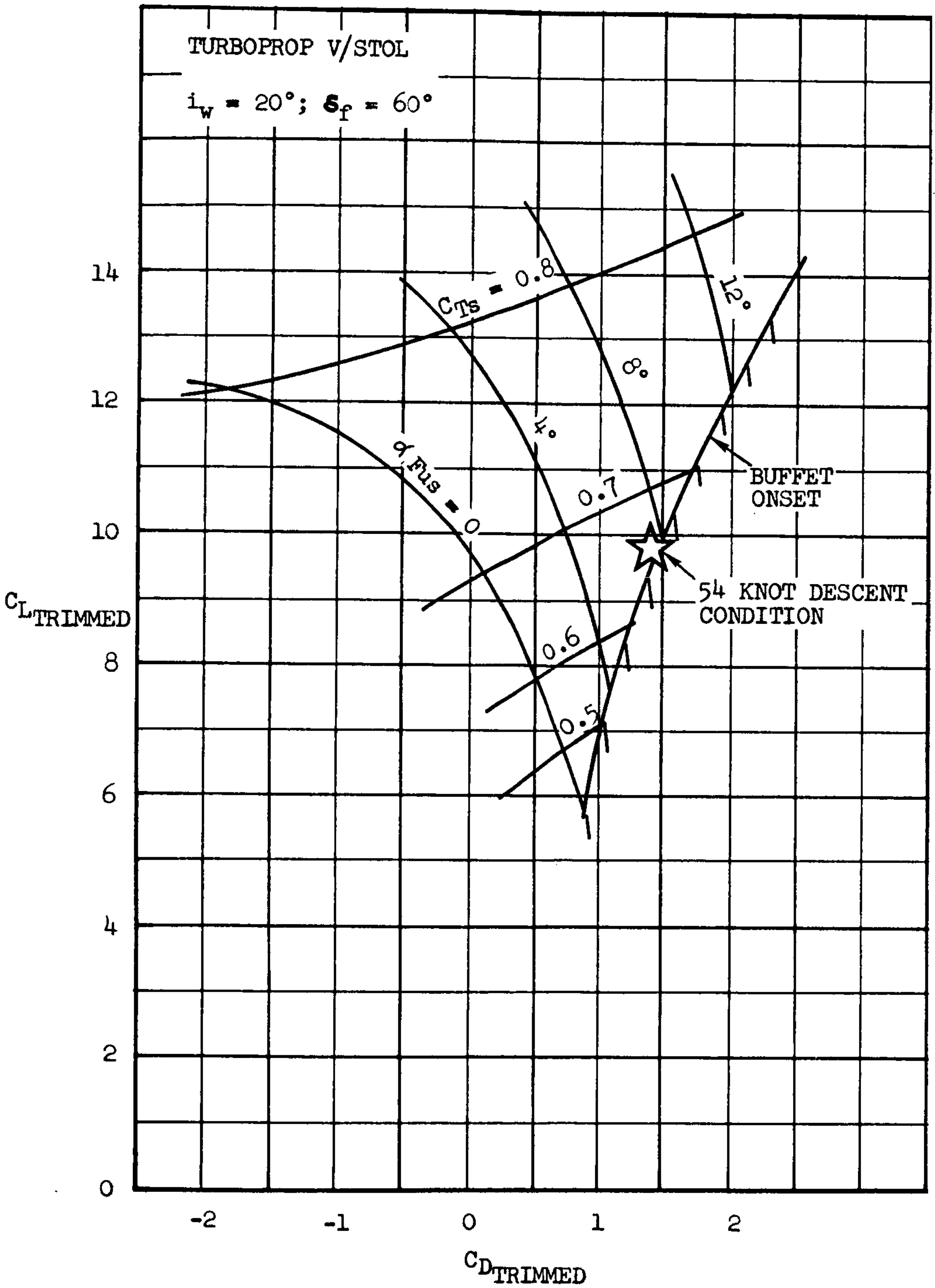


Figure 15. Landing Drag Polar

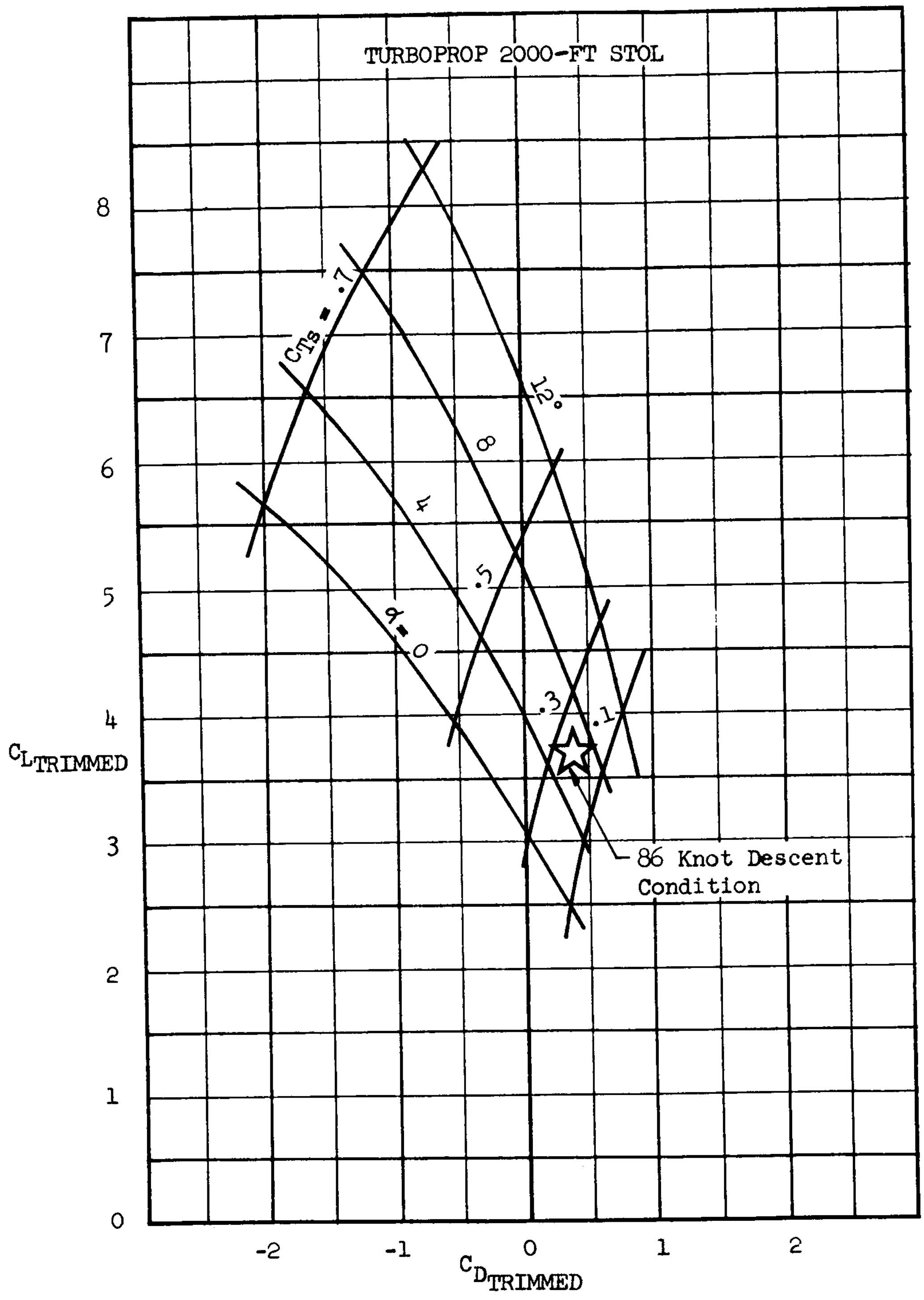


Figure 16. Landing Drag Polar

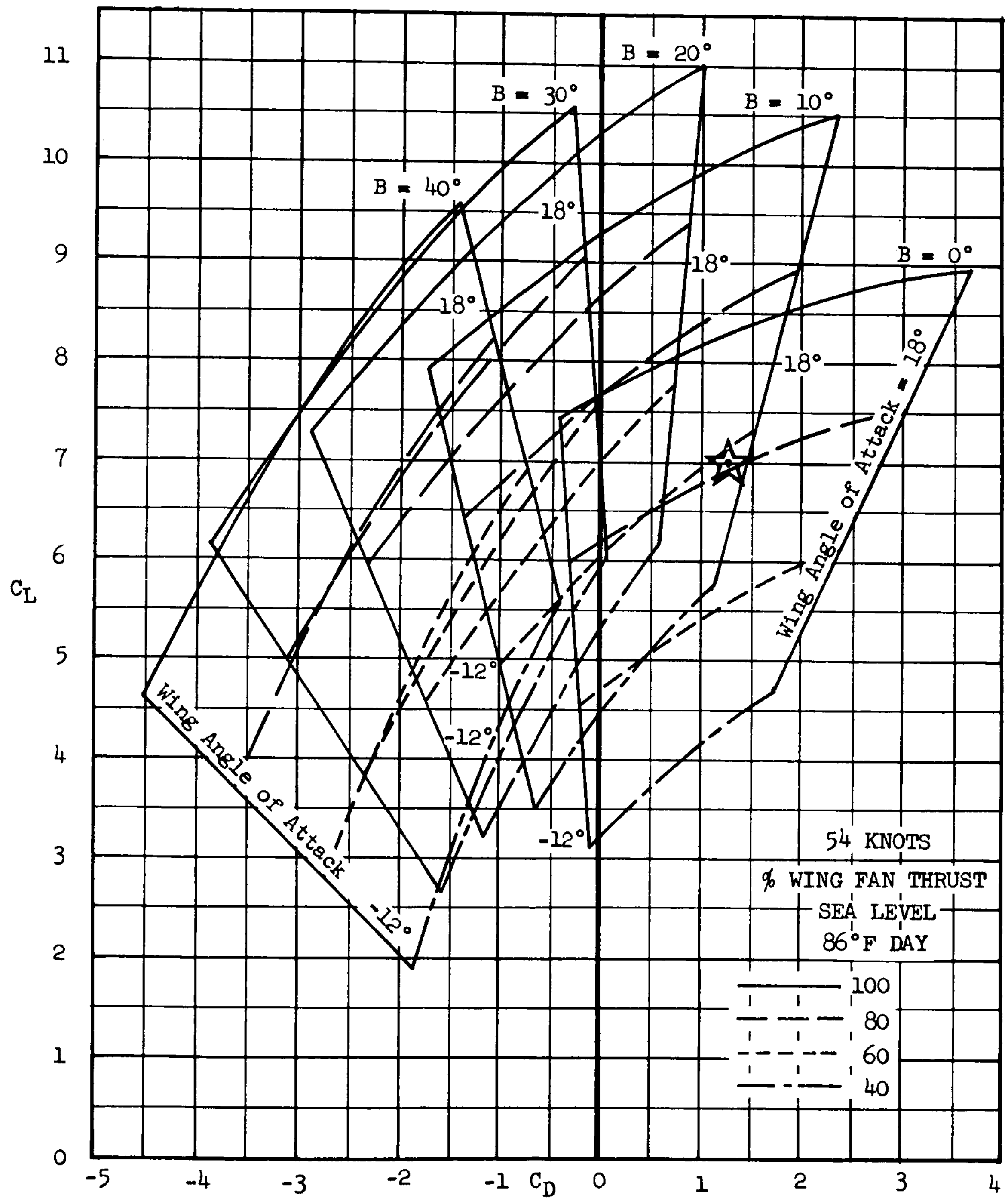


Figure 17. Tail-Off, Nose Fan Inoperative, Power-on Polar for the 60-Passenger Fan-in-Wing V/STOL

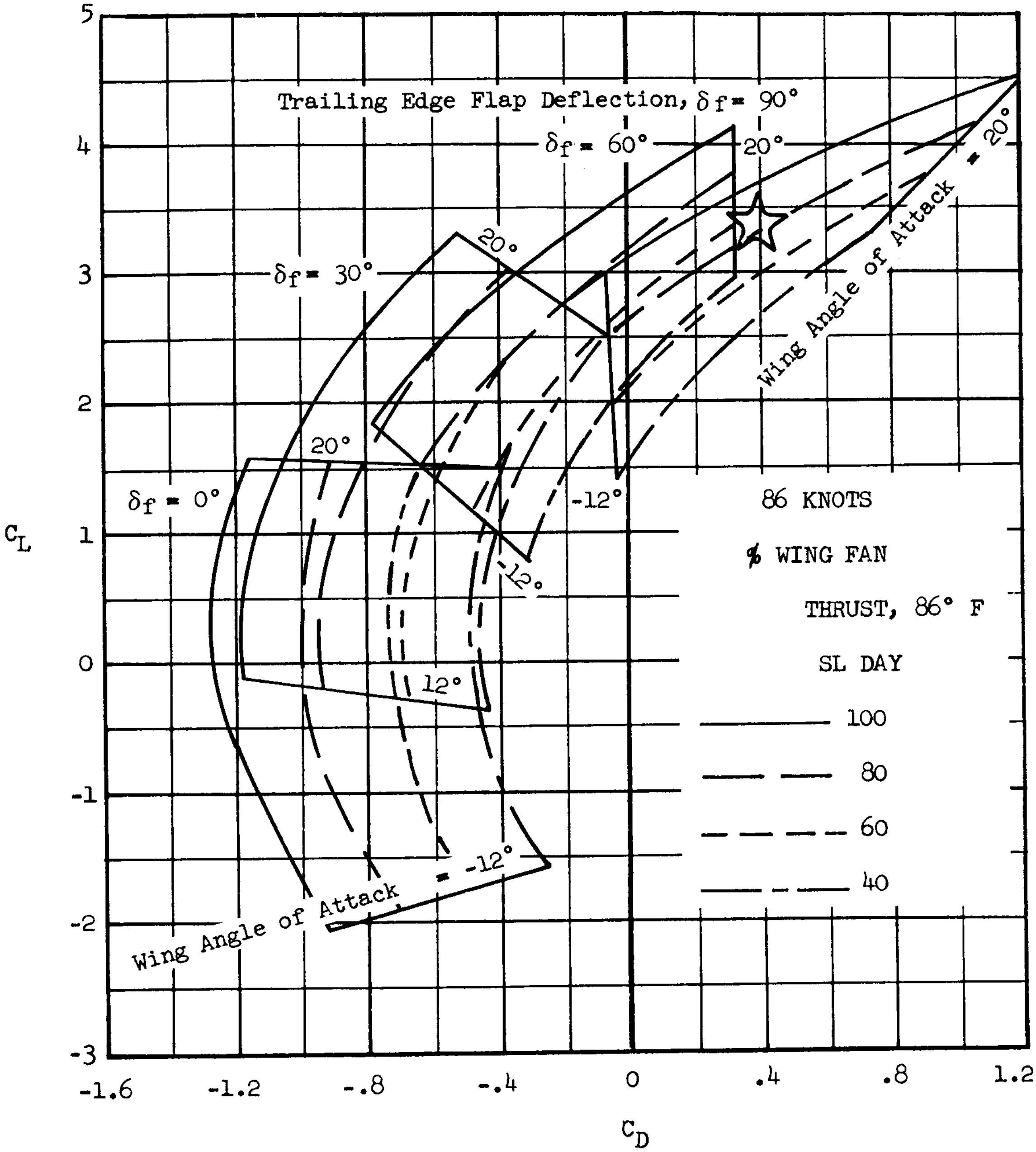


Figure 18. Tail-Off, Nose Fan Inoperative, Power-on Polar for the 60-Passenger Propulsive Wing 2000-Ft STOL

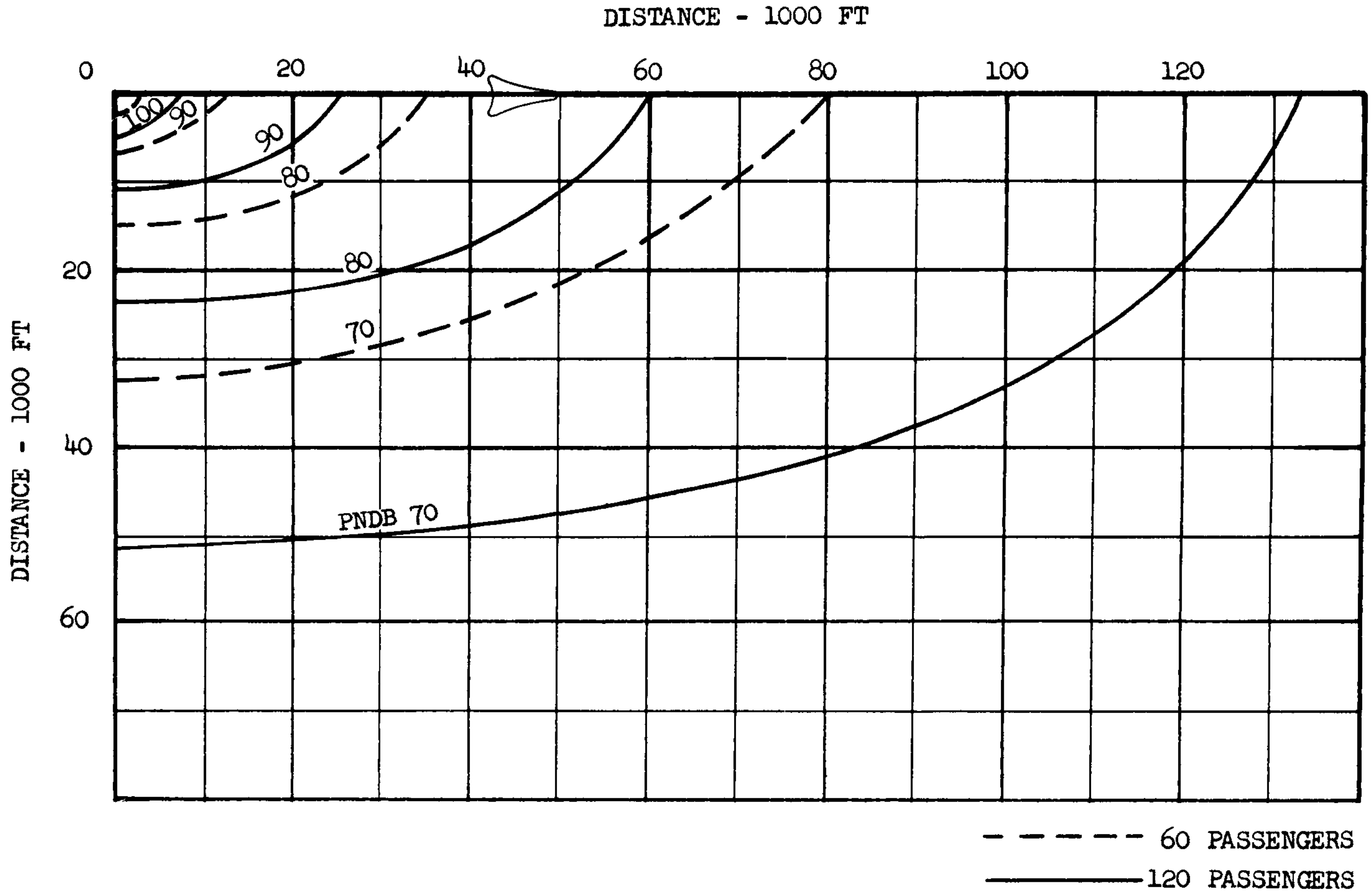


Figure 19. Effects of Size on Perceived Noise Level, Turboprop VTOL

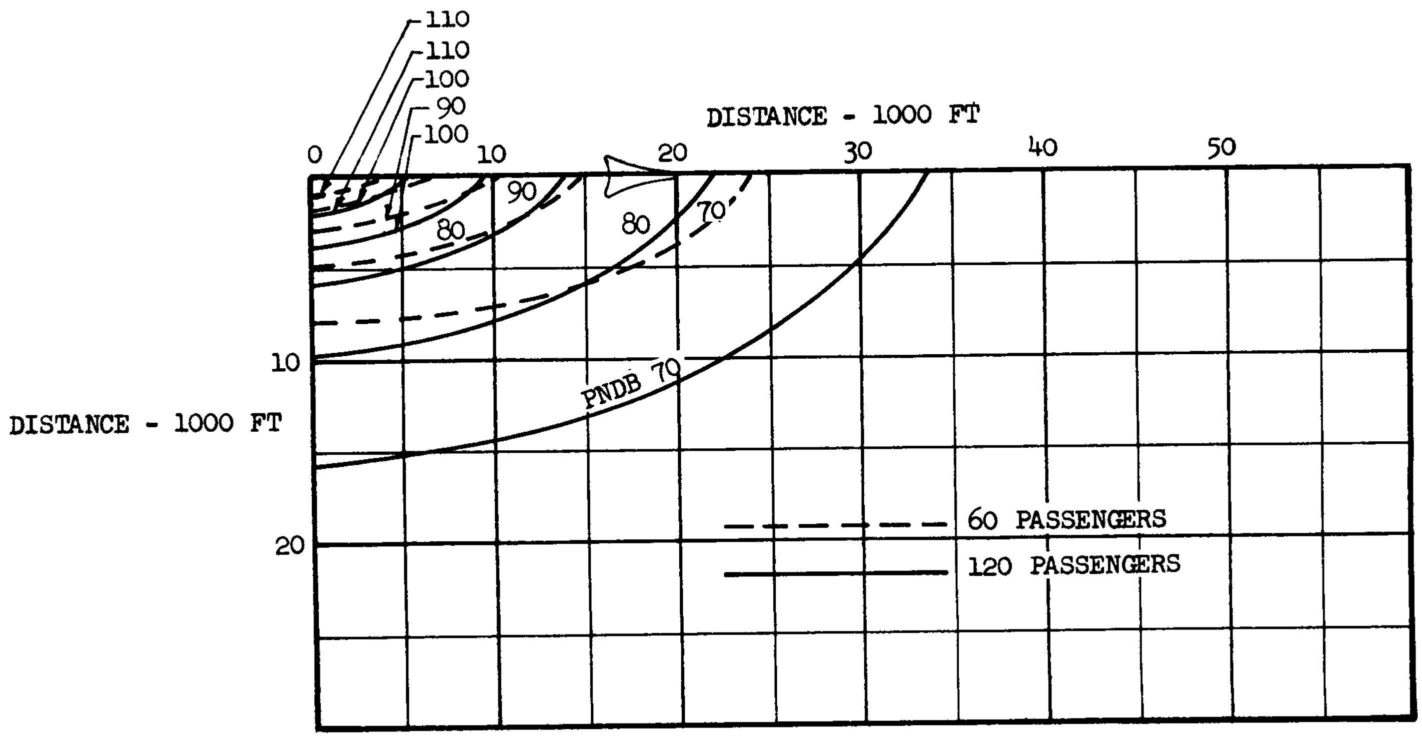


Figure 20. Effects of Size on Perceived Noise Level,
Fan-in-Wing V/STOL, Takeoff

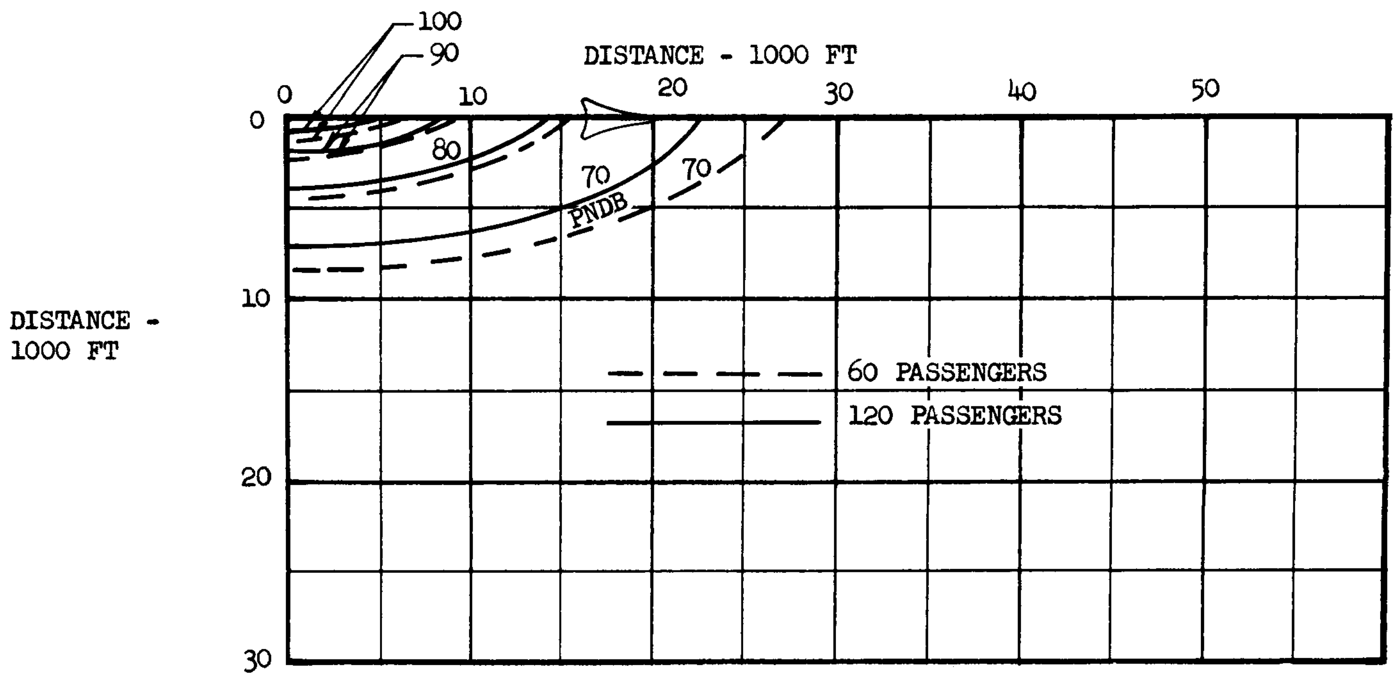


Figure 21. Effects of Size on Perceived Noise Level, Propulsive Wing 2000-Ft STOL, Takeoff

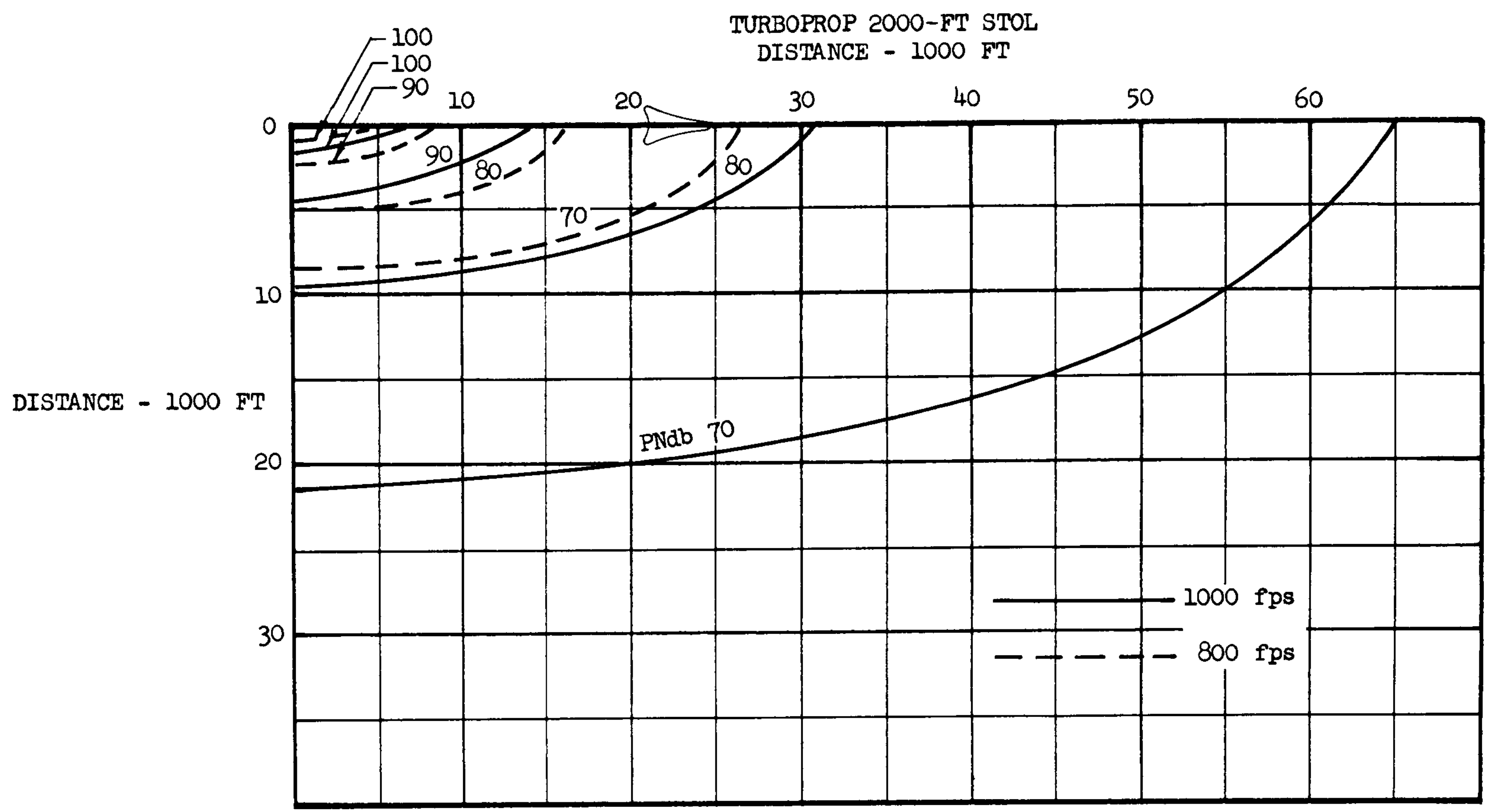
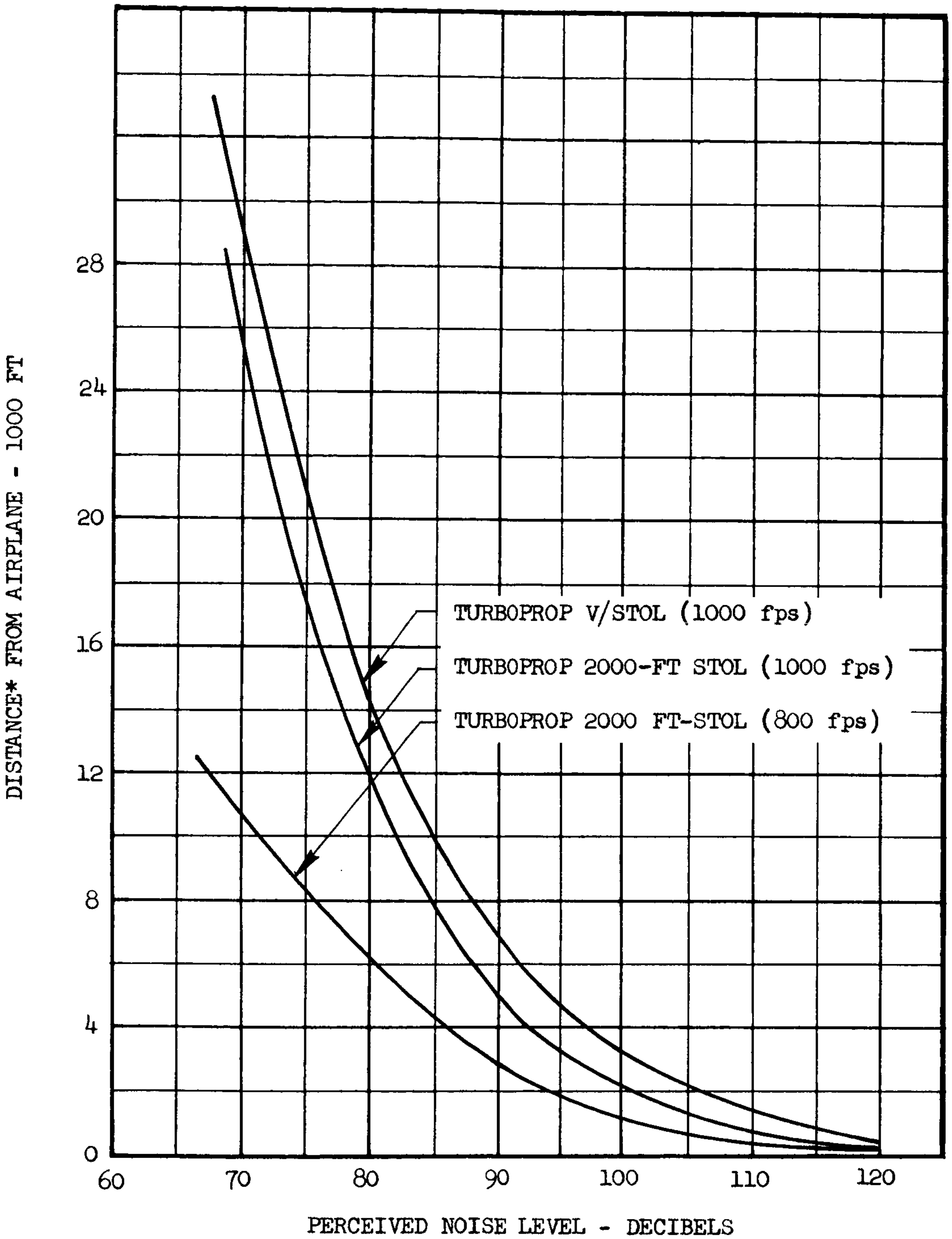


Figure 22. Effects of Propeller Tip Speed on Perceived Noise Level



* 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

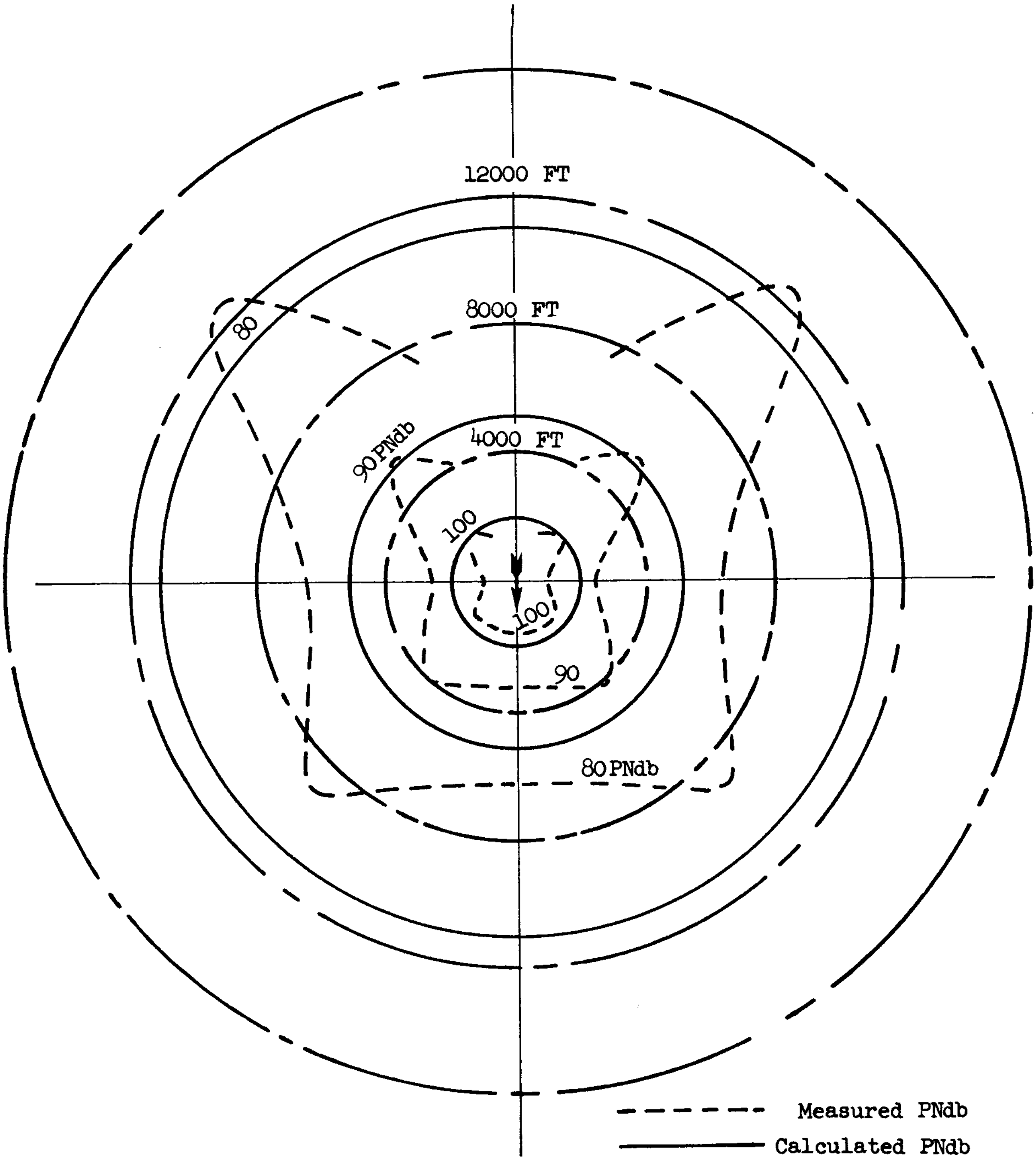


Figure 24. Comparison of Measured and Calculated Perceived Noise

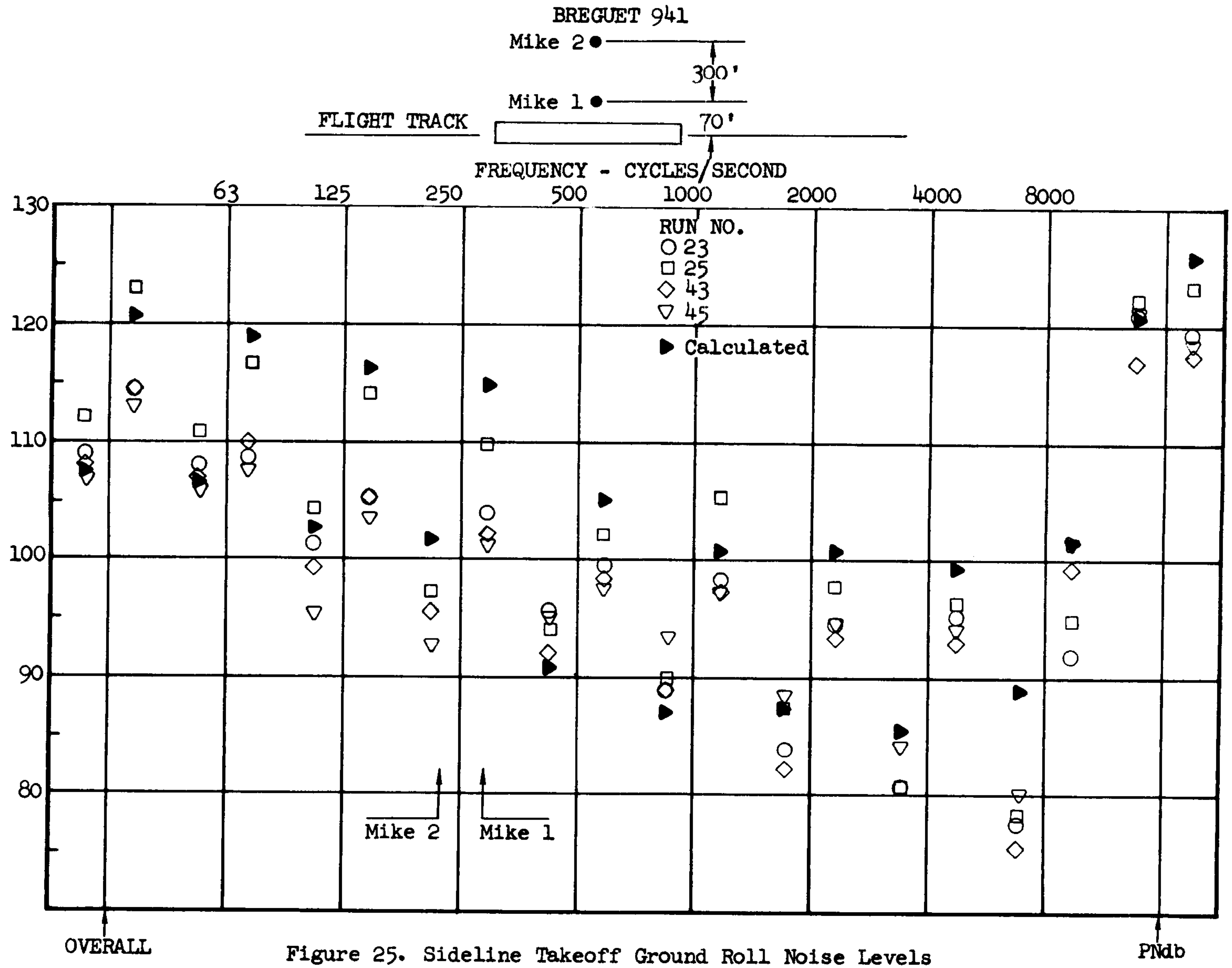


Figure 25. Sideline Takeoff Ground Roll Noise Levels