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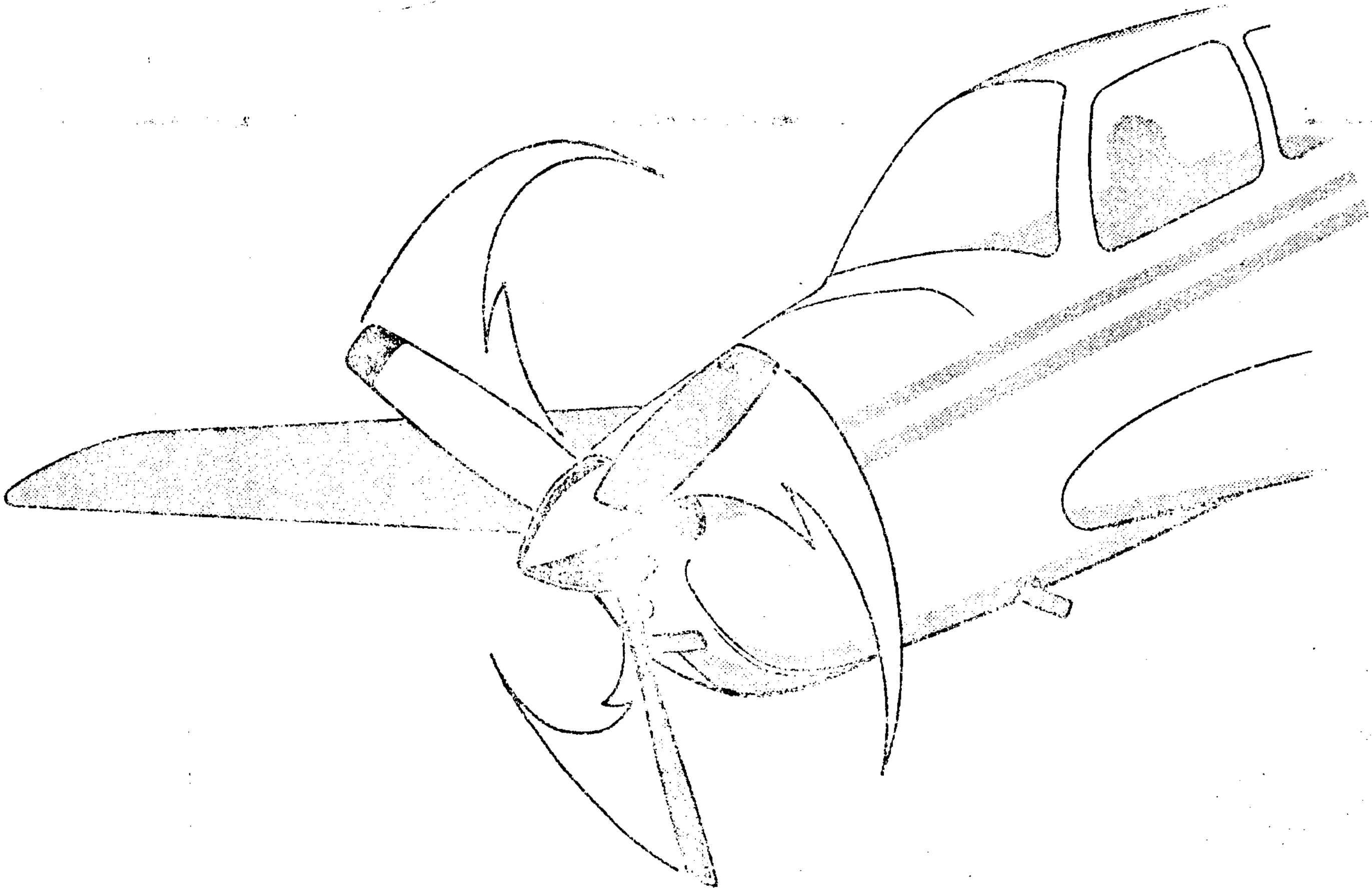

ADVANCED GENERAL AVIATION PROPELLER STUDY

April 1971

Hamilton Standard DIVISION OF UNITED AIRCRAFT CORPORATION
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ADVANCED GENERAL AVIATION PROPELLER STUDY

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ABSTRACT

Methods for predicting the performance, noise, weight, and cost of propellers for advanced general aviation aircraft of the 1980 time period were developed and computerized. A propeller sensitivity study based on the computer program is presented for five representative general aviation aircraft. Conceptual design studies are included for three propellers selected from the sensitivity studies to check the weight and cost estimating procedures. Problem areas exist in the methodology defined and follow-on studies are recommended. A listing of the computer program is presented.

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ADVANCED GENERAL AVIATION PROPELLER STUDY

SUMMARY

The general object of this study sponsored by the Advanced Concepts and Mission Division of NASA under Contract No. NAS2-5885 dated 30 January 1970 is to investigate the effects on the performance, noise, weight and cost of advanced general aviation aircraft propellers as influenced by the application of technology anticipated in the 1980 time period. The study covers a very broad spectrum of aircraft implied by the powerplant size range of 100-1500 SHP specified in the RFPA-15989 (HK-5) dated 18 December 1969. Thus, in order to provide a meaningful study within the scope intended by Advanced Concepts and Missions Division, A. C. M. D., as an initial step, the Contractor classified into five categories the general aviation aircraft envisioned by A. C. M. D. Then, a representative aircraft from each category was selected and its flight profile defined by this Contractor and A. C. M. D. in sufficient detail to establish propeller requirements. Analytical criteria for predicting the performance, noise, weight and cost projected to the 1980 time period were established and programmed in FORTRAN V for the UNIVAC 1108 high speed digital computer. With the aircraft and propeller requirements defined and the computer program established, a comprehensive sensitivity study of the propeller geometric and performance parameters was undertaken for an aircraft configuration selected from each of the five categories. It was generally shown that to reach the 65-75 PNdB noise level, it will be necessary to increase propeller diameters and number of blades significantly and to operate at very low tipspeeds. This will result in not only dimensionally less compatible geometries than those of present aircraft, but also in heavier and more costly propellers. The increased weight of the propeller alone can apparently be offset significantly by utilizing lightweight, high-speed reciprocating engines with appropriate reduction gearing. Yet, it is obvious that, depending on its severity, the anti-noise legislation expected by the 1980 time period could have a major impact on general aviation effecting not only propeller manufacturers but engine and aircraft manufacturers as well.

Detailed hardware conceptual design studies were made for three propeller configurations selected by A.C.M.D. Conceptual drawings, weight and cost have been established for each propeller. These carefully established weight and cost figures, based upon complete conceptual designs for the aforementioned three aircraft categories, showed only fair agreement with the weight and cost generalization included in the computer program. Discrepancies for one of the propeller designs were sufficiently large to conclude that further effort needs to be undertaken to establish more precise weight and cost generalizations for quiet, slow turning propellers.

An attractive alternative to the large, quiet propellers was indicated in the study of other concepts. This is the Prop-Fan concept which is a small diameter multiblade, variable pitch ducted fan coupled to high speed reciprocating engines without the speed reduction gearing. On the basis of a brief study of the Cessna 210J aircraft, this concept can generally meet both the low noise objectives of this study and performance requirements of this aircraft with compatible geometry and some reduction in total propulsion weight. Although considerably more work is required, the initial study strongly indicates that this new concept would be particularly attractive for multi-engine aircraft. Moreover the concept appears to have most of the favorable characteristics of the turbofan, i.e. compactness and high-speed capability at less expense since modification of existing high-speed reciprocating engines may be utilized.

Finally a major contribution of this study is the new methodology which was derived to predict propeller aerodynamic performance. This methodology was utilized in the sensitivity studies, and it is intended that the reader of this report will have sufficient data to permit similar propeller studies for any general aviation aircraft. A complete listing of the computer program with detailed instruction on its use are included. All the curves and equations for the analytical methods included in the computer program are presented with instructions of usage in lieu of the computer.

INTRODUCTION

Aviation forecasts for the next ten to fifteen year time period, indicate continued steady growth of general aviation. The attainment of this forecasted growth and even a more rapid expansion is dependent upon the continued improvement in the safety, utility, performance and cost of general aviation aircraft.

Acoustic improvement is a goal which may be of increasing importance since noise pollution has become a serious concern to almost every community in the country. The effect of increasing numbers of general aircraft operating from landing strips close to populated areas will further aggravate the problem. Consequently, the general aviation industry may be required to significantly reduce the noise levels of current and future aircraft. Thus, to insure the forecasted growth of general aviation, the noise problem must be seriously considered along with improvements in the other areas mentioned above.

General aviation is a heterogeneous category covering all civil aviation except the certified commercial air carriers. The category includes a wide range of aircraft from small single place private airplanes to multiplace, multiengine aircraft utilized by the air taxi operators, businesses and third tier air carriers. Generally the category includes aircraft of gross weights up to 12,500 pounds. The projected growth of this classification even by experts in the field has been difficult due to the large variety and application of the aircraft included and its dependence on various economic factors. However, the forecast by the Federal Aviation Administration (ref. 1, 2) is probably as accurate as is available. This agency's forecast on general aviation growth is impressive by the number of aircraft included and is summarized below.

From a current base of about 114,000 active aircraft, it is expected that this fleet will increase to over 214,000 units by 1980. Single engine, piston aircraft currently number about 96,500 with an expected ten year growth to over 170,000 aircraft. Their portion of the fleet is currently nearly 85 percent with only a slight decrease in this percentage predicted by 1980. The number of multiengine piston aircraft is forecast to about double from approximately 13,500 to 26,500 by 1980. The growth in turbine engine powered aircraft is expected to undergo the most spectacular growth from about 1300 today to over 7800 aircraft over the coming decade. Most of these latter aircraft will be turboprop with the turbofans beginning to make a significant showing. Currently these engines are being installed only on the larger aircraft in this category. The growth of turbofan aircraft is dependent almost entirely on the ability of the engine manufacturers to develop low cost, low noise, reliable engines. New technology and hardware development will be required before economically feasible turbofan engines could become serious competitors to the advanced reciprocating engines for application across the general aviation aircraft spectrum.

From the above summary of the projected growth of general aviation, it is apparent that most of these aircraft, even into the 1980 time period, will be propeller driven utilizing primarily reciprocating engines with turbine engines coming on as their economics improve. Thus, it is obvious that the aircraft improvements in the areas mentioned above must be matched by parallel improvements in propeller technology and hardware. Accordingly, this study has been undertaken to provide some visibility into the performance, noise, weight and cost characteristics of advanced general aviation propellers of the 1980 time period as influenced by anticipated restriction on noise.

The study involves the derivation of appropriate propeller performance, noise, weight and cost criteria incorporated into a computer program to permit sensitivity studies of these factors to be made for advance propeller configurations designed for general aircraft of the 1980 time period. These analytical criteria have been established utilizing existing performance and noise prediction methodology combined with the weight and cost criteria developed from the results of the mechanical design, material, and manufacturing technique studies and the market survey accomplished under this contract.

SYMBOLS AND ABBREVIATIONS

AF	propeller blade activity factor, $\frac{100,000}{16}\int_{.15}^{1.0}\left(\frac{b}{D}\right)x^3\,dx$
A.C.M.D.	Advanced Concepts and Missions Division Office of Advanced Research and Technology.
b	blade section width, ft
B	number of blades
BMEP	piston engine brake mean effective pressure
C	average O.E.M. propeller cost for a no. of units/year, \$/lb
C_1	single unit O.E.M. propeller cost, \$/lb
C_{L_D}	blade section design lift coefficient
C_{L_i}	propeller blade integrated design lift coefficient, $4\int_{.15}^{1.0} C_{L_D}\,x^3\,dx$
C_P	power coefficient, $\frac{SHP\,(\rho o/\rho)\,10^{11}}{2N^3\,D^5}$
C_{P_E}	effective power coefficient, $C_P \times P_{AF}$
$C_{P_{EE}}$	effective power coefficient, $C_P \times P_{AF} \times PF_{C_{L_i}}$
$C_{P_{EC}}$	effective C_P used in defining compressibility correction, $C_P \times P_{AF} \times P_{BL}$
C_T	thrust coefficient, $\frac{1.514\,T\,(\rho o/\rho)}{N^2\,D^4}$
C_{T_E}	effective thrust coefficient, $C_T \times T_{AF}$
$C_{T_{EE}}$	effective thrust coefficient, $C_T \times T_{AF} \times TF_{C_{L_i}}$
C_W	weight of propeller counterweight, pounds
D	propeller diameter, ft
dB	decibel, 0.0002 dynes/cm^2 (reference value)
E	empirical cost factor
EPNL	effective perceived noise level

F	cost factor based on quantity
°F	degrees Fahrenheit
F_t	compressibility correction factor (fig. 9)
H	labor time, hrs
h	maximum blade section thickness
J	advance ratio, $\frac{101.4\, V_K}{N\, D}$
K	constant based on single unit cost
K_W	constant propeller weight multiplier
LF	learning curve factor for no. of units/year
LF_1	learning curve factor for a single unit
M	free stream Mach number
M_{CRIT}	propeller critical Mach number (fig. 8)
N	propeller speed, rpm
O.E.M.	original equipment manufacturer
P_{AF}	power coefficient adjustment (fig. 7)
P_{BL}	number of blades correction used in defining compressibility correction (fig. 8)
$P_{C_{L_i}}$	C_P dependency of C_{L_i} adjustment for C_P (fig. 11)
$PF_{C_{L_i}}$	J dependency of C_{L_i} adjustment for C_P (fig. 10)
PNdB	units of perceived noise, dB
PNL	perceived noise level, PNdB
PNLT	tone - corrected PNL, dB
PP	cost of purchased parts and raw material, $
Q	propeller torque, ft-lb
R	blade radius at propeller tip, ft
r	radius at blade element, ft
r/c	rate of climb, fpm

SHP	shaft horsepower
SPL	overall sound pressure level, dB
T	propeller thrust, pounds
T_{AF}	thrust coefficient adjustment (fig. 7)
TAF	total activity factor, AF x number of blades
$T_{C_{L_i}}$	C_T dependency of C_{L_i} adjustment for C_T (fig. 12)
$TF_{C_{L_i}}$	J dependency of C_{L_i} adjustment for C_T (fig. 10)
T.O.	take-off
V_{cl}	climb velocity, mph
V_K	free stream velocity, knots
V_S	take-off stall velocity, mph
W	gearbox weight, lbs
W_T	propeller weight, lbs
x	fraction of propeller tip radius, r/R
Y	labor rate, \$/hr
Z	learning curve factor ratio, $\frac{LF}{LF_1}$
$\beta_{3/4}$	propeller blade angle at 3/4 radius
η	propeller efficiency, $\left(\frac{C_T}{C_P}\right) J$
γ	minimum climb angle = $\tan^{-1}(1/12)$
ρ	density, lb sec^2/ft^4
ρ_o	density at sea level standard day = 0.002378

AIRCRAFT CLASSIFICATION

Categorization of General Aviation

The task of classifying any large array of items in a significant number of groups, is dependent on the particular characteristic(s) of the items chosen as the basis for the classification. For this study, the Contractor categorized general aviation aircraft into five basic groups on the basis of number of seats as the prime characteristic with propeller complexity, installed power, gross weight, cruise airspeed and number of engines as secondary characteristics. From the extensive aircraft listings in aviation periodicals (ref. 3, 4), from reports (ref. 1, 2) available to the Contractor, and from consultation with several knowledgeable persons in this field including the Deputy Transportation Commissioner, Bureau of Aeronautics for the State of Connecticut, the aircraft classifications presented in Table I were selected by the Contractor as representing the prime aircraft groups upon which this study would be based. It is recognized that general aviation aircraft could be classified on the basis of other criteria resulting in different categories with more or fewer groups. For example, agricultural aircraft do not fit in any of the proposed groupings and would represent a sixth category. Moreover, a clear cut demarcation between classifications is not always obvious among the wide variety of aircraft included in general aviation. However, the suggested classifications are deemed sufficient to permit a complete and inclusive study of propellers for general aviation aircraft. The classifications were reviewed and approved by A. C. M. D.

Selection of Representative Aircraft for Five Classifications

An initial presentation meeting was held on 15 July, 1970 at Hamilton Standard with Mr. Mark Waters of A. C. M. D. and Mr. Michael Comberiate of NASA Headquarters attending. At that time, the following representative aircrafts from each aircraft classification (Table I) were selected for detail study.

Aircraft Classification		Propeller Type	Representative Aircraft
I.	Single Engine, Fixed Gear	Fixed Pitch	Piper Cherokee
II.	Single Engine, Retractable Gear, IFR Equipment	Constant Speed	Cessna Centurion 210J
III.	Light Twin, Retractable Gear, IFR Equipment	Constant Speed, Full Feather, Deicing	Beech Baron 55

Aircraft Classification		Propeller Type	Representative Aircraft
IV.	Medium Twins, Retractable Gear, IFR Equipment	Constant Speed, Full Feather, Deicing	Beech Queen Air
V.	Heavy Twins, Retractable Gear, IFR Equipment	Constant Speed, Full Feather, Deicing, Reverse	DeHavilland - Twin Otter

Definition of Mission Profiles and Propeller Requirements

For this study, the mission profile for each aircraft listed above was defined to include take-off, climb, single engine climb and maximum cruise operating conditions for which the corresponding propeller requirements were established. Thus, a more or less standardized performance base was maintained for the sensitivity study on each aircraft category.

Approximate aircraft performance characteristics and propeller requirements were established from several sources. The take-off and climb conditions and the corresponding propeller requirements for each aircraft were defined by Mr. Mark Waters of A.C.M.D. with the exception that Cessna provided the pertinent information for their latest version of the Cessna 210J. These conditions were obtained based on the following assumptions:

1. Take-off, T.O.

   A. T.O. lift coefficient = 0.8 (maximum lift coefficient) computed for "flap down" at stall speed, V_S.

   B. Coefficient of rolling friction = 0.02 (rubber on cement)

2. Climb-all engines operative

   A. Minimum climb velocity $(V_{cl}) = 1.5\ (V_S)$

   B. Minimum climb angle, γ, $= \tan^{-1}(1/12)$.

   C. Rate of climb at sea level, r/c, $\geq$ 300 fpm

   Note: A and B define $r/c = V_{cl} \sin\gamma$. If this r/c > 300 fpm, it is used as the minimum.

3. Climb-multi engine with one engine inoperative at 5000'.

A. $r/c \geq 0.02 (V_S)^2$

B. Minimum $V_{cl} = 1.3 (V_S)$

The one engine out climb at 5000' is included for aircraft of Categories III, IV, and V.

The cruise conditions were obtained from Jane's All the Worlds Aircraft, 1969-1970 (ref. 5). The maximum cruise condition was selected as representative of cruise operation. These basic operating conditions and propeller requirements for each aircraft are tabulated on Table II. Due to the assumptions made in these calculations, these requirements may differ from those of the actual aircraft.

TECHNOLOGY IDENTIFICATION

Design and performance criteria covering performance, noise, weight, and cost of general aviation propeller systems in the 1980 time period have been derived and incorporated into a computer program utilized for the sensitivity study. Each technology area associated with these criteria has been identified and are discussed in the following text.

Propeller Performance Generalization

Propeller aerodynamics and analytical methods have generally attained a high level of refinement permitting the aerodynamic design of highly efficient propellers for most applications. The forward flight method for conventional and multi-bladed propellers is based on the work of Goldstein (ref. 6, 7) which is an advanced form of the blade element theory. Goldstein combined the vortex theory and the solution for the radial distribution of circulation for a finite number of blades. The blade is considered as a rotating airfoil with each element following a helical path and reacting as an ordinary airfoil section. The aerodynamic forces on a series of radial blade elements are calculated and then integrated over the blade radius to establish the total forces. An analytical method based on this theory and utilizing two-dimensional airfoil data has been developed and continually refined which permits the performance of any arbitrary propeller configuration operating at any imposed flight condition to be accurately calculated.

Due to the extremely complex analytical model including a strong wake contraction required to theoretically define propeller performance at zero airspeed, this basic Goldstein theory has not yet been extended to cover the static case. An approximation of the wake contraction has been included in the Goldstein theory with fair success. However, recently a new propeller vortex theory has been derived for the static case which includes an accurate wake representation obtained experimentally. Although the method is currently limited to lightly loaded VTOL and STOL propellers, it is expected that this method will be extended to cover the higher loaded propellers applicable to general aviation aircraft within the next year or so. Thus, for this contract study, the static performance has been computed based on the Goldstein theory with the aforementioned slipstream contraction adjustment.

Two-dimensional airfoil data from approximately 25 wind-tunnel programs have been utilized by this contractor to generate complete and reliable sets of basic airfoil data for use in conjunction with the calculation procedure outlined above.

This method has been programmed for use in high speed digital computers. With this computer program, propellers can be readily designed and the performance can be predicted for the complete propeller operating spectrum.

During the preliminary design phase, the airframe manufacturer has need to study propeller performance characteristics over the entire aircraft flight spectrum. Hamilton Standard has recognized this need for rapidly evaluating propeller performance characteristics and consequently has published generalized performance calculation methods based on the aforementioned theory for aircraft propellers operating at static and in-flight conditions. These methods incorporate a series of performance maps each accurately defining the propeller performance for a broad spectrum of propeller geometric configurations over the complete range of potential operating conditions. By providing such maps for a systematic variation of each major propeller shape parameter (number of blades, activity factor, and integrated design lift coefficient), simple interpolation between charts will define performance for any desired propeller configuration. The "Red" book (ref. 8) has been generated for conventional propellers aimed primarily at turboprop engine application, the "Blue" book (ref. 9) for shrouded propeller performance estimation, and the "White" book (ref. 10) for variable camber propeller applications.

Performance Method. - Although these aerodynamic methods do exist and have been used in support of this study program, a new method was developed and computerized specifically for this general aviation aircraft propeller study which permits the simultaneous evaluation of performance, noise, weight and cost for a wide range of propeller geometries. This method is the basis of the sensitivity study described later in the text and is discussed in detail below. It is to be noted that the performance predicted by this method is for the isolated propeller since no single body blockage effect could be generalized to cover the wide variety of aircraft included in general aviation.

The family of propellers used for this generalization was selected on the basis of blade shapes which prior study had shown to be most favorable for minimum weight, low noise characteristics and good performance for general aviation application. The planforms for 80 to 200 activity factor are shown on figure 1, the corresponding thickness ratios on figure 2, the twist distribution on figure 3, and the camber distribution for the selected integrated design lift coefficient of 0.5 is shown on figure 4. For low drag characteristics, the NACA Series 16 airfoil sections have been used on the outer portion of the blade and the NACA Series 64 sections have been included for the thick shank sections.

The horsepower, thrust, propeller rotational speed, velocity and diameter are included in the non-dimensional form of power coefficient, C_P, thrust coefficient, C_T, and advance ratio, J defined as follows:

$$C_P = \frac{SHP\ (\rho_o/\rho)\ 10^{11}}{2N^3\ D^5}$$

$$C_T = \frac{1.514 \times 10^6\ T(\rho_o/\rho)}{N^2\ D^4}$$

$$J = \frac{101.4\ V_K}{N\ D}$$

where:

SHP - shaft horsepower

ρ_o/ρ - ratio of density at sea level standard day to density for a specific operating condition

N - propeller speed, rpm

D - propeller diameter, ft.

T - propeller thrust, pounds

V_K - forward speed velocity, knots

It was decided to present propeller performance in terms of thrust coefficient instead of efficiency as used in the propeller performance handbooks described previously to make the method more adaptable for computerization. Furthermore, the operating conditions can be defined with the thrust given and the corresponding horsepower computed as well as with the horsepower given and the corresponding thrust calculated. Propeller blade angle, $\beta_{3/4}$ has been included so that the method can be used for predicting the performance of fixed pitch and two-position propellers as well as constant speed propellers.

Base curves have been defined in this non-dimensional form presenting the performance of 2, 4, 6 and 8 bladed propellers referenced to an activity factor of 150. In order to minimize the number of curves and consequently the complexity of the computer program, the terms effective power coefficient, Cp_E and effective thrust coefficient, CT_E have been introduced into these curves. These terms incorporate adjustment factors for the effects of variation in blade activity factor and integrated design lift coefficient. The activity factor adjustment factor is given for 2, 4, 6, and 8 bladed propellers, but the integrated design lift coefficient adjustment factor is given for a 4-bladed propeller only. The adjustment factors are discussed later in the text. Thus, the base curves while referenced to a basic activity factor and integrated design lift coefficient are applicable to the complete range of these shape parameters covered in this study. This performance generalization format is shown for 2-bladed propellers referenced to 150 activity factor and 0.5 integrated design lift coefficient in figures 5 and 6 for the effective power coefficient chart and the effective thrust coefficient chart, respectively. Similar plots for 4, 6 and 8-bladed propellers together with a sample calculation are presented in APPENDIX A.

The ranges of effective power and thrust coefficients were selected to span peak thrust and minimum power at each advance ratio as shown in figures 5 and 6. However, in the cases where windmilling operation is possible, minimum effective power coefficient is taken to be zero, although engine out drag torque will result in some small negative power. It is to be noted that a curve defining the condition where the propeller is stalled over the inner 50% of the blades has been included on these generalizations. As will be explained in more detail in the section on Noise Generalization, test data have indicated that no significant reductions in perceived noise level, PNL, can be obtained by tipspeed reductions if the propeller becomes greater than 50% stalled. Thus, it is recommended that propellers be selected so as to operate to the left of the indicated 50% stall line for the critical noise condition.

As indicated previously, to minimize the number of curves and consequently the complexity of the computer program, a study was made to investigate the feasibility of obtaining adjustment factors to both power and thrust coefficients to account for the effects of activity factor, number of blades, and integrated design lift coefficient. Adjustment factors for propeller activity factor have been successfully defined using 150 activity factor as the base. On figure 7 are presented curves for the power coefficient adjustment, P_{AF} and the thrust coefficient adjustment, T_{AF}. It is to be noted that the factors for advance ratio $J = 0$ differ from those for $J \geq 0.5$. A straight line interpolation is used to obtain the adjustment factors for $0.0 < J < 0.5$. The effective power and thrust coefficients are defined as follows:

$$C_{P_E}\ (AF) = C_{P_E}\ (150) \times P_{AF}$$

$$C_{T_E}\ (AF) = C_{T_E}\ (150) \times T_{AF}$$

Such an adjustment was originally derived for the number of blades parameter. However, the accuracy of this adjustment in the low propeller advance ratio range was not adequate and consequently the 150 activity factor base plots, i.e., the effective power coefficient and effective thrust coefficient plots discussed above, were generated for 2, 4, 6 and 8-bladed propellers (APPENDIX A) with performance for 3, 5 and 7-bladed propellers being obtained by interpolation. The activity factor adjustments, P_{AF} and T_{AF}, are independent of the number of blades.

Today's general aviation aircraft are operating at moderate speeds and are not significantly affected by propeller compressibility losses. However, it has been projected that general aviation aircraft will be operating at significantly higher speeds by the 1980 time period. Accordingly, a compressibility correction for the base curves of 0.5 integrated design lift coefficient has been derived for use in conjunction with these plots. A critical Mach number, M_{CRIT} for each value of advance ratio, J, has been defined as the limiting free stream Mach number, M limit at which no compressibility losses are encountered (fig. 8). If the free stream Mach number exceeds the critical Mach number, the compressibility factor, F_t is defined. It is dependent on the difference between M and M_{CRIT} and the effective power coefficient defined as

$$C_{P_{EC}} = C_P \times P_{AF} \times P_{BL}$$

P_{BL}, number of blades correction is defined on figure 8. F_t is defined on figure 9 and the thrust is multiplied by the F_t to correct for compressibility losses.

The complete performance computational procedure is defined in APPENDIX A with pertinent sample calculations included.

Variation in integrated design lift coefficient, C_{L_i}, has not been included in this computer program since previous studies of propellers for general aviation aircraft indicated that a value of $C_{L_i} \backsim 0.5$ is about optimum for most installations. However, during the course of the sensitivity study, preliminary results indicated an attractive potential for using increased camber to minimize the activity factor increase required to attain the low noise objectives of the study. The advantage of a lower activity factor is a lighter weight propeller. Accordingly, a limited study was undertaken to investigate the feasibility of deriving an adjustment factor for integrated design lift coefficient. As shown in figures 10, 11 and 12, a suitable adjustment was successfully generated for C_{Li} = 0.7 and 0.8 with 0.5 as a base and limited to a 4-blade propeller. The advance ratio dependency is defined in figure 10 as $PF_{C_{Li}}$ for power doefficient and as $TF_{C_{Li}}$ for thrust coefficient. The power coefficient adjustment, $P_{C_{Li}}$ is read from figure 11 and the thrust coefficient adjustment $T_{C_{Li}}$ is from figure 12. Thus, the base charts can be used with the effective power coefficient and effective thrust coefficient being defined as follows:

$$C_{P_E} = C_P \times P_{AF} \times P_{C_{Li}}$$

$$C_{T_E} = C_T \times T_{AF} \times T_{C_{Li}}$$

It appears that the adjustment can be expanded to include the complete range of integrated design lift coefficient and number of blades. The compressibility adjustment would need to be expanded to include C_{Li} variations should this parameter be added to the computational procedure.

The method described above is based on the current technology. The aerodynamic performance of today's conventional propellers designed by this technology approach maximum attainable levels at design conditions with current low drag airfoils. Further improvements in efficiency at the design conditions are expected to be small. Consequently, the performance method should be applicable to the 1980 time period.

Noise Generalization

The major source of noise from aircraft is the propulsion system. In the case of general aviation aircraft, this usually consists of one or more propellers driven by internal combustion engines of the reciprocating or rotating piston type with turbine engines beginning to make a strong showing in the larger aircraft. Although, generally, propeller noise is more intense than engine noise, the engine does contribute to the aircraft's perceived noisiness. Furthermore, the engine is very likely to become the major noise source when efforts are made to reduce the propeller-generated noise. This is particularly true for those aircraft which are not equipped with engine exhaust silencers. Since this generalization is for propellers only, it is emphasized that the low noise levels which may be achieved through selected design and operating conditions as presented in this report will not be representative of those from the complete aircraft unless a parallel effort is made to reduce the noise from other sources (particularly from the engine) as these will become predominant and set the perceived noise level of the aircraft.

Noise Computational Procedure. - In recognition of the increased emphasis on aircraft noise abatement, Hamilton Standard has been actively involved over the past 10 years in advancing the technology of propeller noise analysis. From this work, two propeller noise calculation methods have evolved. One is essentially empirical and based on the works of Beranek, Hubbard, and others (ref. 11, 12, 13, 14) plus experimental test data collected by Hamilton Standard. The other is a theoretical method based on the work of Garrick and Watkins, Arnoldi, Widnall, and Sperry (ref. 15, 16, 17, 18) plus empirical adjustments based on measurements.

The empirical method has been selected for this study in view of its relative simplicity and ease of use.

The empirical method was derived from a correlation of extensive near and far-field noise measurements on full scale and model propellers of medium and large diameters operating in the 700 to 900 ft/sec tip speed range where rotational noise predominates. However, at the low tip speeds antcipated to meet the desired 65 to 75 perceived noise levels (PNdB), it is expected that vortex noise will be an important noise source. Thus, the method was extended for this study to smaller diameters and lower tip speeds based on a limited amount of data available on noise generated by small diameter, low power, low tipspeed propellers during normal flight. This estimating method for far-field propeller noise and a sample calculation are presented in APPENDIX B.

The required inputs to the propeller noise estimating method are:

1. Propeller diameter
2. Number of blades per propeller
3. Propeller RPM or tipspeed
4. Horsepower per propeller
5. Coordinates of desired field point of interest
6. Aircraft forward speed
7. Number of propellers installed
8. Ambient temperature

Detailed blade shape characteristics such as twist, camber, and thickness distributions, activity factor, planform shape, and airfoil section are not considered. However, for properly sized propellers, these factors generally have a minor influence on the noise and are thus neglected for method simplification.

In order to make a noise estimate, a summation is made of partial levels based on design and operating conditions. The partial levels are provided in graphical form to minimize calculations. The method allows quick estimates of overall sound pressure level (SPL) in decibels (dB) and of perceived noise level (PNL) in perceived noise decibels (PNdB).

Recent test data on highly loaded low tipspeed propellers have indicated that the reduction in noise with tipspeed is a function of propeller stall characteristics. From this limited stall data, it appears that noise reductions can be achieved with decreasing tipspeed at a given power only to the point where the propeller becomes stalled over approximately the inner 50% of the blades. This stall criteria is defined as a function of power coefficient for a given advance ratio as is shown on figures 5 and 6 for the 2-bladed propeller. Similar curves for 4, 6 and 8-bladed propellers are included in APPENDIX A. In order for the above empirical method to be accurate, it is recommended that propellers be selected so as to operate to the left of the indicated 50% stall line for the critical noise condition as defined in the section on Performance Generalization.

It should be noted that at the high tipspeeds (near 1000 ft/sec) of some general aviation aircraft in use today, it appears that estimates obtained by use of the method deviate from the meager test data available on these types of aircraft. A tentative explanation for this is that these high tipspeeds exceed the propeller blade critical tipspeeds (the speed at which the peak load velocity of the air over the surface of the blade airfoil reaches that of sound). Limited experience shows that when a propeller is operating above its critical speed, the formation of a shock wave occurs, thereby raising the noise level as much as 10 PNdB over that which is generated at tipspeeds just below critical. The empirical method does not attempt to distinguish between subcritical and supercritical operating conditions as this involves detailed aerodynamic calculations which are outside the intended scope of this noise estimating method. Rather, the method calculates levels which are between the two. Thus, for a propeller operating at near but below critical speed the method will tend to over estimate the noise levels, while at above critical speeds, the method will underestimate the noise.

A recent evaluation of the accuracy of the generalized propeller noise estimating method showed that for propellers operating between 700 and 900 ft/sec tipspeeds, the calculations of peak PNL agreed within ±3 PNdB of the measured peak PNL. Also, a very limited data sample for propellers in the 1000 ft/sec range indicated that the agreement between calculations and measurements was of the order of ±6 PNdB, presumably because of supercritical operation. Noise data for low tipspeed propellers under flight is not available so no precise assessment of accuracy can be made for the estimates of advanced quiet propeller concepts defined in other parts of the study. Noise measurements are urgently needed in this area to provide a basis for checking the method and to make empirical adjustments as required.

<u>Maximum Noise Level Criterion.</u> - In evaluating the reaction expected when a listener is subjected to noise generated by general aviation aircraft two points must be considered: 1) noise measurement location, and 2) the procedure used to evaluate subjective reaction to the noise of interest. Of course, these two points must be considered with respect to the noise source under evaluation. Therefore, the following discussion is related to propeller noise from general aviation aircraft.

1. Noise Measurement Location: The measurement location selected for the study is that point on the 500 foot sideline at which the maximum noise after lift-off occurs. This location was selected for the following reasons:

   a) At any location directly under this take-off flight path, the noise will be affected by variations in aircraft attitude, altitude, power, and speed. However, at a sideline location, variations in altitude will not have as much effect on the noise since the slant distance to the aircraft will not vary very much from 500 ft as the altitude of the aircraft varies. Also, under the flight path, the aircraft's attitude influences the noise since it alters the directivity. At a sideline location little or no change in directivity occurs with aircraft attitude changes.

   b) The noise measured while the aircraft is still on the ground will be significantly influenced by the reflections from the ground. These reflections usually cause reinforced low frequencies, depressed mid-frequencies, and variable reinforcements and cancellations at high frequencies. These effects depend on the frequency spectrum of the source, the distance from the source to the receiver, the terrain composition, and the heights above the ground of the source and receiver. If the measurement location is selected such that the maximum noise occurs after lift-off, the effect of ground reflections on the noise will be reduced since the aircraft will be at some altitude above the ground.

   c) A static (i.e. at zero forward speed) propeller operating at high power and low speed will generally have a significant portion of the blade operating at very high angles of attack. The result is flow separation and an increase in the broad band noise resulting in a higher perceived noise level than for an unstalled propeller operating at the same tipspeed, power, and thrust. However, as the aircraft gains speed during take-off roll, the blade sections unstall until at approximately lift-off speed the whole blade is operating at angles of attack below stall. Therefore, the sideline measurement location selected will provide a good indication of the maximum take-off noise as the aircraft approaches populated areas around the airport.

   d) A final consideration is the relative location of houses, farms, etc. which would be subjected to the noise. The general configuration of small airports and airfields is such that more land is purchased along the approach and take-off paths. In addition, the maneuverability of small planes at low altitudes and slow speed allows them to alter their courses relatively soon after take-off to avoid populated areas. Thus, the area where listeners are most likely to be annoyed lies to the side of the runway. Airfield boundaries of 500 ft to either side of the centerline of the runway appear reasonable, considering the general layout of present and planned general aviation airfields.

2. Noise Rating Scale: At the present time, there is much controversy on the scale to be used in rating the annoyance of aircraft noises. Commonly proposed aircraft noise annoyance rating scales are Perceived Noise Level (PNL), Tone-Corrected PNL (PNLT), and Effective Perceived Noise Level (EPNL). PNLT is PNL with a correction for the presence of discernable tones, and EPNL applies a duration correction to PNLT to account for the time the noise is within 10dB of the peak PNLT.

It is the contention of many psychoacousticians in the aircraft industry that PNLT and EPNL do not significantly improve the correlation between the subjective judgement of listeners and the calculated annoyance rating of aircraft noise. In some cases, the scatter in subjective evaluation was increased when PNLT and EPNL were used. Also, EPNL being dependent on the time the signal is between its peak value and 10dB below the peak value, the procedure for estimating EPNL becomes very complicated. The aircraft's position and attitude, as well as the directivity pattern and frequency spectrum of the noise, must be defined since PNLT's are calculated at 1/2 second intervals while the noise is less than 10dB below the peak value. The time between 10dB down points may be up to 20 seconds depending on aircraft speed and altitude requiring 41 PNLT calculations. As a consequence, it was decided at Hamilton Standard to select PNL as the noise rating scale because: 1) It is a good measure of the relative annoyance of the various aircraft designs considered in this study, 2) It can be estimated by use of a relatively simple calculation procedure, and 3) It is a reasonable indication of the subjective reaction to aircraft noise. The latter is true, since for propeller noise, the duration correction generally cancels with the tone correction.

The method described above presents a means of calculating propeller noise for a broad range of design and operating parameters. In order to estimate noise down to the 65-75 PNL range required in this study, the method has been extended to cover propellers in the low tipspeed range to the point where the blades become 50 percent stalled. However, this extension and stall limit concept has been based on minimal test data. Accordingly, more noise measurements on quiet propellers are urgently needed to provide a thoroughly reliable noise prediction method. Again it should be pointed out that quiet aircraft may not be achieved by reductions in propeller noise without comparable reductions in engine noise.

Weight Generalization

An accurate weight generalization of modern aircraft propellers is difficult to achieve for many reasons. While a propeller may be described generally by several well-known parameters, the actual design requirements can introduce a wide range of weights for several propellers all having the same values of these parameters. For example, the type of control system required, the propeller environment, aircraft operating airspeeds and attitudes all influence the propeller design and consequently weight. Thus, only the gross geometric characteristics can be accounted for in any particular generalization.

In preliminary propeller selection studies, there is a need for some means of estimating weight trends and it must be recognized that the final weights may vary significantly after all factors have been considered. This contractor has prepared such weight estimating procedures for various classes of propellers. As an example, weight estimating formulae are presented on figure 13 for two classes of propellers:

1. Conventional shaft mounted turbo-props with solid aluminum alloy blades.

2. Lightweight propellers with fiberglass-shell, steel-spar blades and integral gearbox type hubs.

The propeller geometric parameters (diameter, number of blades, activity factor) and operational parameters (SHP, RPM, Mach number) incorporated in these formulae are the ones which experience has shown to have the most predominant effect on propeller weight and the exponents have been established empirically to best fit the weight trends of current Hamilton Standard propeller constructions.

The same technique was used in defining propeller weight formulae for general aviation aircraft of the 1970 and 1980 period and is discussed in the following text.

Weight Equation for the Present Propellers. - With this successful background in propeller weight prediction, the same methods were applied to the general aviation propellers categorized in Table I. Since this contractor has designed and manufactured propellers only for aircraft of the fourth and fifth categories, a market survey of general aviation propeller manufacturers was conducted to establish weight and cost parameters of propellers for the first three aircraft categories as well as to add to these data for propellers of the fourth and fifth aircraft categories. These data were assembled to provide a basis for the development of a weight generalization to cover propellers for all general aviation aircraft categories.

As a result of this survey and existing data at Hamilton Standard, propellers listed in Tables III and IV were used in defining a new weight generalization equation. The same exponents are used for the propeller geometric parameters and operating condition parameters as were generated previously for the conventional solid dural blades (fig. 13) but with revised constant multipliers, K_W, for counterweighted propellers. These equations as shown on Table V were found to be valid for the 1970 general aviation propeller categories defined in Table I. Agreement between actual and calculated weights was good except for one propeller listed in Tables III and IV. In some cases, the propellers listed were not tailored for minimum weight so they were heavier than the weight calculated by the equation This often occurs when the same hub mechanism is used for several different blade sizes. Each propeller must be designed for minimum weight for the equations to be effective.

Weight Equation for Propellers for the 1980 Time Period. - Propellers for the 1980's must necessarily be larger, heavier and more costly than present propellers in order to obtain reductions in noise levels. It was an objective of this study to obtain the lowest propeller weights for the 1980 time period commensurate with competitive costs in the general aviation market. Weight reduction requires a change in materials, processes and/or design concepts within the constraint of acceptable costs. In pursuit of these objectives, the following material changes were considered:

1. Hard aluminum blades
2. Fiberglass shell and solid aluminum core blades
3. Aluminum barrels for propellers applicable to airplanes in Categories III, IV and V (Categories I and II are already aluminum).

The following design concept changes were considered:

1. Integrated propeller and gearbox on geared engines
2. Integral propeller oil reservoir
3. Integral propeller governor control
4. Double acting hydraulic pitch change system with feathering and pitch lock

Other material and concept changes could be employed for weight reduction (i.e. titanium blades and barrels) but these were not considered to be economically feasible for general aviation in the 1980's. The changes listed above were assessed based on a cost/weight trade-off for application to propellers in each of the five aircraft categories.

The higher strength hard aluminum material was selected for blades and blade cores in all five categories based on approximately five percent reduction in blade weight for a small increase in cost.

Significant weight savings are possible with fiberglass shell and solid aluminum core blades but the cost based on present manufacturing methods is believed prohibitive for the general aviation market. Certainly new processes and fabrication methods can be developed to reduce costs to more acceptable levels before 1980. However, it is estimated that even these reduced costs would still be approximately twice that of solid aluminum blades so the fiberglass blades were considered in only Category IV and V propellers for the 1980's. This is not to say that fiberglass blades could not be incorporated in all aircraft categories if the higher cost is acceptable.

Aluminum barrels were not utilized in propellers in aircraft Categories III, IV and V because no weight reduction was obtained in these larger propellers and the cost reduction was negligible.

Integration of the propeller, including oil reservoir and control, with the engine gearbox has been used to advantage for cost and weight reduction on high-powered propulsion systems but the complexity of such a concept study was found to be outside the scope of this general aviation program. The benefits of such a concept are considered to be significant and a separate study in close cooperation with the engine manufacturer is recommended.

A significant weight saving is gained in larger propellers by replacing blade counterweights with a double acting pitch change system. This concept was incorporated in the Category V propeller.

As a result of this study, the constant multiplier in the generalized weight equation was reduced in Categories IV and V for 1980 over the 1970 factors. These are shown on Table V. It should be noted that the weights do not include deicing, spinner and governor. Weights of blade deicing and spinner were not included in the generalized weight equation because they are optional components not universally used on all propellers. Governor weight was not included because several different types of governors of different weight can be used on aircraft in the same category. Moreover, these are often provided by the engine manufacturer.

These generalized weight equations have been established to indicate the weight trends with variations in propeller geometric shape parameters. In a later section of this report, representative propellers have been selected from the sensitivity study for each of the aircraft categories, and a detail concept design has been undertaken for each of these propellers and the weights precisely established. The accuracy of the weight generalization is assessed by a comparison with these weights.

Cost Generalization

Selling price is the least adaptable to generalization of all items in this study because prices are negotiable and manufacturers' cost structures differ. Because of this, the generalized cost equation for the sensitivity studies was derived using the cost to the aircraft original equipment manufacturer, O.E.M. as a base. A more definitive base would be the inherent time, i.e. number of hours required to manufacture a propeller. This would eliminate the variables inherent in the overhead and profit margin factors used to convert inherent time into sell price. The disadvantage with this method of cost generalization is that the inherent cost of a product includes purchased parts, material and labor. These items do not convert readily from price to a time basis because purchased parts cost depends upon overall usage. Parts costs increase as usage digresses from universal use in several industries to use in propellers only or to use in only certain propeller models. The use of original equipment manufacturer, O.E.M., cost as a base avoids the problems associated with these variables.

Cost Equation for Propellers in 1969. - End user price lists and weights were obtained for representative industry propellers in the five aircraft categories being studied. Original equipment manufacturer, O.E.M. costs were estimated by taking 60% of the list prices. This percentage is only an assumed value for this study and can be varied by the user. The prices and weights for selected propeller models are listed in Table VI. The price and weight figures were averaged for each category and were used in conjunction with an 89% learning curve (fig. 14) to define costs as shown below:

$$C = ZF\,(3B^{0.75} + E)$$

$$C_1 = F\,(3B^{0.75} + E)$$

where:

C = average O.E.M. propeller cost for a number of units per year, \$/lb.

C_1 = single unit O.E.M. propeller cost, \$/lb.

$$Z = \frac{LF}{LF_1}$$

LF = learning curve factor for a number of units/year.

LF_1 = learning curve factor for a single unit.

B = number of blades.

F = single unit cost factor.

E = empirical factor.

The factor E is an empirical function of category only whereas the factor F is a function of single unit cost. A private market survey was used to obtain the number of propellers supplied by a typical manufacturer in 1969 and that projected for 1980 (APPENDIX C, Table 1C). F and E factors are defined in Table VII for each propeller category in 1969 and 1980.

Cost Equation for Propellers of the 1980 Time Period. - Cost predictions for the 1980 time period must reflect the projected change in yearly units manufactured by a single supplier and changes in materials, processes and design concept between 1969 and the 1980 time period. At this time, it does not appear that any change in materials is justified for Categories I, II and III for the 1980 propellers. Also, it is not possible to predict any significant improvements in design concepts or manufacturing processes other than those represented by the learning curve. Thus, in Categories I, II and III, the F-factors for 1980 are shown to be identical to the established 1969 values. However, for Categories IV and V, there is a substantial increase in the 1980 F-factors due principally to the change to the lightweight, but higher-cost fiberglass shell blade. It should be recognized that the actual cost comparison between 1980 and 1969 will be more favorable than the relative F-factors due to the offsetting effects of the reduced weight and improved learning factors due to increased production rates. The factors for Categories IV and V were specifically modified for the following changes in materials and design concepts which will be discussed in the section on Propeller Hardware Concept Study.

1. Blades incorporating a fiberglass reinforced plastic shell with solid aluminum core construction were projected for use in propellers in Categories IV and V for the 1980 time period.

2. A double-acting governor and pitch change actuator system was assigned to the Category V propeller to replace counterweights and spring packs but adding a retractable take-off stop and pitch lock.

Factors for all categories are listed with the generalized cost equation in Table VII. Propeller design changes for 1980 discussed above are not necessarily the only changes which were incorporated during the detailed concept phase of this study, but they represent modifications that can be incorporated by any manufacturer.

This cost equation is quite simplified, but correlates sufficiently well with the available industry price data to serve as a proper basis for the sensitivity study. The computer program presents the cost on the basis of a unit cost plus a learning curve. A learning curve slope of 89 percent was assumed for this study although this can be altered by the user.

Computer Program

The performance generalization for conventional propellers and multi-bladed propellers and the corresponding noise, weight and cost generalizations described in the previous text have been computerized. The computer program has been coded in FORTRAN V and has been run on the UNIVAC 1108. With this computer program, the aforementioned propeller characteristics can be readily calculated for a range of propeller geometries and operating conditions.

The required inputs are the following:

Propeller

1. Diameter range
2. Number of blades range (2-8)
3. AF range (80-200)
4. $C_{L_i} = 0.5$

Operating condition (maximum of 10)

1. Horsepower or thrust
2. Altitude, ft
3. Velocity, knots
4. Temperature, °F
5. Tipspeed range

Other

1. Number of engines
2. Coordinate of field point for noise computation
3. Airplane classification (1 through 5)
4. Flight design Mach number
5. Performance computation options
6. Cost computation options

There are three performance computation options available. First, if an engine is specified, then the operating condition is defined with the horsepower and the corresponding propeller thrust is computed. Second, if a propeller thrust requirement is defined, then the thrust is included as input and the horsepower is computed, thus indicating engine size. Third, for operating conditions defined by horsepower or thrust, it is possible to define the tipspeed corresponding to 50% stall. This would be the tipspeed for minimum noise. Cost can be computed based on the 89% slope learning curve and the unit costs and quantities selected by Hamilton Standard from available surveys as discussed in the cost generalization section. There are the options of varying learning curve, unit costs, and quantities.

A sample print out is included as Table VIII. The output consists of performance, weight, and cost per propeller and the noise per airplane since it is adjusted for number of engines. The weight and cost for both 1970 and 1980 time periods are included. The corresponding blade angle for each performance point is printed out for the fixed pitch propeller application. The asterisks under PNL heading specify that for this condition the propeller is more than 50% stalled. As was specified in the section on noise generalization, it is recommended that the propellers be selected which do not exceed the 50% stall limit. The asterisks under the thrust heading indicate that the condition is beyond the limits of the generalization. As additional information, compressibility correction factor, F_t, free stream Mach number, M, advance ratio, J, power coefficient, C_P, and thrust coefficient, C_T, are included on the print out. For example, from an examination of these parameters, an indication of the presence and magnitude of compressibility losses and the blade loading characteristics may be established.

The program is coded in FORTRAN V and has been run on a UNIVAC 1108. Approximately 2000 performance points can be computed per minute. A list of the program and pertinent input-output instructions are included as APPENDIX D.

SENSITIVITY STUDIES

Conventional and Multi-Bladed Propellers

Having developed a computer program incorporating the propeller performance, noise, weight, and cost criteria derived under this program, a sensitivity study was undertaken to evaluate the trade-offs among these factors for propeller configurations applicable to the representative aircraft from each general category described in Tables I and II. As specified in RFP A-15989 (HK-5) dated 18 December 1969, the trade-off studies were targeted at noise level objectives down to the range of 65 to 75 PNL at a distance of 500 ft at maximum power. For these studies, only the isolated propeller was considered. The aircraft and engine parameters were not varied and have been included only as implied by the operating conditions specified for each aircraft. The results of the studies covering the propellers for the representative aircraft of Categories I through V as defined in Table II are discussed below.

For each aircraft a study was made for a series of propellers incorporating variations in diameter, number of blades from 2 to 8, blade activity factor from 100-200 all at the same integrated design lift coefficient of 0.5 as explained previously. For Category I, an activity factor range of 80-200 was used. To investigate noise levels down to the 65-75 PNL range, a tipspeed range from 350 ft/sec to 900 ft/sec was examined. The parametric studies were made using the computer program previously discussed under the section on Technology Identification. Performance has been computed for the take-off, climb and cruise regimes as defined on Table II. The corresponding 500 foot side line noise (PNL) for the take-off condition was computed with the minimum tipspeed limited by the 50% propeller stall criteria. The weight and cost are based on 1980 technology. For each aircraft category, the 1970 technology weight and costs are included on the curves corresponding to the number of blades and activity factor of the propeller currently on the aircraft.

Curves of performance (T.O., climb, and cruise), noise, weight and cost were plotted versus tipspeed for constant values of diameter for a range of activity factors and number of blades. The data for 2, 4 and 6-bladed propellers were plotted on figures 15, 16, and 17 for the Piper Cherokee. For the fixed pitch propellers associated with aircraft Category I, propeller blade angles as independent variables have been included on the performance curves. Thus, the blade angle providing the best performance compromise for take-off, climb and cruise can be selected as desired by the particular operator. Similar data for 2, 4, and 6-bladed propellers were plotted on figures 18, 19, and 20 for the Cessna 210J Centurion Category II aircraft and on figures 21, 22, and 23 for the Beech Baron B55, Category III aircraft. The same data for 3, 4 and 6-bladed propellers were plotted on figures 24, 25, and 26 for the Category IV Beech Queen Air and on figures 27, 28, and 29 for the Category V DeHavilland Twin Otter. The 8-bladed propeller data were not included because of their excessively high propeller costs for minimal noise and performance gains. As a reference, the present day propeller configuration was noted on the chart with the appropriate propeller number of blades. The required thrust at cruise is not tabulated in Table II, but it can be found from these reference points. It should be noted that Table II was set up to establish approximate values of aircraft thrust requirements at key operating conditions to set up constraints for the sensitivity studies. The actual thrust requirements for each of the aircraft will differ in varying degrees from the Table II data, but the important point is that the constraints of required thrust at takeoff, climb, and cruise must be considered in evaluating the tradeoffs for low noise propellers.

From an inspection of these sensitivity studies, the effect of the primary geometric and operating parameters inherent to each of the five aircraft applications are discussed below.

Noise

1. Tipspeed - It is expected that the slope of the noise curves with tipspeed would tend to flatten out at the lower tipspeeds as stall approaches 50% of the blade radius. However, as was discussed in the section on Noise Generalization, the noise characteristics of propellers operating in the very low tipspeed range have not been clearly established. Accordingly, the curves were conservatively terminated at the tipspeed corresponding to 50% blade stall. An approximate 6 PNdB reduction in PNL per 100 ft/sec reduction in tipspeed can be obtained as long as the propeller is operating with no stall outboard of the 50% radius.

2. Diameter - For a given tipspeed, there is a further 1.5 PNdB reduction per foot increase in diameter. Furthermore, increasing diameter permits operating at a lower tipspeed before 50% stall occurs and consequently results in further noise reduction.

3. Number of blades - A 3 PNdB reduction in PNL is attained by the addition of a blade. Furthermore, with increased number of blades, it is possible to operate at a reduced tipspeed before 50% stall occurs.

4. Activity factor - By increasing AF, it is possible to operate at a lower tipspeed before the propeller is 50% stalled and consequently somewhat lower noise levels are attainable.

In summary, on the basis of the above discussion, minimum perceived noise level is obtained by reducing tipspeed, and increasing diameter, number of blades, and activity factor relative to the present propeller configurations.

Performance

1. Tipspeed - For a given propeller configutation (i.e. diameter, number of blades, and activity factor) peak performance is obtained at the tipspeed where the propeller is operating at blade sectional angles of attack corresponding to maximum lift to drag ratios. At the tipspeeds below this optimum and corresponding to the lower noise levels, efficiency is reduced, resulting in the need to increase diameter, activity factor and or number of blades to attain the performance levels obtained at the higher tipspeed.

2. Diameter - At the lower tipspeeds corresponding to reduced noise levels, performance increases as diameter increases.

3. Number of blades - The addition of more blades also increases performance at the lower tipspeed.

4. Activity factor - Increases in activity factor at the lower tipspeeds result in better performance.

In summary, as noted in the noise discussion for the reduced tipspeeds required for low perceived noise levels, increases in diameter, number of blades and activity factor are required to maintain performance as well as to reduce noise.

Weight and Cost

1. Tipspeed - Weight and cost reductions can be obtained by reducing tipspeed.

2. Diameter - The increases in diameter required to meet the low noise objectives for the 1980 time period and the performance requirements, will result in increased propeller weight and cost.

3. Number of blades - Increase in number of blades to offset at least in part the diameter increases required for quiet propellers will also result in increases in weight and cost.

4. Activity factor - Weight and cost increase with increases in activity factor.

Thus, for the reduced tipspeeds, increases in diameter, activity factor, and number of blades required to attain the significantly lower noise levels and the required performance of the 1980 propellers result in increased cost and weight.

Optimum Low Noise Propeller

The optimum propeller for the aircraft can be obtained from these curves depending upon the relative importance of performance, noise, weight and cost to the aircraft owner. As an indication of how these trade-off studies can be made, for the Cessna 210J, curves of propeller performance, noise, weight and cost were plotted on the assumption that the propeller is always operating at the tipspeed corresponding to 50% stall at take-off and consequently minimum noise. These are plotted as functions of diameter, activity factor and number of blades on figure 30. From plots such as these, the operator can judge the effect of these trade-off parameters and decide upon an optimum propeller configuration which best fits his requirement.

Changes in Integrated Lift Coefficient

Although as previously noted, an integrated design lift coefficient adjustment has not been included in the generalized performance computer program, the effect of integrated design lift coefficient for a sample case has been shown. A sensitivity study was made for the Category II Cessna 210J airplane with a 4-bladed propeller with a 0.7 integrated design lift coefficient and plotted on figure 31. The performance computations were made utilizing the Contractor's propeller performance computer program which was used in deriving the generalized performance for the study. Weight and cost are not functions of integrated design lift coefficient. Consequently, the values are the same as for the corresponding propellers shown on figure 19. Noise is only a function of integrated design lift coefficient in that, with increases in this parameter for the same activity factor, the 50% stall criteria occurs at a lower tipspeed with correspondingly lower levels of perceived noise.

As an example of possible ways of evaluating this effect, activity factor and integrated design lift coefficient, C_{L_i} variations for 4-bladed, 8 ft. diameter propellers for the Cessna 210J operating at 400 ft/sec at take-off are shown on figure 32. The following evaluation was made from these data based on constant take-off performance.

C_{L_i}/AF	0.5/190	0.7/156	0.3/164	0.5/150	0.7/129
T.O. Thrust (300 SHP-400 ft/sec -S.L.-71.2 Knots)	900	900	820	820	820
Climb Thrust (285 SHP-378 ft/sec-S.L.-95.5 Knots)	742	730	676	710	708
Cruise Thrust (214 SHP-346 ft/sec-7500'-163.2 Knots)	372	364	363	370	364
PNL	75	76	75.5	76	77.5
Weight	114	90	95	86	76
Cost	1060	920	950	885	790

It can be seen that for the same take-off performance, reductions in activity factor are possible with increases in integrated design lift coefficient. Consequently, weight reductions of up to 20% can be realized and cost reductions of up to 10% are realized for essentially the same noise at the expense of some loss in cruise performance.

Similar studies can be made to investigate the effects of increasing integrated design lift coefficient on diameter from the data presented on figure 19 and figure 31.

Summary

It is immediately apparent from an inspection of these sensitivity data that to achieve significant reductions in perceived noise levels leads to low tipspeed propellers with appreciable increases in overall size, weight and cost. The reality of such drastic changes in general aviation propellers is dependent entirely upon how stringent the anti-noise requirements may be by the 1980 period. Moreover, it should be apparent that these large changes in propeller configuration and operating tipspeeds required to attain low noise levels imply significant modifications to the engines to provide the associated large reductions in propeller shaft speed and probably to the aircraft to accommodate these propellers. Thus, while the effect of low noise propellers on engine and aircraft design is beyond the scope of this study, it is obvious that this will need to be thoroughly investigated by engine and aircraft manufacturers before the requirement for quiet propellers can be completely assessed. Moreover, the contribution of the engine and aircraft to total aircraft noise needs to be evaluated. Thus, it is evident that the impact of the possible noise restrictions in the 1980 period on general aviation will have a significant effect on the design and cost of the entire aircraft to a degree dependent on the severity of the restrictions.

The sensitivity studies discussed above were all based on using the same horsepower as is presently available on the aircraft. Another approach would be to define a take-off thrust requirement and to conduct a sensitivity study to select an optimum tipspeed, horsepower and propeller to meet the noise and performance requirements. Thus, an engine size as well as a propeller size could be defined. These analytical procedures (APPENDICES A and B) and the corresponding computer program (APPENDIX D) provide the capability of undertaking sensitivity studies similar to the ones accomplished herein for establishing the optimum propeller configuration for any aircraft on the basis of the trade-off criteria specified by the user.

Other Concepts

Variable Camber Propellers. - The Variable Camber propeller was developed by Hamilton Standard as an effective solution to the special aircraft problem of stringent performance requirements at more than one operating condition. A preliminary look at the application of this propeller concept to general aviation aircraft indicated no significant performance and noise advantage with a considerable increase in weight and cost. Consequently, this concept was not further considered in this study. However, particularly for the large aircraft, if the cruise speed should increase significantly, this concept should be given further consideration.

Engine Revisions Required to Reduce Propeller Noise. - Early in the sensitivity study it became apparent that large reductions in propeller rpm would be required to reduce noise level. The question of cost and weight change associated with modifications to the engine then became of interest. A definitive answer to this question requires study by engine manufacturers and cannot be provided within the scope of this study, but a preliminary examination of a typical engine modification and the impact on total engine weight was made.

Direct drive piston engines must have reduction gearing incorporated and geared engines must have larger gear ratios in order to attain the very low tipspeeds required for quiet propellers. Small gear reduction ratios (up to approximately 2:1) can be attained by either incorporating or modifying existing simple spur gear trains. Higher gear ratios (approximately 4:1) require more complex gear trains; i.e., compound spur or multi-stage and planetary.

Figure 33 shows a preliminary sketch of typical modifications proposed for the gear train of the Continental Tiara 6-260A engine to obtain a relatively small change in gear reduction. The cam shaft of the present engine configuration is driven directly from the propeller shaft by a spline. In the modified version, the propeller drive shaft would be spaced further away from the engine shaft to increase the ratio of the drive gears. This requires that the cam shaft be supported on a separate bearing and driven by a single mesh spur gear train at its original speed of twice engine rpm. More axial space is required to install this additional gear train. Since the cam shaft and propeller shaft are no longer in line, oil for the propeller must be transferred from the cam shaft to the propeller shaft by a bent tube or manifold. A larger gearcase housing is then required to enclose the modified gear train. These engine changes reduce propeller noise but do not necessarily reduce engine noise. Higher gear ratios would require more extensive modifications to the engine than those described above.

A preliminary study was also made to assess the effect of propeller speed on engine and gearbox weights. The Cessna 210J airplane from Category II with a 285 horsepower engine was used as an example. The present engine on this airplane is the Continental IO-520-A. The Continental 6-285A geared engine was selected for the lower propeller tipspeed applications. Data for these engines is shown in the following table:

Engine	Cyl.	Horsepower	ERPM	Weight	Drive
IO-520A	6	285	2700	471	direct
6-285A	6	285	4000	354	geared

Weight of the basic 6-285A engine without gearing was estimated using an approximate equation for gearbox weight developed by this Contractor for higher power engines. This equation relates gearbox weight to propeller torque as shown below:

$$W = 0.10\ Q^{0.84}$$

where: W = weight of gearbox, lb

Q = propeller torque, ft-lb

Using the Continental 6-2··A engine for a 95 PNL propeller driven at 2000 RPM, the gearbox weight was calculated to be 26 pounds resulting in a basic engine weight of 354 - 26 = 328 pounds. The following table shows total geared engine weights for four PNL values for the 210J airplane using the above equation for gearbox weight.

	PNdB	HP	PRPM	Prop. Torque	ERPM	G/R	Engine Torque	Weights Eng	G/B	Total
1)	102	285	2700	555	2700	1:1	555	471	0	471
2)	95	285	2000	748	4000	2:1	373	328	26	354
3)	85	285	1700	882	4000	2.35:1	373	328	30	358
4)	75	285	1000	1500	4000	4:1	373	328	47	375

Although the lower propeller rpm required to reduce noise levels called for reduction gearing, the engine rpm has been increased over that of a direct-drive engine. Therefore, for the same horsepower, the torque requirement of the engine was reduced and the engine weight decreased more than the additional weight associated with reduction gearing. This resulted in a lighter overall powerplant.

This study is preliminary in nature and applies only to a narrow range of engine powers. No cost estimates were made for this study.. Accordingly, it is evident that a detailed study of weight and cost variations in general aviation reciprocating engines must be made to thoroughly assess the engine revisions required to accommodate low noise propellers.

Integrated Gearbox and Propeller. - An additional weight and cost saving can be gained by making the propeller barrel integral with the engine drive shaft on geared engines and combining the gearing, propeller oil reservoir and control into an integrated assembly. The major weight and cost saving results from elimination of the propeller attaching flanges on the propeller and engine shaft. This would be more advantageous for the higher powered aircraft.

Prop-Fan Propulsion System. - An interesting new propulsion concept currently being extensively studied by this Contractor for application to large STOL aircraft and which has several attractive features desirable for general aviation aircraft propulsors including low noise characteristics is the Prop-Fan. As its name implies, the Prop-Fan lies intermediate in the propulsion spectrum between propellers and fans and is aimed at combining the good take-off and reverse performance and low noise levels of the propeller with the favorable high speed cruise performance and compact size of the fan. This propulsion concept includes a ducted, multiblade, variable pitch fan which can be coupled to a suitable powerplant. Characteristically, the Prop-Fan is a compact, small diameter machine with good performance over a broad flight spectrum and with low noise production which when matched to a lightweight powerplant could be an attractive, geometrically compatible, low noise lightweight propulsion package for general aviation aircraft. Accordingly, a brief study of this concept has been undertaken herein to provide more specific visibility as to its potential application to the rather small aircraft included in general aviation.

As can be seen from an inspection of the propeller sensitivity study curves, the 65-75 PNdB noise level is attainable only by appreciable increases in diameter, number of blades, and activity factor along with large reductions in tipspeeds. Propellers with these large geometric proportions will be heavier and generally less compatible with the geometries of the rather small aircraft included in general aviation than existing propeller installations. In view of the attractive compactness and low noise characteristics of the Prop-Fan propulsor concept, a preliminary study has been undertaken to compare the size, weight, performance and noise characteristics of a Prop-Fan propulsion system to a quiet propeller propulsion system both targeted for 75 PNdB at 500 feet and based on one of the study aircraft.

Since the forecasts predict that the largest portion of the general aviation fleet in the 1980 time period will be the Category II aircraft, the Cessna 210J Centurion was chosen as the Prop-Fan study aircraft. The 4-bladed, 8-foot diameter propeller incorporating blades of 150 activity factor and 0.5 integrated design lift coefficient selected by A. C. M. D. for the hardware conceptual design study is the comparator quiet propeller along with the current propeller installation. The approach then is to compare the low noise propulsors and the current propeller installation with each sized to meet the Cessna 210J performance requirements.

As a first step in establishing a Prop-Fan configuration for this comparison, a plot of horsepower required for the take-off thrust and the corresponding perceived noise level as a function of diameter for a representative 8-bladed Prop-Fan was prepared to permit the selection of a suitable diameter. From these data presented in figure 34, a 3.5-foot diameter was selected as the basis for a more detailed sensitivity study. The effect of tipspeed and blade activity factor on performance (T.O., climb and cruise) and noise at 500 feet during take-off is presented in figure 35 along with similar data on the above quiet propeller. From an inspection of this figure, it is apparent that a 3.5-ft diameter/8-bladed/1100 total activity factor/0.35 C_{L_i} Prop-Fan is aerodynamically and acoustically (in terms of PNL) similar to the 8-foot diameter/4-bladed/600 total activity factor/0.5 C_{L_i} quiet propeller. However the spacial envelope of these two propulsors are grossly different. A sketch showing the comparative size of the present propeller on the Cessna 210J which produces 105 PNdB at 500 ft at the take-off condition, the quiet conventional propeller and the Prop-Fan required to reduce the perceived noise level to 75 PNdB is shown in figure 36 along with other pertinent data. From a study of this figure, the huge differences in the size of the three propulsors is immediately apparent. Moreover, it may be noted that while the Prop-Fan weight (106 pounds) is nearly twice that of the present propeller weight (55 pounds), it is significantly lighter than the quiet propeller (133 pounds). However, the Prop-Fan requires approximately 10 percent more power for the same performance than either conventional propeller. On the other hand, the weight of the large gear reduction required for the quiet propeller for reduced noise level may be eliminated for the Prop-Fan system since with its small diameter, the fan will operate at the desired low tipspeeds at RPM levels similar to the crankshaft speeds of todays high speed, lightweight reciprocating engines. Thus, the total propulsion package of tomorrow's quiet Prop-Fan propulsion system may actually be substantially less than today's propulsion system.

In order to obtain a clearer perspective of this promising possibility, the two quiet propulsors were compared to the present propulsor on a total propulsion package weight basis. Utilizing the lightweight engine concept discussed previously and the Prop-Fan performance data presented in figure 36, the 3.5-foot diameter Prop-Fan selected above, directly driven by a 330 shaft horsepower reciprocating engine, and turning at 4000 rpm adequately fulfills the performance requirements of the Cessna 210J aircraft and meets the low noise objectives of this study with a significant reduction in the total propulsion system weight compared to that of the present propulsion package. Similarly, a total package weight was derived for the 8-foot diameter quiet propeller propulsion system. For both quiet propulsors, the Continental 6-285A basic engine weight as derived in the previous section was scaled for the power required on the conservative assumption that the weight is proportional to engine torque. On this basis, the weights of the two quiet propulsion systems were derived and compared with the present propulsion system in Table IX. While it is recognized that these weights do not necessarily correspond to actual engines, the trend with crankshaft speed appears to be of the correct order.

From Table IX, it is shown that for essentially equal performance and nearly 30 PNdB reduction in perceived noise level, the Prop-Fan system is approximately 4.5 percent lighter than the present propulsion system and nearly 8 percent lighter than the equally quiet larger diameter propeller propulsion system. Even greater weight savings may be realized by further increasing engine speed with a small reduction gear. Thus, the selection of the optimum engine for the Prop-Fan needs to be studied in detail by the engine manufacturer.

On the basis of this cursory study, the Prop-Fan propulsion system appears to be an attractive solution for the low noise restriction which may be imposed on general aviation aircraft of the 1980 time period. It should be emphasized that these weight estimations were based on only one sample Prop-Fan and only a few engines listed in recent periodicals (ref. 4). Moreover, no realistic cost estimates could be made at this time for this concept. Although on a dollars per pound basis, the comparative weights would indicate that the costs would be competitive to present propulsion systems. In view of the foregoing discussions, a thorough, detailed study of the Prop-Fan propulsion system needs to be undertaken including the performance, noise, weight and cost characteristics and future general aviation reciprocating engines, as influenced by the requirement for noise levels in the 70-80 PNL at 500-foot range. Further, the study should be of sufficient scope to include the turbo-prop and the promising light-weight Wankel rotary combustion engine. Although the high cost of these engine types makes them less attractive today than the advanced reciprocating engines, with continued development and increased production, both types may become more competitive.

ADVANCED PROPELLER DESIGN CONCEPT STUDY

Propeller Selections for Conceptual Design Study

From the basic sensitivity study data covering a family of propeller geometries for the representative aircraft of Categories I - V, Advanced Concepts and Mission Division selected the following representative propellers for the conceptual design studies:

Category	Aircraft	Current Diam (ft)	Diam (ft)	No. Blades	AF	Tipspeed (ft/sec)	T.O. Thrust (pounds)	PNL
II	Cessna 210J Centurion	6.8	8.0	4	150	400	820	76
IV	Beech Queen Air	7.75	9.0	3	150	580	2060	87
V	DeHavilland Twin Otter	8.0	10.0	4	150	450	3520	83

Propeller Hardware Concept Study

This design study was conducted to generate conceptual drawings of low noise level propellers in sufficient detail to permit calculation of weight and cost figures for validation of weight and cost generalized equations incorporated in the computer program previously discussed under the section on Technology Identification. The representative propeller parameters for Categories II, IV and V listed in the previous section were used in this study. Advanced blade materials were incorporated where economically feasible (Categories IV and V) and a double-acting pitch change system with protective pitch lock and take-off stop was incorporated in Category V to reduce weight.

The low rpm required for low noise level introduces a blade retention loading condition which is peculiar to this family of propellers. The low centrifugal load acting on the blade due to low rpm is insufficient to keep the blade seated in the simple single row ball retention under moment loading. This is called a "rocking" condition which must be corrected by sizing the blade retention bearing diameter larger than is normally required for centrifugal load capacity. A weight penalty is incurred by this oversize retention which is not encountered in present propellers. The weight penalty is still less than that associated with adding another retention bearing to react blade moments. The introduction of lightweight blades in Category IV and V propellers tends to accentuate this "rocking" condition since even lower centrifugal loads are generated.

The hardware conceptual designs are discussed below for each representative propeller selected by A.C.M.D.

Category II. - This is a 4-bladed constant speed, nonfeathering, nonreversing propeller design using parameters for the single-engine Cessna 210J aircraft. A sectional drawing and a hydraulic schematic of this propeller are shown in figures 37 and 38 respectively. The blades are made from solid aluminum forgings for low cost and the barrel, pitch change piston and dome are also made from aluminum forgings for low cost and low weight. A simple ball retention is provided for the blades which includes steel race inserts and a nylon ball separator cage. A split aluminum blade clamp holds the blade against the retention bearing statically and at low RPM. In operation, the blade is loaded centrifugally against the bearing.

Pitch change is accomplished by motion of the piston transferred to a crank pin on the blade by a simple steel connecting link with bronze bushings. The piston is single-acting and pressurized on the forward side toward high pitch and it reacts against blade and spring loads tending to move toward low pitch. Engine oil under pressure is supplied to the piston from the engine-mounted, single-acting governor through a transfer tube in the engine shaft. A spring acting between the piston and the barrel insures that the blades will move to flat pitch under all operating conditions in case of hydraulic pressure loss.

Piston torque is reacted by the ends of the piston link pins sliding in a slotted steel ring bolted to the barrel. A fiberglass reinforced plastic spinner is shown but is not included in the cost and weight equations since spinners are optional and are not installed on all propellers. Sufficient oil is carried in the barrel cavity to lubricate the blade retention bearings and the pitch change link pin bushings. Blade angle range is 50 degrees measured from flat pitch.

Category IV. - This is a 3-bladed, constant speed, full feathering, nonreversing propeller design using parameters for the twin-engine Beech Queen Air aircraft. A sectional drawing and a hydraulic schematic of this propeller are shown in figures 39 and 40 respectively. Blade construction incorporates a solid aluminum core with reinforced composite shell for low weight. Blade weight and cost are based on solid aluminum core and fiberglass reinforced epoxy shell material, but other more advanced fiber composite materials could be used based on additional study to evaluate their cost effectiveness (APPENDIX E). A simple ball bearing type blade retention incorporates a hardened outer race integral with the steel barrel, a steel inner race insert on the aluminum blade core and a nylon ball separator cage. A split aluminum blade clamp positions the blade against the retention bearing for static and low rpm operation. A rubber lip seal under the blade clamp seals lubrication oil inside the barrel.

The blades are counterweighted toward high pitch. This, in conjunction with springs which load the pitch change piston toward high pitch, permits the blades to move to full feather position in case of hydraulic pressure loss. The piston is single-acting and is pressurized on the inboard side toward low pitch and reacts against net counterweight and spring loads toward high pitch. Pressurized engine oil is supplied to the piston from the engine-mounted, single-acting governor through a transfer tube in the engine shaft. Pitch change is accomplished by motion of the piston transferred to a crank pin roller on the blade through a steel yoke fastened to the piston with a thread. Yoke torque is reacted by a slotted yoke-mounted arm sliding on a guide rod in the barrel. The yoke is straddle-supported on two bulkheads in the barrel, and the aluminum piston has seal clearance with the aluminum dome shell.

The fiberglass-reinforced plastic spinner is not included in the weight and cost equations. Lubricating oil is carried in the barrel cavity at sufficient level to cover the blade retention bearings and the crank pin rollers. The blade angle range is 80 degrees measured from flat pitch.

Category V. - This 4-bladed, constant speed, full feathering and reversing propeller is designed using parameters for the DeHavilland Twin Otter aircraft. A sectional drawing and hydraulic schematic of the propeller are shown in figures 41 and 42 respectively. The blades incorporate the same aluminum core, fiberglass reinforced epoxy shell construction as the Category IV propeller except there are no counterweights. The weight of counterweights for a propeller this size becomes prohibitive.

The blade retention incorporates the integral ball race in a steel barrel as in Category IV but it was necessary to incorporate a full race configuration to aid in reacting moment loads that would unseat the ball bearing. The blade "rocking" condition was of sufficient magnitude in this propeller that enlarging the retention bearing diameter sufficiently to react the moments incurred a prohibitive weight penalty. A lip seal is mounted below the retention bearing and the bearing is grease-packed to save the weight of lubricating oil in the barrel cavity with the complex sealing configuration that would be required around the pitch change links. An outer lip seal is also provided and ball loading holes and plugs are provided in the barrel to permit the bearing to be assembled.

The pitch change actuator has double-acting pistons pressurized to move the blades toward both high and low pitch. Two aluminum pistons translate in a steel cylinder with a stationary steel bulkhead separating them. The length to diameter ratio of the actuator is such that mounting it inside the barrel under the blades is desirable for low weight. The blades are then actuated by spherical rod-end links from piston pins to crank pins on the blades. The spherical bearings are lined with reinforced Teflon so that no lubrication is required. Spherical link bearings were selected to facilitate blade installation without removing the actuator. The actuator is supported on the barrel flange at the rear and on a barrel-mounted aluminum bulkhead at the front end. This bulkhead also reacts piston torque with a sliding spline and provides clearance holes for the blade links.

A four-way control valve spool is mounted inside the actuator piston hub and meters oil to either the high or low pitch piston. The valve is actuated by an Acme-threaded screw driven by a gear motor which receives a hydraulic signal from the engine-mounted, double-acting governor. The screw is grounded axially to the barrel through the motor housing and acts as an in-place pitch lock towards low pitch in the event of pitch change pressure loss. Since the screw, valve and actuator piston move together axially upon signal from the gear motor, a small gap is maintained between the screw and piston at all times. Upon loss of pitch change pressure in the positive blade angle flight range, the blades are prevented from moving toward low pitch except for the few degrees represented by the piston-to-screw gap.

The fiberglass reinforced plastic spinner, being optional equipment, is not included in the cost and weight equations.

An electric motor-driven auxiliary pump provides pressurized oil to move the blades to full-feather blade angle as the normal engine-driven pump becomes inactive due to low engine rpm during the feathering operation.

One side of the hydraulic pitch change motor is subjected to pressure maintained at one half pump supply pressure by a regulating valve at all blade angles above the low pitch take-off angle. This half supply pressure is biased on the other side of the motor by metered pressure from the single-acting governor either higher or lower than the half supply pressure to move toward high and low pitch, respectively. At the low pitch stop take-off angle, an extension of the piston de-activates the half-pressure valve to balance the pressures on each side of the pitch change motor preventing blade motion from this low pitch stop angle.

Reversing is accomplished by actuating the reversing lever which activates a reversing regulating valve maintaining half supply pressure on the low pitch side of the hydraulic pitch change motor. The lever also moves a sleeve valve on the engine shaft which uncovers ports connecting the other side of the motor to drain. A spring-loaded sleeve regulating valve on the inside of the shaft then meters downstream pressure from the motor to hold the blade angle determined by the dump port position. Uncovering more dump ports with the reversing lever causes the blades to move further into reverse. Unreversing is accomplished by moving the reversing lever to the normal operating position. The dump ports in the engine shaft are then blocked-off and the system returns to normal operation on or above the low pitch take-off stop.

The concept drawings of the three representative propellers were utilized by the Contractor's weight and cost evaluation groups to obtain a detailed part-by-part weight and cost figure for each of the propellers. These figures provided a point in each of Categories II, IV and V from which accurate weight and cost estimates could be made for assessing the accuracy of the generalized weight and cost equations particularly as applied to quiet propellers of the 1980 time period.

Discussion of 1980 Propeller Weights. - The generalized weight equation was originally established for high tipspeed propellers and adjusted to the actual weights of current general aviation propellers. To check the applicability of this equation to the projected 1980 low noise propellers, three propellers (Categories II, IV and V) were designed with approximately half the current tipspeed levels and their weights were calculated. Although the Category IV weight checked the equation quite well (Table X), the discrepancies were sufficiently large for Categories II and V to make the weight equation suspect for these low tipspeed propellers.

This weight discrepancy appears to be related to the following factors:

1) Low noise level propellers require blades with low tipspeed and substantial activity factors. Blade centrifugal loads are low and moments about axes perpendicular to the blade axis are sufficiently high so that blade retention size must be increased to prevent the blade from "rocking" or unloading the retention bearing on one side due to the moments. For this reason, the retention bearing is oversized and heavier than current propeller retentions which are basically designed for thrust capacity.

2) Retention weight is a greater proportion of total blade weight.

3) Blade weight is a greater proportion of total propeller weight because blades rotating at slower speeds require less pitch change actuator capacity than blades rotating at higher speeds.

The above changes in propeller weight proportions coupled with a large change in the "ND" term of the equation (TABLE V) indicate the need to calculate the weights of more study propellers at different tipspeed values to generate a valid generalized weight equation. In the absence of such detailed weight calculations, the generalized weight equation of Table V is the best available guide to general aviation propeller weights. In using the equation, it should be remembered that actual weights will likely be somewhat higher than equation weights in Categories I, II and V. Accordingly, the computer program retains the original weight equation as defined in Table V.

Although based on the results of the detailed design study, the weight level of the 1980 quiet propeller configuration for the Category II aircraft will apparently be significantly heavier than indicated from the sensitivity study, the weight of the entire propulsion system is expected to remain approximately the same. Considering the reduced weights attainable with high speed piston engines as discussed under the sensitivity study, the 1980 quiet propulsion package weight is compared to the current 1970 propulsion package weight for the Cessna 210F aircraft on figure 36.

Discussion of Propeller Costs. - In endeavoring to provide a single basic computerized costing method for all general aviation propellers, the following equation was derived:

$$C = KZB^{0.75} = LF \frac{1}{W_T} (H) (Y) + PP$$

where K = Constant based on single unit cost for each propeller category,

C = Average O.E.M. propeller cost based on number of units/year (\$/lb)

B = Number of blades

LF = Learning curve factor for a number of units/year (fig. 14)

LF_1 = Learning factor for a single unit. (fig. 14)

W_T = Propeller weight (lbs)

H = Labor time (hours)

Y = Labor rate (\$/hour)

PP = Cost of purchased parts and raw material (\$)

$$Z = \frac{LF}{LF_1}$$

$$K = \frac{LF_1}{W_T B^{0.75}} \left[(H) (Y) + PP \right]$$

Note: Y and PP include mark-up for O.E.M. cost.

Single unit cost C_1 is obtained by omitting the Z factor from the equation.

1969 Propeller Costs. - Costs of 1969 propellers in Categories II, IV and V were taken directly from manufacturers' end user price lists and converted to O.E.M. costs by applying a factor of 60 percent. Cost and weight for several propellers in each of the three categories studied were listed and then averaged to obtain the O.E.M. cost/lb. (Table VI). With cost/lb and number of blades known, the O.E.M. cost equation was solved for the factor K for each category using learning factor LF_1 for a single unit. Factor Z was then calculated, using the ratio of learning curve factor based on the number of propellers manufactured in 1969 to the learning factor for a single unit in each category. Factors K and Z are listed in Table XI for each of the three categories. The K and Z factors were then used to calculate O.E.M. and single unit cost for each of the three propeller categories. (Table XII.)

1980 Propeller Costs. - The same equations and cost structure (i.e., labor rates and purchased parts cost base) for 1969 were used for 1980. New K and Z factors were calculated for 1980 based on propeller configuration, material and manufacturing process changes and changes in quantities to be manufactured. As noted in the sections on Propeller Selections for Conceptual Design Study and Propeller Hardware Concept Study, a representative low noise level propeller was selected for detailed design study in each of Categories II, IV and V for 1980.

Based on design concept drawings generated for these propellers, the contractor's cost evaluation group compiled labor time and purchased part and raw material costs for each of the three propellers. Based on an assumed labor rate of $13.50/hour and purchased part costs, both reflecting mark-up to O.E.M. cost, new K and Z factors were calculated using the quantities forecast for manufacture in 1980 listed in Table XI. The Category II propeller design changed only in number and size of blades and utilized the same materials and design concept as the 1969 propeller. Propellers in Categories IV and V were modified to incorporate aluminum core and fiberglass reinforced epoxy shell blades. This change represents a blade weight saving of approximately 25 percent compared with solid aluminum blades. With new shell design concept and manufacturing processes, the blade cost was evaluated as twice solid aluminum blade cost. Category V propeller also incorporates a dual-acting actuator with pitch lock which represents a significant weight saving over a counterweighted single-acting propeller for a moderate increase in cost.

Cost Summary. - Table XIII shows a comparison of O.E.M. costs for the representative propellers as calculated from the original generalized equation where factors F and E were estimated and hardware study equation where K was calculated based on cost evaluation of detailed parts from the concept drawings.

Agreement of the costs is good for Categories IV and V but a large variation occurs in Category II. This discrepancy is undoubtedly due to the weight of the Category II propeller being higher than expected, as discussed in the previous section. This lowers the cost/pound accordingly. Due to the few propellers studied in detail, it is recommended that additional propellers at various tipspeeds be studied to validate both the weight and cost equations. In lieu of this additional study, the generalized cost equation developed for the sensitivity study is the best available at this time (Table VII). This equation has been computerized along with the weight equation (TABLE V) for general use.

IDENTIFICATION OF FUTURE RESEARCH ITEMS

During the course of this study, the Contractor has been identifying certain areas where the technology utilized in preparing the design critera and the state-of-the-art advancements required for developing improved, quiet general aviation aircraft propellers will require further study and research. These areas are presented below with recommendations for further study and research.

Refinements and Extensions to the Generalized Methods and Computer Program.

1. Integrated Design Lift Coefficient - Although this propeller blade shape parameter was not included as a variable in the performance generalization, a cursory study has shown that increased blade section design lift coefficient is effective in reducing the activity factor required to provide the performance and noise levels of quiet propellers, thereby relieving somewhat the increasing weight trend with reduced noise levels. Accordingly, it is recommended that the performance generalization be extended to include a variation in integrated design lift coefficient from 0.3 through 0.8. Along with this extension, the compressibility correction factor would need to be extended to cover this range of integrated design lift coefficients. This addition to the method would be included in the computer program.

2. Reverse Thrust - Since it is necessary to know the landing runway distances for aircraft design and operation, it is recommended that a procedure for computing reverse thrust for a range of velocities corresponding to the landing run associated with any aircraft configuration with reversing propellers be included with this general aviation aircraft computational procedure. The analytical method would be based on the adaptation of an existing analytical procedure and cover the same ranges of integrated design lift coefficient, activity factor and number of blades included in the performance generalization. The procedure would be computerized and included as part of the existing computer program.

3. Feather Drag - For aircraft with two or more engines, propeller feather drag is usually required in assessing the engine out performance, stability and control characteristics of the aircraft. It is recommended that a feather drag computational procedure for general aviation propellers be developed and included in the computer program.

4. Improved Noise Generalization - As discussed above, the noise generalization was based upon limited experimental test data on small diameter, low power, low tipspeed propellers. In this connection, Hamilton Standard has been conducting some testing on quiet propellers under Air Force funding. These results were not available in time to incorporate into the empirical noise generalization. It is expected that new experimental data from other sources is also now available or will be soon. Also, data on existing high tipspeed general aviation aircraft are required to verify the accuracy of the method. It is recommended that a survey be made to obtain all the available experimental data and that the data be used in modifying the noise generalization as required. The improved method would replace the present method in the computer program.

5. Weight and Cost Generalizations for the 1980 Time Period - As indicated in the Propeller Hardware Concept Study section, the generalized weight equation for 1980 could not be adequately corrected for the effects of low propeller tipspeeds. Studies of additional propellers over a pertinent range of different tipspeeds and propeller sizes are required to determine the exponents and constants for the generalized weight equation which will take into account tipspeed effects on weight. Cost evaluation studies of these additional propellers would also be conducted to further strengthen the accuracy of the generalized cost equation. These studies would be conducted for all aircraft categories, in the same detail and with the same advanced materials and design concepts utilized for the three representative propellers of this report. The refined weight and cost criteria would be included in the improved computer program.

6. Engine Weight Cost Generalizations - It is evident from this study of quiet propellers, that the performance, noise, weight and cost trade-offs should be based on the total propulsion package including the powerplant and speed reduction gearing. Accordingly, it is recommended that engine and gearbox weight and cost be generalized and included in the computer program to provide a more complete evaluation of the impact of noise restrictions on general aviation aircraft of the 1980 time period.

7. Develop and Publish a Users Manual - With any or all of the above recommended extensions and refinements incorporated into the basic computer program, a very useful tool is provided for examining the various trade-off criteria of performance, noise, weight and cost as may be established by each manufacturer

and operator in selecting the optimum propulsion system for quiet advanced general aviation aircraft. Accordingly, it is recommended that a users manual be prepared and published covering the complete program. The manual would include a complete listing of the program with detailed instructions on its use. Furthermore, all the curves and equations for the analytical methods included in the computer program would be presented with instructions of usage in lieu of a computer. Thus, this users manual would present all the detailed instruction and data needed for computing propeller and/or total propulsion package performance, noise, weight and cost by computer or by hand.

Aerodynamic/Acoustic Research. - Although the aerodynamic performance and noise generalizations developed for this study are based on established methodology, actual performance and noise test data on these very quiet propellers are quite limited since only a few such configuration have been tested. Accordingly, it is recommended that the following experimental research be conducted.

1. An experimental quiet propeller should be built for an appropriate general aviation aircraft, for instance the Cessna 210J, and flight tested over a range of typical operating conditions to establish the performance characteristics of this propeller.

2. As a result of the noise test data survey proposed above, the regions where additional data is required should be established. Very likely two areas will be found where test data is not generally available. The first of these is in carefully controlled acoustic noise surveys on existing moderate to high tipspeed aircraft. The second is on the very low tipspeed, small diameter propellers.

   For the first area of investigation, it is recommended that experimental programs be conducted on, for instance a Cessna 210J, to obtain suitable noise test data for refinement of the generalized propeller noise calculation method. For example, flyover noise measurements could be conducted under ideal test conditions on an aircraft with the current, high tipspeed propellers.

   The second area would be an investigation with the same aircraft and a low tipspeed, quiet propeller designed for the performance of the original equipment propeller. The noise investigation outlined above would be repeated and the data used to check out and refine the noise calculation method.

3. Available test data indicate that engine noise may be a significant contributor to the total noise level of the propulsion systems of current aircraft. If propeller noise reductions projected in this study are to be achieved, a study including the weight, performance, and noise trade-offs of engine mufflers as they relate to total propulsion system noise should be conducted.

Design Study of Integral Gearbox Propellers. - Lower noise levels in general aviation propellers require greater reduction of engine speed to reduce propeller blade tip-speeds to the required levels. Cost and weight figures for this engine change are of particular interest to the aircraft manufacturer and user. A natural out-growth of changes in engine gear reduction is the integration of the propeller, including oil reservoir and governor control, with the gearbox assembly for significant weight and cost savings.

Meaningful cost and weight studies of either the gear reduction alone or gear reduction coupled with propeller integration require design concept studies of representative engines in detail similar to that used in the propeller study of this report. From the results of these studies, credible cost and weight generalized equations could be formulated for advanced powerplants for general aviation in 1980. The nature of this design study would, of course, require close coordination with engine and airframe manufacturers.

Design Study of Lightweight, Low-Cost Blades for Advanced Propellers. - In the course of this study, it became apparent that good visibility for producing lightweight composite structure blades economically for 1980 would require additional study. APPENDIX E shows the multitude of material systems and processes that are applicable to fabrication of an advanced blade.

The lowest cost blade shell using conventional materials and processes is obtained with bulk molding compounds in sheet form compression molded in matched dies. Use of this system is dependent upon the ability to align the reinforcement fibers to obtain strength in the desired direction (i.e., matching the strength of the material to the stress locations in the blade shell). It is proposed first that the material development be conducted on specimens which would be subjected to the appropriate laboratory strength tests.

Design Study of Prop-Fan/Piston Engine Propulsion Package. - As discussed in this study, the concept of the Prop-Fan directly driven by a high-speed piston engine offers the potential of a compact propulsion package which meets the performance requirement and the low perceived noise levels (75 PNdB at 500') objectives of this study with a significant weight saving over today's installations. As was indicated, these conclusions were based on a very limited study of the weight for both the propulsor and the engine. Moreover, no cost estimates were made. In view of the importance of noise abatement for propulsion systems of advanced general aviation aircraft and the attractive solution represented by the Prop-Fan, it is recommended that a comprehensive design study be made of this concept including the complete Prop-Fan/powerplant package to thoroughly evaluate its potential compared to a quiet conventional propeller propulsion system. The study should cover Prop-Fan propulsion systems for each of the aircraft categories except Category I. Because of the uncertainty as to the severity of the noise restrictions, it is recommended that the study consider noise levels from 75 - 95 PNdB at 500-foot sideline.

CONCLUDING REMARKS

1. A computer program has been developed for a generalized method of performance, noise, weight and cost estimation for general aviation propellers.

2. A building block concept permits revised performance, noise, weight and cost criteria to be easily introduced into the program.

3. Stringent noise restrictions on general aviation aircraft will lead to low tipspeed propellers with appreciable increases in overall size, weight and cost.

4. Engine gearboxes with approximately twice the reduction ratios of present geared engines will be required with these large propellers.

5. Advanced materials and manufacturing techniques can be effectively utilized to offset some of the weight penalties associated with the large, quiet propellers.

6. Based on limited study, the total propulsion system weight of these large, quiet propellers coupled to high RPM, lightweight reciprocating engines may not be increased appreciably over today's propulsion systems.

7. A brief study based on the Cessna 210J aircraft indicates that a prop-fan coupled directly to a high RPM, lightweight reciprocating engine offers a compact propulsion package which fulfills the performance requirements of the aircraft and meets the low noise objectives of this study with a significant reduction in propulsion system weight compared to the existing propulsion system.

8. If low noise is not an objective, general aviation propellers of the 1980 time period incorporating advanced technology can be lighter but probably more expensive compared with today's propellers based on today's dollars.

9. Even if low noise and weight are not objectives, the application of advanced fabricating techniques will result in only small cost savings for general aviation propellers of the 1980 time period.

10. Assuming that low noise levels will be a prime objective of general aviation propellers of the 1980 time period, more study and research by the propeller, engine and aircraft manufacturers will be required to attain this objective with propulsion systems and aircraft of acceptable performance, weight and cost.

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ADVANCED GENERA

AIRCRA

	Aircraft Class	Seats	Cruise Vel., MPH	Engine Power	Propeller Typ
I.	Single Eng. Fixed Gear	2-4	100-160	100-200 Recip DD	Fixed Pitch 2 Blades
II.	Single Eng. Adv. Retract Gear IFR Equip.	4-6	120-250	150-300 Recip DD & Geared Some Small Turboprops	Constant Speed 2 Blades-Some 3 B
III.	Light Twins Retract Gear IFR Equip.	4-6	150-300	150-300 Recip DD & Geared Some Small Turboprops	Constant Speed 2 Blades-Some 3 B Full Feather, Dei
IV.	Medium Twins Retract Gear IFR Equip	6-11	150-300	250-450 Turboprops, Recip DD & Geared	Constant Speed Full Feather, Dei 3 Blades
V.	Heavy Twins Retract Gear IFR Equip.	11 & Up	175-400	600-1500 Turbines	Constant Speed Full Feather Deicing, Reverse 3 and 4 Blades

TABLE I

AVIATION PROPELLER STUDY

CLASSIFICATION

Application	Gross Weight, lbs.	Price Range	Example Aircraft
Student, Private Rental, Aerobatic	1000-2500	$8-25K	CESSNA 150, 172, Skyhawk BEECH Musketeer A23-19 PIPER Super Cub, Cherokee
Adv. Student Private (Family) Survey, Business	2000-4000	$20-50K	CESSNA Skywagon 180, 206, 207, 210 BEECH Bonanza, Musketeer Super 300 PIPER Comanche C, Cherokee Arrow MOONEY M20F
Private (Family) Survey, Business	3500-6000	$40-120K	CESSNA Super Skymaster, 310Q BEECH Turbobaron, Baron 55 PIPER Twin Comanche C, Aztec D MOONEY Aerostar
Executive Charter, Air Taxi	6000-8000	$100-200K	CESSNA 401B, 402B, 414, 421 BEECH Queen Air, Duke PIPER Navajo 300, Turbo Navajo NORTH AMERICAN ROCKWELL-Shrike Commander BRITTEN-NORMAN ISLANDER, Helio Twin Stallion
Large Executive Charter, Third Tier Air Liners	8000-12,500	$400-600K	DEHAVILLAND Twin Otter MOONEY MU-2G NORTH AMERICAN ROCKWELL Hawk Commander BEECH King Air HANDLEY PAGE Jetstream

TABLE II

MISSION PROFILES AND PROPELLER REQUIREMENTS

Classification	Representative Aircraft	Condition	BHP	RPM	Altitude	Velocity (Knots)	R/C (1/Min.)	Aircraft Thrust Requirement (Pounds)
I	Piper Cherokee PA-28-140B (1 Lycoming 0-320 engine)	T.O.	150	2700	S.L.	52.5		405
		Climb	150	2700	S.L.	70.5	593 (min.)	387
		Max. Cruise	112	2450	7,000'	115.0		
II	Cessna Centurion 210J (1 Continental IO-520J engine)	T.O.	300	2850	S.L.	71.2		728
		Climb	285	2700	S.L.	95.5	860	688
		Max. Cruise	214	2450	7500'	163.2		
III	Beech Baron B55 (2 Continental IO-470-L engines)	T.O.	(Total) 520	2700	S.L.	75.5		1658
		Climb	520	2700	S.L.	101.2	855 (min.)	791
		1 Engine Out Climb	260	2700	5,000'	87.6	122 (min.)	471
		Max. Cruise	390	2450	7,000'	195.0		
IV	Beech Queen Air "65" & H50 (2 Lycoming IGSO-480-A1E6 engines)	T.O.	(Total) 680	2185	S.L.	77.5		2060
		Climb	680	2185	S.L.	104.0	876 (min.)	1194
		1 Engine Out Climb	340	2185	5,000'	90.1	128 (min.)	723
		Max. Cruise	510	1768	15,000'	186.0		
V	DeHavilland Twin Otter (2 P&W PT6A Engines)	T.O.	(Total) 1304	2200	S.L.	64.5		3390
		Climb	1304	2200	S.L.	87.1	735 (min.)	1977
		1 Engine Out Climb	652	2200	5,000'	75.2	90 (min.)	1229
		Max. Cruise	979	2000	10,000'	175.0		

TABLE III
TYPICAL 1970 PROPELLER WEIGHTS

Aircraft	Class	Speed (MPH)	Prop Model	No. Blades	Prop Type	Dia. (in.)	A. F.	SHP	RPM	Weight Actual	Weight Calc.	K
Piper PA-28-235 Cherokee	I	170	PFA8069/1P235	2	Fixed	80.0	77.5	260	2700	38.0	38.4	170
---	I	---	IAI75/SFC 8040	2	Fixed	80.0	77.5	175	2400	33.0	32.8	170
Beech Bonanza V-35TC	II	190	3A32C76/82ND-2	3	No Cwt-No Fea	80.0	90.5	285	2700	66.0	65.0	180
Cessna 210D, 206	II	190	D2A34C58/90-8	2	No Cwt-No Fea	82.0	103.5	285	2700	55.0	55.0	180
Cessna 205, 210	II	175	D2A34C49/90A-8	2	No Cwt-No Fea	82.0	103.5	260	2625	52.0	51.0	180
Cessna 180	II	130	2A34C50/90A-8	2	No Cwt-No Fea	82.0	103.5	230	2600	52.0	48.5	180
Cessna 180	II	130	BHC-A2XF-1A/8433	2	Cwt-No Fea	84.0	103.5	260	2625	62.0	73.9	240
Piper PA-24	II	160	HC-92ZK-8D/8477A-12A	2	No Cwt-No Fea	72.0	105.0	180	2700	66.0	48.5	240
Beech 35-33	II	160	HC-92ZK-1D1/8477	2	Cwt-No Fea	84.0	103.5	240	2600	68.0	71.4	240
Cessna 32OE Twin Skyknight	III	210	3AF32C87/82NC-5.5	3	Cwt-Fea	76.5	90.5	300	2700	75.0	78.3	240
Beech 95-55	III	210	2AF36C89/78BFS-0	2	Cwt-Fea	78.0	103.5	260	2625	66.0	63.3	240
Cessna 336, 337	III	180	D2AF34C61/L76C-0	2	Cwt-Fea	76.0	105.0	210	2900	58.0	60.0	240
Cessna 336	III	180	D2AF34C46/76C-0	2	Cwt-Fea	76.0	105.0	210	2800	54.0	60.0	240
Cessna 310	III	200	HC-A2XF-2-2B/8433-4	2	Cwt-Fea	80.0	103.5	260	2625	65.0	67.0	240
Piper Comanche 250	III	180	HC-A2XK-1/8433-7	2	Cwt-No Fea	77.0	105.0	250	2575	60.0	60.9	240
Cessna 310	III	200	HC-A2XK-2/8433-4	2	Cwt-Fea	80.0	103.5	260	2625	65.0	67.9	240

TABLE IV
TYPICAL 1970 PROPELLER WEIGHTS

Aircraft	Class	Speed (MPH)	Prop Model	No. Blades	Prop Type	Dia. (in.)	A. F.	SHP	RPM	Weight Actual	Weight Calc.	K
Riley 310 Conversion	IV	---	HC-A3VK-2/V8433-4	3	Cwt-Fea	80.0	103.5	290	2600	87.0	87.6	240
Beech C50	IV	180	PHC-A3VF-4/V8433-2	3	No Cwt-No Fea.	82.0	103.5	285	2700	88.0	91.0	240
Aero Commander 560-A	IV	210	HC-A3X20-2/8433	3	Cwt-Fea.	84.0	103.5	280	2180	91.0	93.0	240
Twin Otter - Prototype	V	184	23LF-321	3	Cwt-Fea.	102.0	110	550	2200	149.0	162.8	240
Handley Page HP 137	V	200	23LF-329	3	Cwt-Fea.	102.0	110	800	1783	152.0	162.3	240
Handley Page HP 137	V	200	23LF-333	3	Cwt-Fea.	96.0	120	800	1783	144.0	153.1	240
Aero-Commander	V	250	33LF-307	3	Cwt-Fea.	84.0	109	575	2000	120.0	111.0	240
Aero-Commander	V	250	33LF-327	3	Cwt-Fea.	93.0	96	575	2000	120.0	122.7	240
1500 HP	V	305	1500 HP	3	Cwt-Fea.	132.0	133	1500	1563	355.0	354.0	240
1500 HP	V	305	1500 HP	3	Double-Acting Hyd - Feather	132.0	133	1500	1563	309.0	309.0	225
DHC-7	V	270	DHC-7	4	Solid Aluminum Blades/Cwt	135.0	116	1140	1210	377.0	363.0	240
DHC-7	V	270	DHC-7	4	Fiberglass Blades Cwt-Fea.	135.0	116	1140	1210	320.0	320.	210

TABLE V
GENERAL AVIATION

Generalized Propeller Weight Equation:

$$W_T = K_W \left[\left(\frac{D}{10}\right)^2 \left(\frac{B}{4}\right)^{0.7} \left(\frac{A.F.}{100}\right)^{0.75} \left(\frac{ND}{20,000}\right)^{0.5} \left(\frac{SHP}{10\ D^2}\right)^{0.12} (M+1.0)^{0.5} \right] + C_W$$

Where:

W_T = Prop. Weight, lbs. (excludes spinner, deicing and governor)

D = Prop. Dia., Ft.

B = No. of Blades

A. F. = Blade activity factor

N = Prop.Speed, RPM (take-off)

SHP = Shaft Horsepower, HP (take-off)

M = Mach No. (Design Condition: Max. Power Cruise)

C_W = Counterweight wt., lbs.

K_W and C_W factors for use in weight equation are taken from table below:

Aircraft Class	Technology 1969	Technology 1980
I	(1)	(1)
II	(2)	(2)
III	(3)	(3)
IV	(3)	(4)
V	(3)	(5)

(1) $K_W = 170,\ C_W = 0$

(2) $K_W = 180,\ C_W = 0$

(3) $K_W = 240$
$C_W = 2.5 \left[\left(\frac{SHP}{N}\right) \left(\frac{M}{D}\right) (A.F.)\ (B)\right]$

(4) $K_W = 210$
$C_W = 2.5 \left[\left(\frac{SHP}{N}\right) \left(\frac{M}{D}\right) (A.F.)\ (B)\right]$

(5) $K_W = 195,\ C_W = 0$

Propeller types associated with above K_W and C_W are as follows:

(1) All fixed - pitch props.
(2) McCauley non-counterweighted, non-feathering, constant speed prop.
(3) All Hartzell, All HSD Small props, and feathering McCauley
(4) Fiberglass-bladed, constant-speed, counterweighted, full feathered
(5) Fiberglass-bladed, constant-speed, double-acting (non-counterweighted), full feathered, reverse

TABLE VI
O.E.M. PRICES FOR 1969 PROPELLERS

Category	Number Blades (B)	Cost ($)	Weight (lbs)	Category	Blades (B)	Cost ($)	Weight (lbs)
I	2	180	38	III	2	390	60
I	2	176	33	III	3	822	75
II	2	420	55	III	2	445	65
II	2	390	68	III	2	630	58
II	2	411	52	IV	3	700	91
II	3	660	66	IV	3	642	88
II	2	390	62	IV	3	717	87
II	2	411	52	V	3	1430	150
II	2	390	68	V	3	1075	117
III	2	445	65	V	3	1015	123
III	2	717	87				

Note: O.E.M. prices were obtained by taking 60% of end user list prices for all categories.

TABLE VII
GENERALIZED COST EQUATION

$$C = ZF\,(3B^{0.75} + E)$$

$$C_1 = F\,(3B^{0.75} + E)$$

where:

C = Average O.E.M. propeller cost for a number of units/year, \$/lb.

C_1 = Single unit O.E.M. propeller cost \$/lb.

$Z = \dfrac{LF}{LF_1}$

LF = Learning curve factor for a number of units/year

LF_1 = Learning curve factor for a single unit.

B = Number of blades.

F = Single Unit cost factor

E = Empirical factor

Note: Reference Figure 14 for LF and LF_1 values based on an 89% slope learning curve.

	1969		1980	
Category	F	E	F	E
I	3.5	1.0	3.5	1.0
II	3.7	1.5	3.7	1.5
III	3.2	3.5	3.2	3.5
IV	2.6	3.5	3.5	3.5
V	2.0	3.5	3.4	3.5

TABLE VIII
SAMPLE COMPUTER PRINTOUT

HAMILTON STANDARD COMPUTER DECK NO. H432
COMPUTES PERFORMANCE,NOISE,WEIGHT,AND COST FOR
GENERAL AVIATION PROPELLERS

1 CESSNA 210J AIRCRAFT CLASSIFICATION II

2 SAMPLE PRINT OUT

OPERATING CONDITION

SHP =	300.	NO. OF ENGINES =	1.	UNIT FACTOR L.C.	= 3.22
ALT-FT =	0.	DESIGN FLIGHT M.=	.262	1000 FACTOR L.C.	= 1.02
V-KTAS =	71.2	CLASSIFICATION =	2.		
TEMP R =	519.	FIELD POINT FT. =	500.		

NUMBER OF BLADES= 4. ACTIVITY FACTOR=150.

				*** 1970 TECHNOLOGY ***			*** 1980 TECHNOLOGY ***								
DIA.FT.	T.S.FPS	THRUST	PNL	QUANTITY	WT-LBS	$COST	QUANTITY	WT-LBS	$COST	ANGLE	FT	M	J	CP	CT
8.	850.	802.	94.	2810.	144.	1423.	5470.	144.	1274.	11.5	1.000	.1077	.445	.0548	.0721
8.	750.	960.	90.	2810.	136.	1337.	5470.	136.	1197.	15.0	1.000	.1077	.504	.0798	.1108
8.	650.	999.	86.	2810.	126.	1244.	5470.	126.	1114.	19.1	1.000	.1077	.582	.1225	.1535
8.	550.	987.	82.	2810.	116.	1145.	5470.	116.	1025.	24.7	1.000	.1077	.687	.2022	.2117
8.	450.	905.	78.	2810.	105.	1035.	5470.	105.	927.	32.9	1.000	.1077	.840	.3692	.2901
8.	350.****************			2810.	93.	913.	5470.	93.	817.	45.8	1.000	.1077	1.080	.7847	.3618
9.	850.	676.	93.	2810.	178.	1751.	5470.	178.	1567.	9.9	1.000	.1077	.445	.0433	.0480
9.	750.	898.	89.	2810.	167.	1645.	5470.	167.	1472.	13.2	1.000	.1077	.504	.0630	.0818
9.	650.	1038.	85.	2810.	155.	1531.	5470.	155.	1371.	17.5	1.000	.1077	.582	.0968	.1260
9.	550.	1031.	81.	2810.	143.	1408.	5470.	143.	1261.	22.4	1.000	.1077	.687	.1598	.1748
9.	450.	983.	76.	2810.	129.	1274.	5470.	129.	1140.	29.9	1.000	.1077	.840	.2917	.2488
9.	350.**********		71.	2810.	114.	1124.	5470.	114.	1006.	42.3	1.000	.1077	1.080	.6200	.3540

OPERATING CONDITION

SHP =	214.	NO. OF ENGINES =	1.
ALT-FT =	7500.	DESIGN FLIGHT M.=	.262
V-KTAS =	163.2	CLASSIFICATION =	2.
TEMP R =	492.	FIELD POINT FT =	-0.

NUMBER OF BLADES= 4. ACTIVITY FACTOR=150.

DIA.FT.	T.S.FPS	THRUST	PNL	ANGLE	FT	M	J	CP	CT
8.00	850.	319.	0.	21.7	1.000	.2534	1.019	.0489	.0359
8.00	750.	372.	0.	25.2	1.000	.2534	1.155	.0712	.0538
8.00	650.	374.	0.	29.2	1.000	.2534	1.333	.1094	.0719
8.00	550.	375.	0.	34.5	1.000	.2534	1.575	.1805	.1008
8.00	450.	380.	0.	41.6	1.000	.2534	1.925	.3296	.1525
8.00	350.	369.	0.	51.2	1.000	.2534	2.476	.7006	.2447
9.00	850.	220.	0.	20.9	1.000	.2534	1.019	.0336	.0195
9.00	750.	339.	0.	24.5	1.000	.2534	1.155	.0563	.0307
9.00	650.	365.	0.	28.5	1.000	.2534	1.333	.0864	.0555
9.00	550.	376.	0.	33.7	1.000	.2534	1.575	.1426	.0797
9.00	450.	382.	0.	40.3	1.000	.2534	1.925	.2604	.1210
9.00	350.	376.	0.	49.3	1.000	.2534	2.476	.5535	.1968

TABLE IX
WEIGHT COMPARISONS OF SEVERAL PROPULSION SYSTEMS FOR THE CESSNA 210J AIRCRAFT

	1970	1980	
	PRESENT PROPULSION SYSTEM	QUIET PROPELLER SYSTEM	PROP-FAN SYSTEM
PROPELLER	2 BLADE 6.83' DIAM. 102 AF 0.5 C_{L_i}	4 BLADE 8' DIAM. 150 AF 0.5 C_{L_i}	8 BLADE 3.5' DIAM. 138 AF 0.35 C_{L_i}
ENGINE REQ.	300 SHP 2850 ERPM 2850 PRPM	300 SHP 4000 ERPM 955 PRPM	330 SHP 4000 ERPM 4000 PRPM
WEIGHTS			
	IO-520-D		
RECIP. ENGINE	454 LB.	345 LB.	380 LB
GEARBOX	------	50 LB.	----
PROPULSOR	55 LB.	133 LB.	*106 LB.
TOTAL	509 LB.	528 LB.	486 LB.
NOISE LEVEL			
PNL	105 PNdB	76 PNdB	77 PNdB

* INCLUDES SHROUD

TABLE X
WEIGHT SUMMARY OF REPRESENTATIVE PROPELLERS FOR 1980

Category	Generalized Equation Weight (lbs.)	Calculated Design Weight (lbs.)	Weight Variation (%)
II	98	133	+35
IV	155	150	-3
V	187	216	+15

TABLE XI

COST EQUATION FACTORS K AND Z

	1969			1980		
Category	Number of Props/year	K	Z	Number of Props/year	K	Z
II	2810	14.8	0.27	5470	10.3	0.24
IV	295	11.6	0.39	680	17.0	0.34
V	65	9.1	0.50	368	14.6	0.37

Note: Number of propellers/year is the number expected to be manufactured by a typical major propeller manufacturer during the year indicated. (Ref. Table 1C, Appendix C).

TABLE XII
PROPELLER O.E.M. AND SINGLE UNIT COSTS ($/LB)

	1969			1980		
Category	Number of Blades (B)	C	C_1	Number of Blades (B)	C	C_1
II	2	6.75	25.00	4	7.00	29.00
IV	3	10.30	26.50	3	13.10	38.50
V	3	10.30	20.60	4	15.25	41.00

TABLE XIII
O.E.M. SINGLE UNIT COST SUMMARY OF REPRESENTATIVE PROPELLERS FOR 1980

Category	Sensitivity Study Generalized Equation (Estimated F&E) $/lb.	Design Study Equation (Calculated K) $/lb.	Cost Variation %
II	37.00	29.10	-21
IV	36.30	38.50	+6
V	40.00	41.20	+3

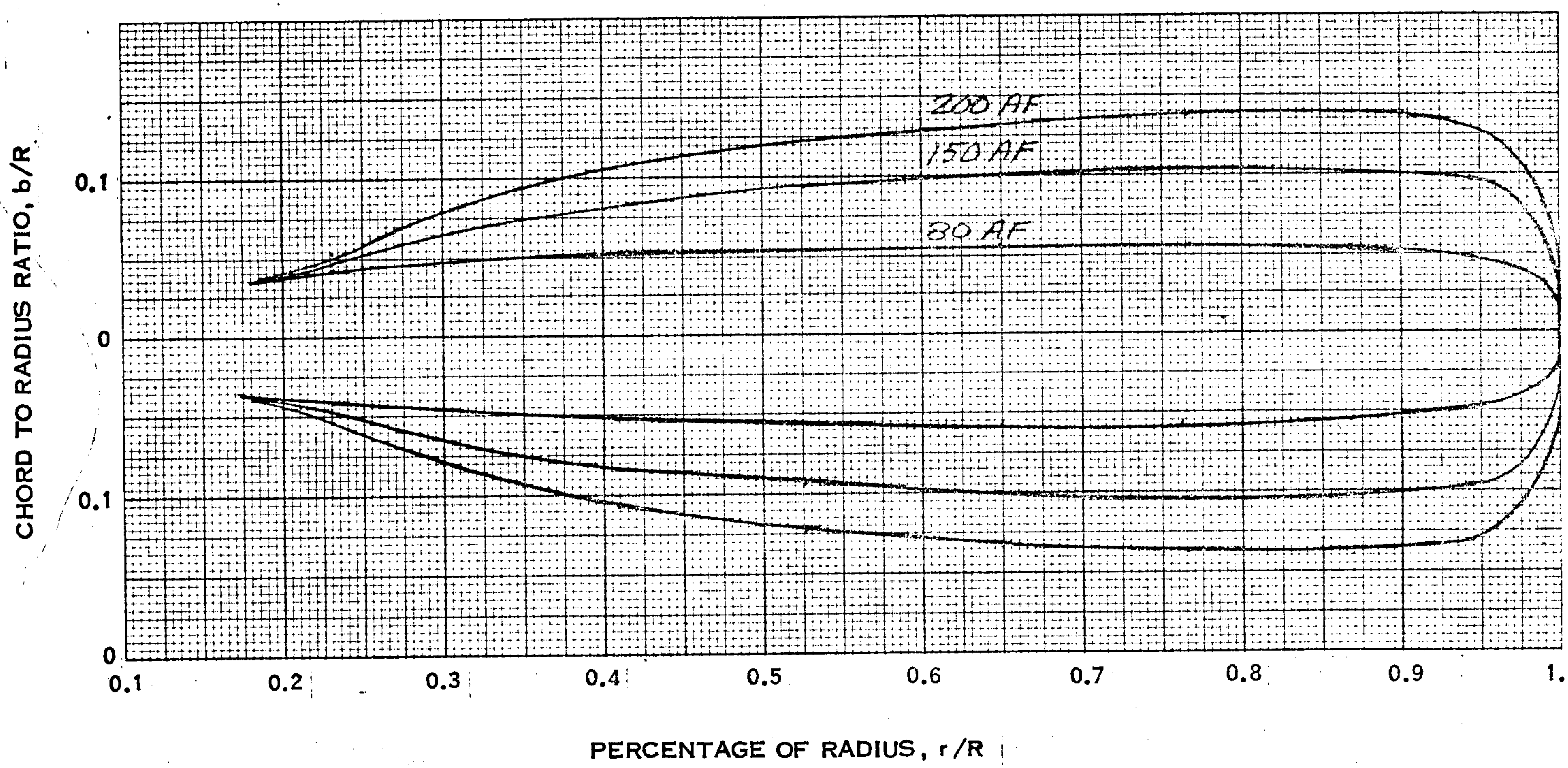


FIGURE 1. BLADE PLANFORM DISTRIBUTION

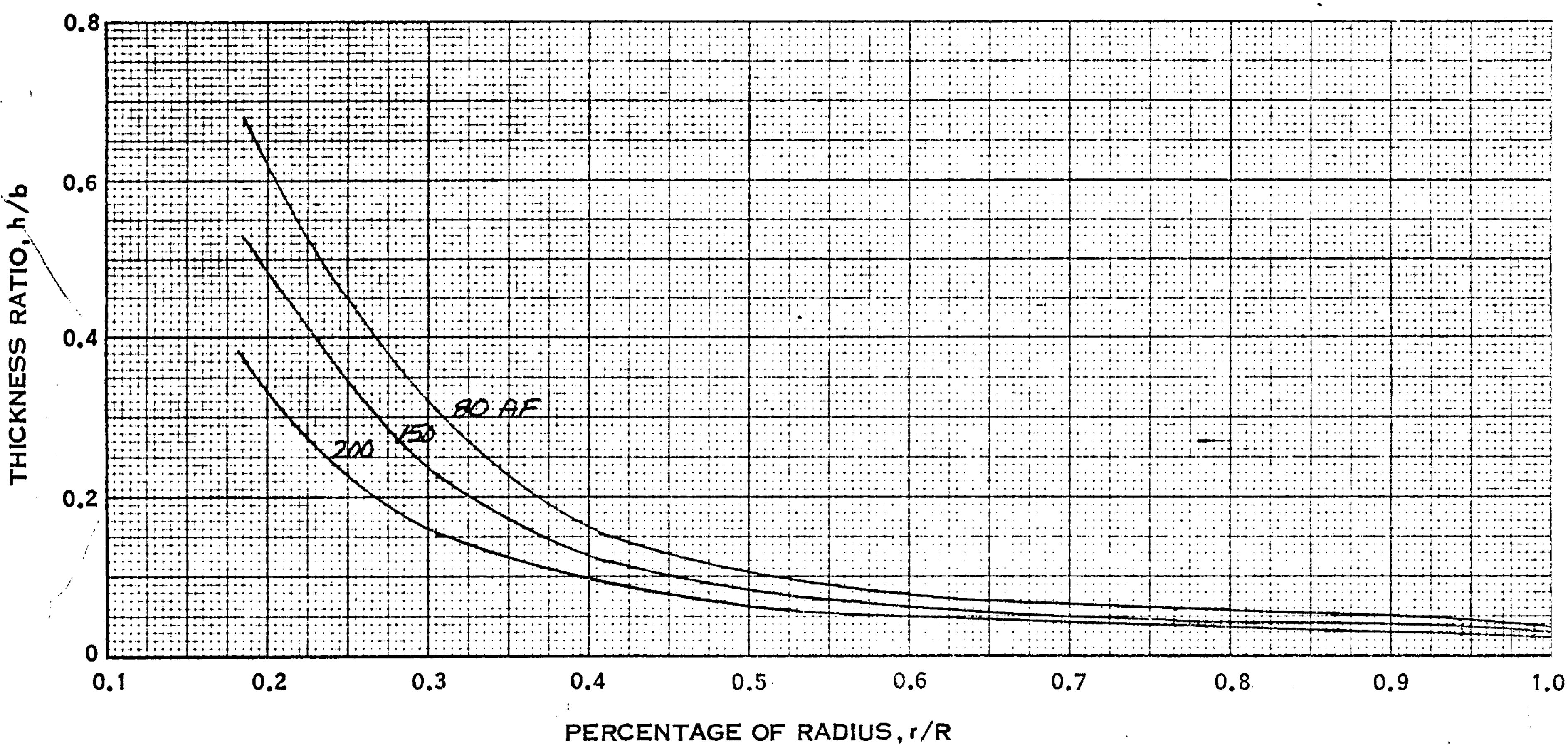


FIGURE 2. BLADE THICKNESS DISTRIBUTION

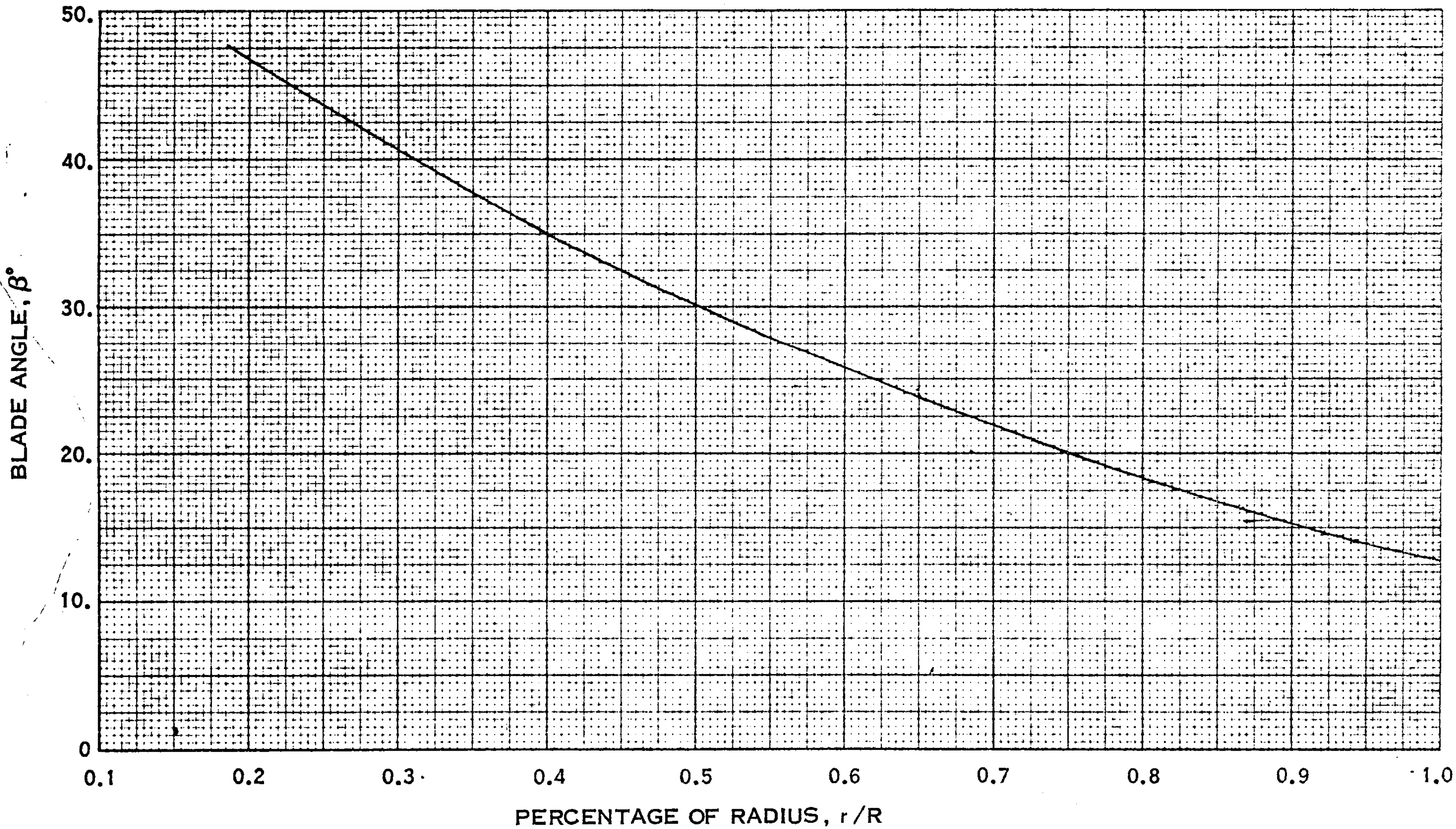


FIGURE 3. BLADE PITCH DISTRIBUTION

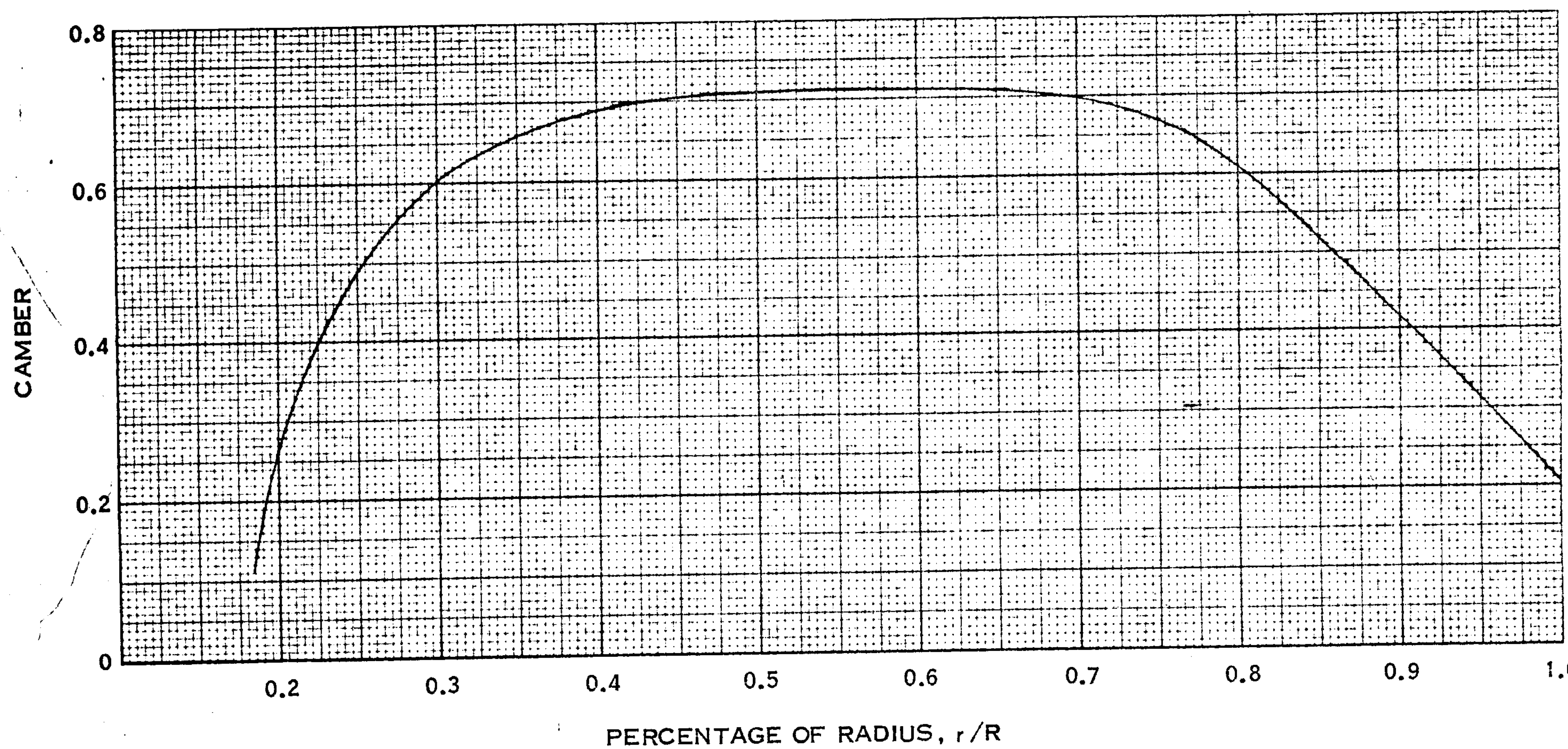


FIGURE 4. BLADE CAMBER DISTRIBUTION INTEGRATED DESIGN $C_{L_i} = 0.500$

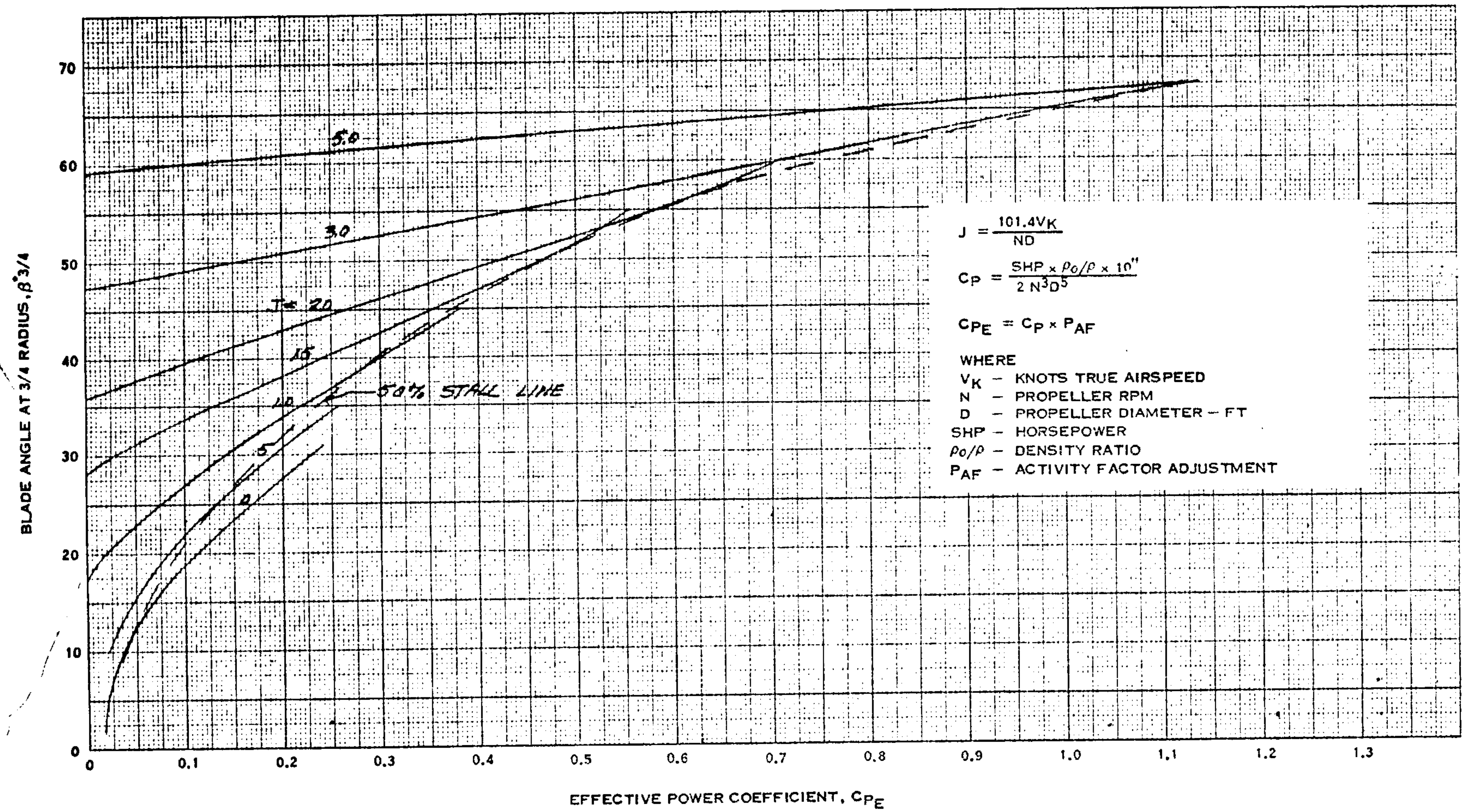


FIGURE 5. POWER COEFFICIENT CHART FOR A 2 BLADED, 150 ACTIVITY FACTOR, 0.500 INTEGRATED DESIGN C_L; PROPELLER

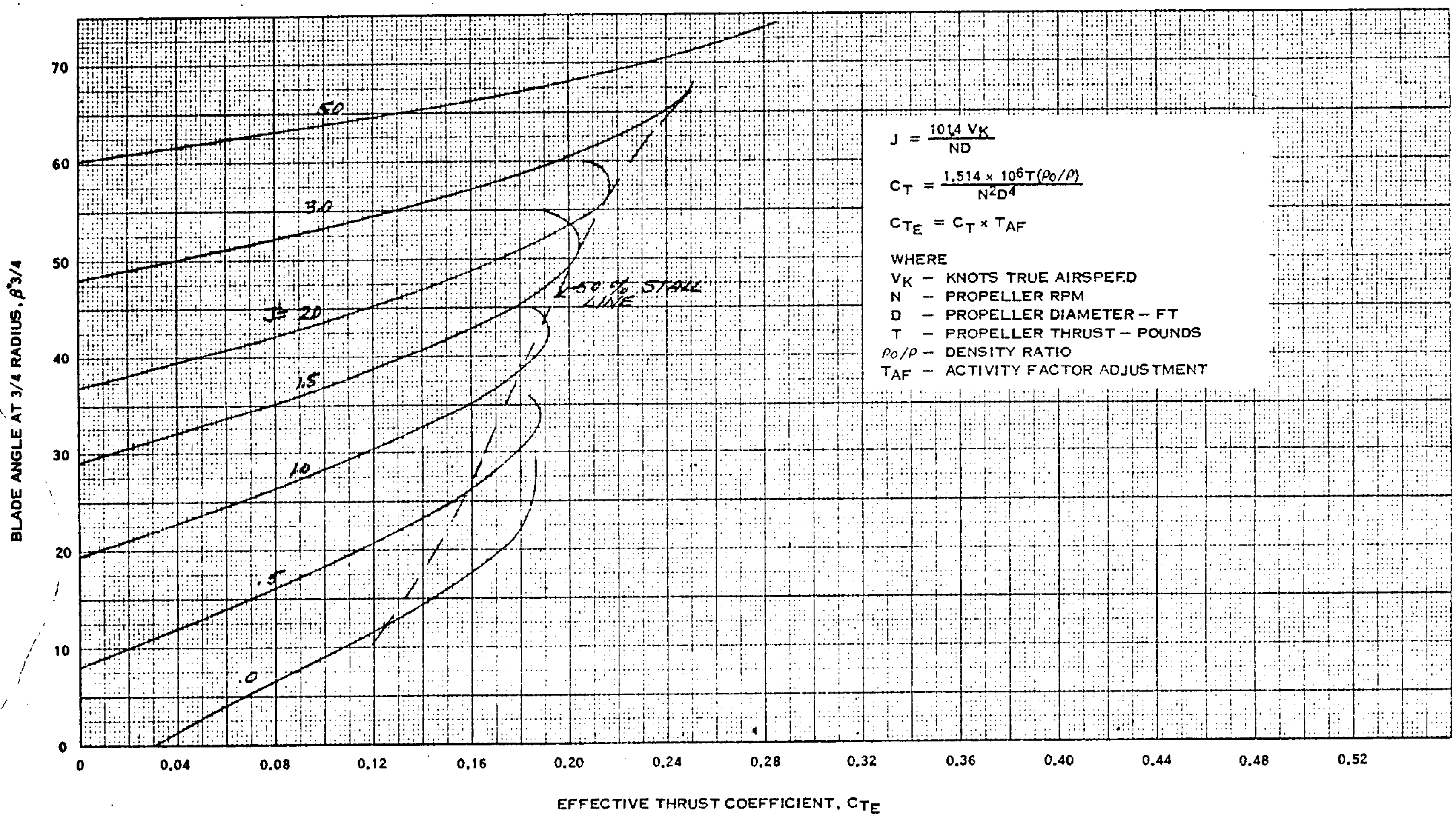
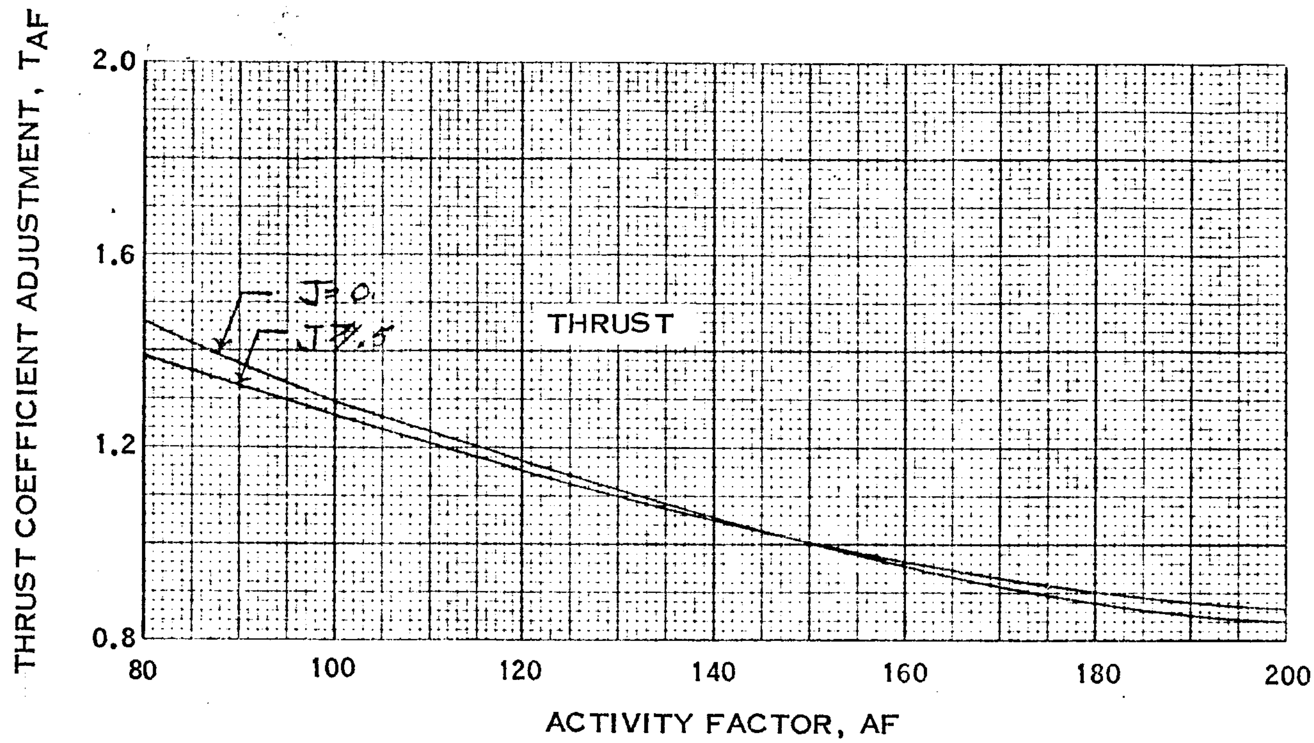


FIGURE 6. THRUST COEFFICIENT CHART FOR A 2 BLADED, 150 ACTIVITY FACTOR, 0.500 INTEGRATED DESIGN C_{L_i} PROPELLER



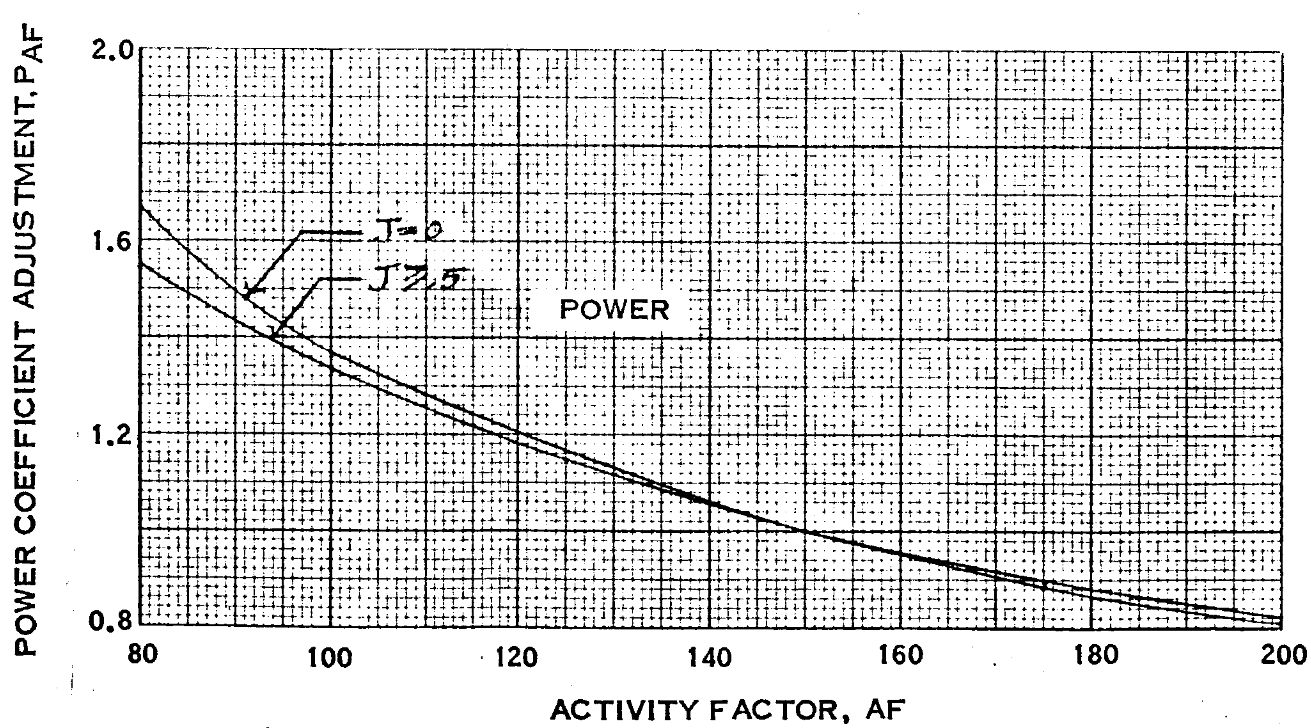


FIGURE 7. ACTIVITY FACTOR ADJUSTMENT

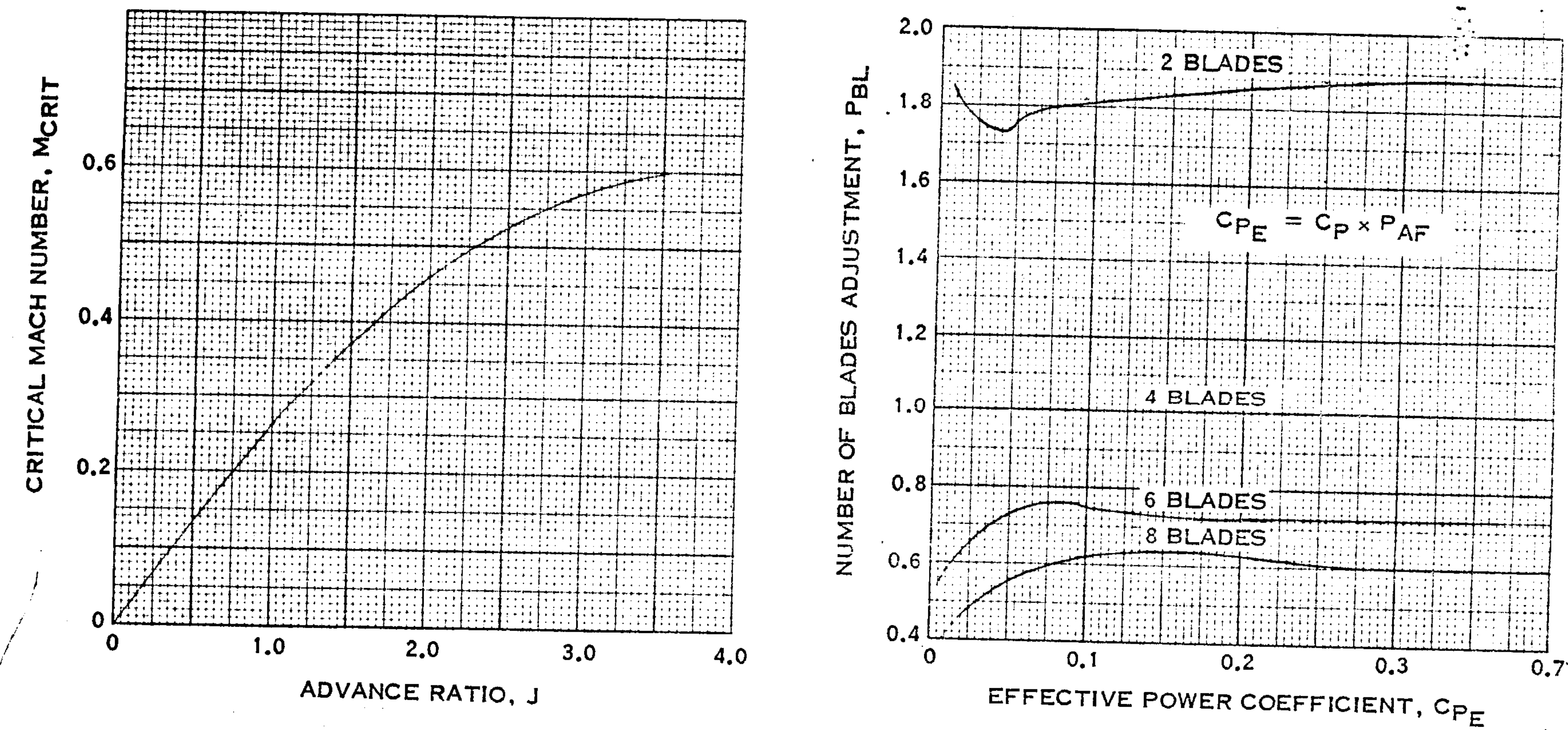


FIGURE 8. COMPRESSIBILITY ADJUSTMENT FOR 0.500 INTEGRATED DESIGN C_{L_i}

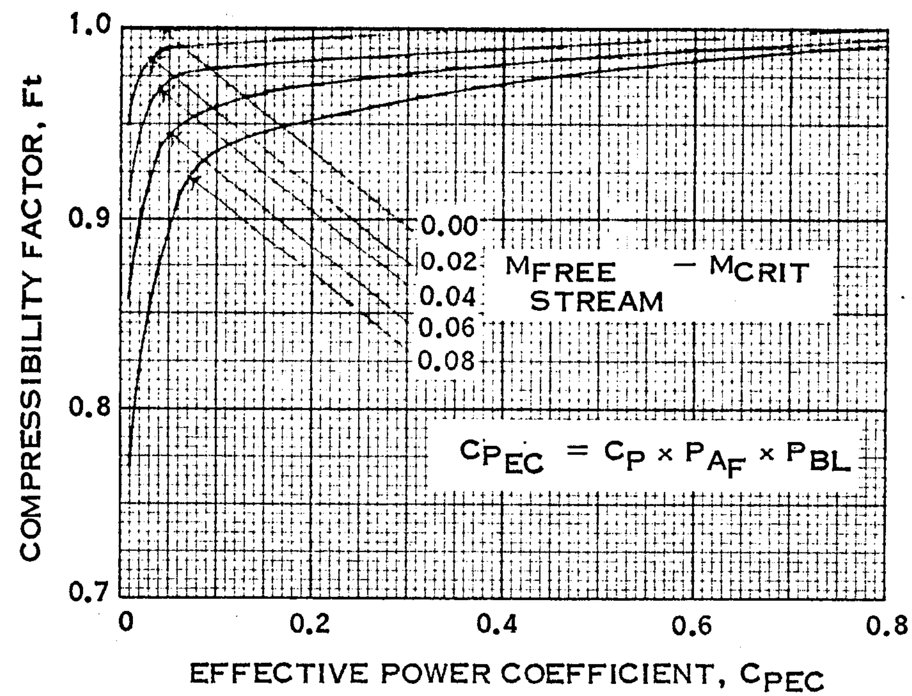


FIGURE 9. COMPRESSIBILITY FACTOR, Ft FOR 0.500 INTEGRATED DESIGN C_{L_i}

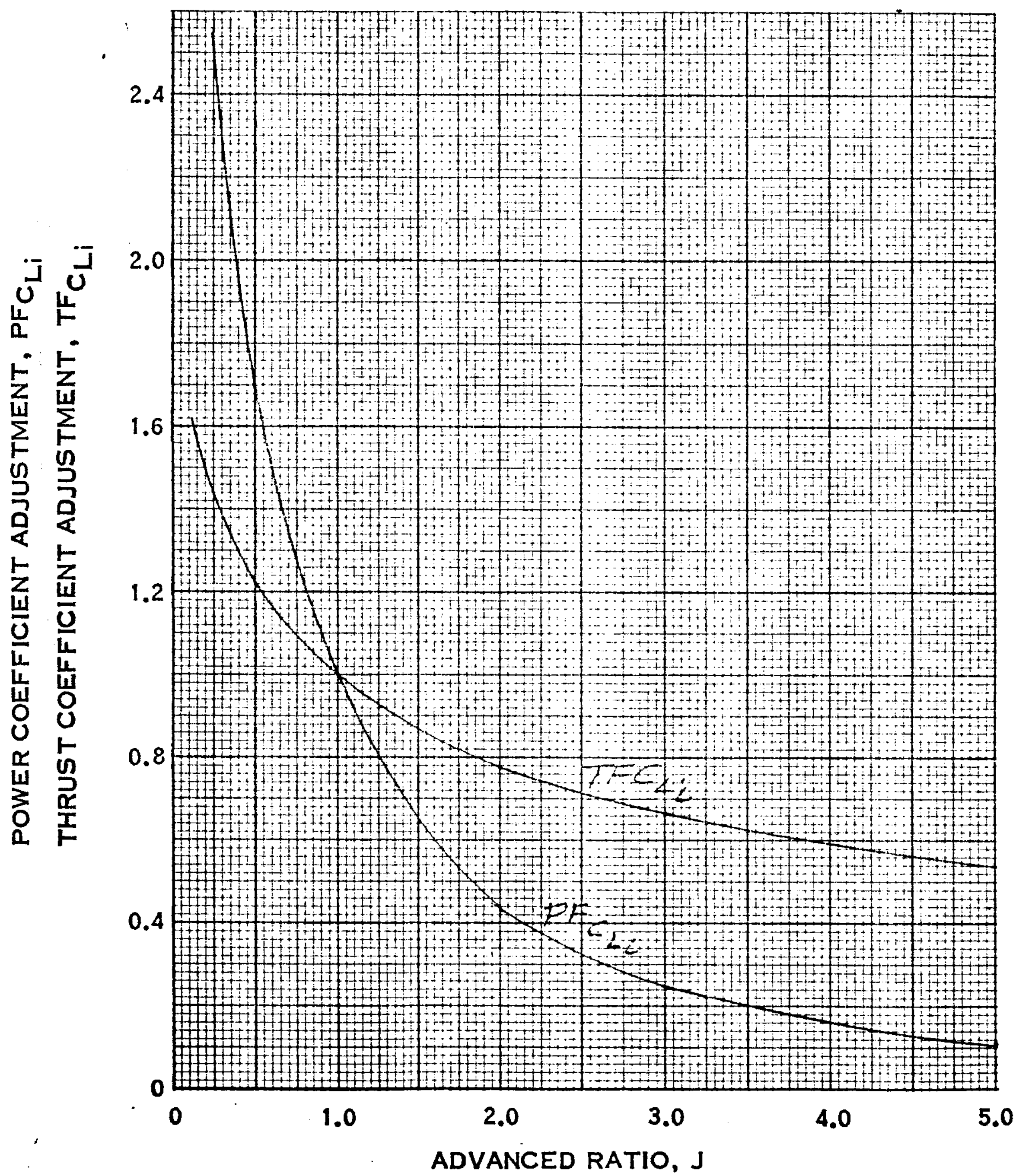


FIGURE 10. CAMBER FACTOR ADJUSTMENT FOR 4–BLADED PROPELLER (LIMITED TO 0.7 & 0.8 INTEGRATED DESIGN LIFT)

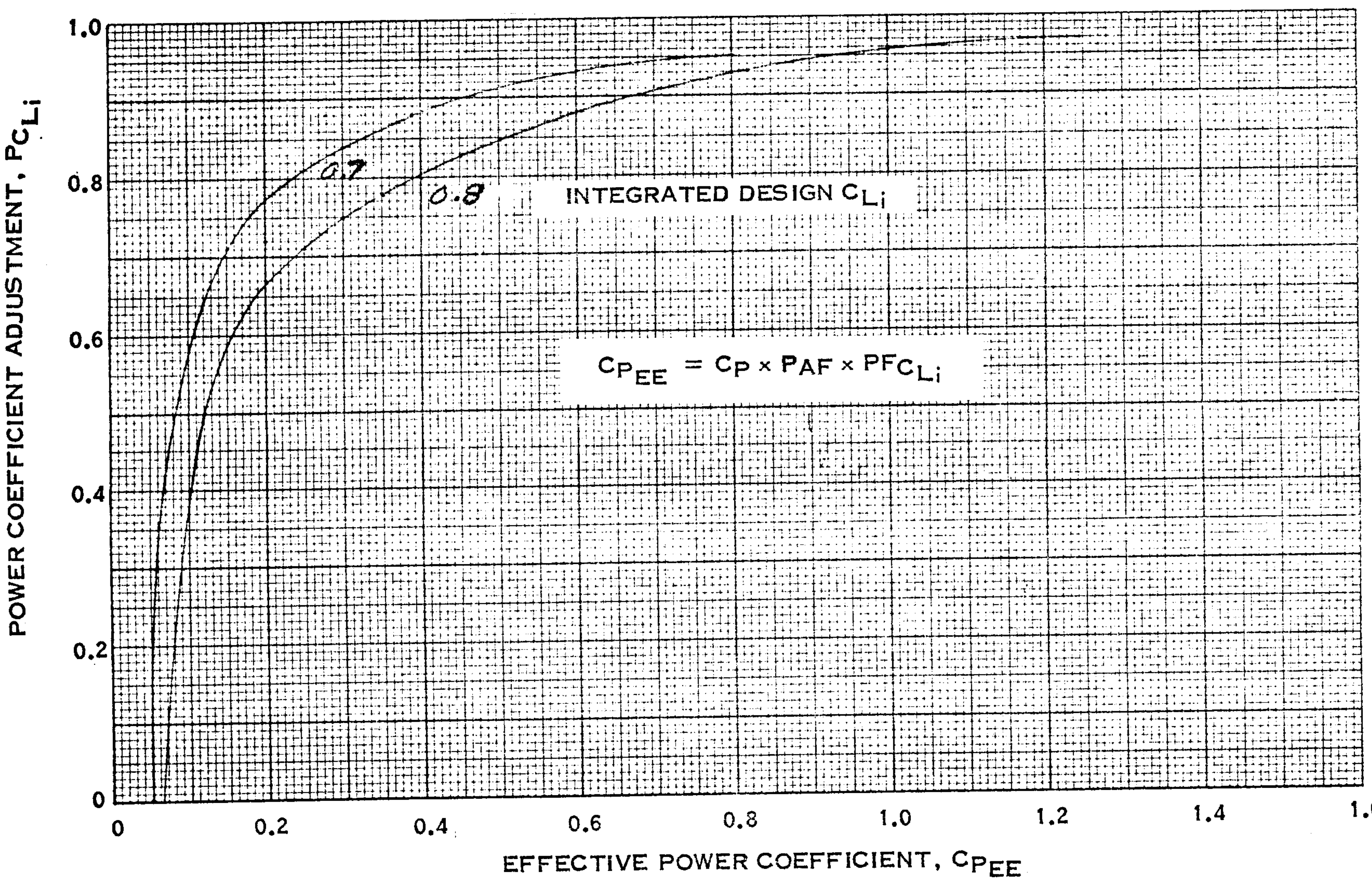


FIGURE 11. CAMBER ADJUSTMENT FOR 4–BLADED PROPELLERS
(TO POWER COEFFICIENT)

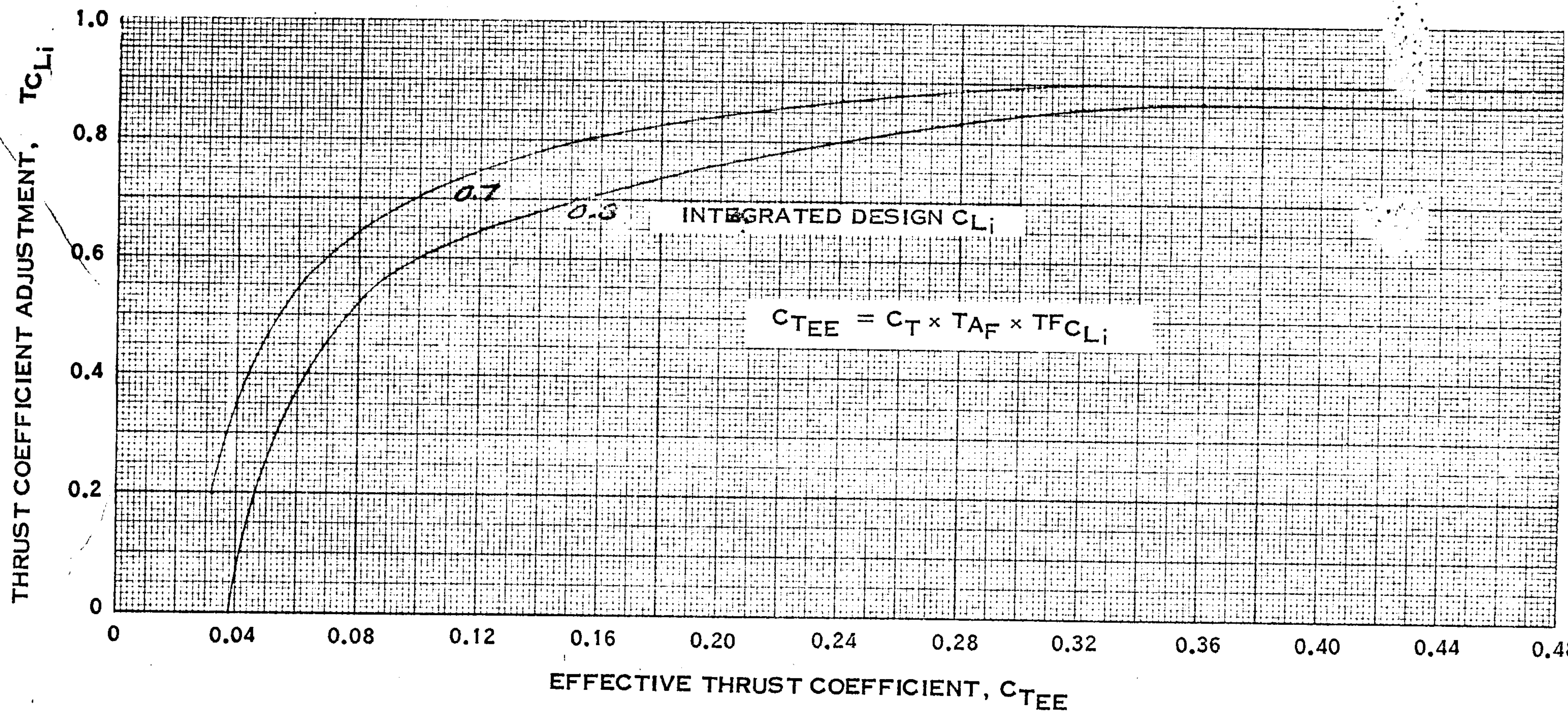


FIGURE 12. INTEGRATED DESIGN C_{L_i} ADJUSTMENT FOR 4 BLADED PROPELLERS (TO THRUST COEFFICIENT)

$$W_T = 355 \left[\left(\frac{D}{10}\right)^{2.00} \left(\frac{B}{4}\right)^{0.70} \left(\frac{AF}{100}\right)^{0.75} \left(\frac{ND}{20000}\right)^{0.50} \left(M+1.0\right)^{0.50} \left(\frac{SHP/D^2}{10}\right)^{0.12} \right]$$

CONVENTIONAL (SOLID DURAL BLADES)

$$W_T = 285 \left[\left(\frac{D}{10}\right)^{1.85} \left(\frac{B}{4}\right)^{0.70} \left(\frac{AF}{100}\right)^{0.60} \left(\frac{ND}{20000}\right)^{0.50} \left(M+1.0\right)^{0.50} \left(\frac{SHP/D^2}{10}\right)^{0.12} \right]$$

LIGHT WEIGHT (FIBERGLAS BLADES IGB HUB)

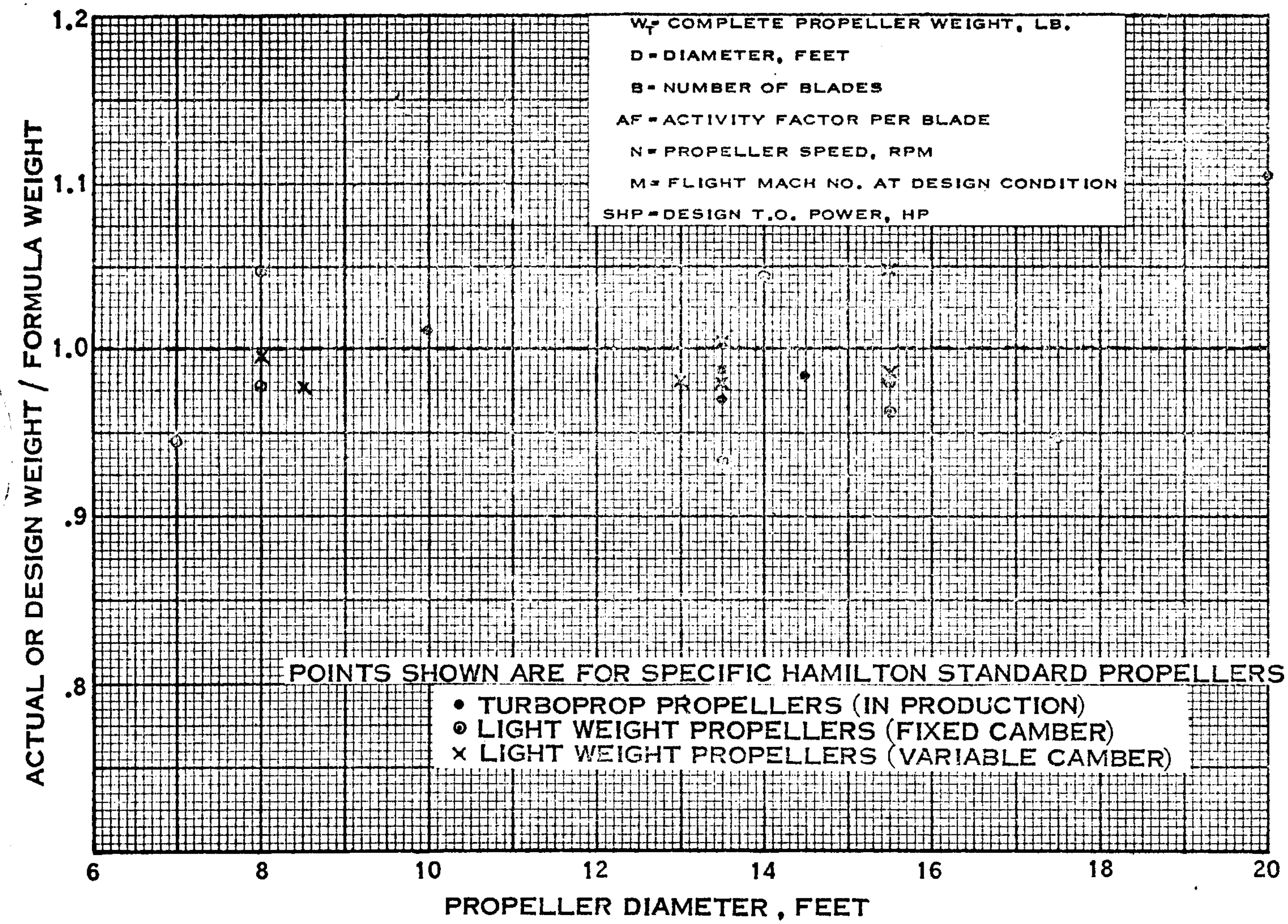


FIGURE 13. HAMILTON STANDARD PROPELLER WEIGHT GENERALIZATION

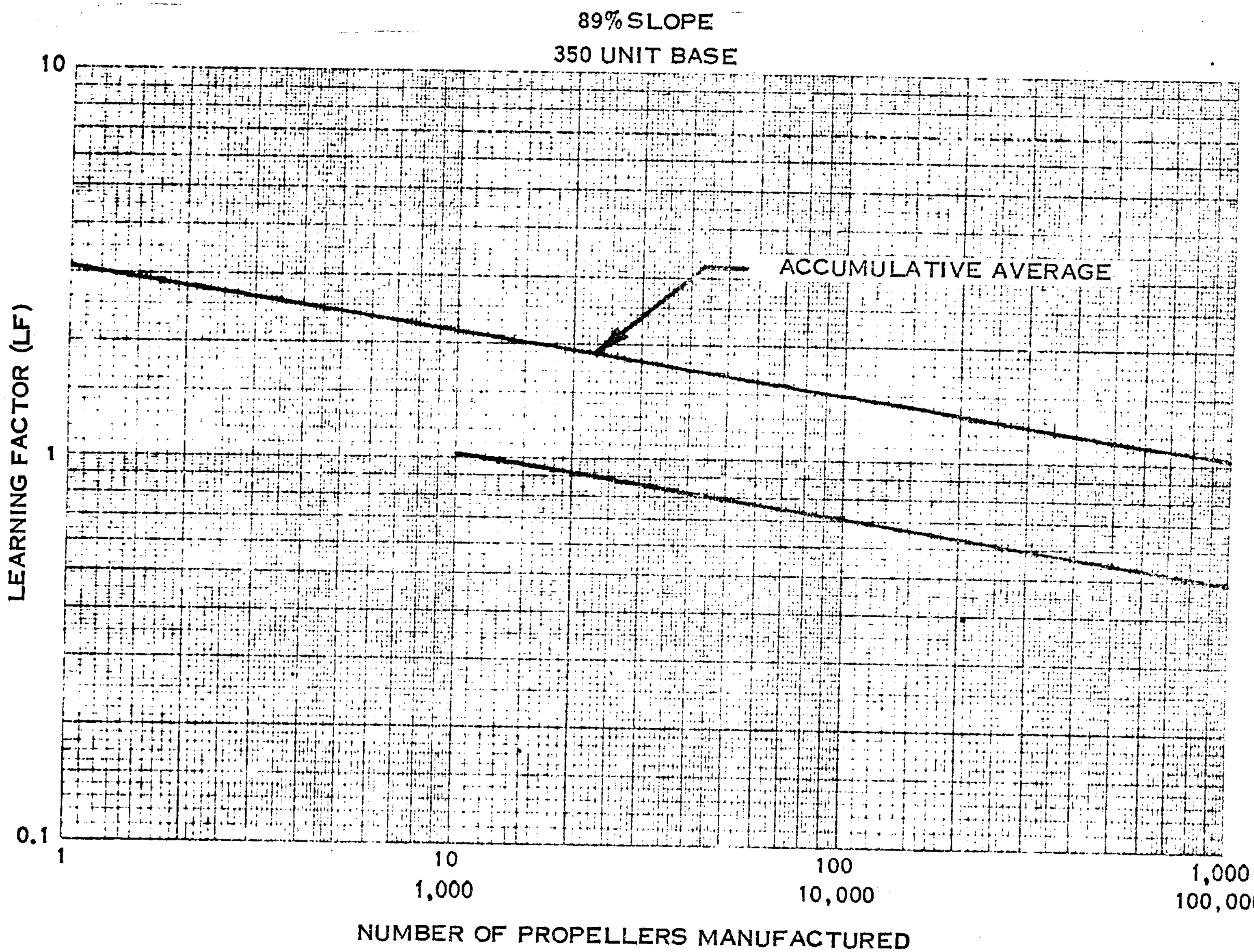
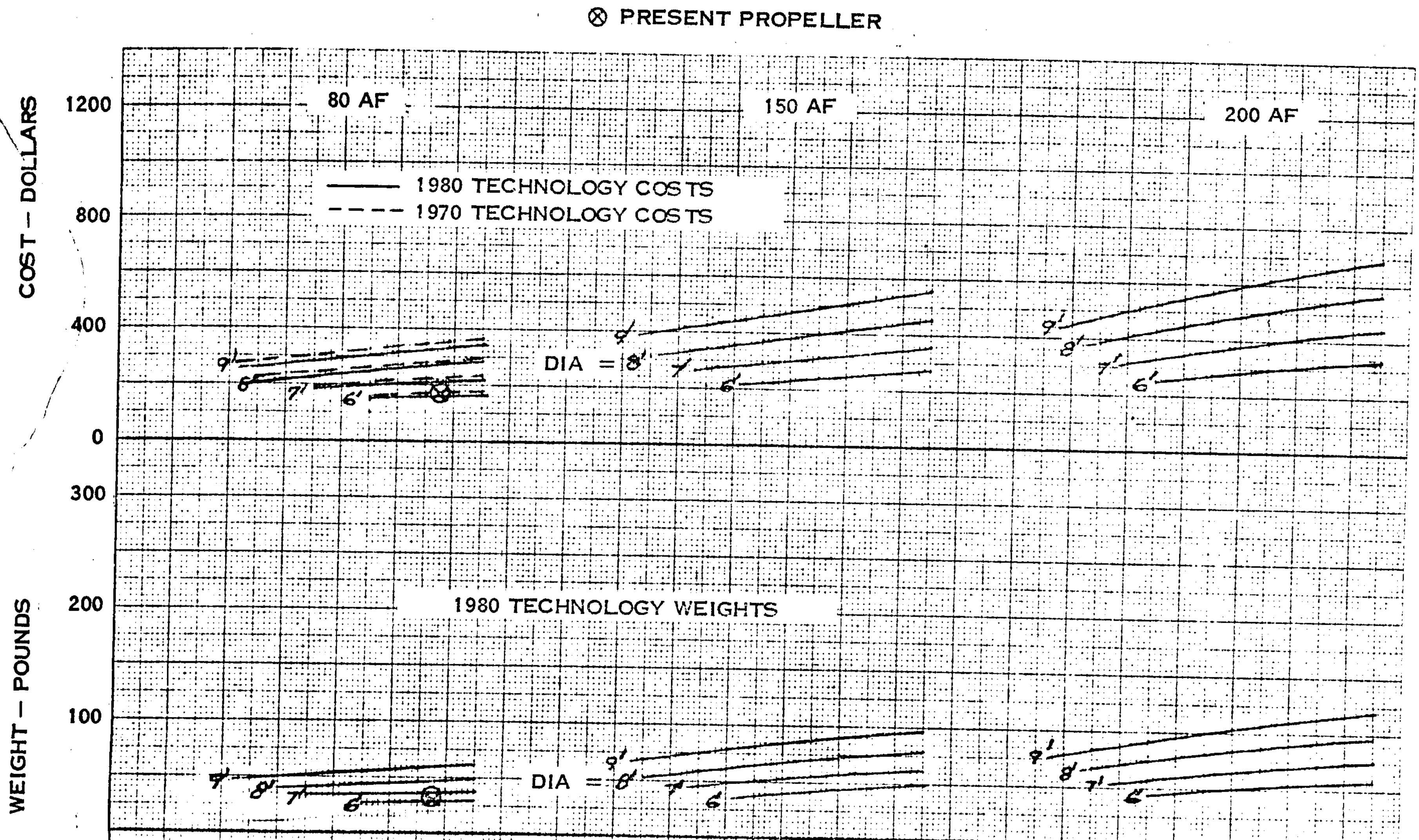


FIGURE 14. LEARNING CURVE FOR GENERAL AVIATION PROPELLERS



⊗ PRESENT PROPELLER
COST – DOLLARS
1200
800
400
0
300
200
100
WEIGHT – POUNDS
80 AF
150 AF
200 AF
1980 TECHNOLOGY COSTS
1970 TECHNOLOGY COSTS
DIA = 9' 8' 7' 6'
1980 TECHNOLOGY WEIGHTS
DIA =

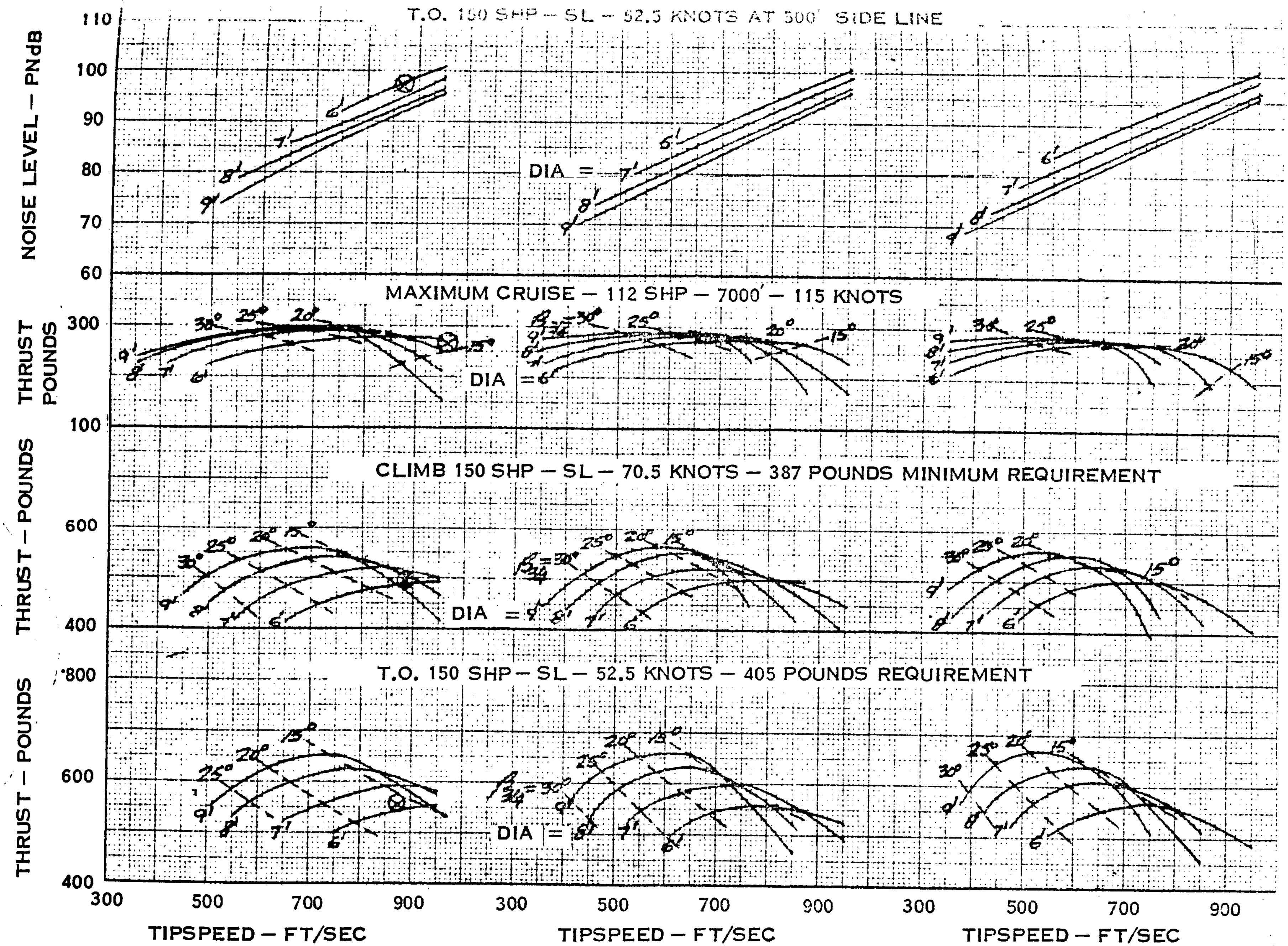
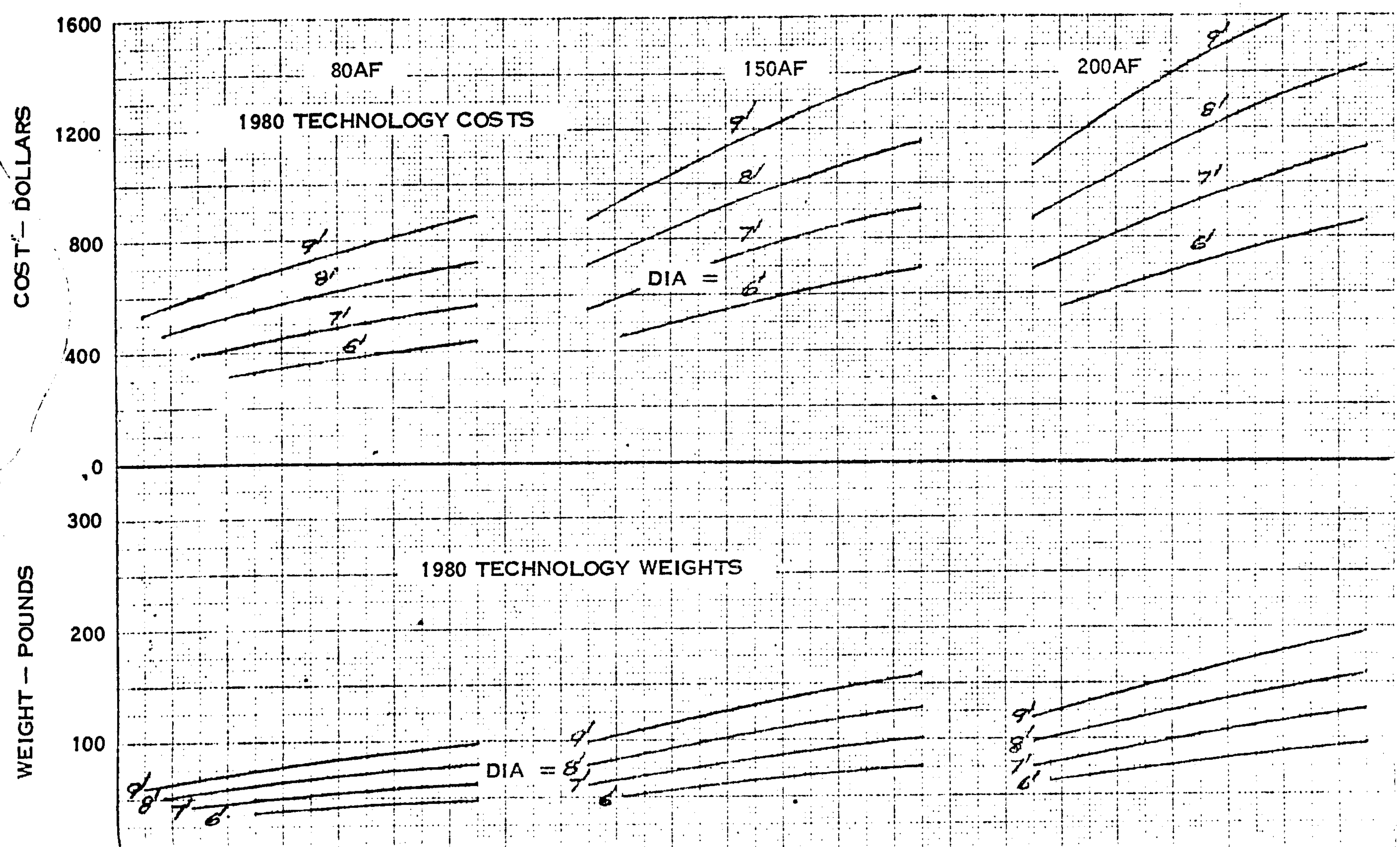


FIGURE 15. CATEGORY I SENSITIVITY STUDY FOR THE PIPER CHEROKEE
2 BLADED PROPELLER 0.5 INTEGRATED DESIGN C_{L_i}



1600
1200
800
400
0
300
200
100
COST – DOLLARS
WEIGHT – POUNDS
80AF
150AF
200AF
1980 TECHNOLOGY COSTS
1980 TECHNOLOGY WEIGHTS
DIA =
DIA =
9'
8'
7'
6'

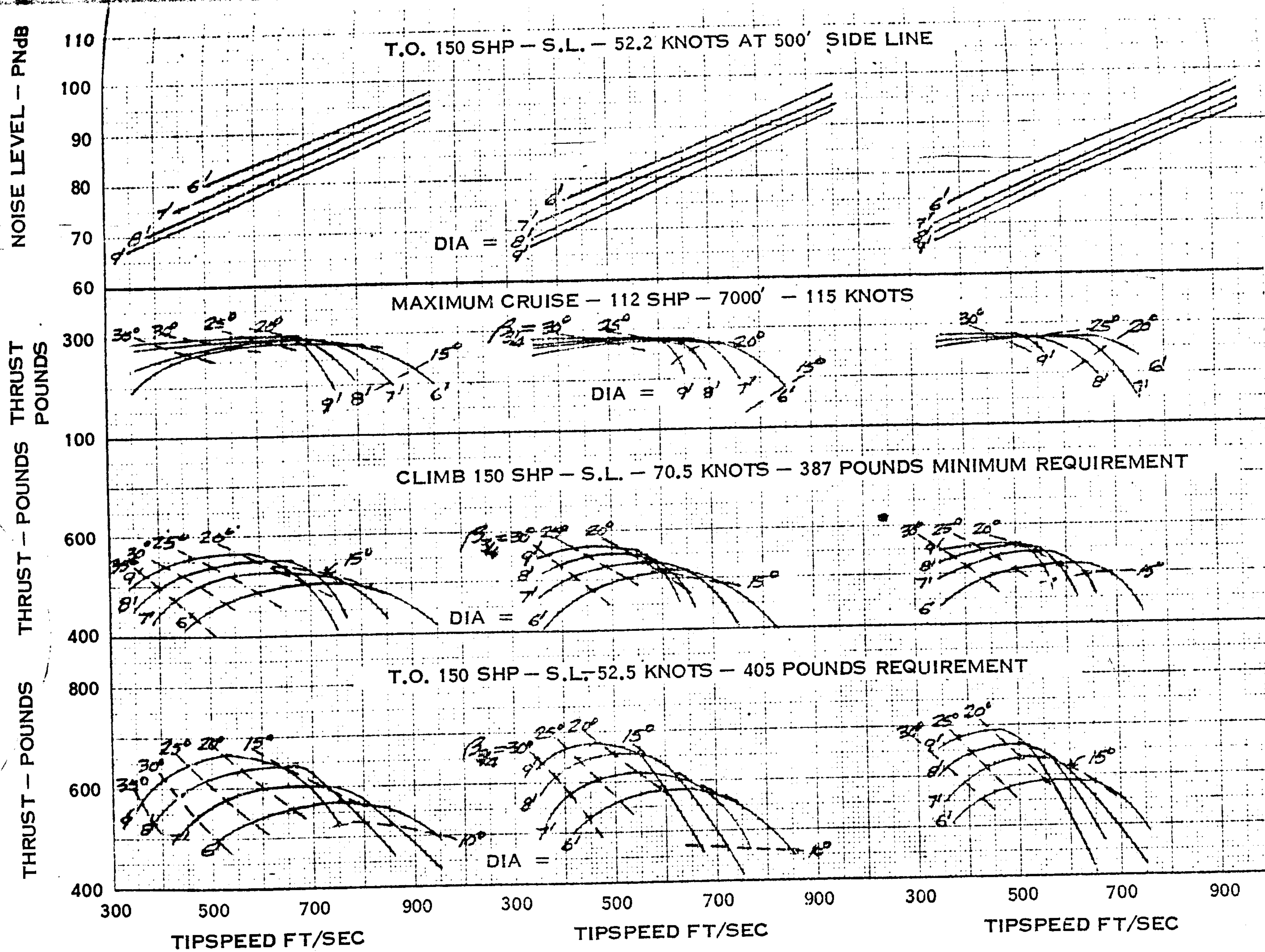
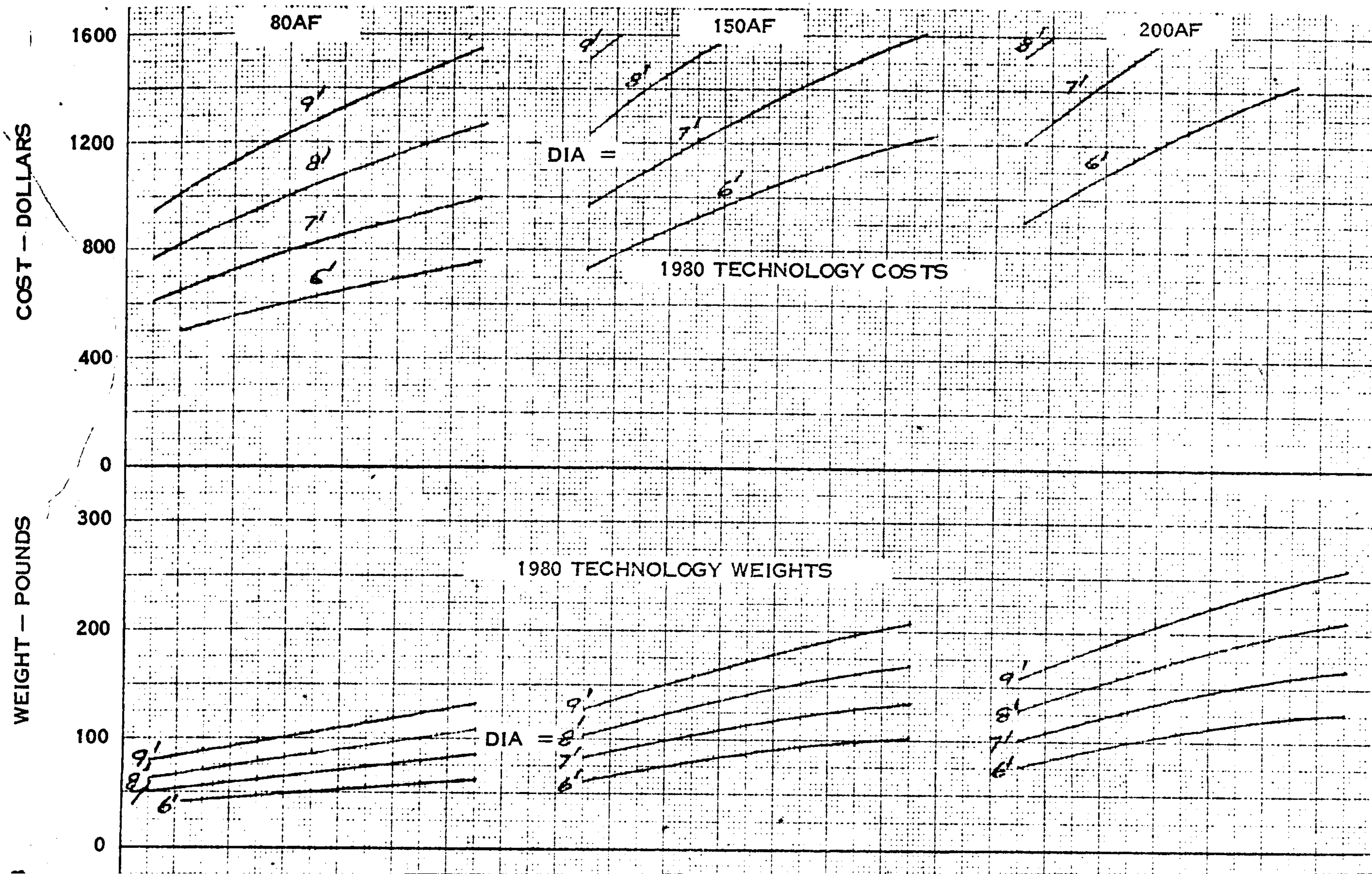


FIGURE 16. CATEGORY I SENSITIVITY STUDY FOR THE PIPER CHEROKEE 4–BLADED PROPELLER 0.5 INTEGRATED DESIGN C_{L_i}



80AF
150AF
200AF
1980 TECHNOLOGY COSTS
1980 TECHNOLOGY WEIGHTS
DIA =
COST — DOLLARS
WEIGHT — POUNDS
1600
1200
800
400
0
300
200
100
0

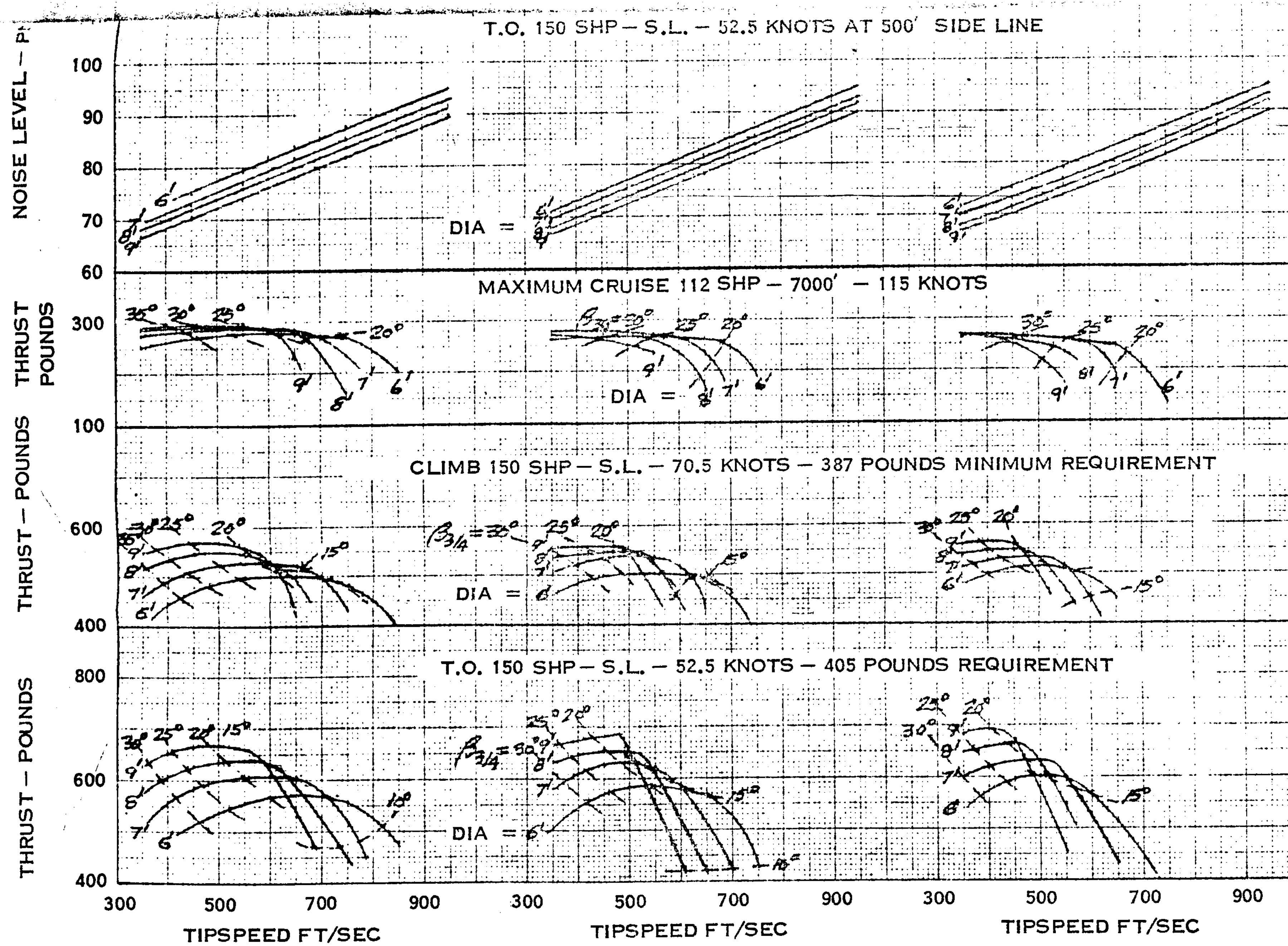
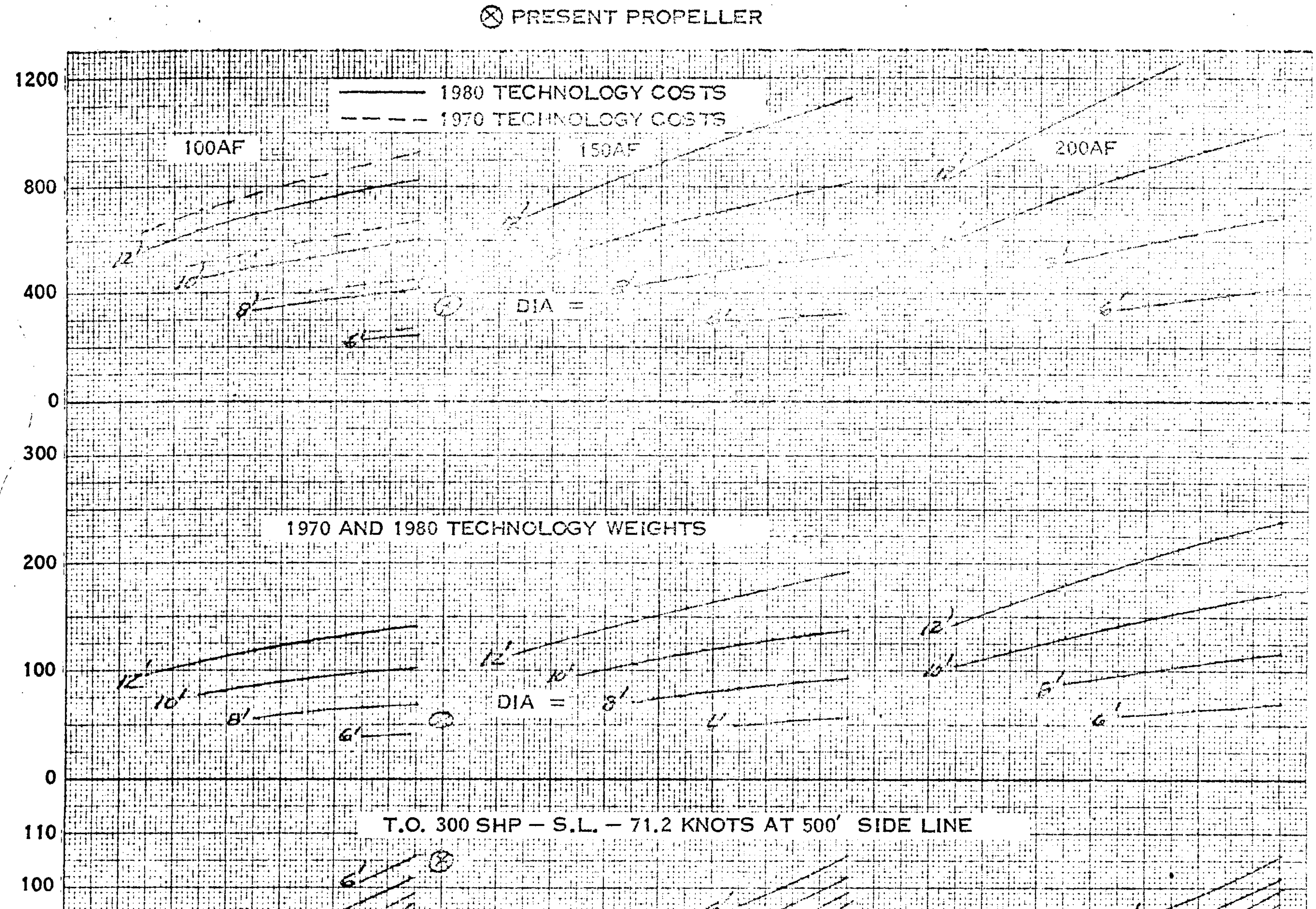


FIGURE 17. CATEGORY I SENSITIVITY STUDY FOR THE PIPER CHEROKEE
6–BLADED PROPELLER 0.5 INTEGRATED DESIGN C_{L_i}



⊗ PRESENT PROPELLER
1980 TECHNOLOGY COSTS
1970 TECHNOLOGY COSTS
100AF
150AF
200AF
DIA =
COST – DOLLARS
1200
800
400
0
1970 AND 1980 TECHNOLOGY WEIGHTS
WEIGHT – POUNDS
300
200
100
0
DIA =
T.O. 300 SHP – S.L. – 71.2 KNOTS AT 500′ SIDE LINE
VEL – PNdB
110
100

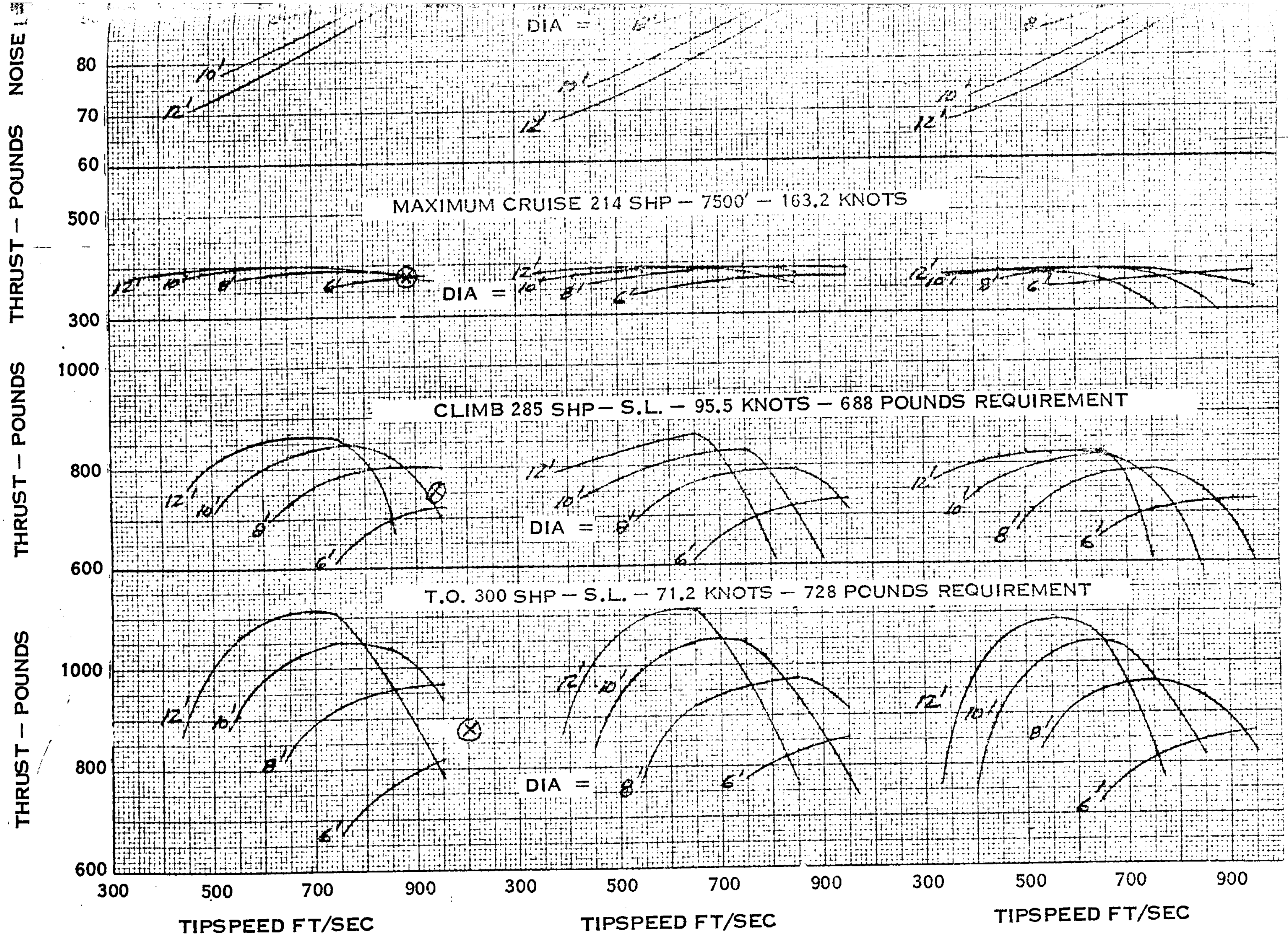
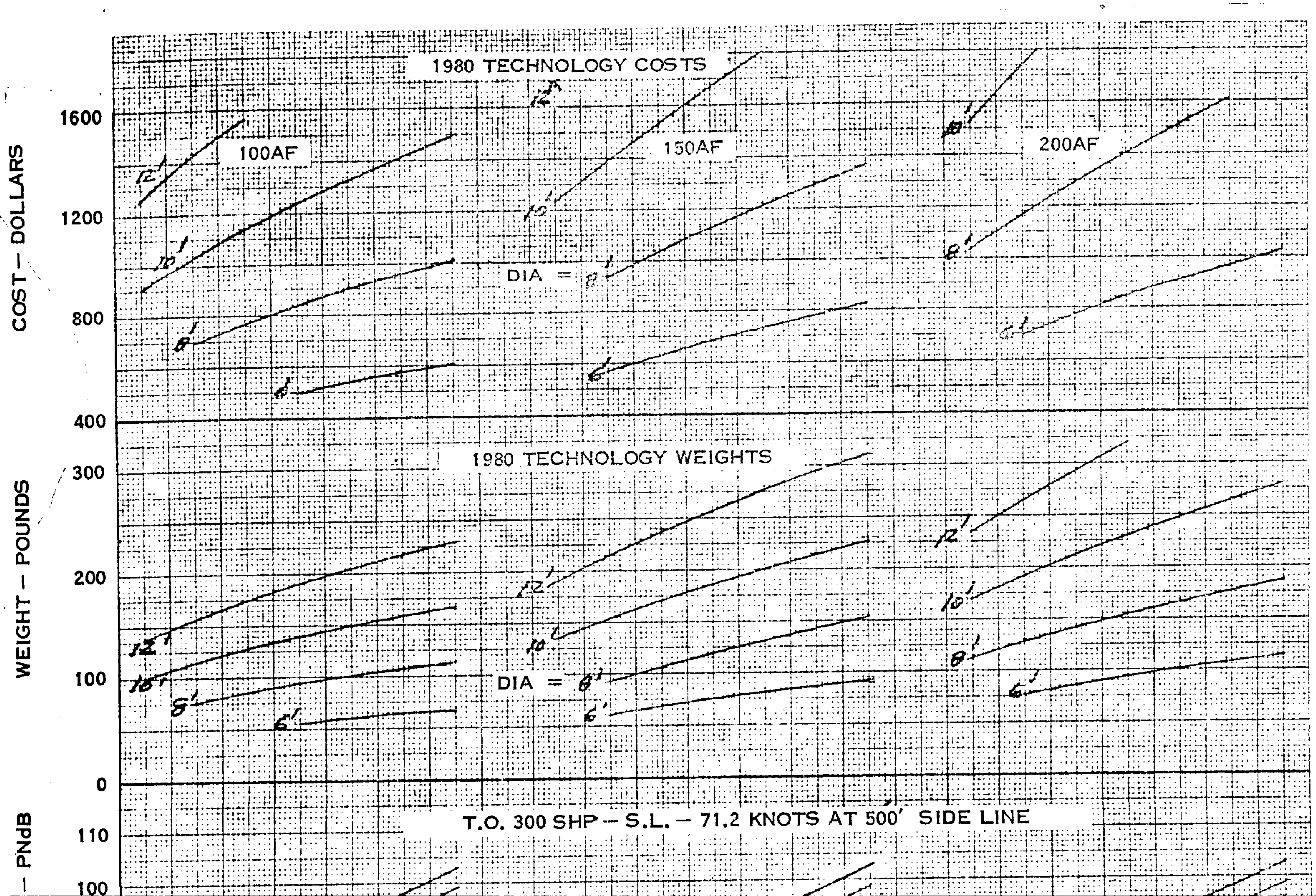


FIGURE 18. CATEGORY II SENSITIVITY STUDY FOR THE CESSNA 210J
2 BLADED PROPELLER 0.5 INTEGRATED DESIGN C_{L_i}



1980 TECHNOLOGY COSTS
100AF
150AF
200AF
DIA = 8'
12'
10'
8'
6'
1980 TECHNOLOGY WEIGHTS
DIA = 8'
T.O. 300 SHP – S.L. – 71.2 KNOTS AT 500' SIDE LINE
COST – DOLLARS
WEIGHT – POUNDS
– PNdB
1600
1200
800
400
300
200
100
0
110
100

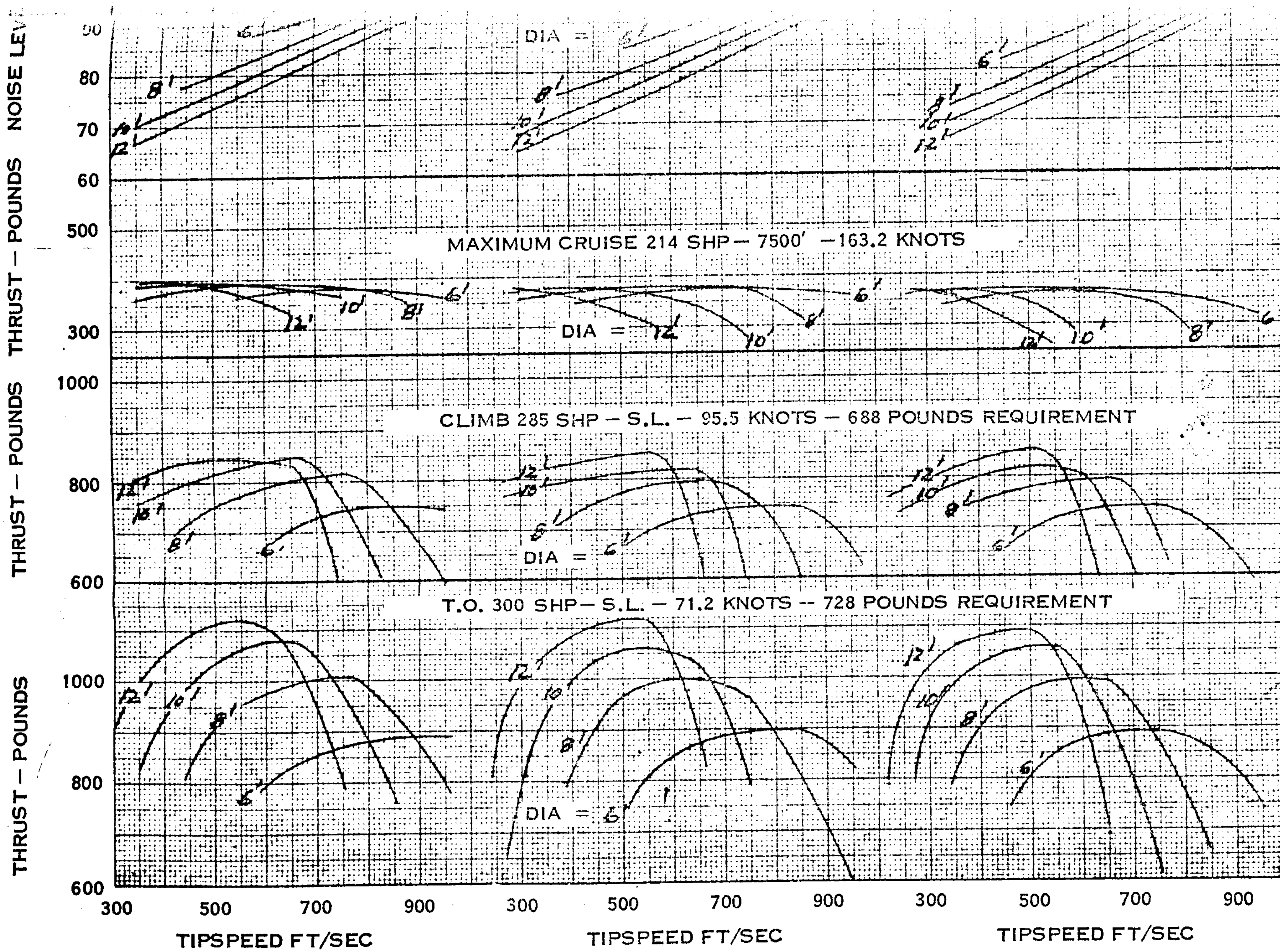
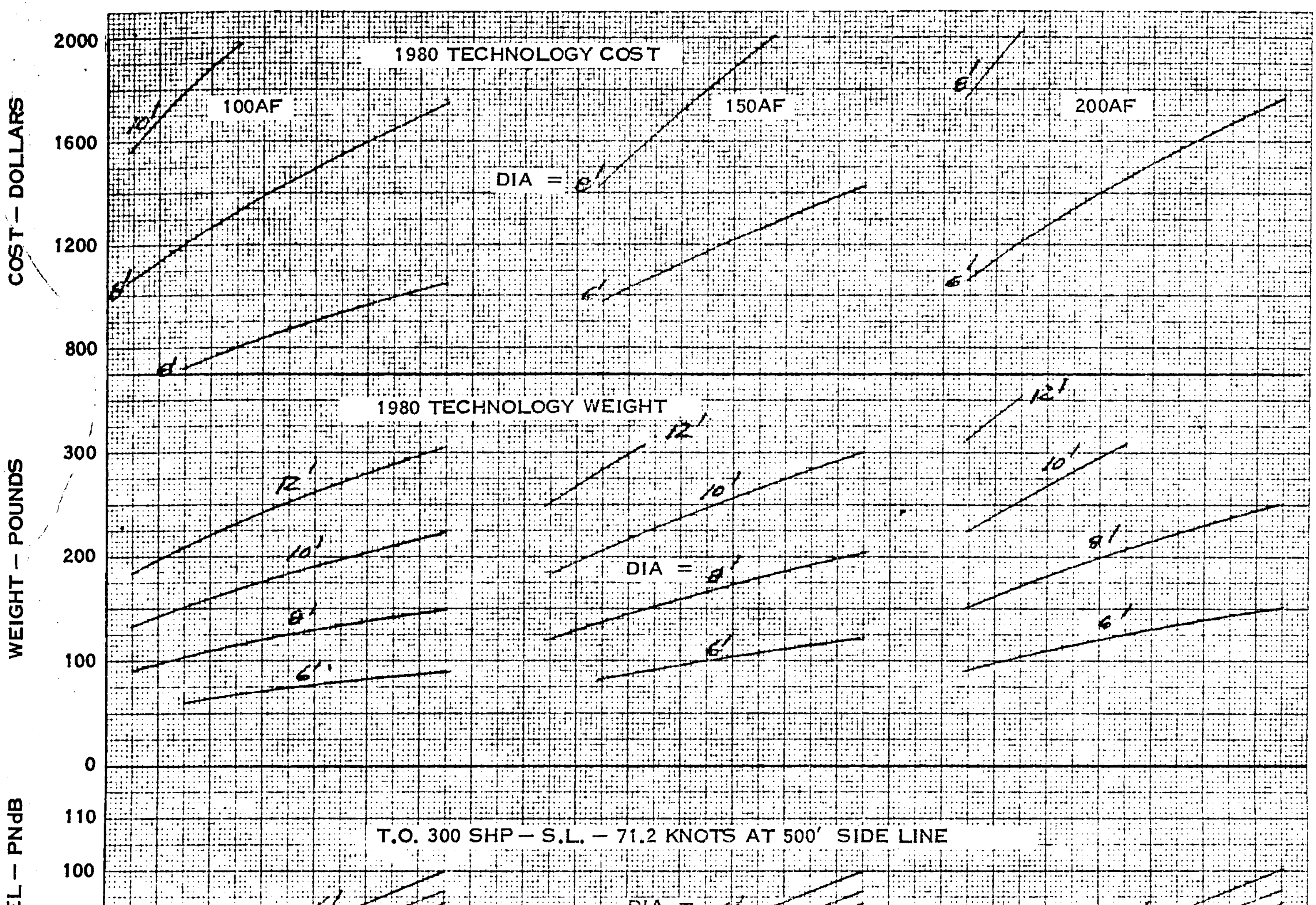


FIGURE 19. CATEGORY II SENSITIVITY STUDY FOR THE CESSNA 210J 4 BLADED PROPELLER 0.5 INTEGRATED DESIGN C_{L_i}


1980 TECHNOLOGY COST
100AF
150AF
200AF
DIA =
COST — DOLLARS
2000
1600
1200
800
1980 TECHNOLOGY WEIGHT
WEIGHT — POUNDS
300
200
100
0
110
100
T.O. 300 SHP — S.L. — 71.2 KNOTS AT 500′ SIDE LINE
PNdB

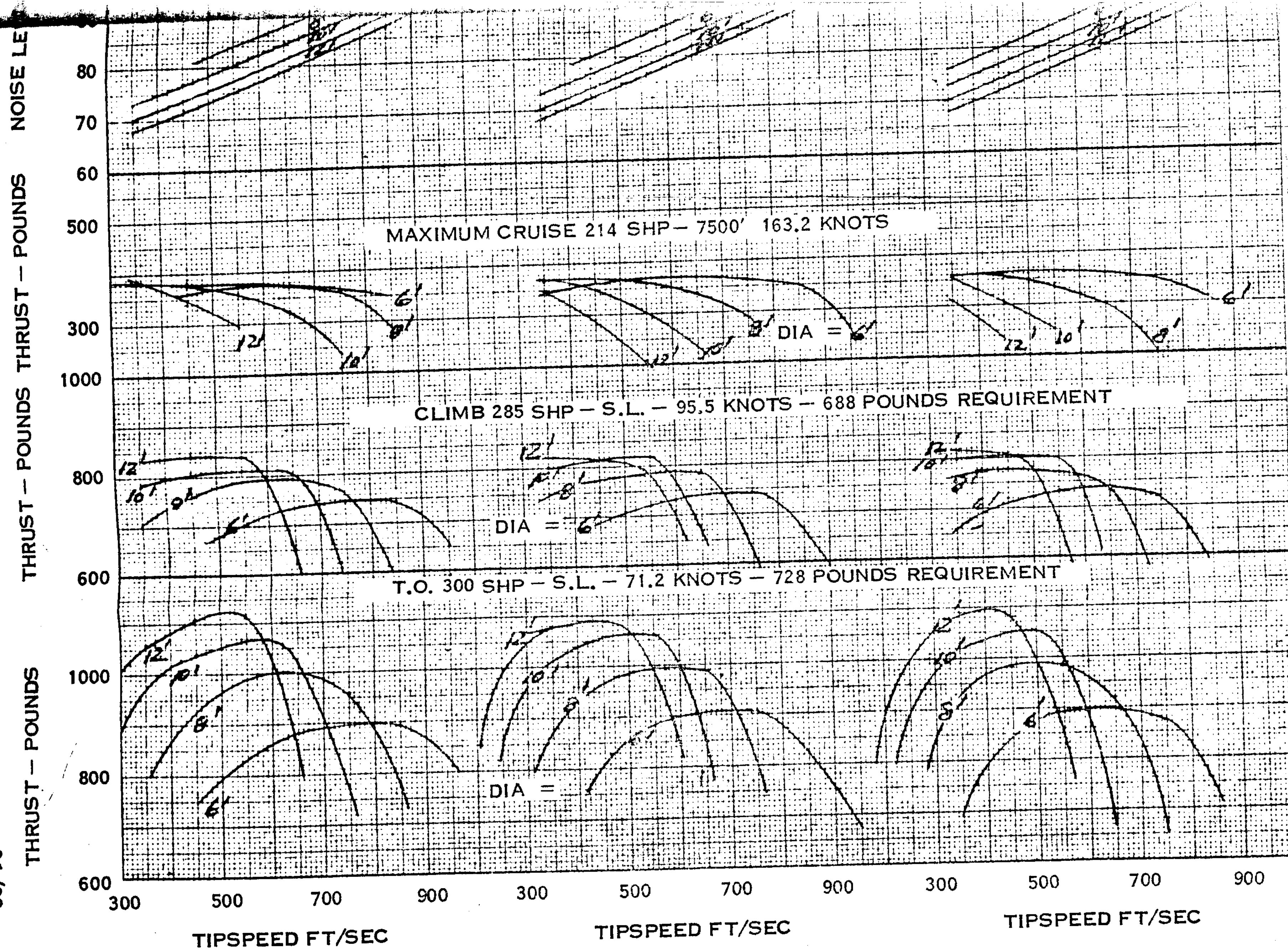
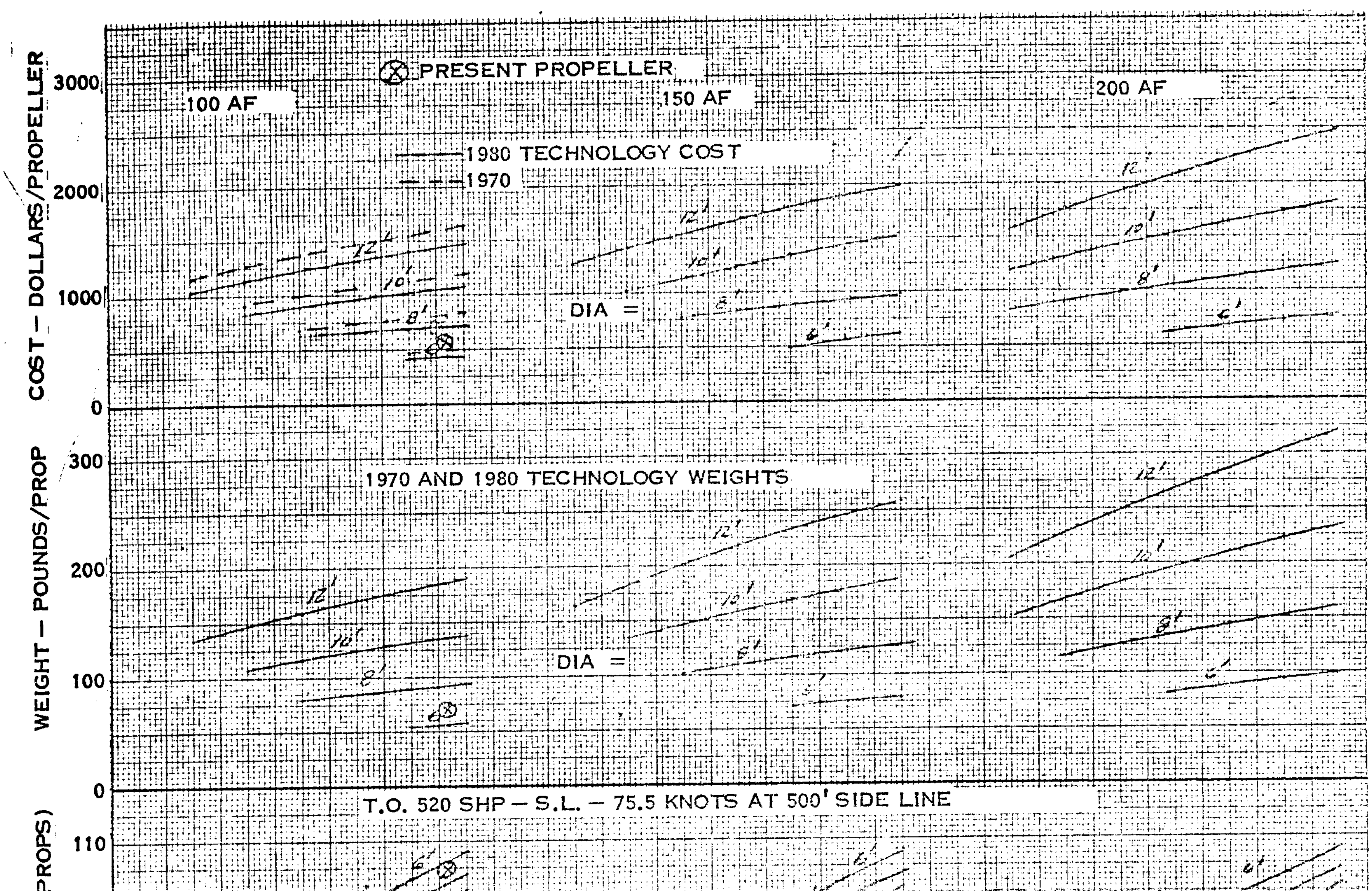


FIGURE 20. CATEGORY II SENSITIVITY STUDY FOR THE CESSNA 210J
6 BLADED PROPELLER 0.5 INTEGRATED DESIGN C_{L_i}


PRESENT PROPELLER
100 AF
150 AF
200 AF
1980 TECHNOLOGY COST
1970
DIA =
1970 AND 1980 TECHNOLOGY WEIGHTS
DIA =
T.O. 520 SHP – S.L. – 75.5 KNOTS AT 500' SIDE LINE
COST – DOLLARS/PROPELLER
WEIGHT – POUNDS/PROP
3000
2000
1000
0
300
200
100
0
110

98/94

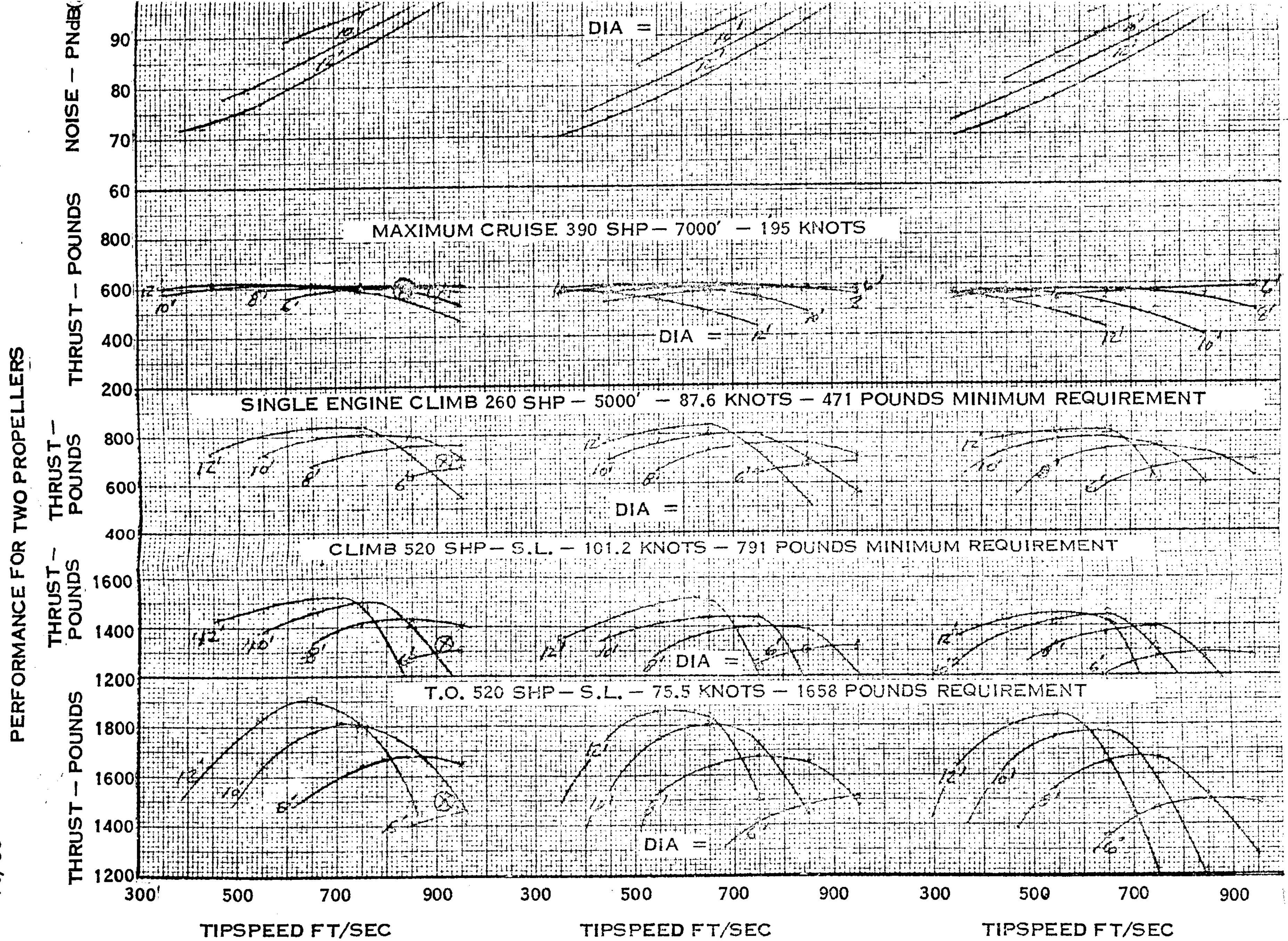
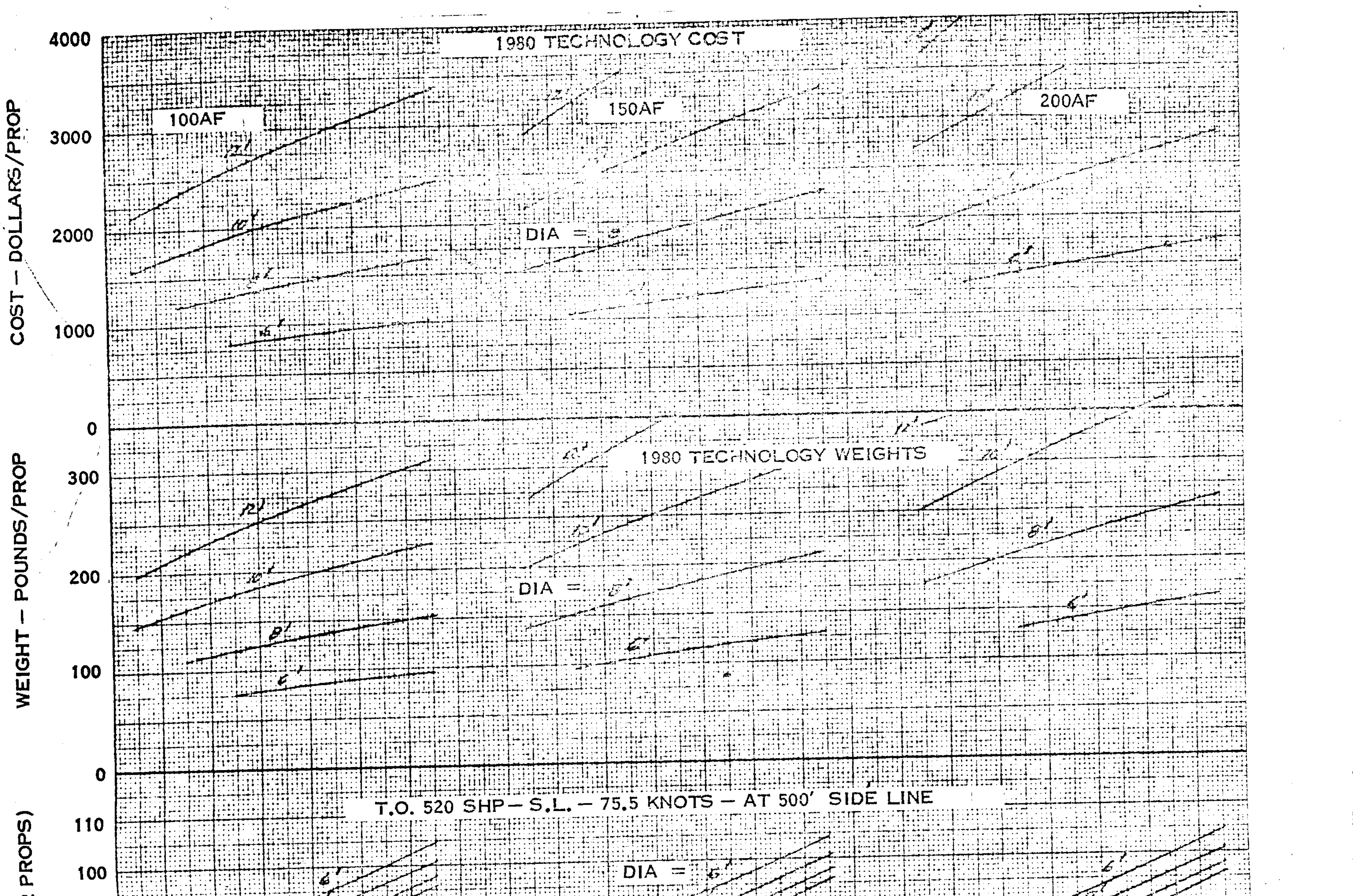


FIGURE 21. CATEGORY III SENSITIVITY STUDY FOR THE BEECH BARON B55
2 BLADED PROPELLER 0.5 INTEGRATED DESIGN C_{L_i}



1980 TECHNOLOGY COST
100AF
150AF
200AF
DIA =
COST — DOLLARS/PROP
4000
3000
2000
1000
0
1980 TECHNOLOGY WEIGHTS
WEIGHT — POUNDS/PROP
300
200
100
0
T.O. 520 SHP — S.L. — 75.5 KNOTS — AT 500' SIDE LINE
PROPS)
110
100

95/96

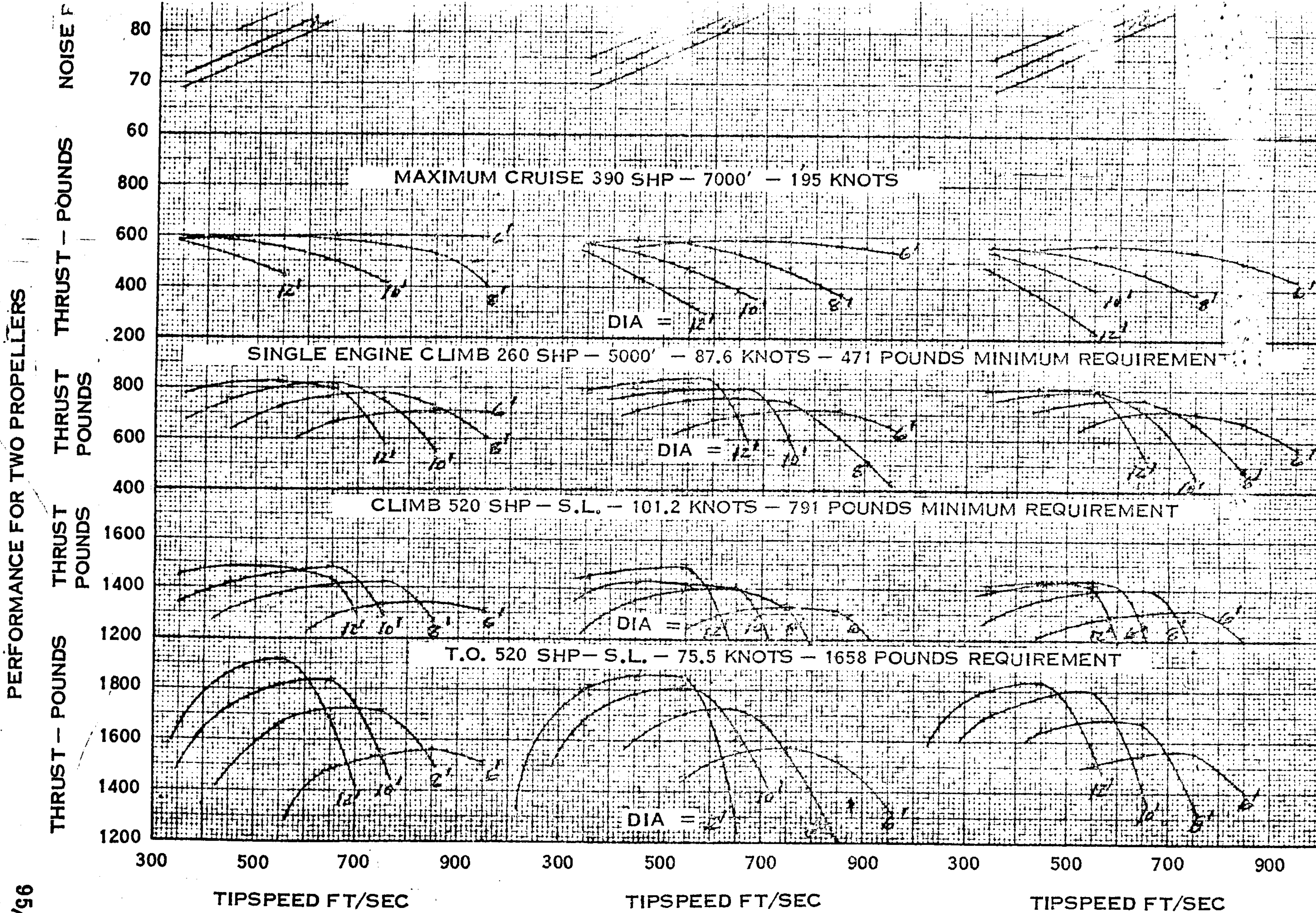
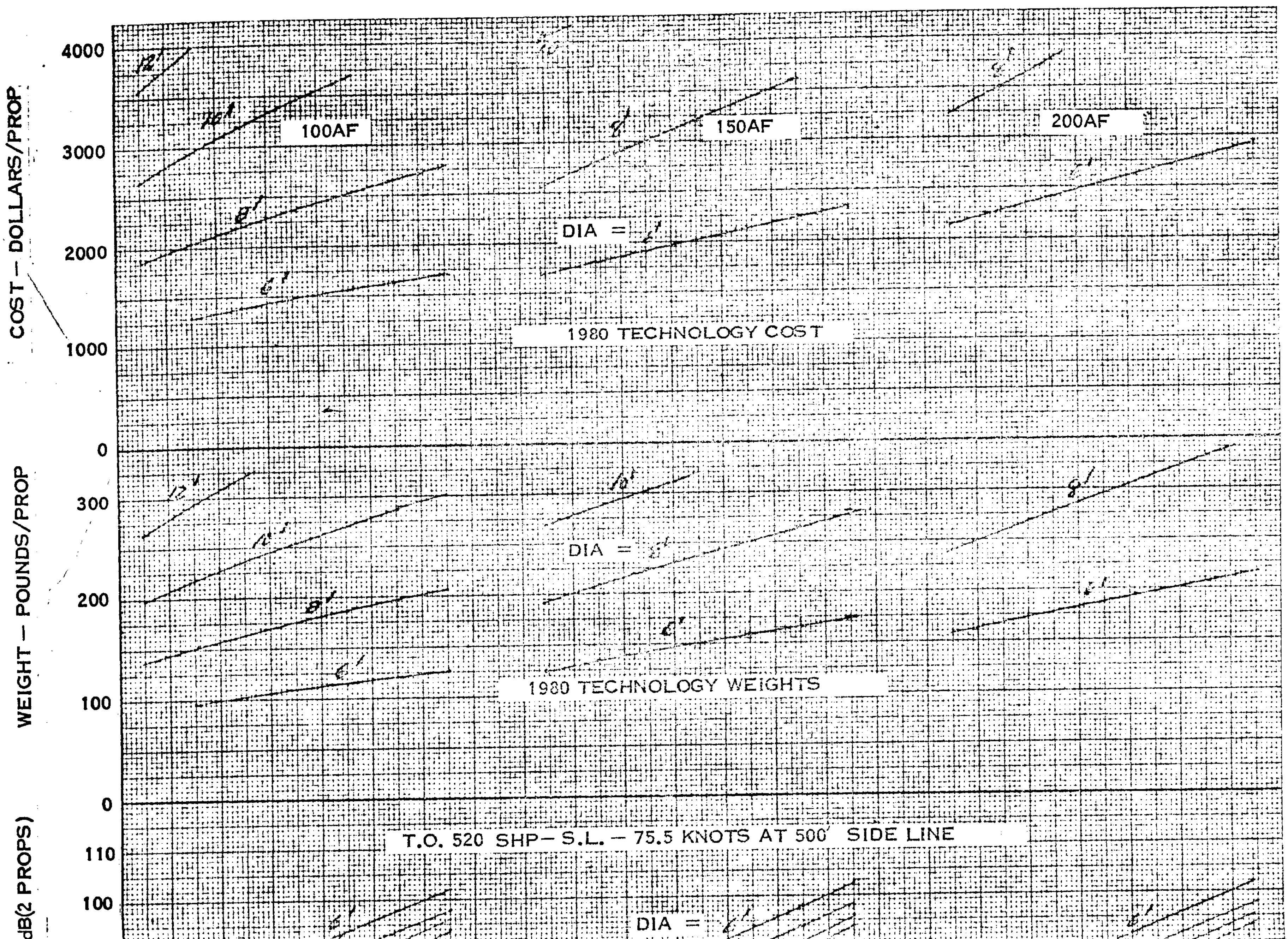


FIGURE 22. CATEGORY III SENSITIVITY STUDY FOR THE BEECH BARON B55
4 BLADED PROPELLER 0.5 INTEGRATED DESIGN C_{L_i}



COST – DOLLARS/PROP
4000
3000
2000
1000
0
100AF
150AF
200AF
DIA =
1980 TECHNOLOGY COST
WEIGHT – POUNDS/PROP
300
200
100
0
DIA =
1980 TECHNOLOGY WEIGHTS
T.O. 520 SHP – S.L. – 75.5 KNOTS AT 500′ SIDE LINE
dB(2 PROPS)
110
100
DIA =

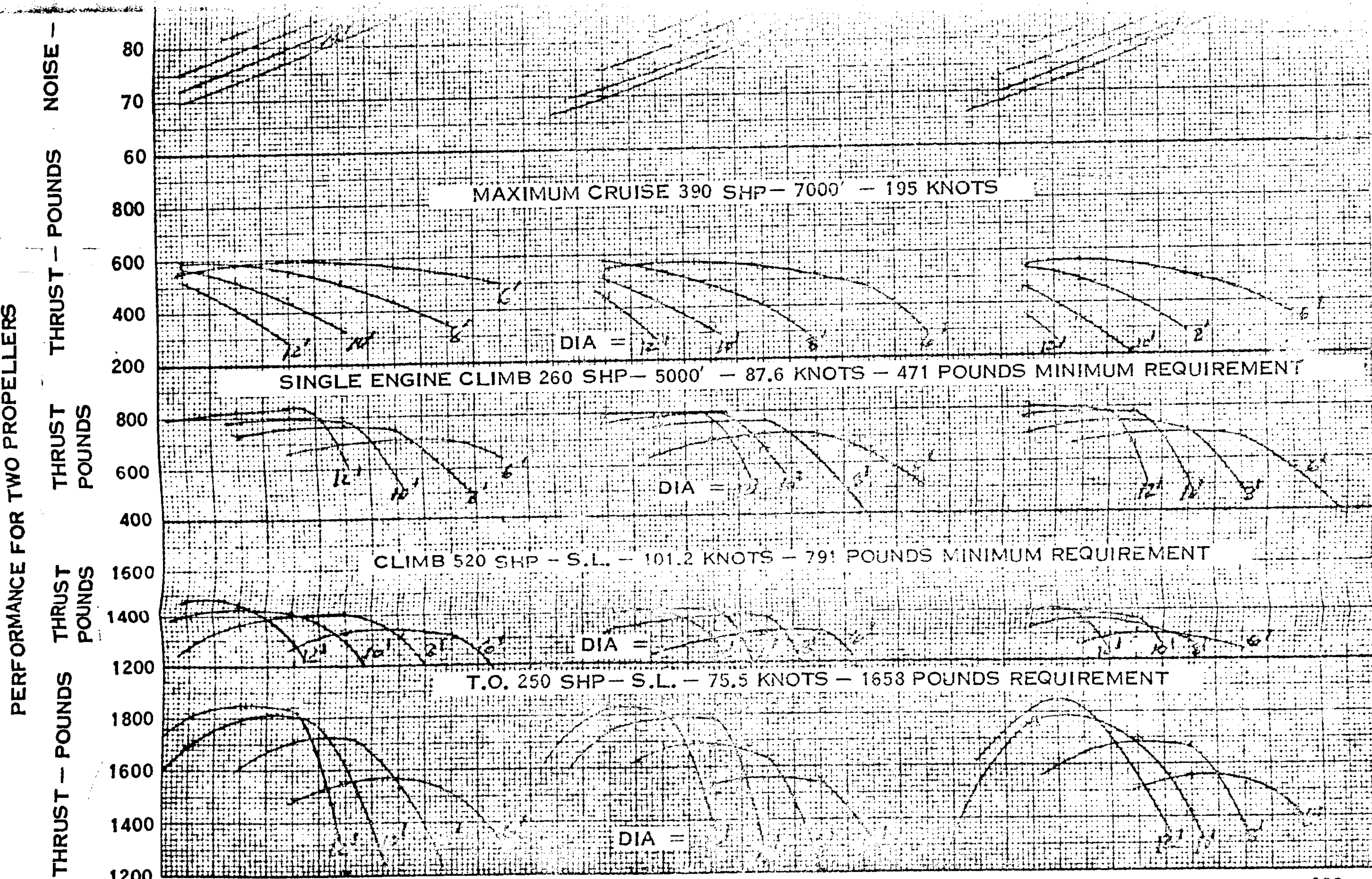
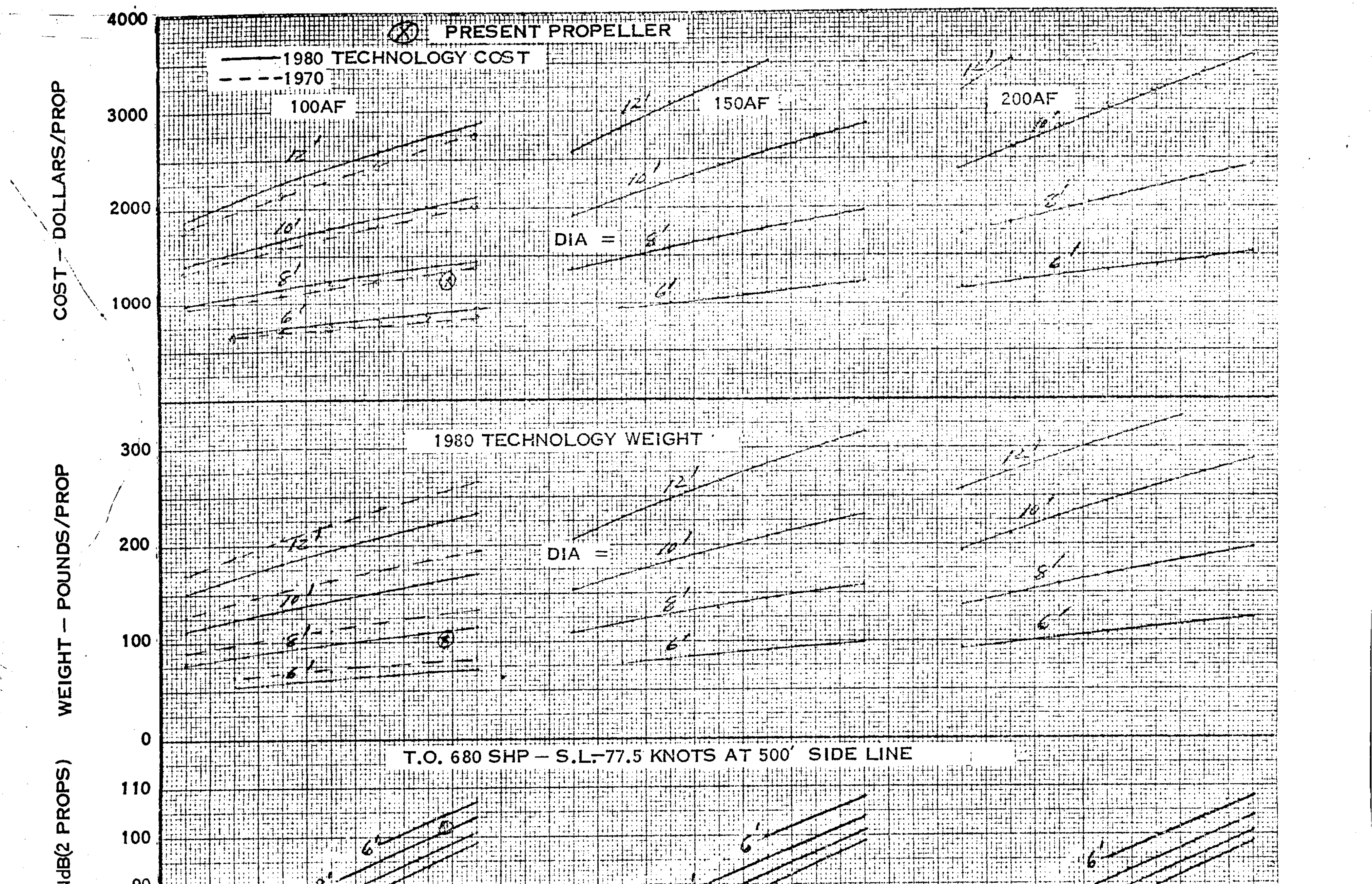


FIGURE 23. CATEGORY III SENSITIVITY STUDY FOR THE BEECH BARON B55
6 BLADED PROPELLER 0.5 INTEGRATED DESIGN C_{L_i}



PRESENT PROPELLER
1980 TECHNOLOGY COST
1970
100AF
150AF
200AF
DIA =
12'
10'
8'
6'
COST – DOLLARS/PROP
4000
3000
2000
1000
1980 TECHNOLOGY WEIGHT
WEIGHT – POUNDS/PROP
300
200
100
0
T.O. 680 SHP – S.L.–77.5 KNOTS AT 500' SIDE LINE
dB(2 PROPS)
110
100

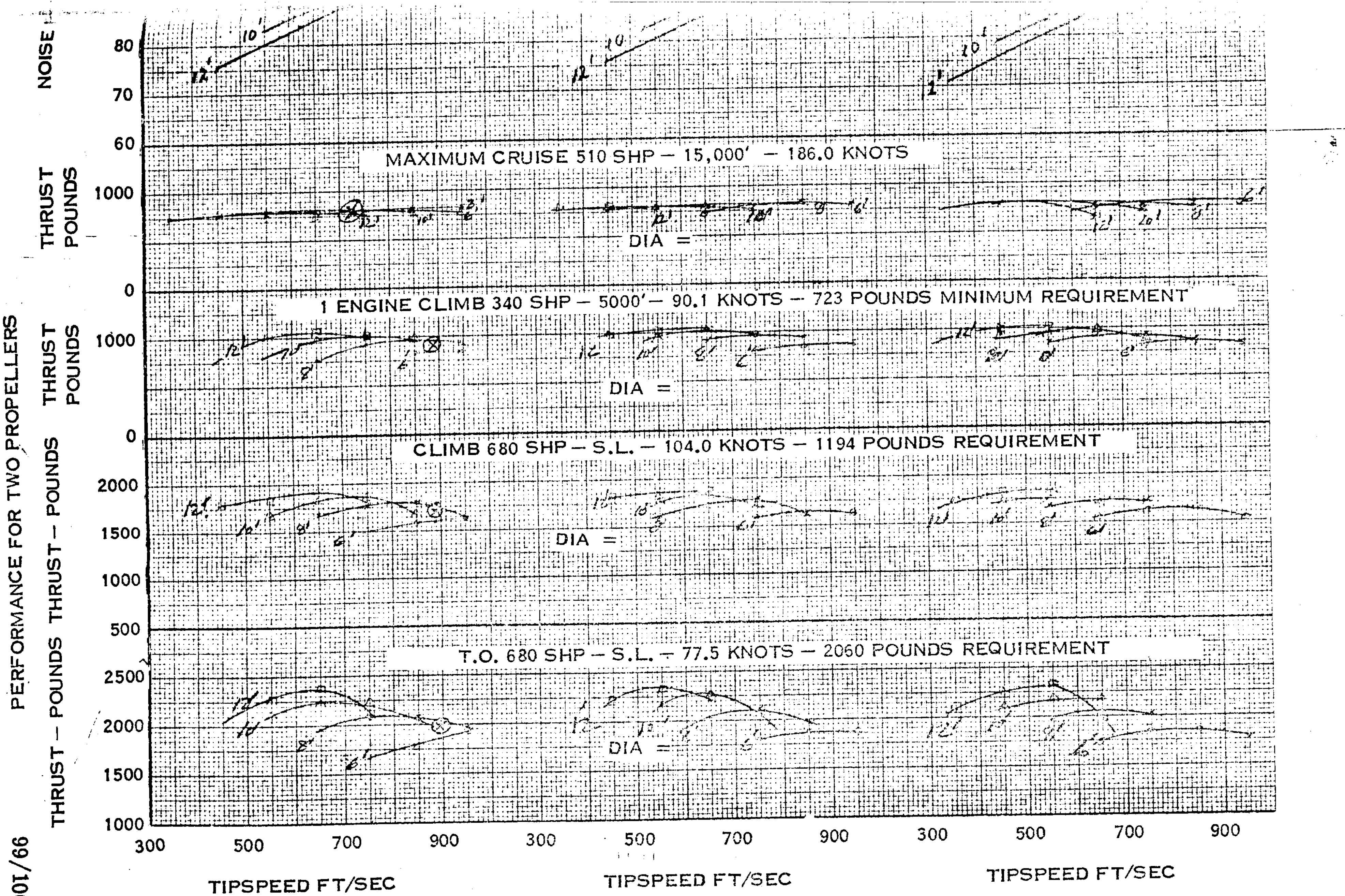
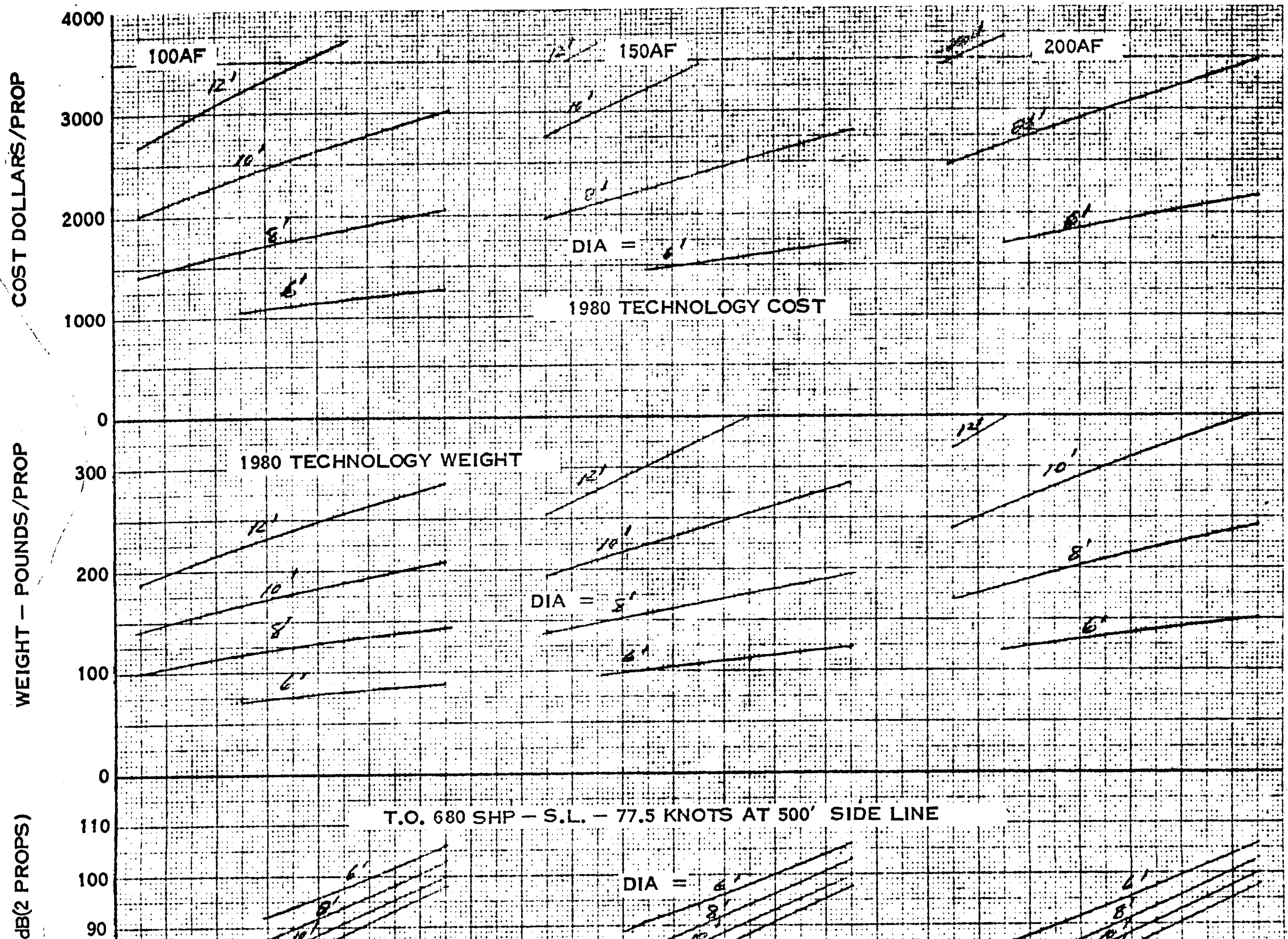


FIGURE 24. CATEGORY IV SENSITIVITY STUDY FOR THE BEECH QUEEN AIR
3 BLADED PROPELLER 0.5 INTEGRATED DESIGN C_{L_i}



COST DOLLARS/PROP
WEIGHT – POUNDS/PROP
dB(2 PROPS)
4000
3000
2000
1000
0
300
200
100
0
110
100
90
100AF
150AF
200AF
DIA =
1980 TECHNOLOGY COST
1980 TECHNOLOGY WEIGHT
DIA =
T.O. 680 SHP – S.L. – 77.5 KNOTS AT 500′ SIDE LINE
DIA =

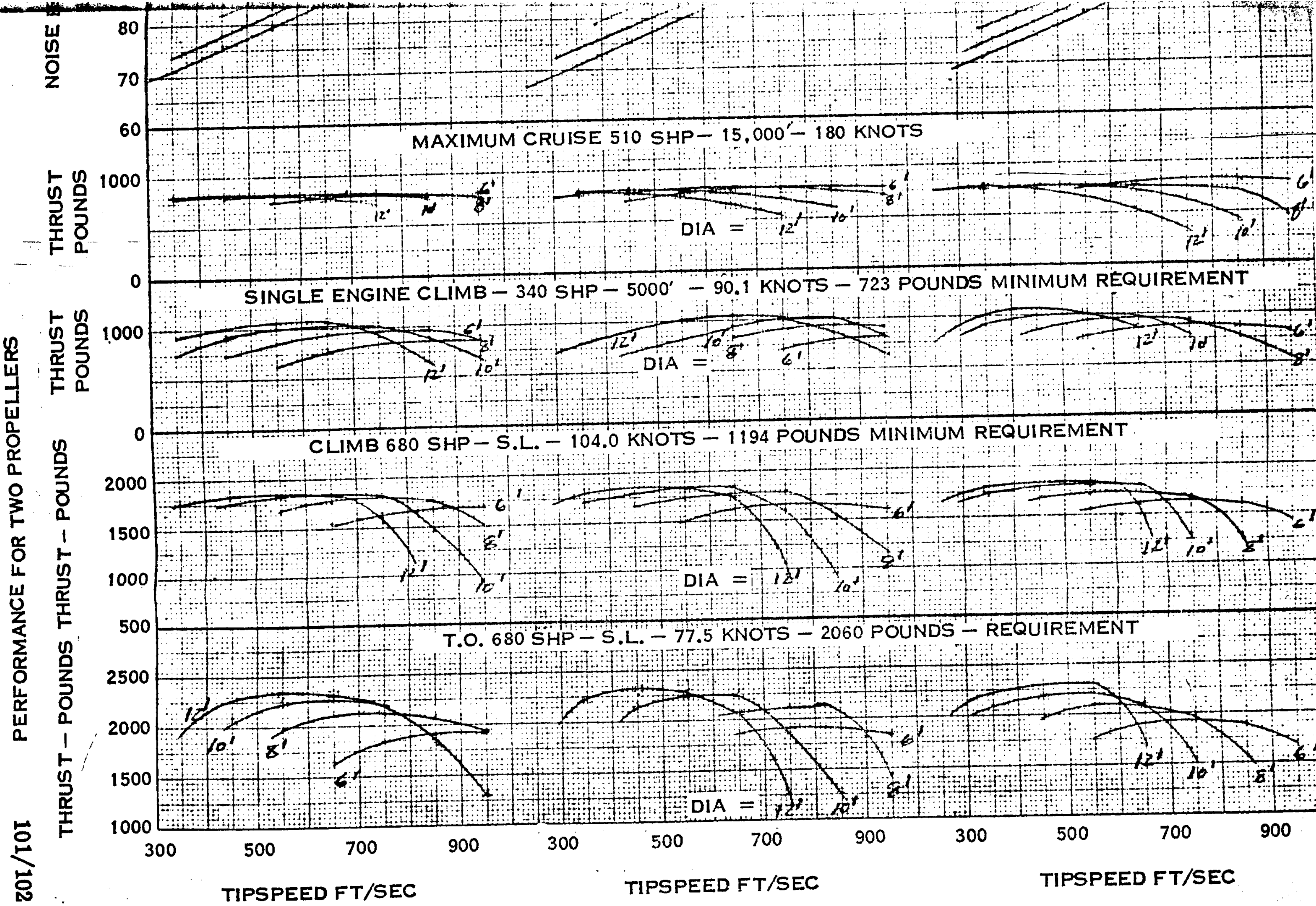
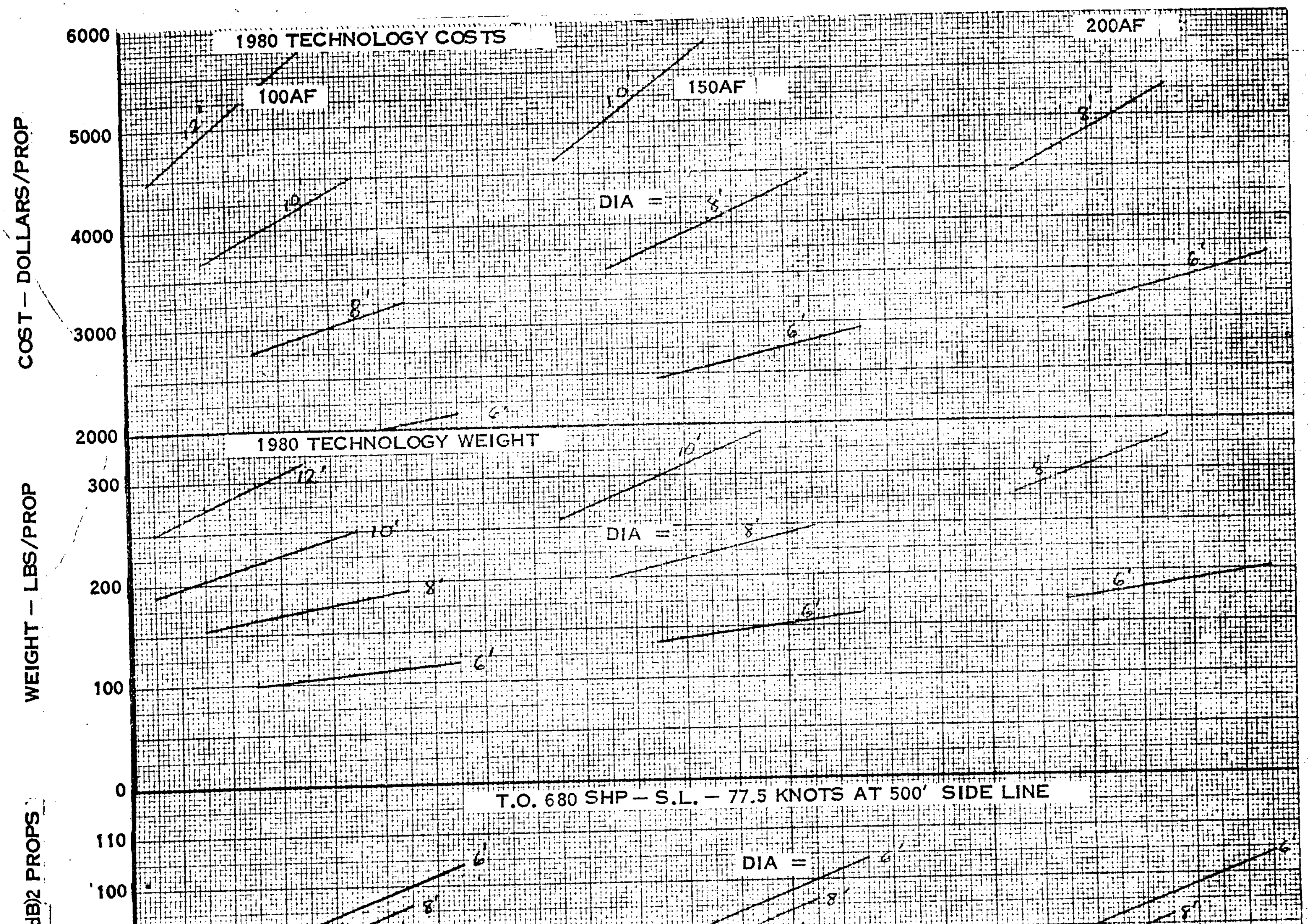


FIGURE 25. CATEGORY IV SENSITIVITY STUDY FOR THE BEECH QUEEN AIR
4 BLADED PROPELLERS 0.5 INTEGRATED DESIGN C_{Li}


1980 TECHNOLOGY COSTS
100AF
150AF
200AF
DIA =
1980 TECHNOLOGY WEIGHT
DIA =
T.O. 680 SHP – S.L. – 77.5 KNOTS AT 500′ SIDE LINE
DIA =
COST – DOLLARS/PROP
WEIGHT – LBS/PROP
dB)2 PROPS
6000
5000
4000
3000
2000
300
200
100
0
110
100

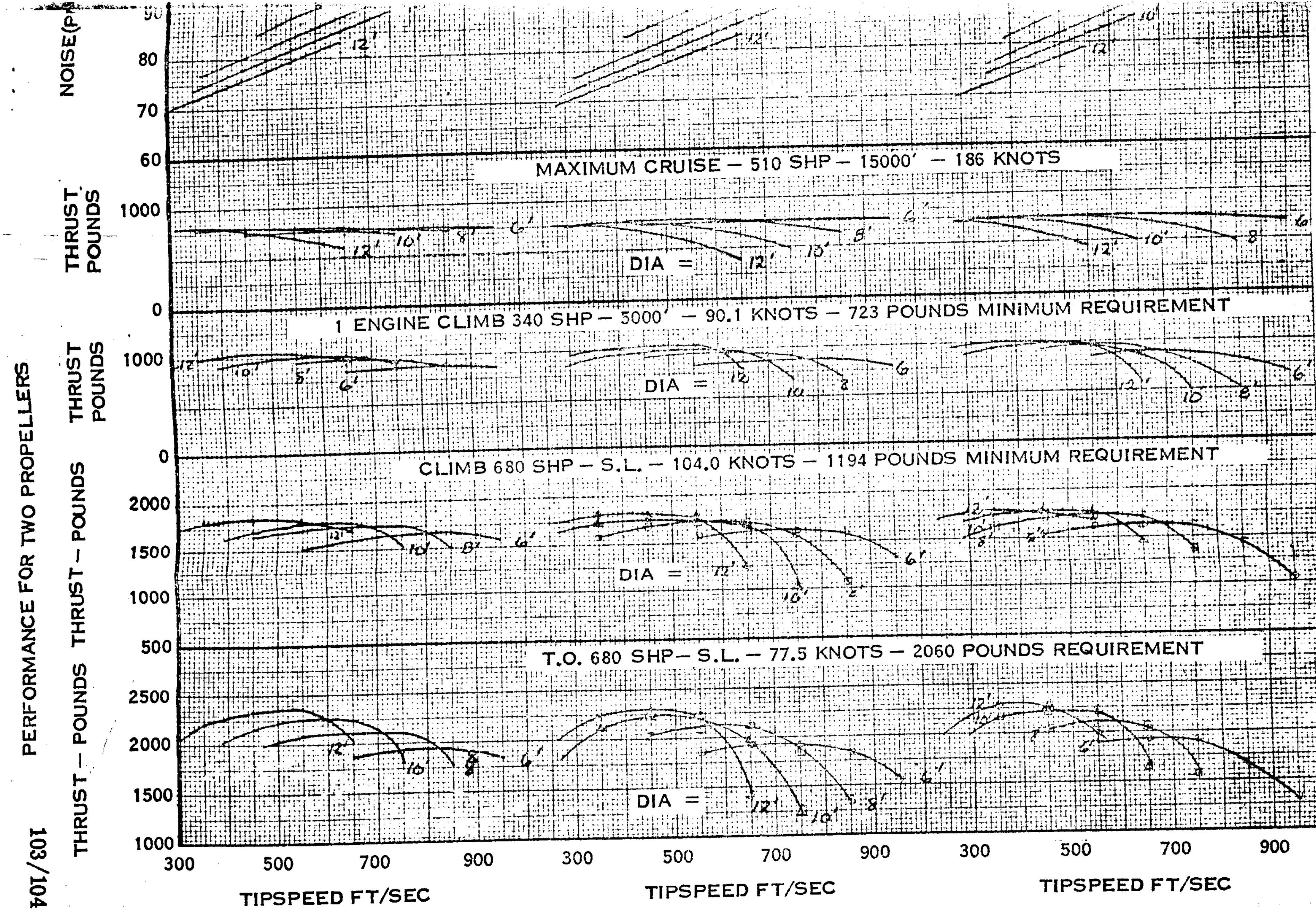
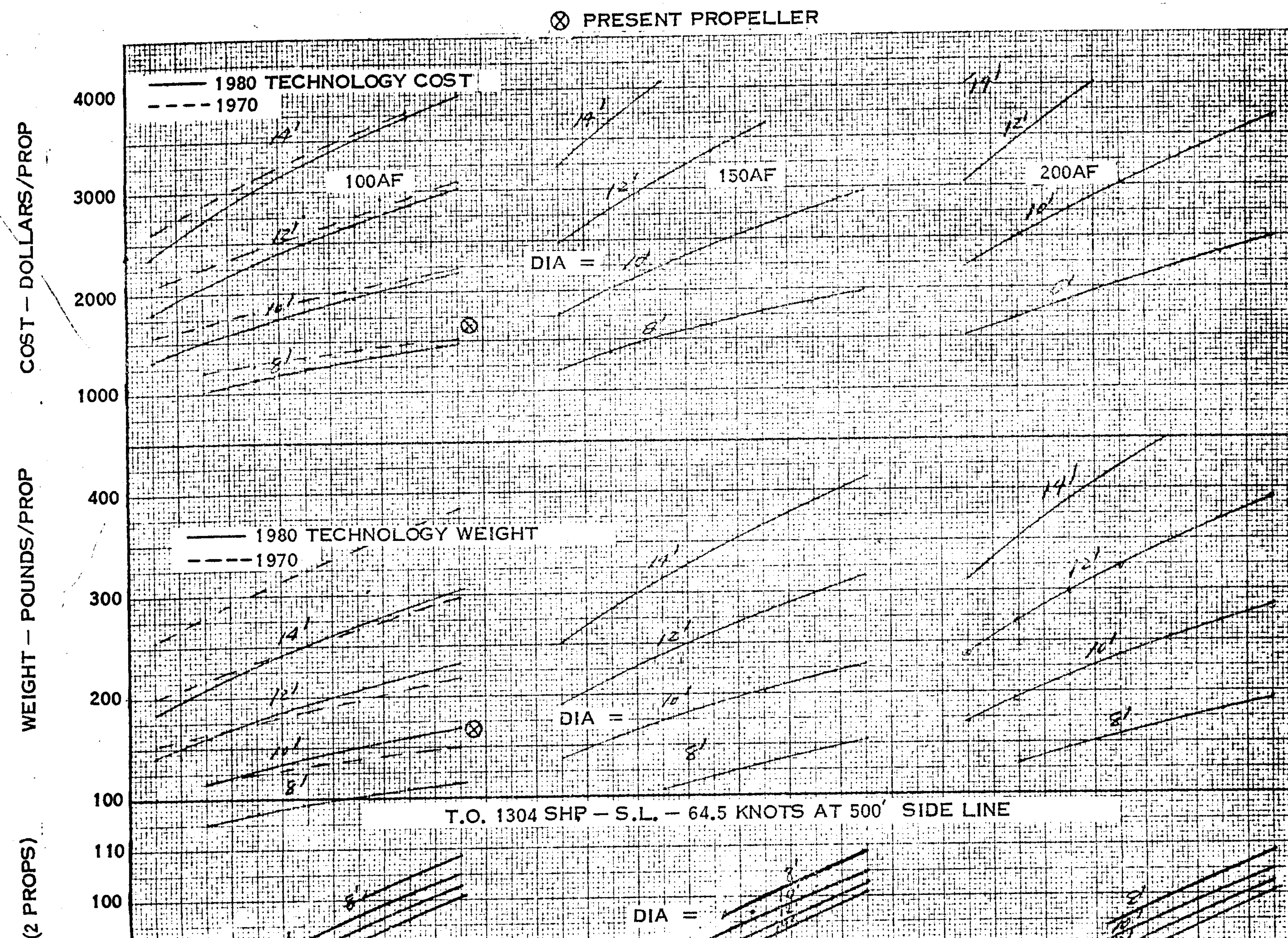


FIGURE 26. CATEGORY IV SENSITIVITY STUDY FOR THE BEECH QUEEN AIR 6 BLADED PROPELLER 0.5 INTEGRATED DESIGN C_{L_i}


⊗ PRESENT PROPELLER
1980 TECHNOLOGY COST
1970
COST – DOLLARS/PROP
4000
3000
2000
1000
100AF
150AF
200AF
DIA =
1980 TECHNOLOGY WEIGHT
1970
WEIGHT – POUNDS/PROP
400
300
200
100
T.O. 1304 SHP – S.L. – 64.5 KNOTS AT 500′ SIDE LINE
(2 PROPS)
110
100

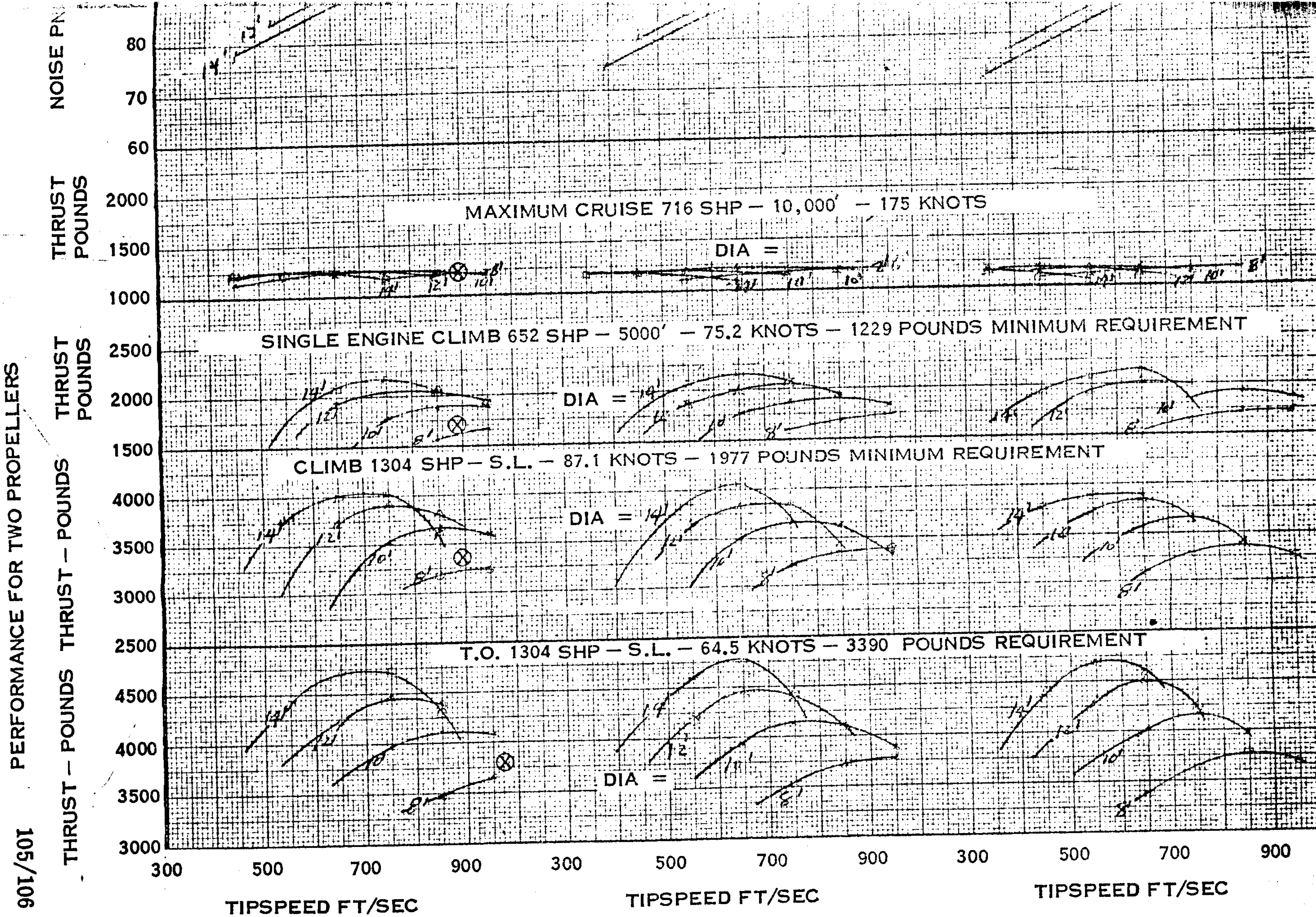
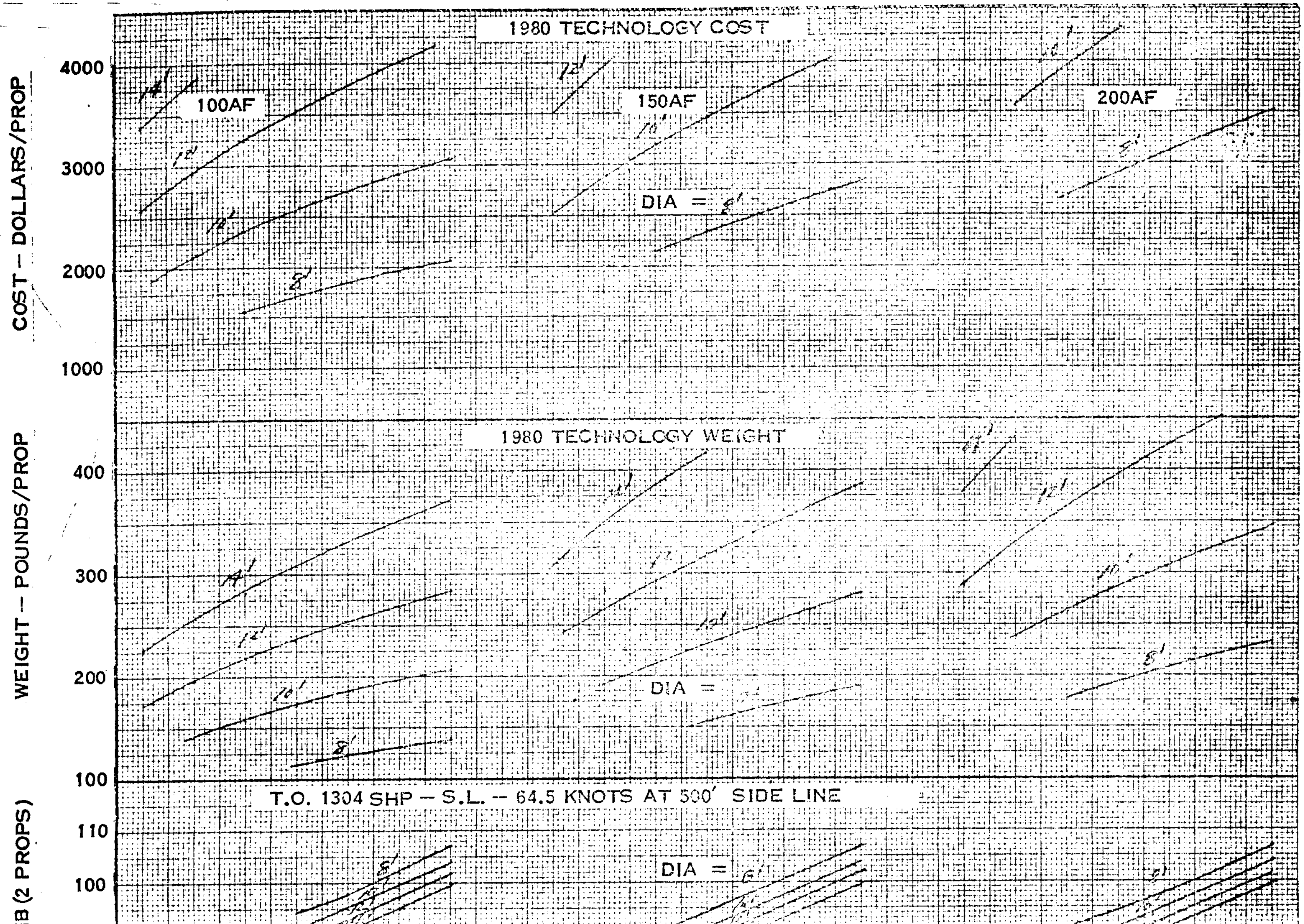


FIGURE 27. CATEGORY V SENSITIVITY STUDY FOR THE DEHAVILLAND TWIN OTTER 3 BLADED PROPELLERS 0.5 INTEGRATED DESIGN C_{L_i}


1980 TECHNOLOGY COST
COST – DOLLARS/PROP
4000
3000
2000
1000
100AF
150AF
200AF
DIA =
1980 TECHNOLOGY WEIGHT
WEIGHT – POUNDS/PROP
400
300
200
100
DIA =
T.O. 1304 SHP – S.L. – 64.5 KNOTS AT 500′ SIDE LINE
B (2 PROPS)
110
100
DIA =

107/108

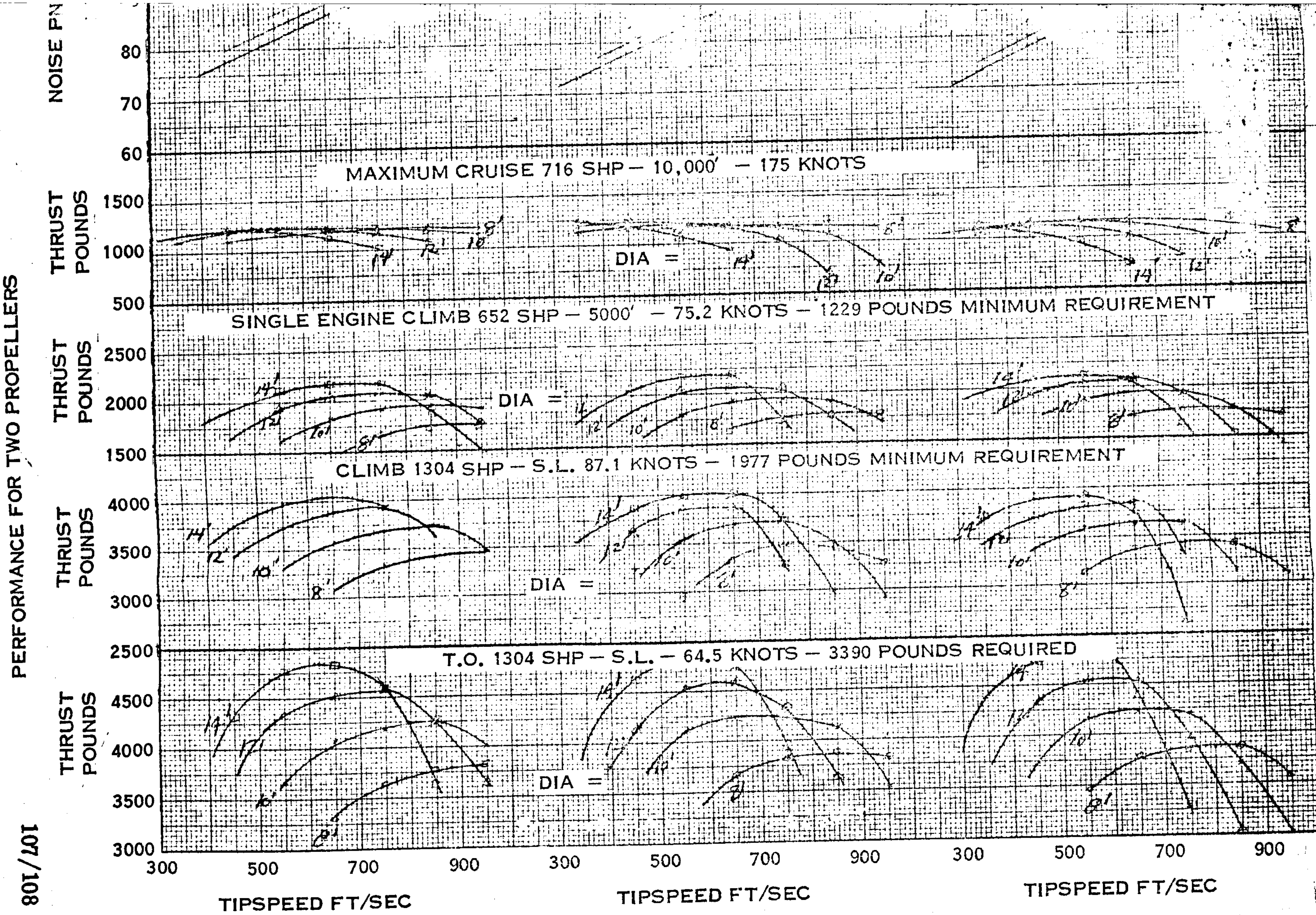
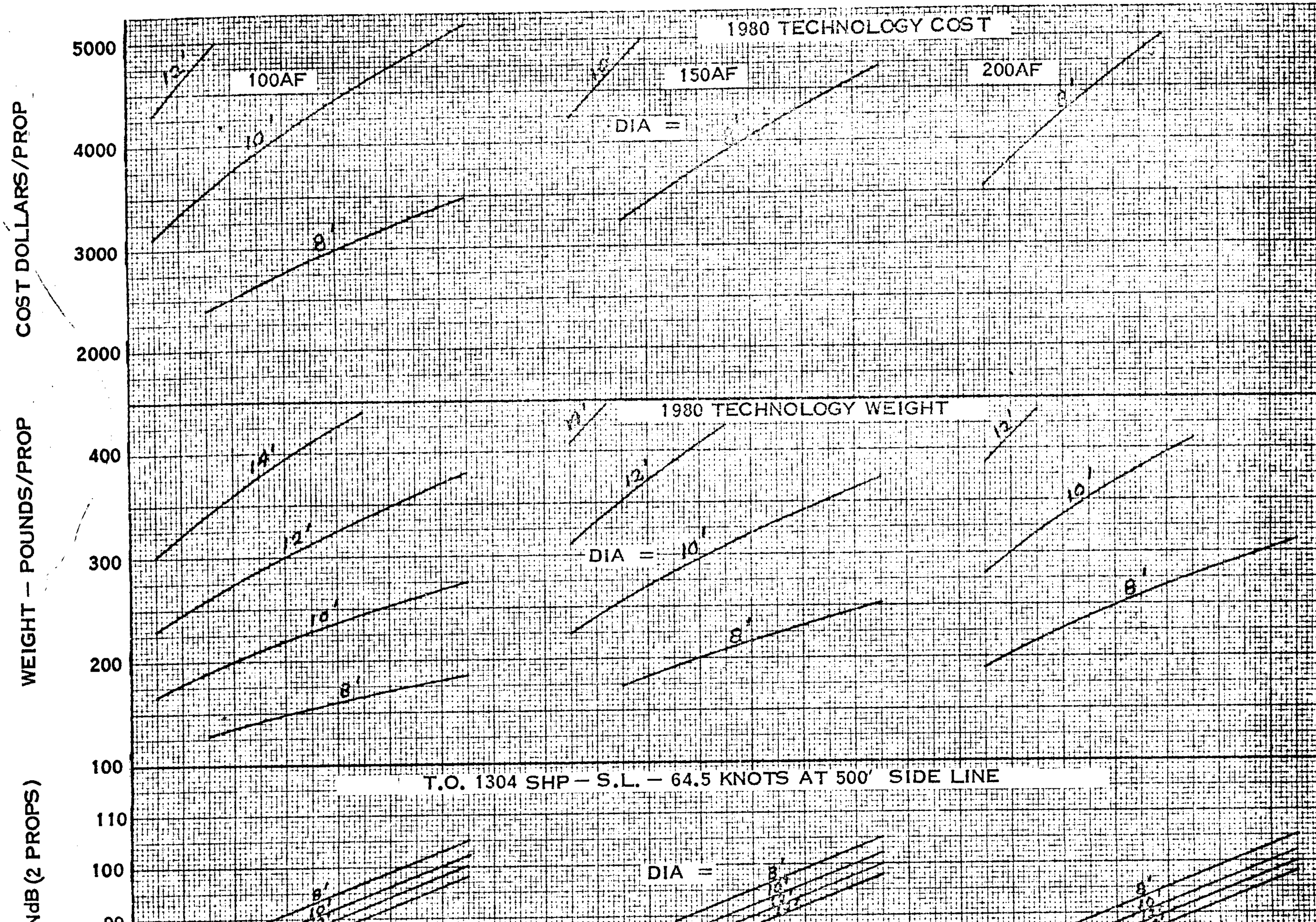


FIGURE 28. CATEGORY V SENSITIVITY STUDY FOR THE DEHAVILLAND TWIN OTTER 4 BLADED PROPELLERS 0.5 INTEGRATED DESIGN C_{L_i}


1980 TECHNOLOGY COST
100AF
150AF
200AF
DIA =
COST DOLLARS/PROP
5000
4000
3000
2000
1980 TECHNOLOGY WEIGHT
WEIGHT – POUNDS/PROP
400
300
200
100
T.O. 1304 SHP – S.L. – 64.5 KNOTS AT 500′ SIDE LINE
110
100
90
dB (2 PROPS)

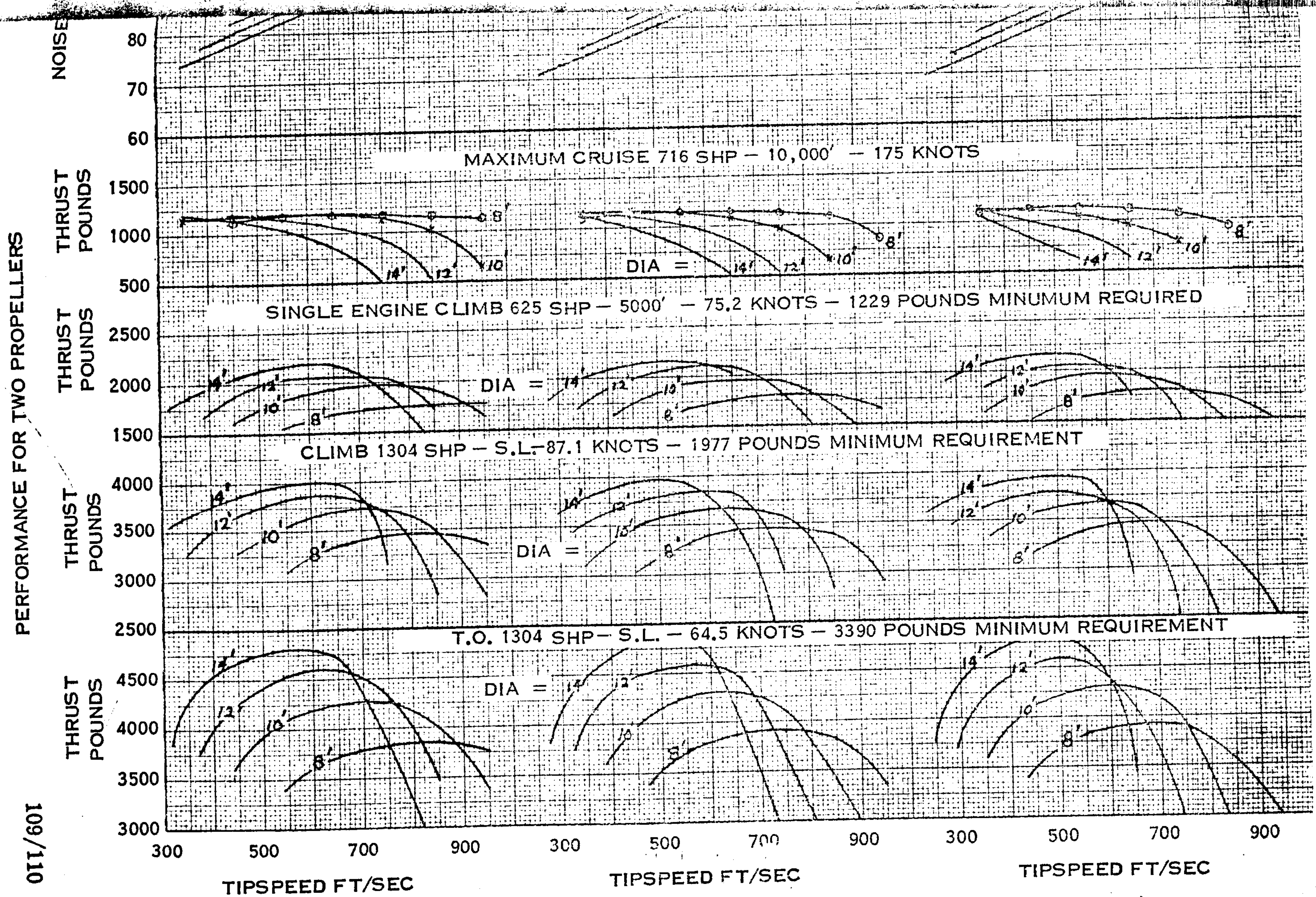
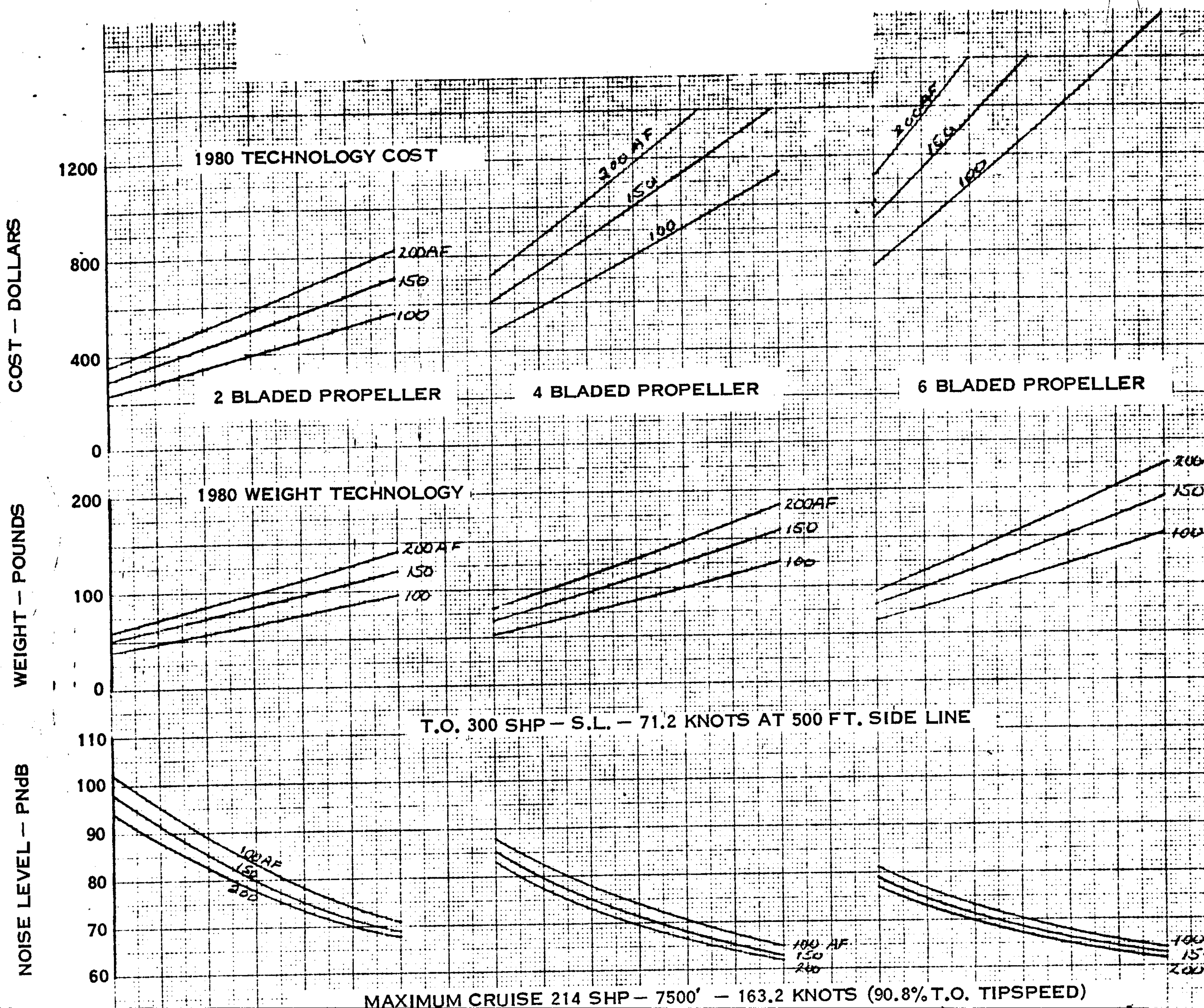


FIGURE 29. CATEGORY V SENSITIVITY STUDY FOR THE DEHAVILLAND TWIN OTTER 6 BLADED PROPELLERS 0.5 INTEGRATED DESIGN C_{L_i}


1980 TECHNOLOGY COST
COST — DOLLARS
1200
800
400
0
200AF
150
100
2 BLADED PROPELLER
4 BLADED PROPELLER
6 BLADED PROPELLER
1980 WEIGHT TECHNOLOGY
WEIGHT — POUNDS
200
100
0
T.O. 300 SHP — S.L. — 71.2 KNOTS AT 500 FT. SIDE LINE
NOISE LEVEL — PNdB
110
100
90
80
70
60
100AF
150
200
MAXIMUM CRUISE 214 SHP — 7500' — 163.2 KNOTS (90.8% T.O. TIPSPEED)

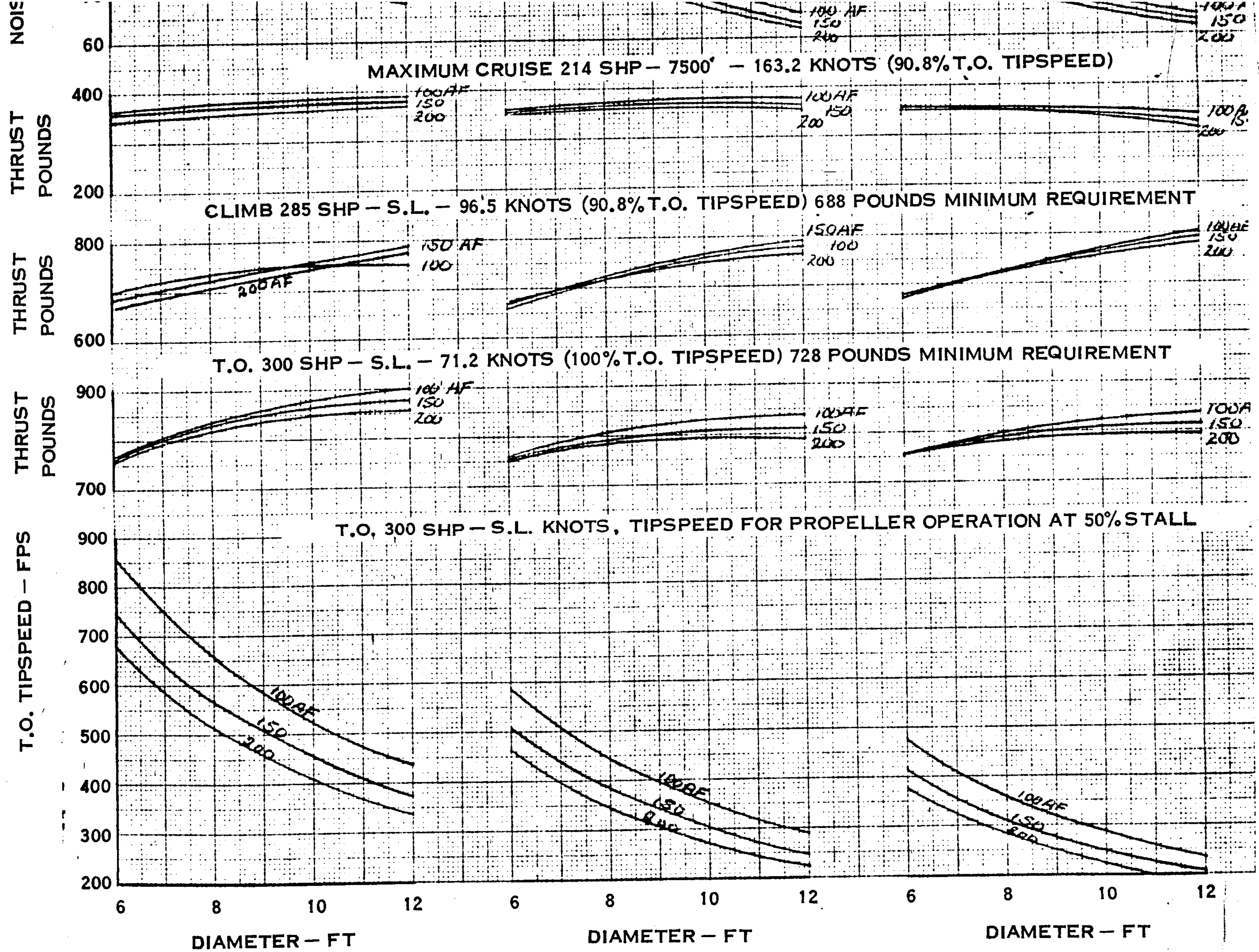
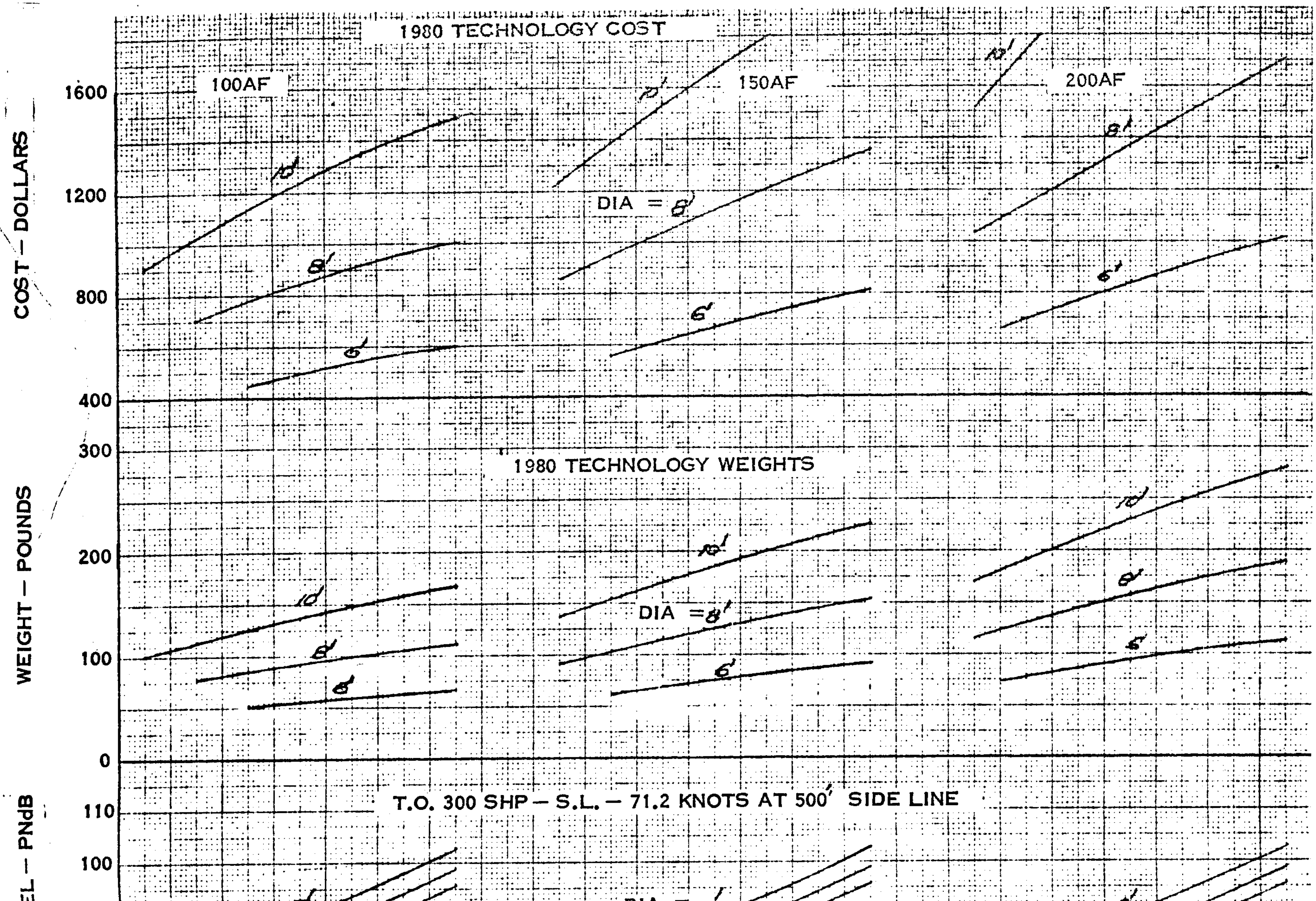


FIGURE 30. CATEGORY II SENSITIVITY STUDY FOR THE CESSNA 210J PROPELLER OPERATING AT 50% STALL 0.5 INTEGRATED DESIGN C_{L_i}


1980 TECHNOLOGY COST
100AF
150AF
200AF
DIA = 8'
10'
8'
6'
COST — DOLLARS
1600
1200
800
400
300
200
100
0
110
100
1980 TECHNOLOGY WEIGHTS
DIA = 8'
WEIGHT — POUNDS
T.O. 300 SHP — S.L. — 71.2 KNOTS AT 500' SIDE LINE
EL — PNdB

113/114

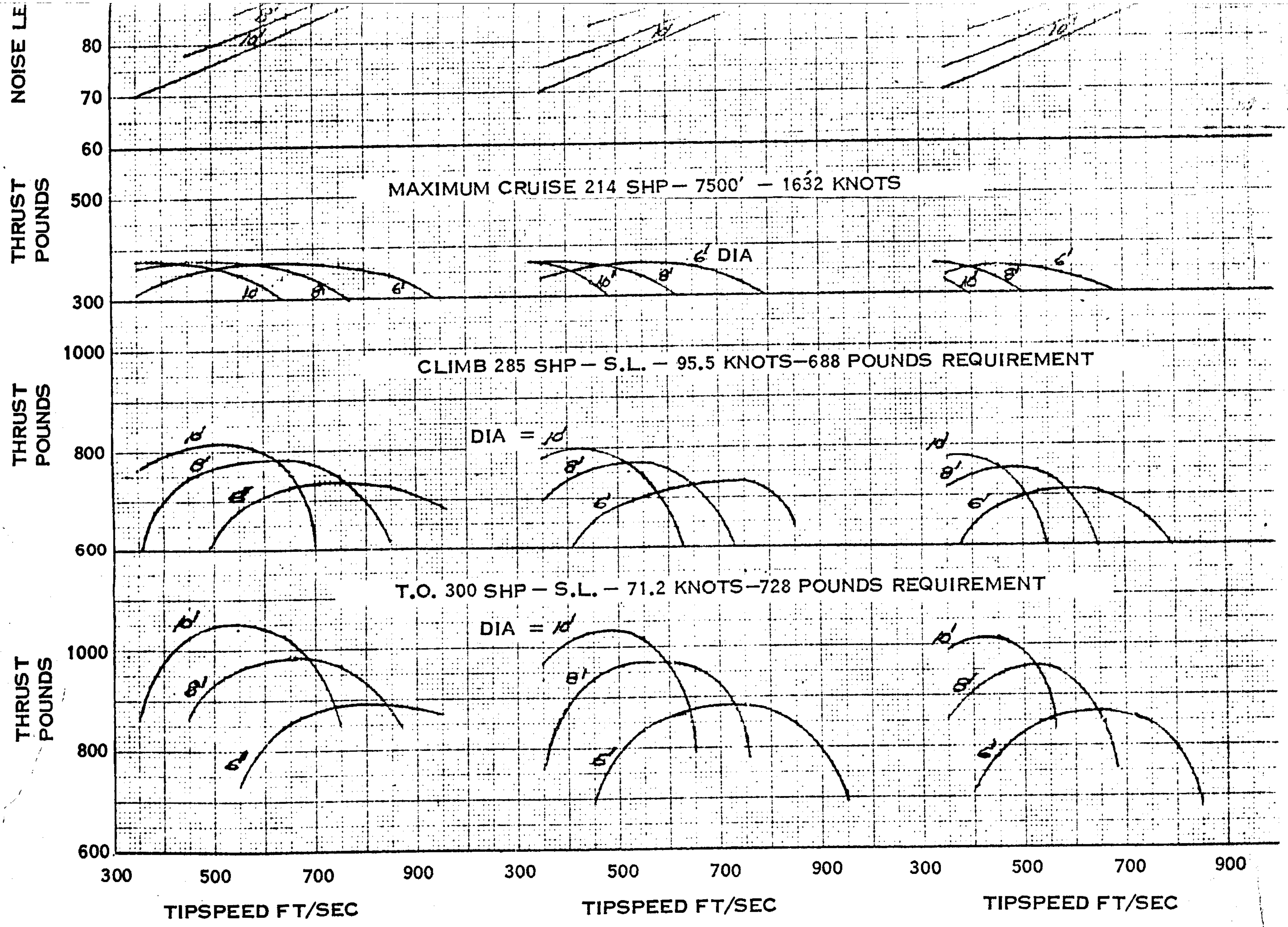


FIGURE 31. CATEGORY II SENSITIVITY STUDY FOR THE CESSNA 210J 4 BLADED PROPELLER 0.7 INTEGRATED DESIGN C_{L_i}

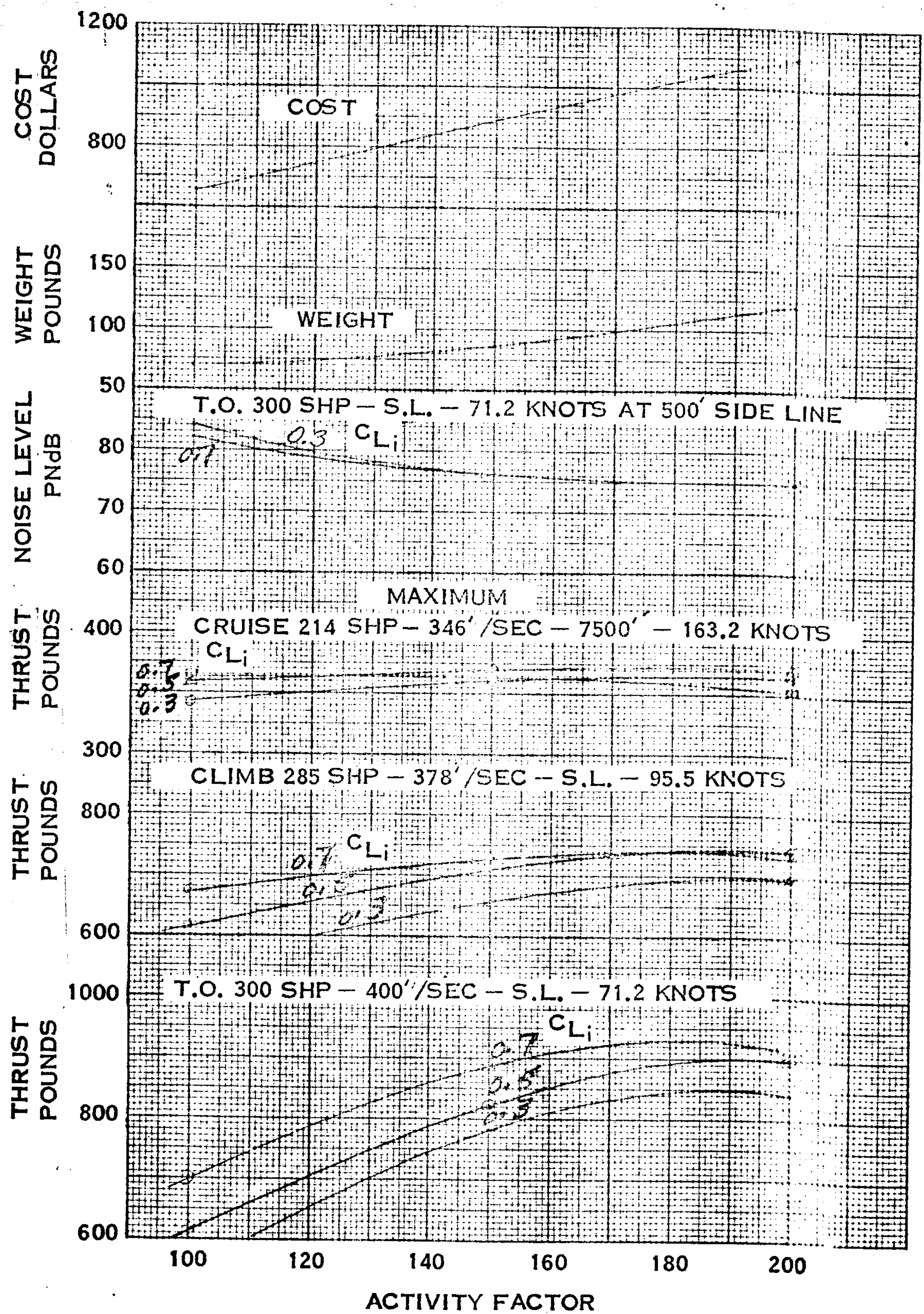


FIGURE 32. CATEGORY II INTEGRATED DESIGN C_{L_i} SENSITIVITY STUDY FOR THE CESSNA 210J

DIAMETER = 8′

NO. OF BLADES = 4

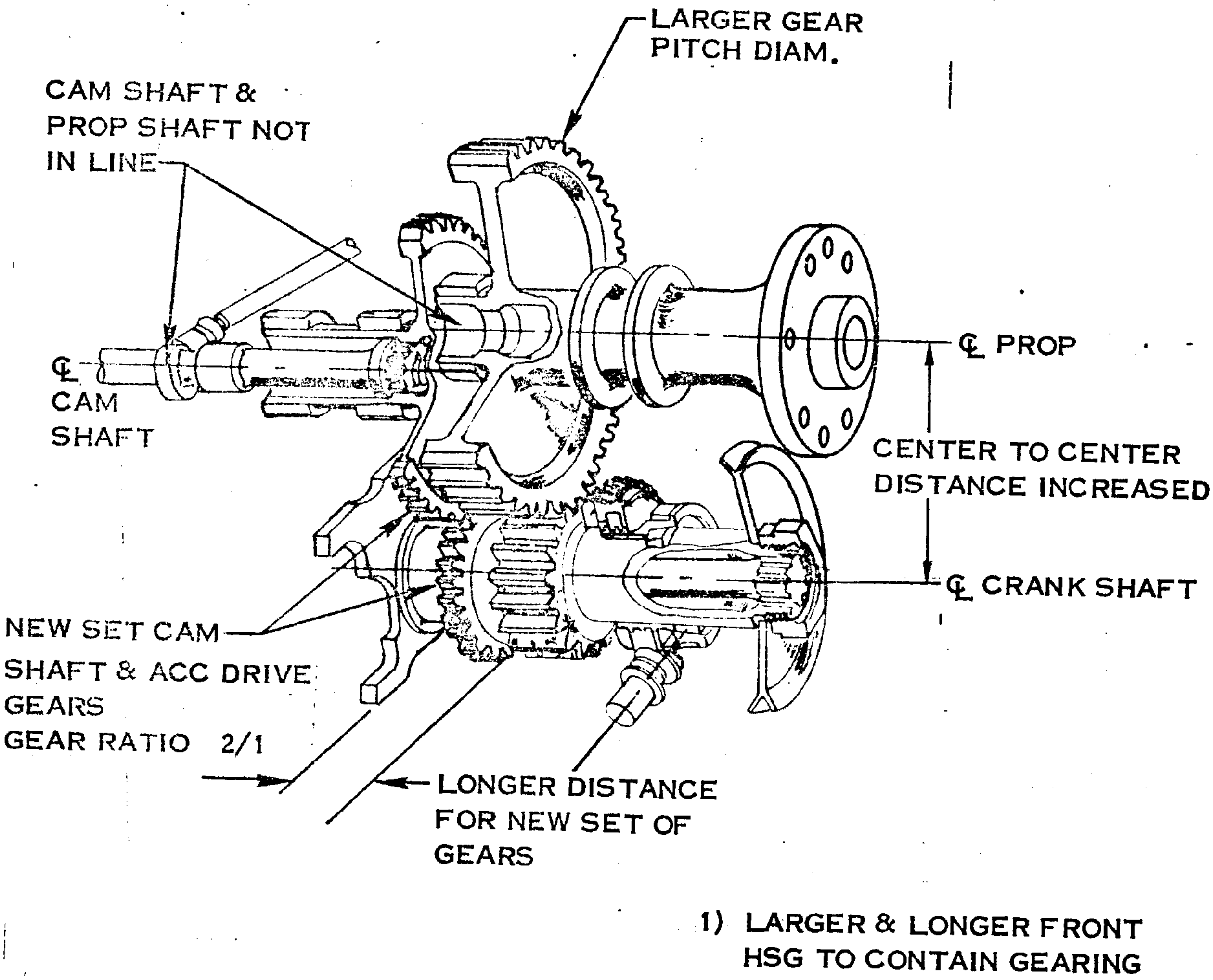


FIGURE 33. TYPICAL ENGINE GEAR REDUCTION REVISIONS

T.O. 820 POUNDS THRUST – S.L. – 71.2 KNOTS

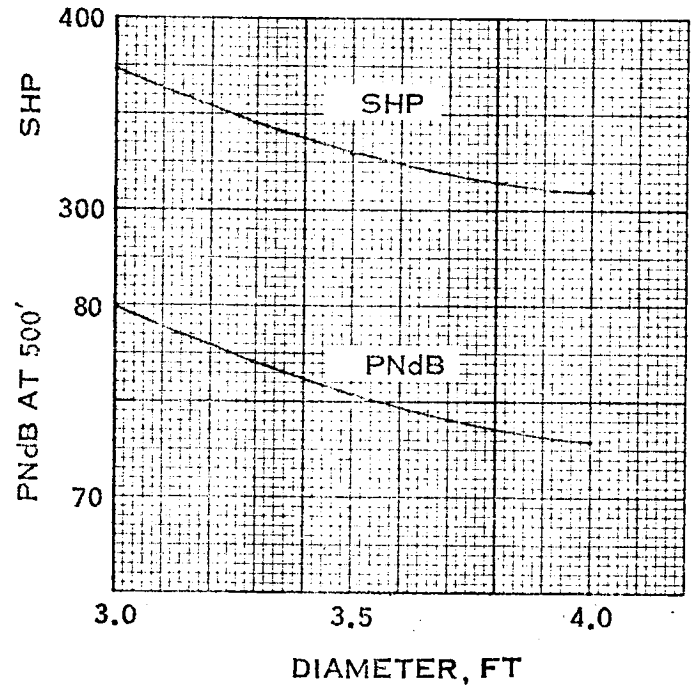


FIGURE 34. CATEGORY II SENSITIVITY STUDY FOR THE CESSNA 210J PROP–FAN 8 BLADES/1650 TAF/0.35 C_{L_i}, 600 FT/SEC. TIPSPEED

● CONVENTIONAL PROPELLER 4 BLADES/8.0 DIA/150AF/0.5C_{L_i} CLIMB & CRUISE PERFORMANCE PLOTTED VERSUS T.O. TIPSPEED

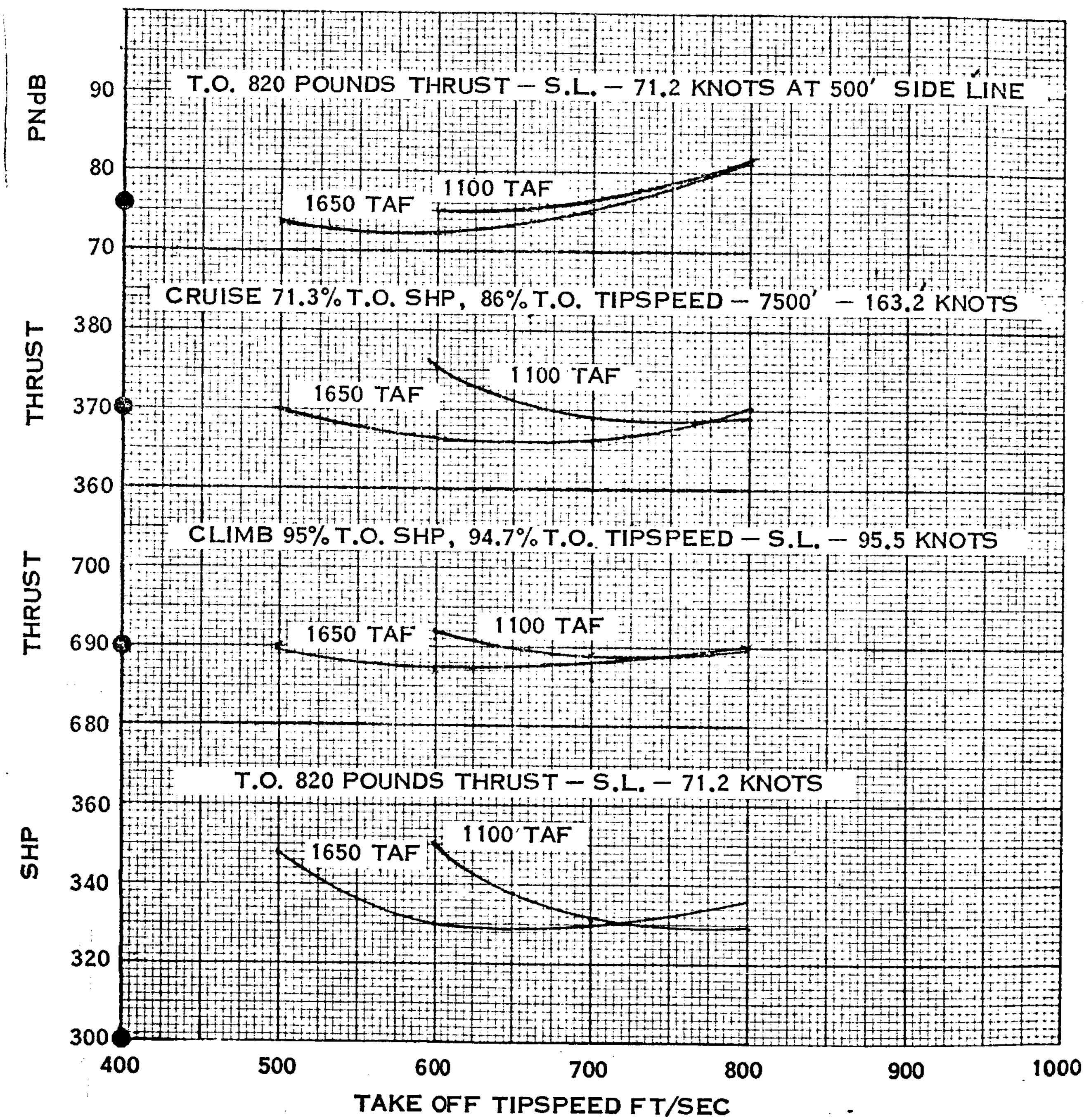


FIGURE 35. CATEGORY II SENSITIVITY STUDY FOR THE CESSNA 210J PROP-FAN 8 BLADES/3.5 DIAMETER/0.35 C_{L_i}

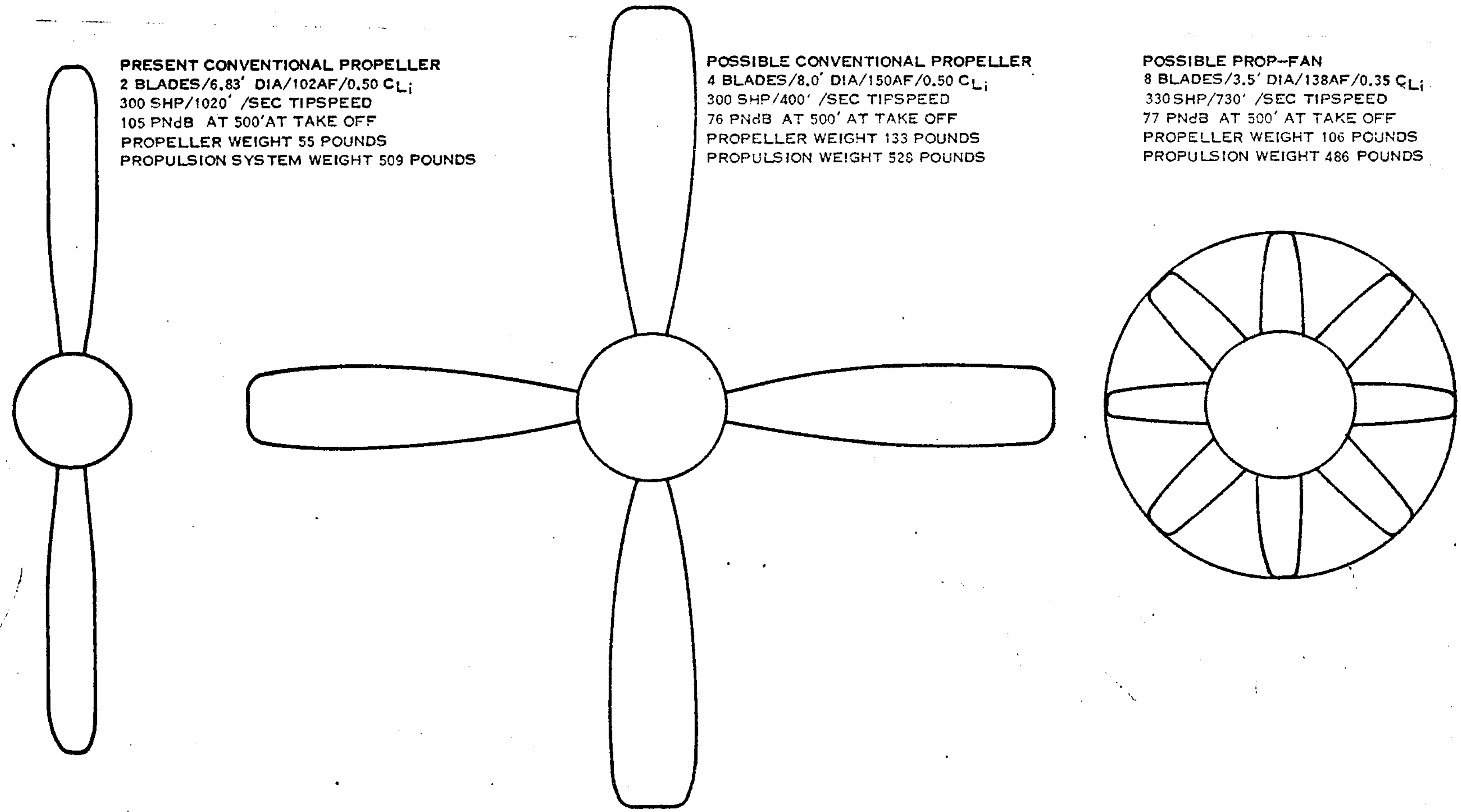


FIGURE 36. PROPULSORS FOR THE CESSNA 210J

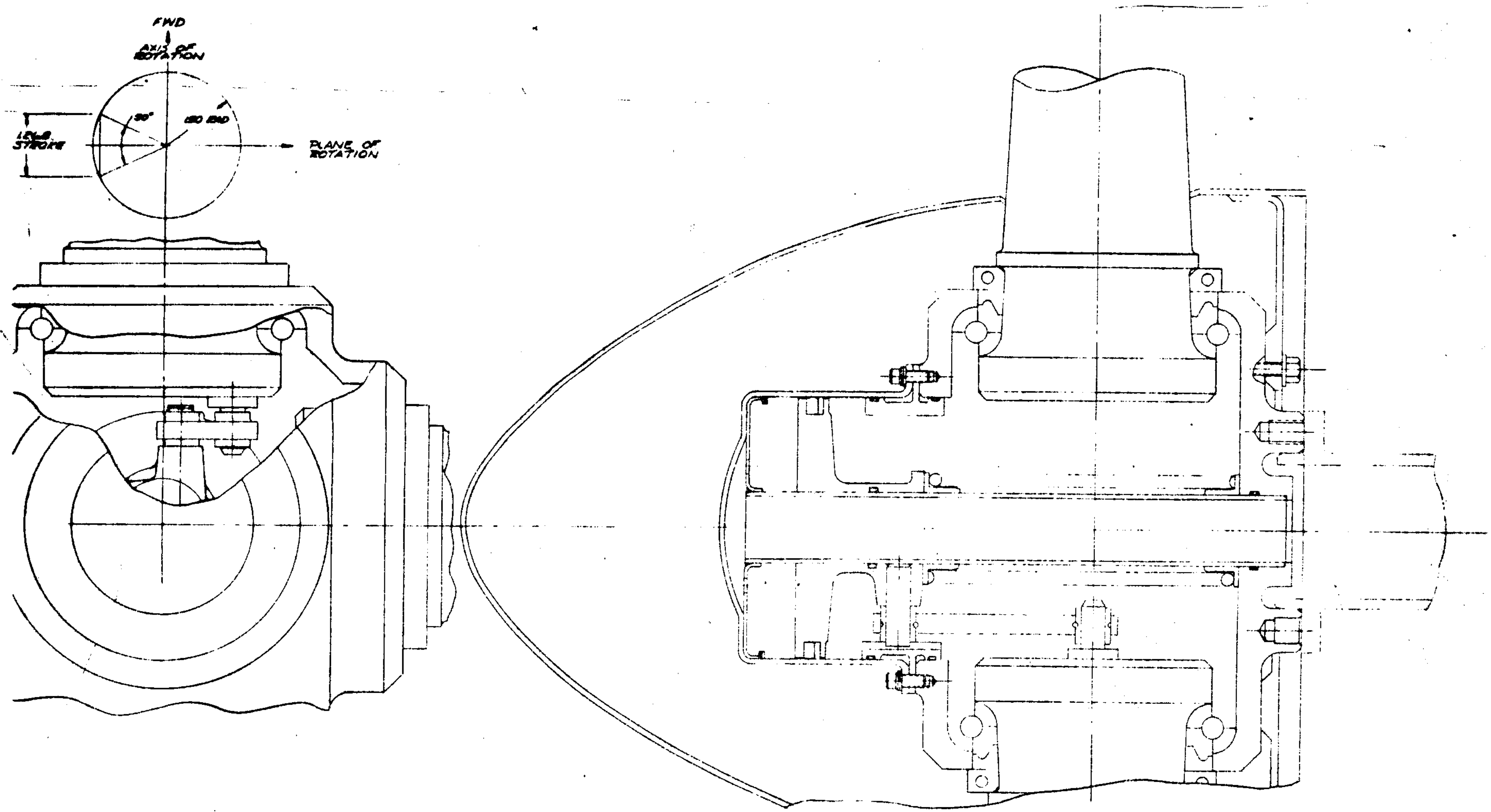


FIGURE 37. ADVANCED PROPELLER CONCEPT
CATEGORY II

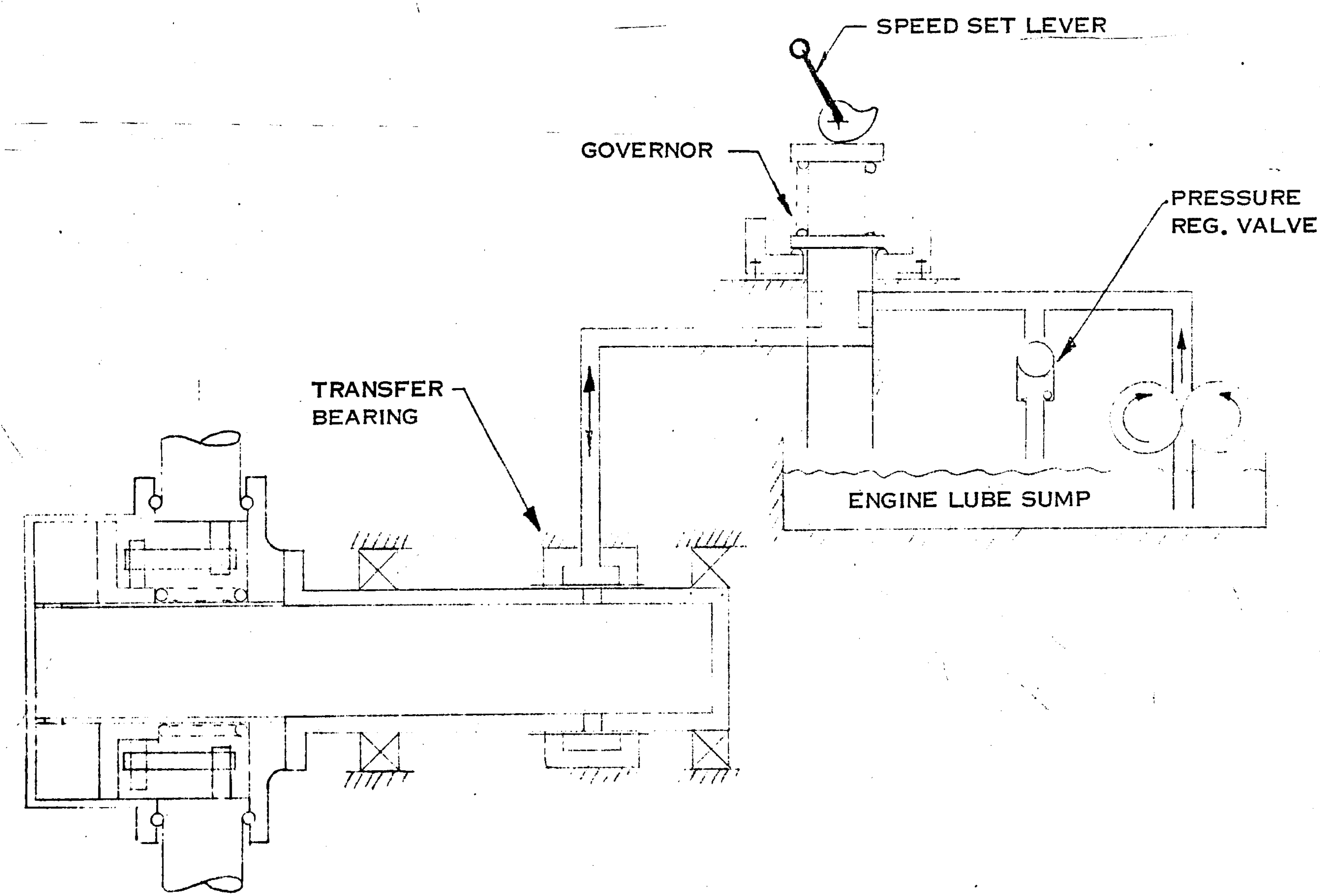


FIGURE 38. PROPELLER HYDRAULIC SCHEMATIC CATEGORY II

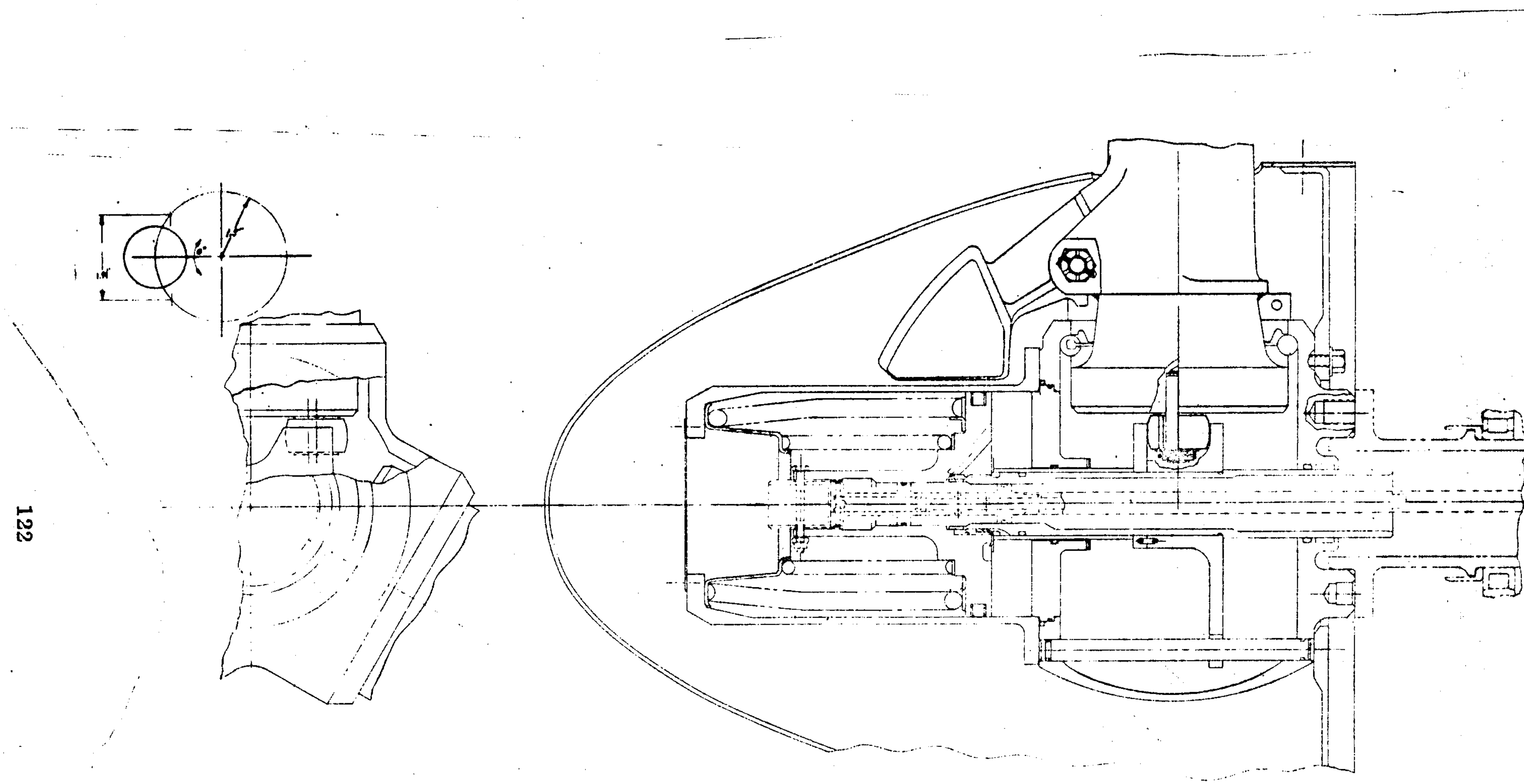


FIGURE 39. ADVANCED PROPELLER CONCEPT
CATEGORY IV

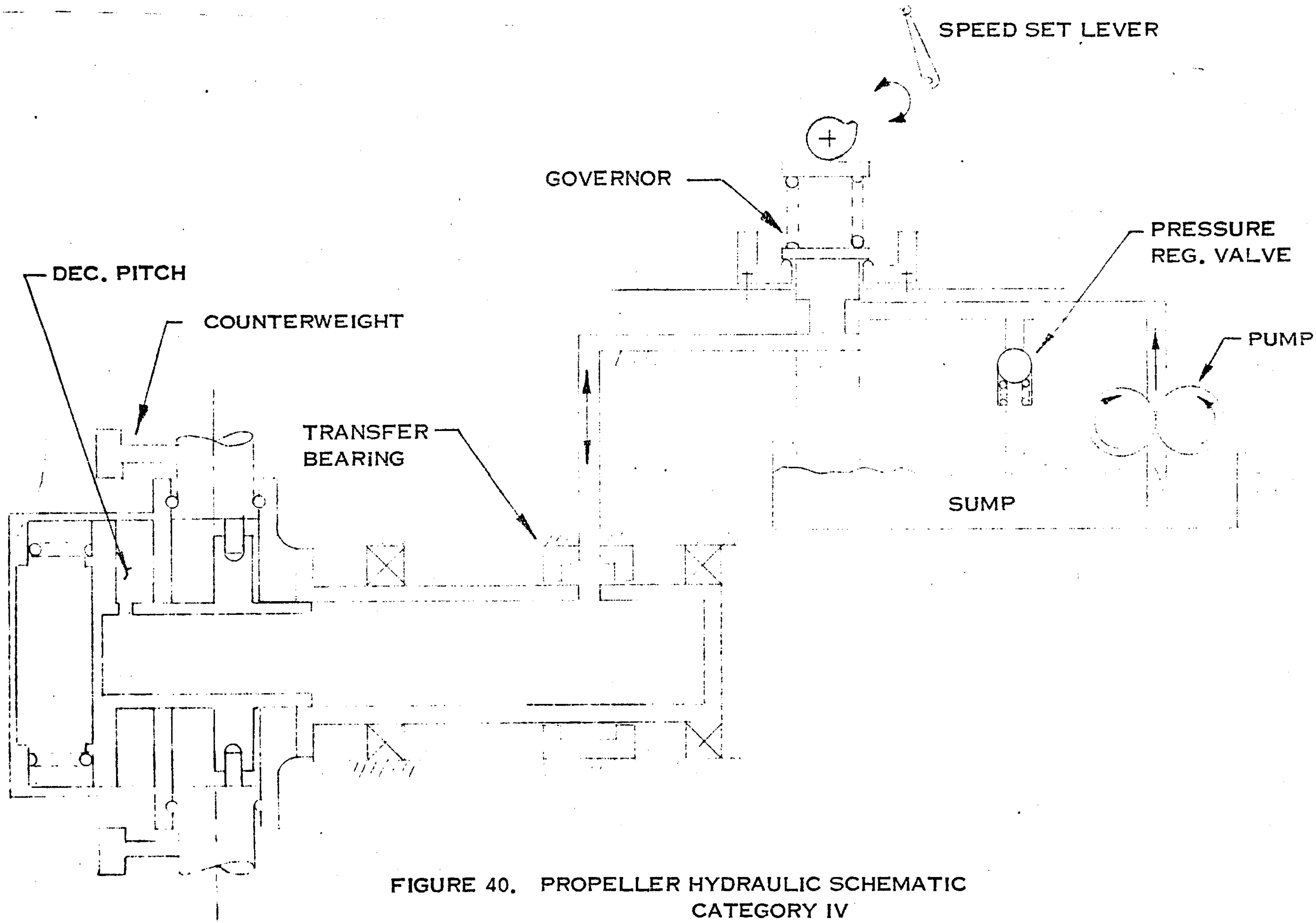


FIGURE 40. PROPELLER HYDRAULIC SCHEMATIC
CATEGORY IV

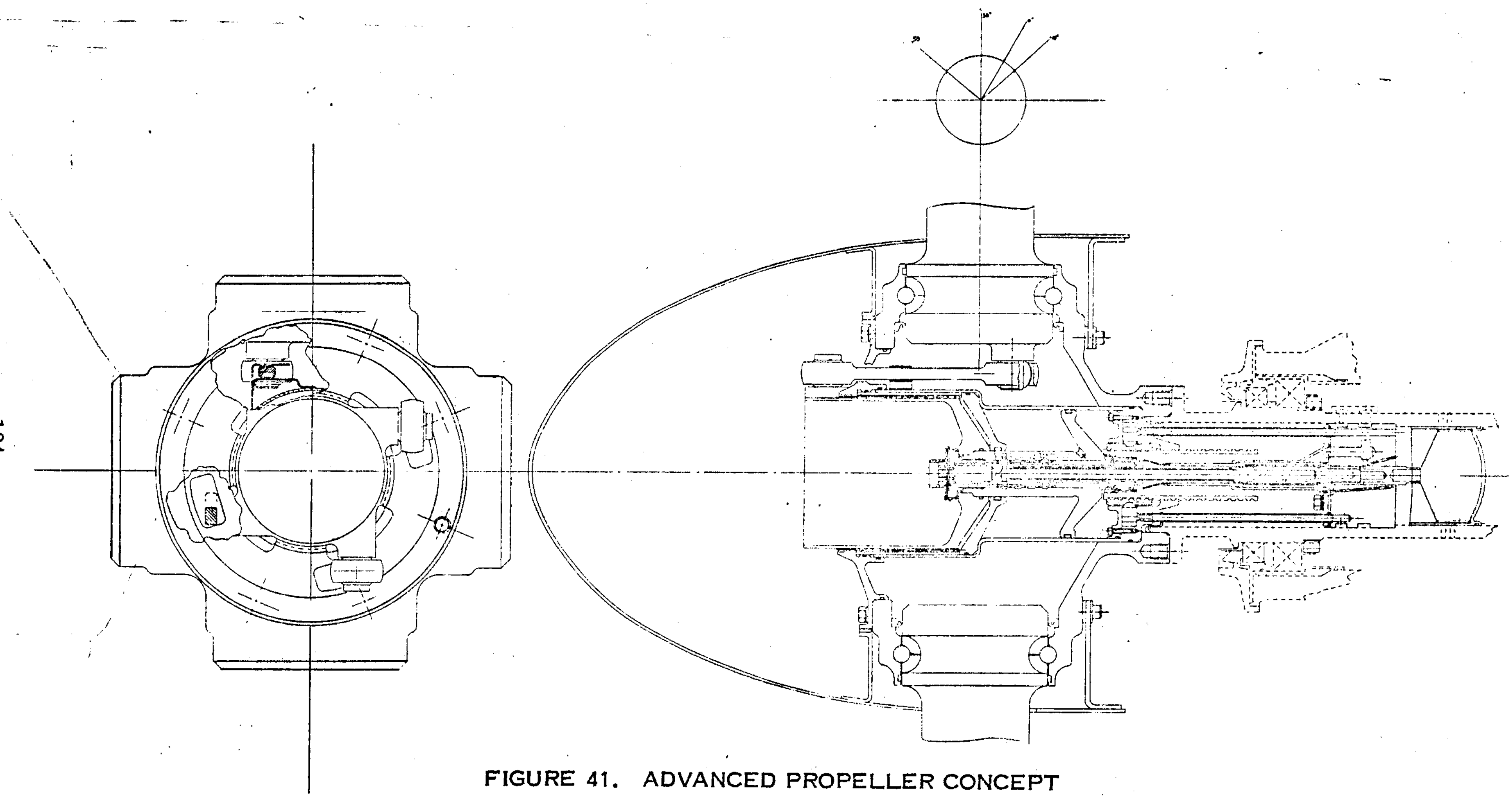


FIGURE 41. ADVANCED PROPELLER CONCEPT
CATEGORY V

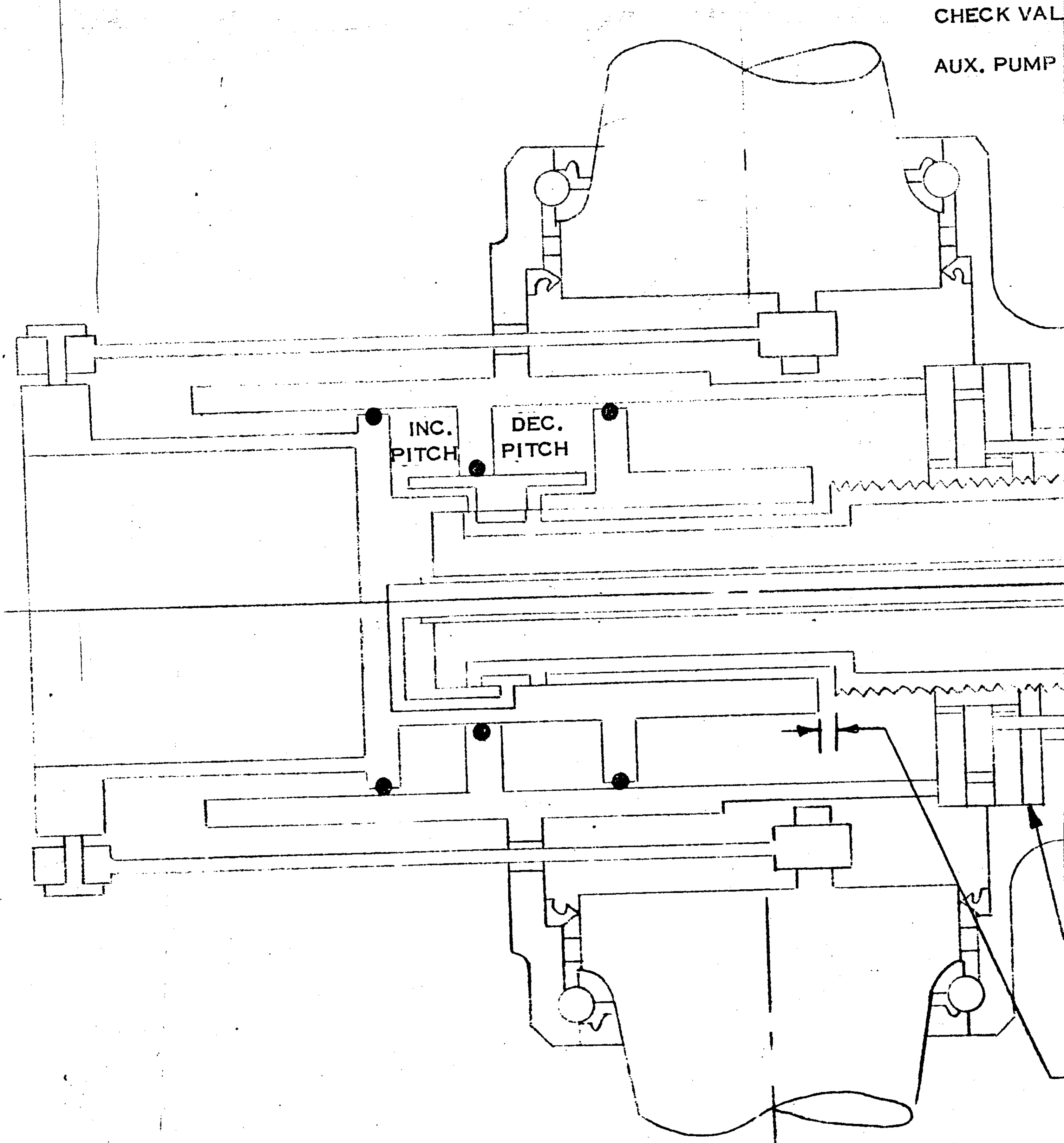


FIGURE 42. PROPELL

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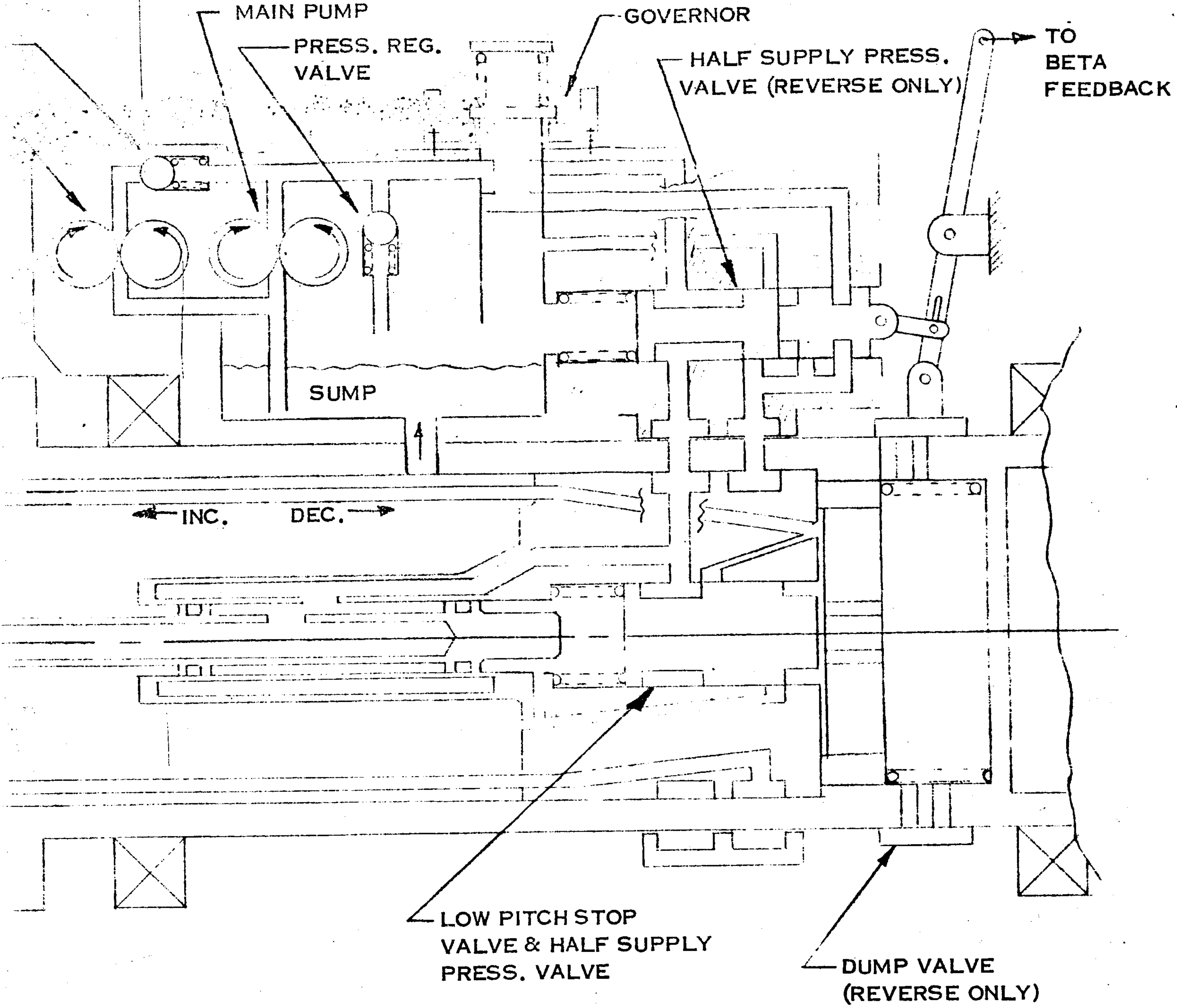


OR. PITCH
ANGE MOTOR

ITCH LOCK GAP

HYDRAULIC SCHEMATIC CATEGORY V

APPENDIX A

GENERALIZED METHOD OF PROPELLER PERFORMANCE ESTIMATION FOR GENERAL AVIATION AIRCRAFT

This appendix provides a generalized performance calculation method for conventional and multi-bladed propellers applicable for general aviation aircraft operating at static and in-flight conditions. The method can be used in predicting performance for constant speed, fixed pitch and two-position propellers. The form of method selected was governed primarily by the consideration of ease of usage and computerization. Accordingly, the method incorporates a series of performance maps for 2, 4, 6 and 8 bladed propellers all with 0.5 integrated design lift coefficient, C_{L_i}. Adjustments for activity factor variations are incorporated as well as a limited integrated design lift coefficient adjustment. Furthermore, a compressibility adjustment is included.

Performance Calculation Procedure

The method of calculating the static and flight performance, as described in the main text section on Technology Identification, is present below. A sample problem is included as figure 1A for constant speed propellers and figure 2A for fixed pitch propellers.

Constant Speed Propellers. With the airplane flight and engine conditions given, and the propeller blade characteristics known, the procedure as outlined on the sample computation sheet (figure 1A) is as follows:

A. From known data, complete the top of the computation sheet. Identify airplane, engine and gear ratio (G.R.) and items 1 through 4 which are number of blades, propeller diameter (D), activity factor (AF), and integrated design lift coefficient (C_{L_i}). All data in this report are for a C_{L_i} of 0.5 with the exception of the data for 4 bladed propellers which include a C_{L_i} of 0.7 and 0.8 as well as 0.5.

B. Determine items numbered 5 through 9 from the airplane flight and engine conditions which have been selected for analysis as explained below:

Item No.

5. Attitude — Identifying flight condition

6. SHP or Thrust — There is the option of defining the engine shaft-brake horsepower/propeller and computing the corresponding propeller thrust/propeller or specifying propeller thrust requirement and computing the corresponding brake horsepower/propeller.

7. Engine RPM — N_e - Engine speed (rev./min.)

8. Pressure Altitude — Feet

9. Velocity — V_K - Airplane forward velocity (knots, true airspeed)

C. Calculate items numbered 10 through 15.

10. ρ_o/ρ — Density ratio

11. f_c — Ratio of speed of sound at standard day sea level to speed of sound at operating condition

12. N — Propeller speed = Engine RPM x G.R.

13. Mach No. — Airplane Mach Number $= \dfrac{V_K f_c}{661.2}$

14. Cp or C_T — If item 6 contains SHP, then

$$C_P = \frac{SHP\ (\rho_o/\rho)\times 10^{11}}{2N^3\ D^5}$$

If item 6 contains thrust, then

$$C_T = \frac{1.514 \times 10^6\ T\ (\rho_o/\rho)}{N^2\ D^4}$$

15. J — Propeller advance ratio - $101.4\ V_K/ND$

D. The following items are read from curves or calculated.

16. P_{AF} or T_{AF} — Activity Factor adjustments (fig. 3A). Use P_{AF} if SHP specified in item 6 and T_{AF} if thrust specified in item 6.

17.	$P_{C_{L_i}}$	Integrated design lift coefficient adjustment (see items 29 - 31) ($P_{C_{L_i}} = 1.0$ for $C_{L_i} = 0.5$)
18.	C_{P_E} or C_{T_E}	$C_{P_E} = C_P \times P_{AF} \times P_{C_{L_i}}$ $C_{T_E} = C_T \times T_{AF} \times T_{C_{L_i}}$
19.	$\beta_{3/4}$	If SHP is specified in item 6, read $\beta_{3/4}$ for the proper number of blades (fig. 4A, 6A, 8A or 10A) for the computed J and C_{P_E}. For 3, 5 or 7 bladed propellers, an interpolation is required. If thrust is specified in item 6, read $\beta_{3/4}$ for the proper number of blades (fig. 5A, 7A, 9A or 11A) for the computed J and C_{T_E}. For 3, 5 or 7 bladed propellers, an interpolation is required.
20.	C_{T_E} or C_{P_E}	If SHP is specified in item 6, read C_{T_E} for the proper number of blades (fig. 5A, 7A, 9A, 11A) for the J and $\beta_{3/4}$. For 3, 5, or 7 bladed propellers, an interpolation is required. If thrust is specified in item 6, read C_{P_E} for the proper number of blades (fig. 4A, 6A, 8A or 10A) for the J and $\beta_{3/4}$. For 3, 5, or 7 bladed propellers, an interpolation is required.
21.	T_{AF} or P_{AF}	Activity Factor adjustment (fig. 3A). Use T_{AF} if SHP specified in item 6 and P_{AF} if thrust specified in item 6.
22.	$T_{C_{L_i}}$	Integrated design lift coefficient adjustment (see items 32 - 36) ($T_{C_{L_i}} = 1.0$ for $C_{L_i} = 0.5$)
23.	C_T or C_P	$C_T = C_{T_E}/(T_{AF} \times T_{C_{L_i}})$ $C_P = C_P/(P_{AF} \times P_{C_{L_i}})$
24.	Thrust or SHP	If item 6 is SHP, compute thrust where $T = \dfrac{0.661 \times 10^{-6}\, C_T\, N^2 D^4}{\rho_o/\rho}$

If item 6 is thrust, compute SHP where

$$SHP = \frac{2\ N^3 D^5 C_P}{\rho_o/\rho \times 10^{11}}$$

25.	F_t	Compressibility correction (see items 37 - 41)
26.	Thrust (corr.)	Thrust x F_t
27.	η	Propeller efficiency, $\eta = \frac{C_T}{C_P}\ J$
28.	50% stall check	Check proper number of blades curve to be certain that C_{P_E} is to the left of the 50% stall line.

E. Integrated design lift coefficient adjustment (available only for four-bladed propellers with 0.7 and 0.8 C_{L_i} are incorporated in items 29 through 31.

29.	$PF_{C_{L_i}}$	Read the corresponding value from figure 12A.
30.	$C_{P_{EE}}$	$C_P \times P_{AF} \times PFC_{L_i}$
31.	$P_{C_{L_i}}$	Read from figure 13A and include also as item 17.

The following iterative procedure is required in defining thrust coefficient since $C_T = C_{T_E}/(T_{AF} \times T_{C_{L_i}})$ and $T_{C_{L_i}}$ is a function of C_T. Repeat items 31 through 35 until C_{T_E} in item 36 equals C_{T_E} in item 20.

32.	C_T	Assume a C_T
33.	$TF_{C_{L_i}}$	Read from figure 12A
34.	$C_{T_{EE}}$	$C_T \times T_{AF} \times TF_{C_{L_i}}$
35.	$T_{C_{L_i}}$	Read from figure 14A
36.	C_{T_E}	$C_T \times T_{AF} \times T_{C_{L_i}}$

Include C_T for converged C_{T_E} as item 23.

F. Compressibility correction (limited to 0.5 C_{L_i})

37.	M_{CRIT}	Read from figure 15A
38.	$M-M_{CRIT}$	If positive, use the following procedure to obtain the compressibility correction, F_t. If negative, $F_t = 1.00$
39.	P_{BL}	Number of blades adjustment is read from figure 15A
40.	$C_{P_{EC}}$	$C_P \times P_{AF} \times P_{BL}$
41.	F_t	Read from figure 16A and include as item 25.

Fixed Pitch Propeller. - For the fixed pitch propeller, select the design condition and repeat the computational procedure defined for constant speed propellers (items 1-41). For the sample case (fig. 2A) the design point is the take-off condition. Only items 1-28 are included since 29-41 are not applicable. For off design conditions the following procedure is used:

A. Determine items 42-44 from the airplane flight conditions which have been selected for analysis.

B. For the $\beta_{3/4}$ (item 19), a range of SHP's and RPM's are defined as shown in items 45-50.

45.	J range	Assume a range of J's
46.	C_{P_E}	Obtain the corresponding C_{P_E} from the proper number of blades curve (fig. 4A, 6A, 8A, 10A) for the J's (item 45) and $\beta_{3/4}$ (item 19)
47.	P_{AF}	Same as item 16
48.	C_P	Items 46 ÷ 47
49.	N	$N = 101.4\ V_K/JD$
50.	SHP	$SHP = \dfrac{2N^3D^5C_P}{\rho_o/\rho \times 10^{11}}$

C. The engine performance data is required to define the proper SHP and RPM for the specific operating condition. For the sample case, it was assumed that BMEP remained constant and therefore the ratio of engine SHP to RPM is constant and the calculation completed as shown in steps 51 through 60.

51.	$(SHP/N)_{prop}$	Compute (items 50÷49)
52.	$(SHP/N)_{constant}$	Items 6 ÷ 12
53.	N	Plot SHP/N (item 51) versus N(Item 49) and select N corresponding to $(SHP/N)_{constant}$ of item 52
54.	SHP	As defined in item 51
55.	J	Advance ratio as defined in item 15
56.	C_{T_E}	Read for the proper number of blades (fig. 4A, 6A, 8A, 10A) for the J and $\beta_{3/4}$. For 3, 5 or 7 bladed propellers, an interpolation is required.
57.	T_{AF}	Figure 3A
58.	C_T	C_{T_E}/T_{AF}
59.	THRUST	See item 24
60	η	See item 27.

Two Position Propellers. - The procedure defined under fixed pitch propellers can be used for two position propellers where:

A. $\beta_{3/4}$'s are defined for two design conditions and the performance for off design conditions obtained, or

B. For a given constant BMEP, performance can be defined for the pertinent operating conditions at several $\beta_{3/4}$'s and the two $\beta_{3/4}$'s selected which give the best performance compromise for these conditions.

Airplane	Cessna 210J	Date	12/6/70	Calc. No.	2680
Engine	Hypothetical	G. R.	0.335	Sheet No.	1
Reference	Constant Speed	Calc. by	R. W.	Checked by	AMS

1.	No. of Blades	4.	4.	4.
2.	Diameter-Feet	8.0	8.0	8.0
3.	AF	150.	150.	150.
4.	Int. Des. C_L	0.500	0.500	0.700
5.	Attitude	T. O.	T. O.	T. O.
6.	BHP or Thrust	300 (BHP)	820. (Thrust)	300 (BHP)
7.	Engine RPM	2850.0	2850.0	2850.0
8.	Altitude	S. L.	S. L.	S. L.
9.	Velocity (knots)	71.2	71.2	71.2
10.	ρ_o/ρ	1.00	1.00	1.00
11.	f_c	1.00	1.00	1.00
12.	N	955.0	955.0	955.0
13.	M	0.1077	0.1077	0.1077
14.	C_P or C_T	0.525 (C_P)	0.332 (C_T)	0.525 (C_P)
15.	J	0.945	0.945	0.945
16.	P_{AF} or T_{AF}	1.00 (P_{AF})	1.00 (T_{AF})	1.00(P_{AF})
17.	$P_{C_{Li}}$	1.00	1.00	0.925
18.	C_{P_E} or C_{T_E}	.525(C_{P_E})	0.332 (C_{T_E})	0.486(C_{P_E})
19.	$\beta_{3/4}$	38.2	38.2	37.5
20.	C_{T_E} or C_{P_E}	0.332 (C_{T_E})	0.525 (C_{P_E})	0.326(C_{T_E})
21.	T_{AF} or P_{AF}	1.00 (T_{AF})	1.00 (P_{AF})	1.00(T_{AF}

Figure 1A. Hamilton Standard Generalized Propeller Performance Computation (1 of 2)

22. $T_{C_{L_i}}$	1.0	1.0	0.90	
23. C_T or C_P	0.332 (C_T)	0.525 (C_P)	0.362 (C_T)	
24. Thrust or BHP	820 Thrust	300 (BHP)	894 (Thrust)	
25. F_t	1.0	1.0	1.0	
26. Thrust (corrected)	820.0	820.0	894.0	
27. η	0.598	0.598	0.652	
28. Check for 50% stall	O.K.	O.K.	O.K.	

C_{L_i} Adjustment (Only for 4-bladed propeller with 0.7 and 0.8 C_{L_i})

29. PFC_{L_i}			1.06	
30. $C_{P_{EE}}$			0.558	
31. $P_{C_{L_i}}$			0.925	
32. C_T			0.360	0.362
33. TFC_{L_i}			1.020	1.020
34. $C_{T_{EE}}$			0.367	0.369
35. $T_{C_{L_i}}$			0.90	0.90
36. C_{T_E}			0.324	0.326

Compressibility Correction

37. M_{CRIT}	0.248	0.248		
38. $M-M_{CRIT}$	- 0.1403	-1403		
39. P_{BL}	-	-		
40. C_{PEC}	-	-		
41. F_t	1.0	1.0		

Figure 1A. Hamilton Standard Generalized Propeller Performance Computation (2 of 2)

Airplane	Piper Cherokee	Date	12/6/70	Calc. No.	2680
Engine	Hypothetical	G.R.	D.D.	Sheet No.	1
Reference	Fixed Pitch	Calc. by	R.W.	Checked by	AMS

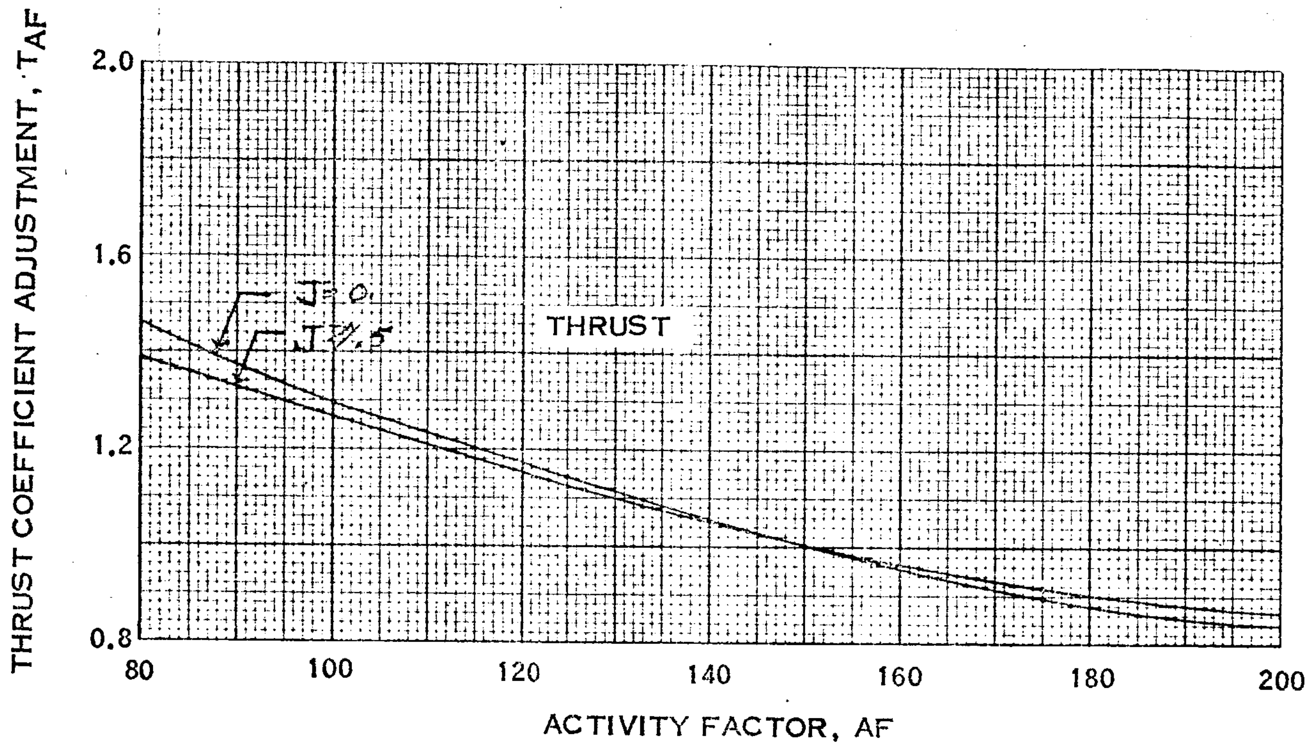
Design Condition

1.	No. of Blades	2
2.	Diameter	6.17
3.	AF	80.
4.	Int. Des. C_L	0.500
5.	Attitude	T.O.
6.	SHP or Thrust	150.0 (SHP)
7.	Engine RPM	2700.
8.	Altitude	S.L.
9.	Velocity (knots)	52.5
10.	ρ_o/ρ	1.00
11.	f_c	1.00
12.	N	2700.0
13.	M	0.0794
14.	C_P or C_T	0.0426(C_P)
15.	J	0.320
16.	P_{AF} or T_{AF}	1.58(P_{AF})
17.	$P_{C_{L_i}}$	1.0
18.	C_{P_E} or C_{T_E}	0.0673(C_{P_E})
19.	$\beta_{3/4}$	16.6
20.	C_{T_E} or C_{P_E}	0.115(C_{T_E})
21.	T_{AF} or P_{AF}	1.41(T_{AF})
22.	$T_{C_{L_i}}$	1.00
23.	C_T or C_P	0.0815(C_T)
24.	Thrust or SHP	570 (Thrust)
25.	Ft	1.00
26.	Thrust (Corrected)	570.0
27.	η	0.611
28.	Check 50% stall	O.K.

Off Design Condition

42.	Attitude	Climb		
43.	Altitude	S.L.		
44.	Velocity (knots)	70.5		
45.	J Range	0.4	0.5	0.6
46.	C_{P_E}	0.065	0.058	0.048
47.	P_{AF}	1.58		
48.	C_P	0.0411	0.0367	0.0304
49.	N	2897.0	2317.0	1931.0
50.	SHP	179.0	82.0	39.0
51.	$(SHP/N)_{prop}$	0.0618	0.0354	0.0202
52.	(SHP/N) (constant)	0.0556		
53.	N	2765.0		
54.	SHP	154.0		
55.	J	0.419		
56.	C_{T_E}	0.10		
57.	T_{AF}	1.41		
58	C_T	0.0709		
59.	Thrust	519.0		
60.	η	0.729		

Figure 2A.. Hamilton Standard Generalized Propeller Performance



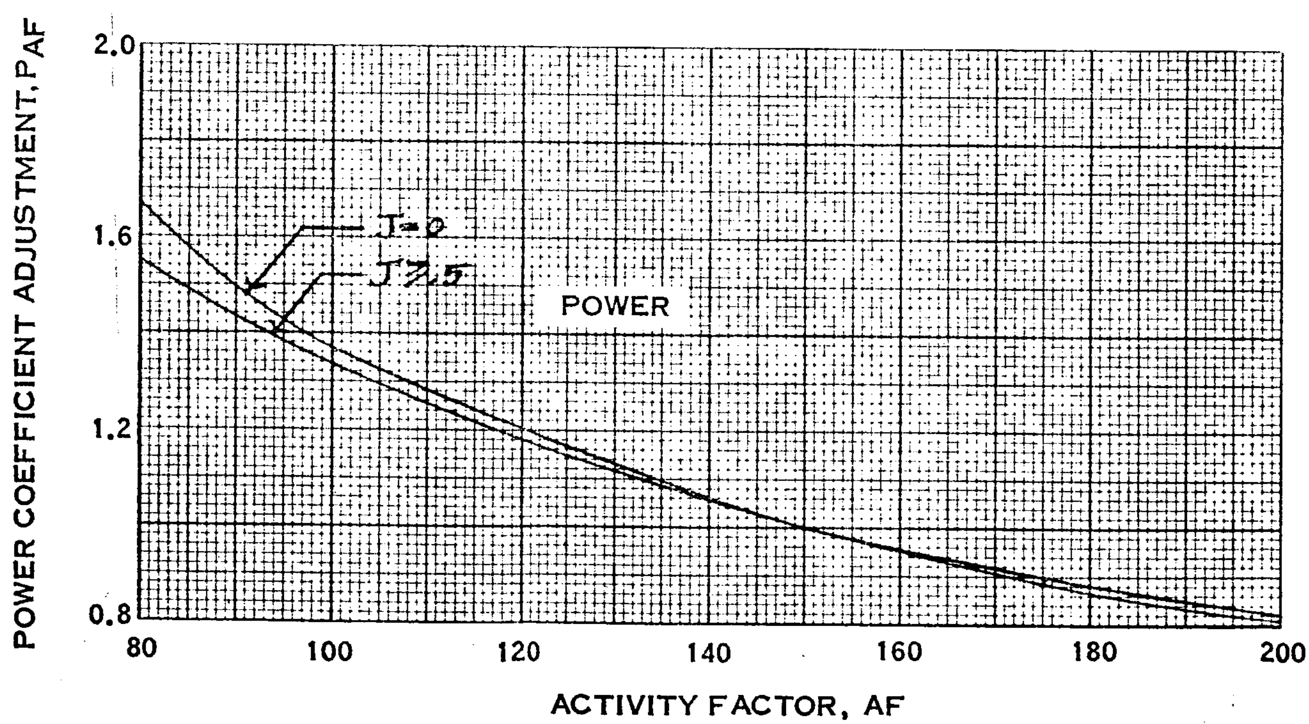


FIGURE 3A. ACTIVITY FACTOR ADJUSTMENT

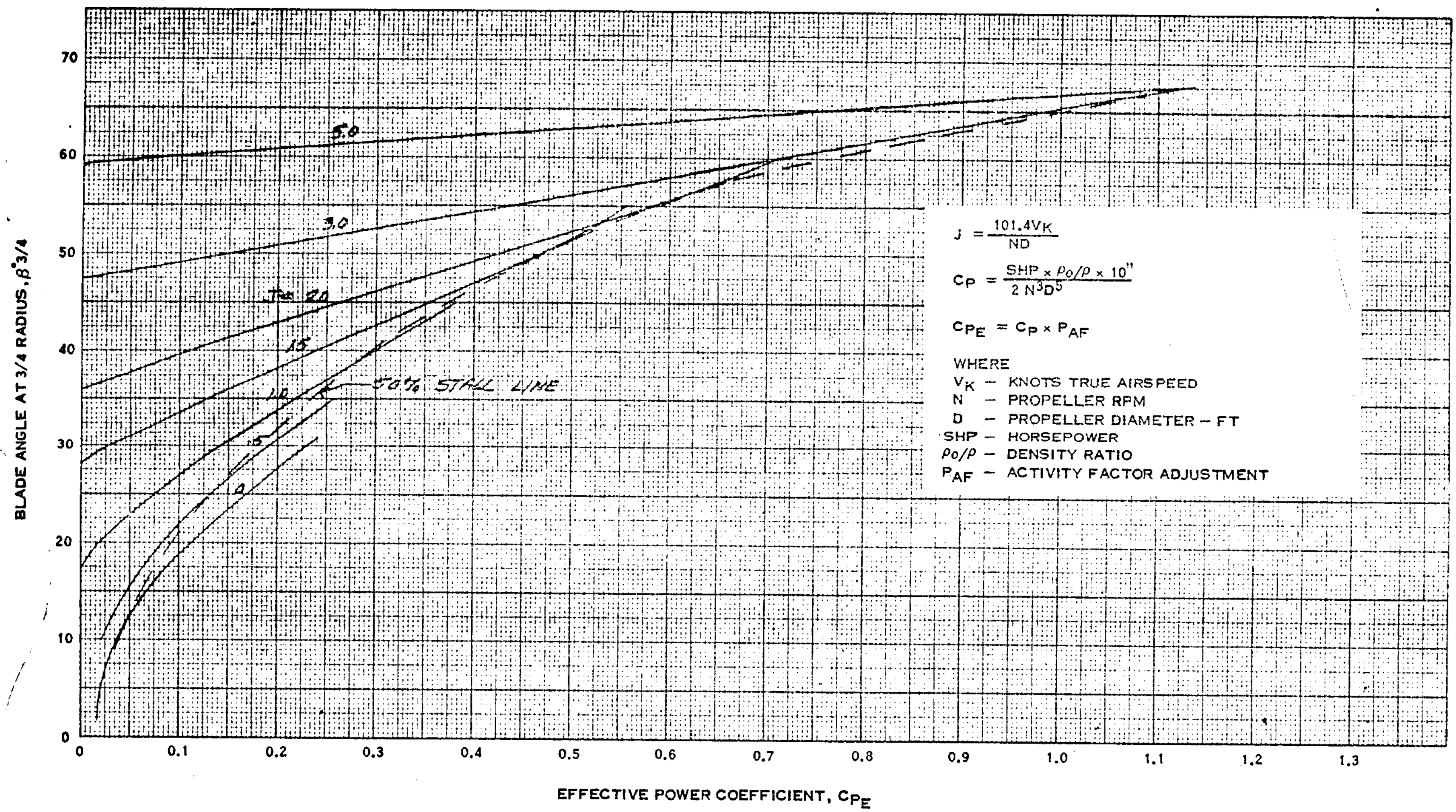


FIGURE 4A. POWER COEFFICIENT CHART FOR A 2 BLADED, 150 ACTIVITY FACTOR, 0.500 INTEGRATED DESIGN C_{L_i} PROPELLER

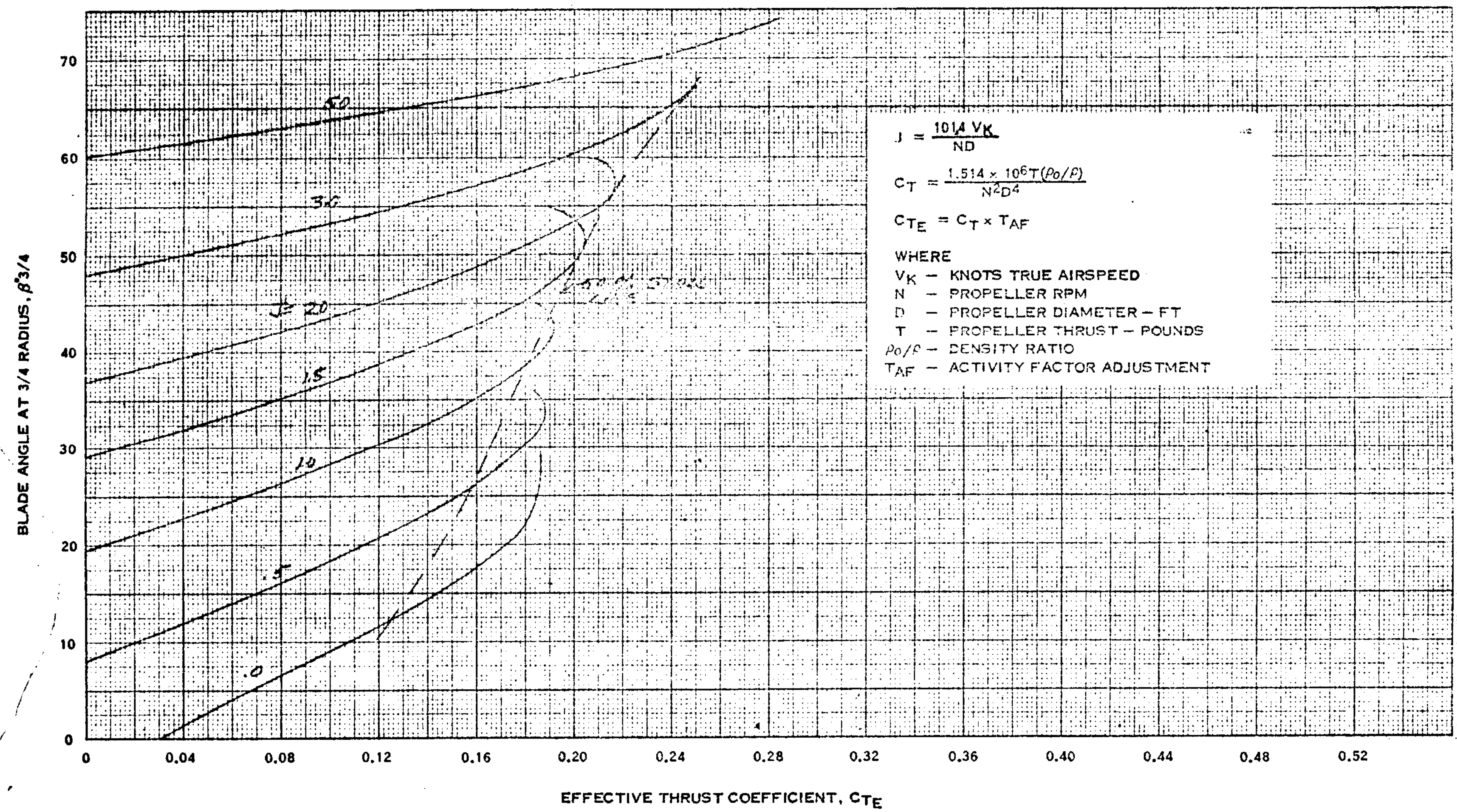


FIGURE 5A. THRUST COEFFICIENT CHART FOR A 2 BLADED, 150 ACTIVITY FACTOR, 0.500 INTEGRATED DESIGN C_{L_i} PROPELLER

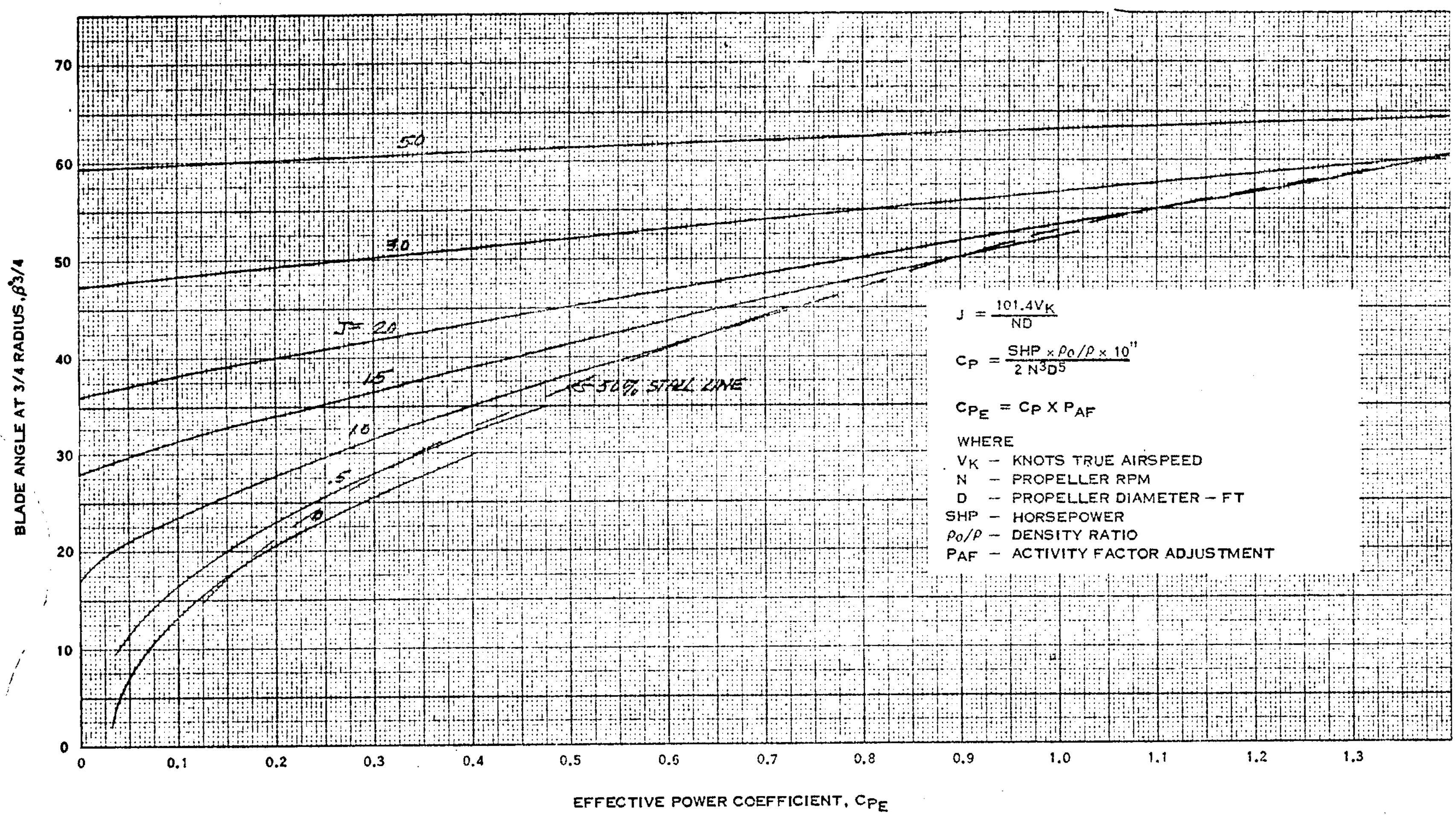


FIGURE 6A. POWER COEFFICIENT CHART FOR A 4 BLADED, 150 ACTIVITY FACTOR, 0.500 INTEGRATED DESIGN C_{L_i} PROPELLER

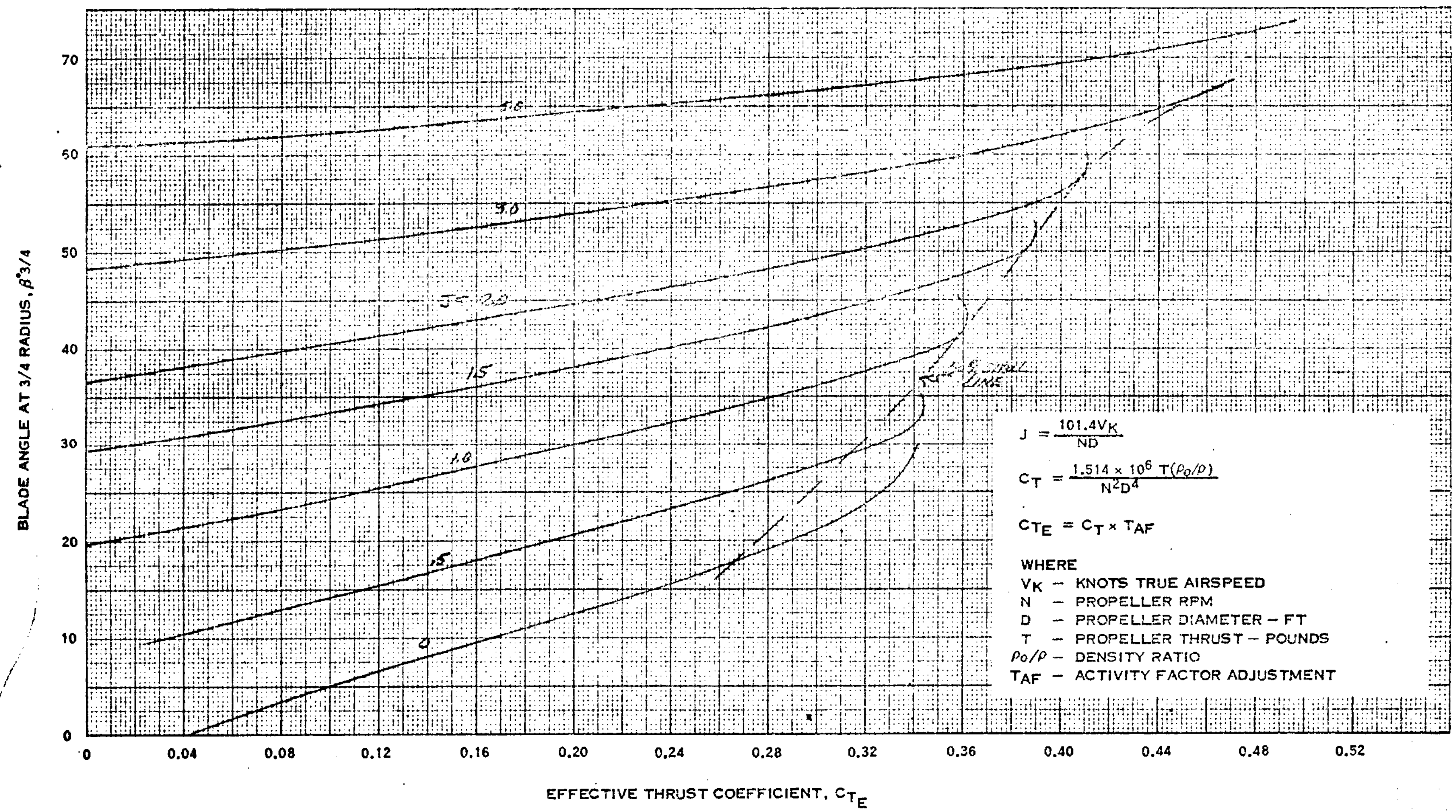


FIGURE 7A. THRUST COEFFICIENT CHART FOR A 4 BLADED, 150 ACTIVITY FACTOR, 0.500 INTEGRATED DESIGN C_{L_i} PROPELLER

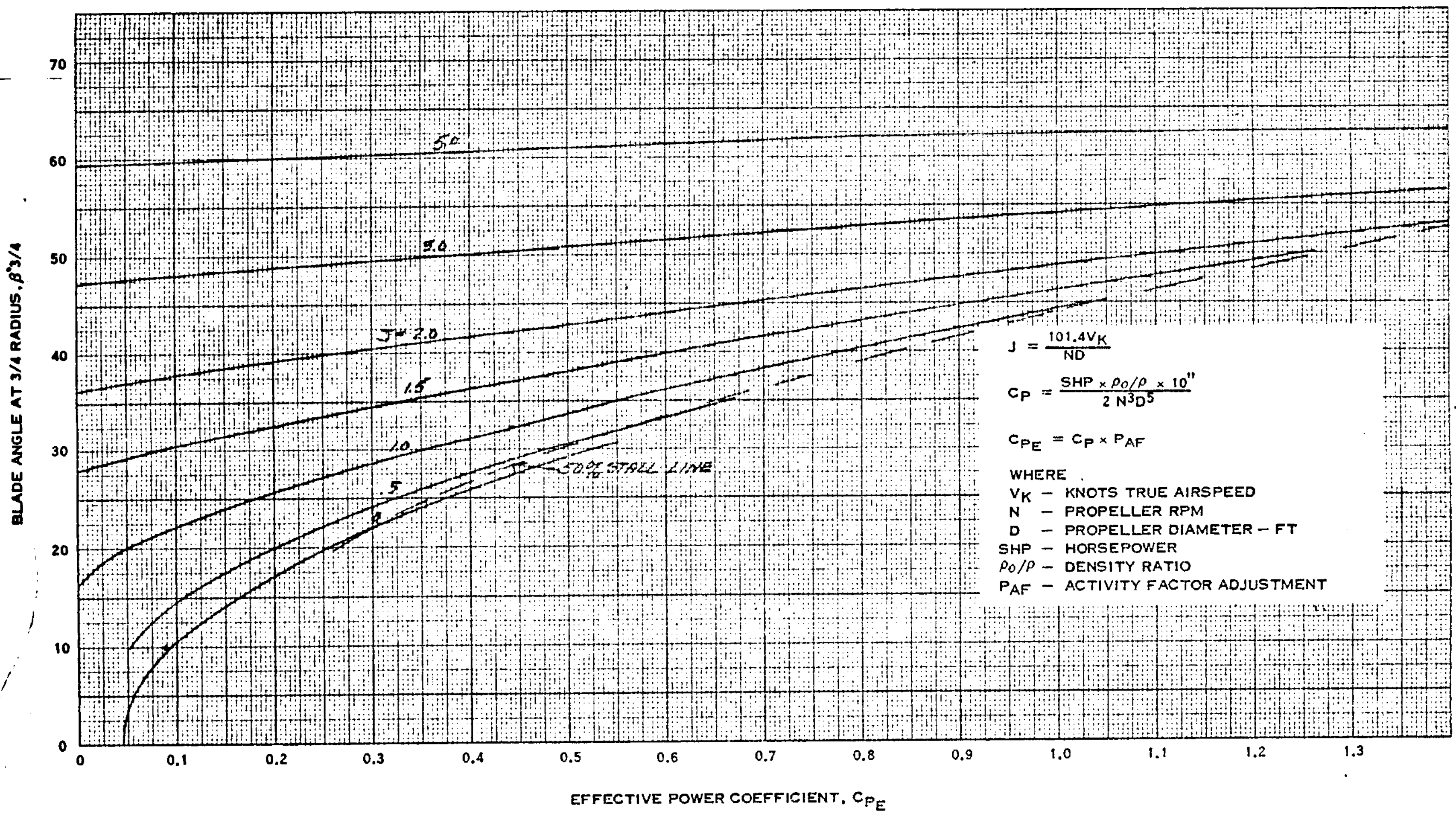


FIGURE 8A. POWER COEFFICIENT CHART FOR A 6 BLADED, 150 ACTIVITY FACTOR, 0.500 INTEGRATED DESIGN C_{L_i} PROPELLER

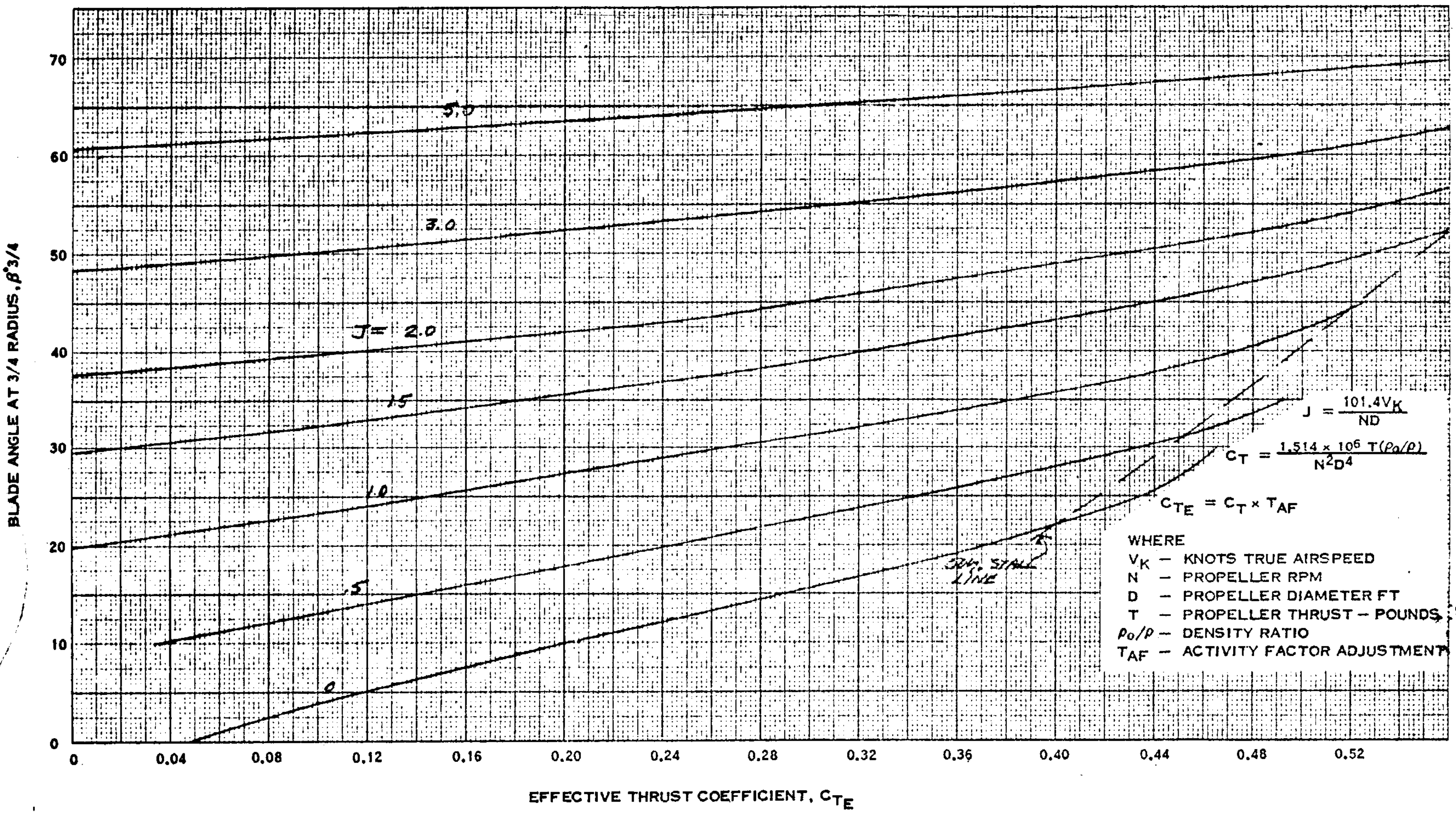


FIGURE 9A. THRUST COEFFICIENT CHART FOR A 6 BLADED, 150 ACTIVITY FACTOR, 0.500 INTEGRATED DESIGN C_{L_i} PROPELLER

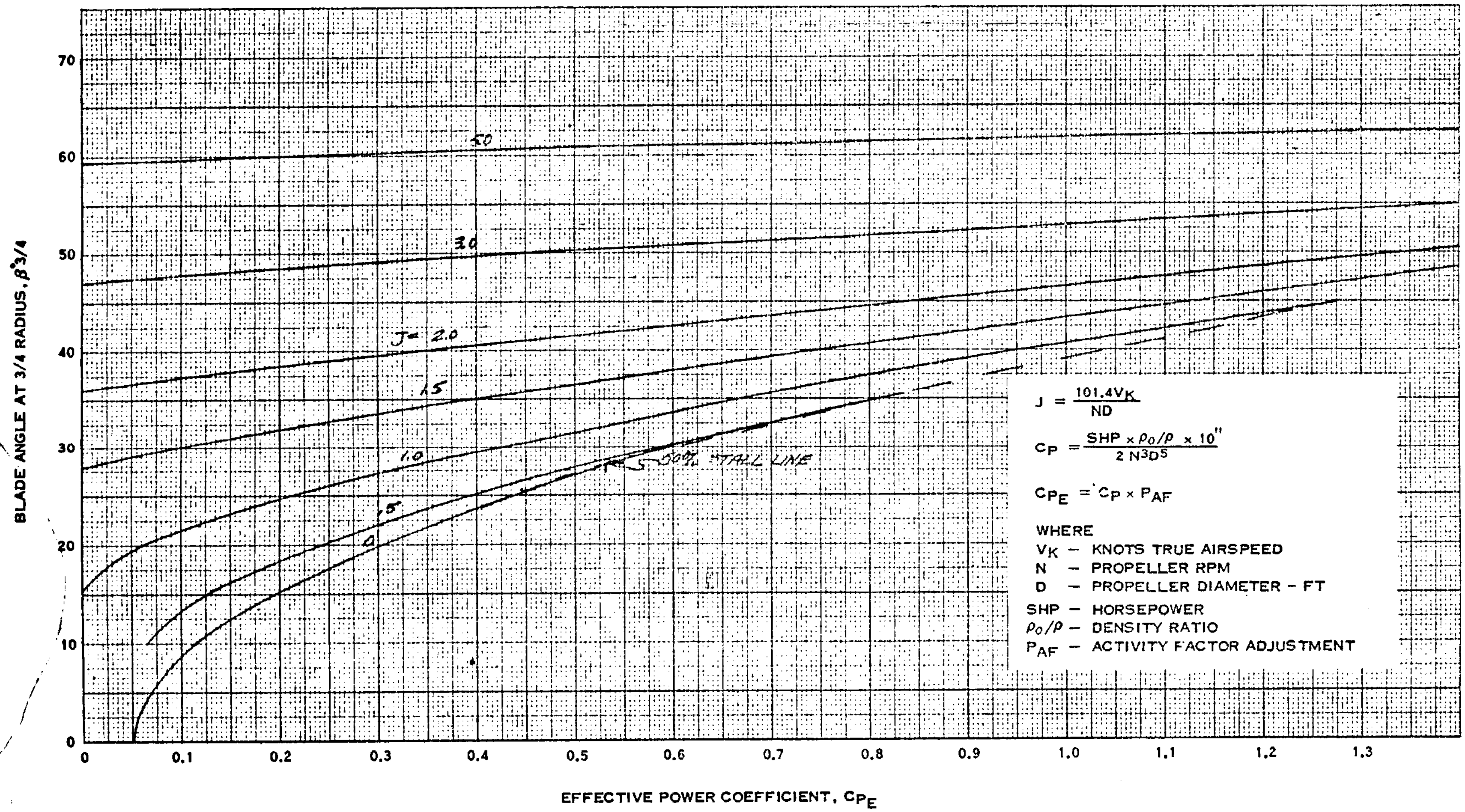


FIGURE 10A. POWER COEFFICIENT CHART FOR AN 8 BLADED, 150 ACTIVITY FACTOR, 0.500 INTEGRATED DESIGN C_{L_i} PROPELLER

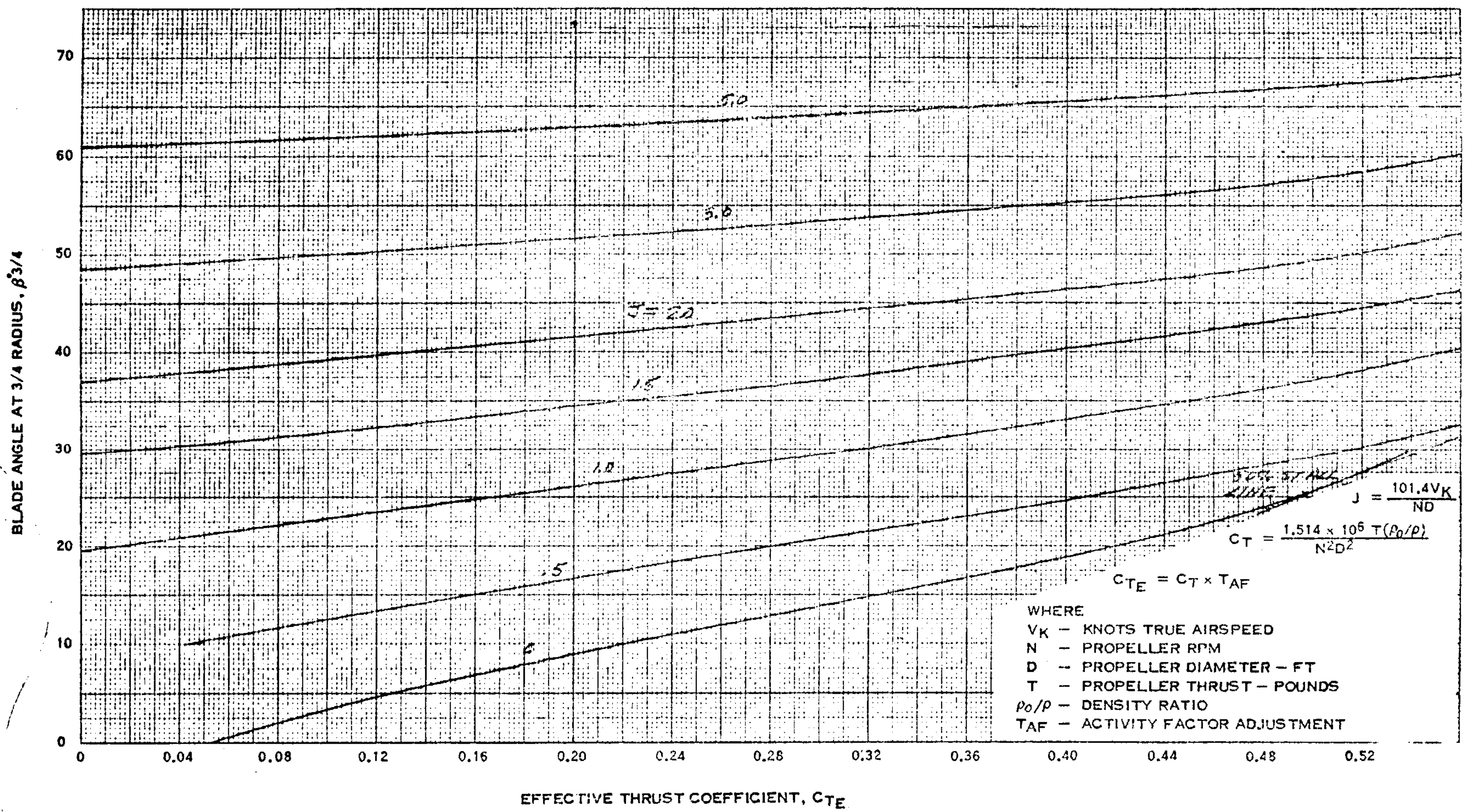


FIGURE 11A. THRUST COEFFICIENT CHART FOR AN 8 BLADED, 150 ACTIVITY FACTOR, 0.500 INTEGRATED DESIGN C_{L_i} PROPELLER

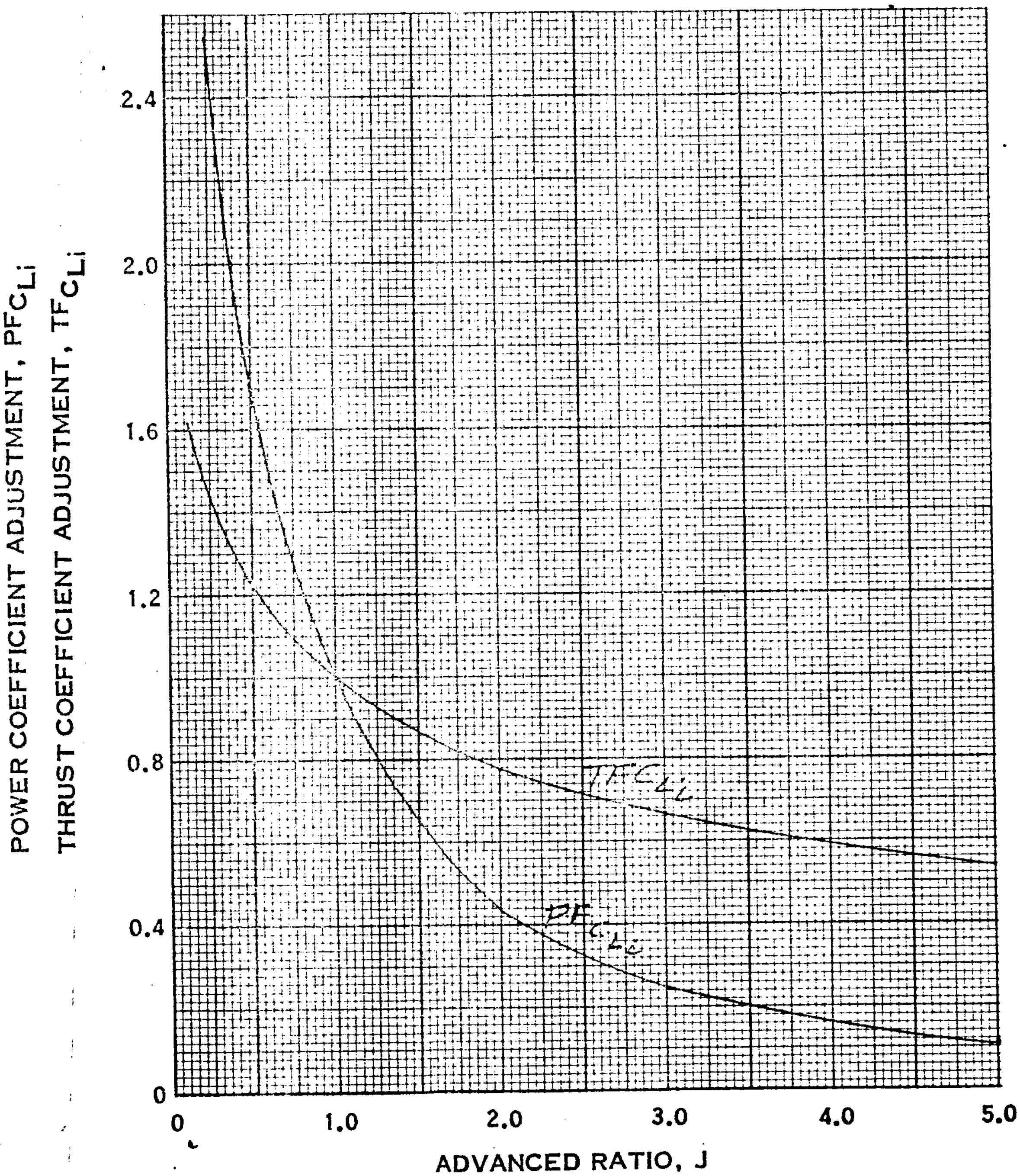


FIGURE 12A. CAMBER FACTOR ADJUSTMENT FOR 4–BLADED PROPELLER (LIMITED TO 0.7 & 0.8 INTEGRATED DESIGN LIFT)

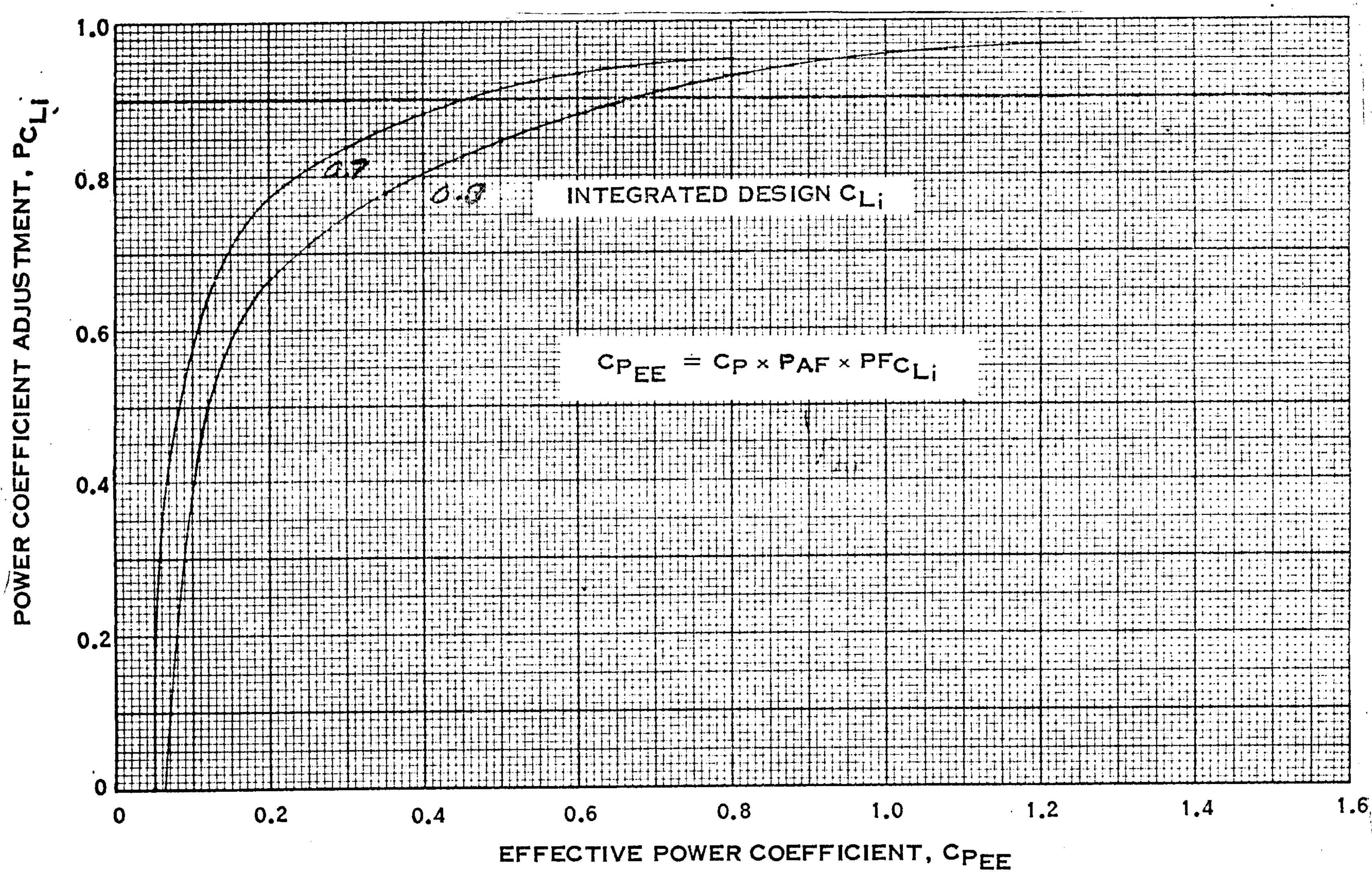


FIGURE 13A. CAMBER ADJUSTMENT FOR 4–BLADED PROPELLERS (TO POWER COEFFICIENT)

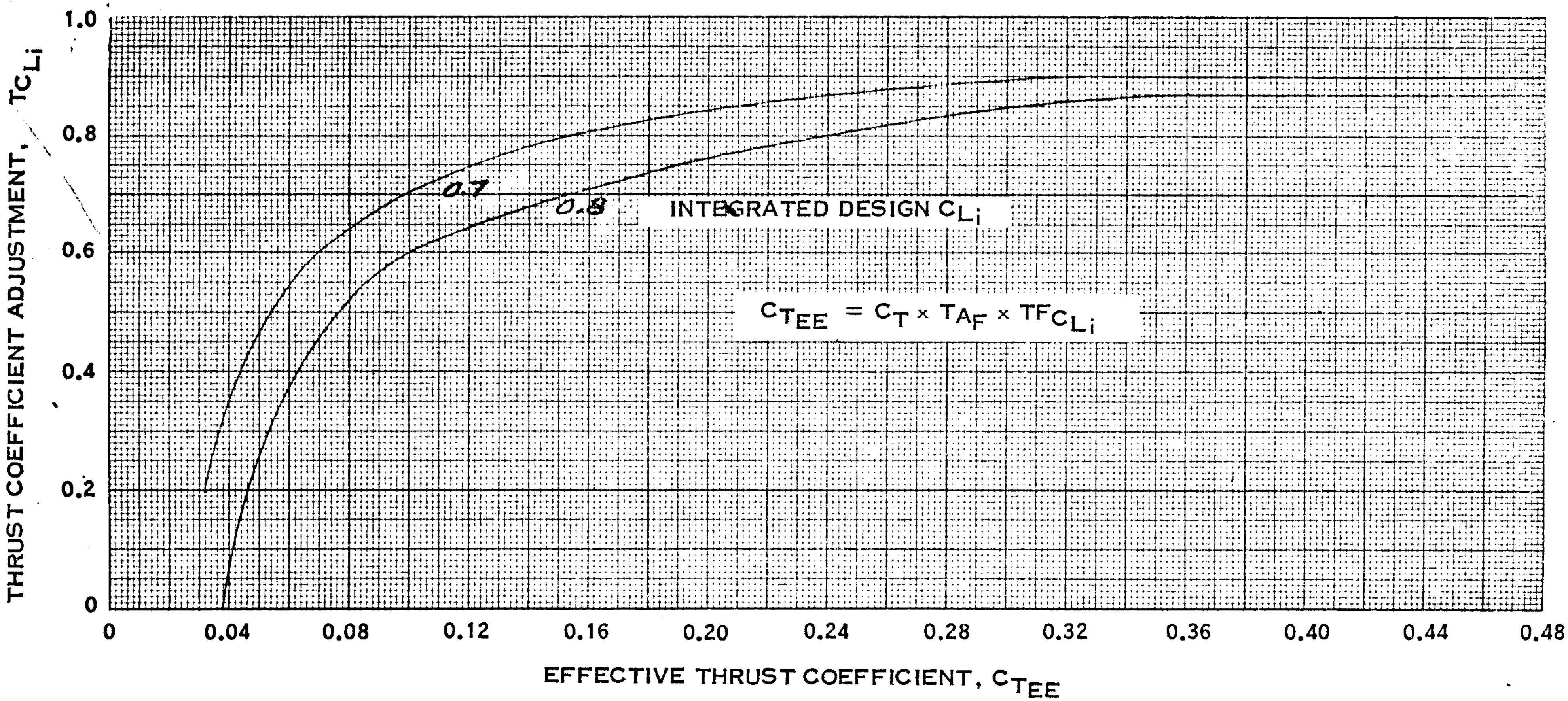
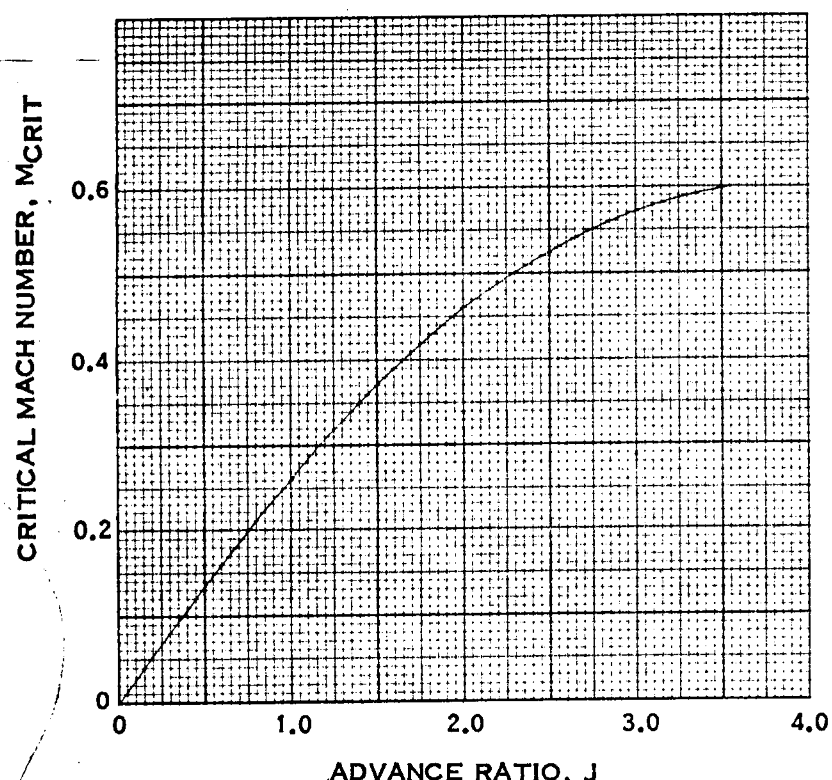


FIGURE 14A. INTEGRATED DESIGN C_{L_i} ADJUSTMENT FOR 4–BLADED PROPELLER (TO THRUST COEFFICIENT)



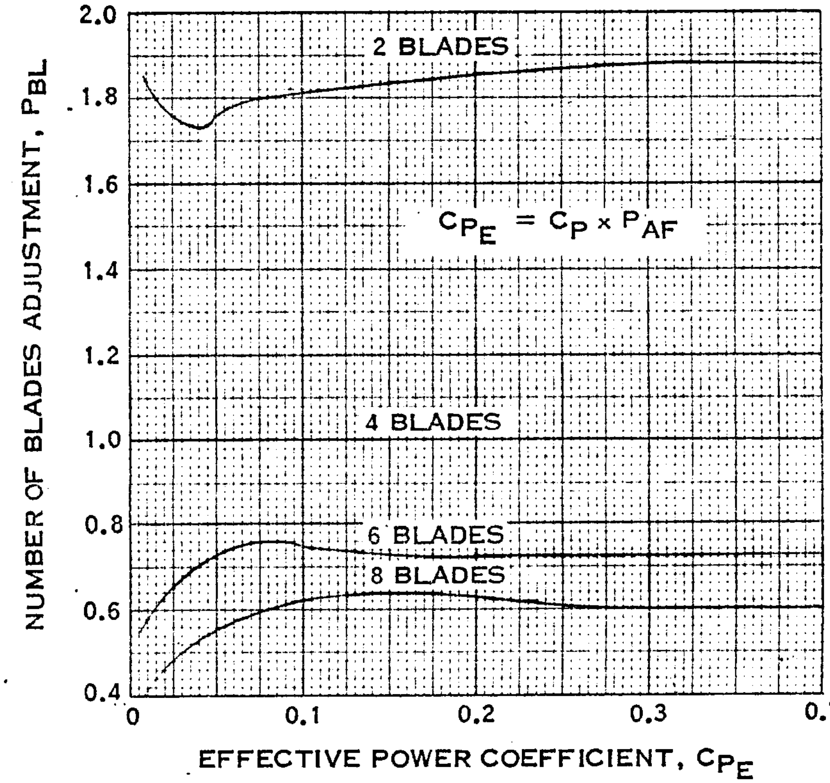


FIGURE 15A. COMPRESSIBILITY ADJUSTMENT FOR 0.500 INTEGRATED DESIGN C_{L_i}

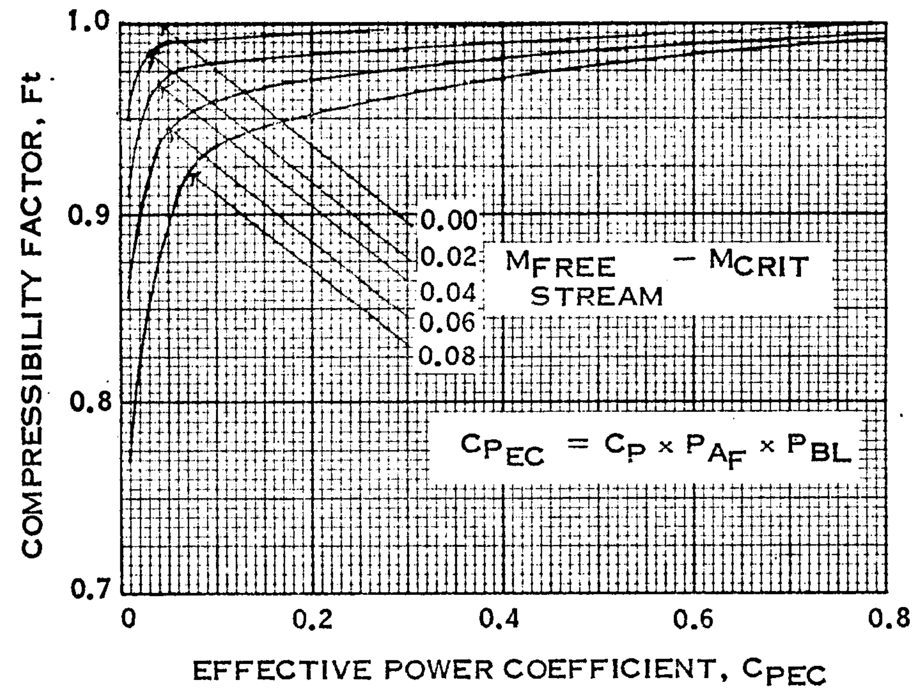


FIGURE 16A. NUMBER OF BLADES ADJUSTMENT USED IN DEFINING THE COMPRESSIBILITY ADJUSTMENT

APPENDIX B

HAMILTON STANDARD GENERALIZED PROPELLER NOISE

ESTIMATING PROCEDURE FOR FAR-FIELD NOISE

The noise field of propellers may be estimated using this generalized procedure from the following propeller design and operating parameters:

1. Diameter
2. Number of blades per propeller (2 to 8 blades)
3. RPM or tipspeed
4. Power input per propeller
5. Location, relative to the propeller(s), of the point at which the noise is to be defined.
6. Forward speed
7. Ambient temperature
8. Number of propellers

The noise estimate is accomplished by summing partial levels based on design and operating conditions. The partial levels are provided in graphical form to minimize calculations.

This procedure is applicable for operating conditions where the propeller is stalled over less than the inner 50% of the blades.

PERFORMANCE CALCULATION PROCEDURE

With the airplane flight and engine condition given, and propeller defined by diameter and number of blades, the procedure as outlined on the sample computation sheet (fig. 1B) is as follows:

A. From the known data, complete the top of the computation sheet. Identify the airplane, engine and gear ratio (G. R.) and items 1 and 2 which are number of blades per propeller and propeller diameter (D).

B. Determine items 3 through 9 from the airplane flight and engine conditions which have been selected for analysis as explained below:

3.	Attitude	Identifying flight condition
4.	SHP	Define engine shaft-brake horsepower/propeller
5.	Engine RPM	N_e - Engine speed (rev/min.)
6.	Velocity	Airplane forward speed (knots, true airspeed)
7.	Temperature	Degrees °F
8.	Distance	Observer field point-ft.
9.	Azimuth (Θ)	Observer field point (directivity): See figure 1B for definition

C. Calculate or read from the proper curves items 10 through 22 as follows:

Item		
10.	RPM	N-Propeller RPM = N_e x G. R.
11.	Tipspeed	The propeller rotational tip speed = $\frac{\pi ND}{60}$ or read from figure 2B.
12.	Rotational Mach No.	The rotational Mach No. $= \frac{\text{Tipspeed}}{1120} \sqrt{\frac{518.7}{T}}$ where T = °Rankine for specific operating condition. The value can be read from figure 3B.
13.	L1	Partial noise level based on SHP and propeller rotational tipspeed (fig. 4B)
14.	L2	An adjustment for propeller diameter and number of blades (fig. 5B)
15.	L3	Accounts for spherical spreading of the sound to the location of interest (fig. 6B)
16.	DI	A correction for the directivity pattern (fig. 7B) where 0 degrees is on the propeller axis in the forward direction. (Note: the pattern is symmetrical about the propeller axis, thus the directivity index for 260 degrees is the same as that for 100 degrees)
17.	No. of Props	Apply the following corrections for number of propellers:

1 propeller	0
2 propellers	3.0

		3 propellers 4.8
		4 propellers 6.0
18.	SPL	The overall sound pressure level is the summation of items 12 through 17
19.	Helical Tipspeed	Calculated by taking the vector sum of the rotational tipspeed and the forward speed of the aircraft. It can be read from figure 8B.
20.	Helical Tip Mach No.	Calculated by dividing helical tipspeed by the speed of sound or read from figure 3B.
21.	PNL Adjustment	The adjustment to convert SPL (item 18) to the perceived noise level (PNL) is obtained from figure 9B for 2 bladed propellers, figure 10B for 3 bladed propellers, figure 11B for 4 bladed propellers, and figure 12B for 6 through 8 bladed propellers. The pertinent information for 5 bladed propellers is obtained by interpolation.
22.	PNL	Perceived noise level = items 18 + 21.

Airplane	Cessna 210J	No. of Props.	1	Calc. No.	2680
Engine	Hypothetical	Calc. by	B. M.	Date	12/6/70
G. R.	0.756	Checked by	R. W.		

1.	No. of Blades	2.0
2.	Diameter (ft.)	7.0
3.	Attitude	T. O.
4.	BHP	300.0
5.	Engine RPM	2700.0
6.	Velocity (knots)	71.0
7.	Temperature (°F)	59°
8.	Distance (ft)	500.0
9.	Azimuth (θ)	105°
10.	RPM	2040.0
11.	Tipspeed (ft/sec)	748.0
12.	Tip Mach No.	0.67
13.	L1	84.0
14.	L2	+10.0
15.	L3	0.0
16.	DI	0.5
17.	No. of Props	0.0
18.	Σ Items 12 to 17	94.5
19.	Helical Tipspeed (ft/sec)	757.0
20.	Helical Tip Mach No.	0.68
21.	PNL Adjustment	0.5
22.	PNL	95.0

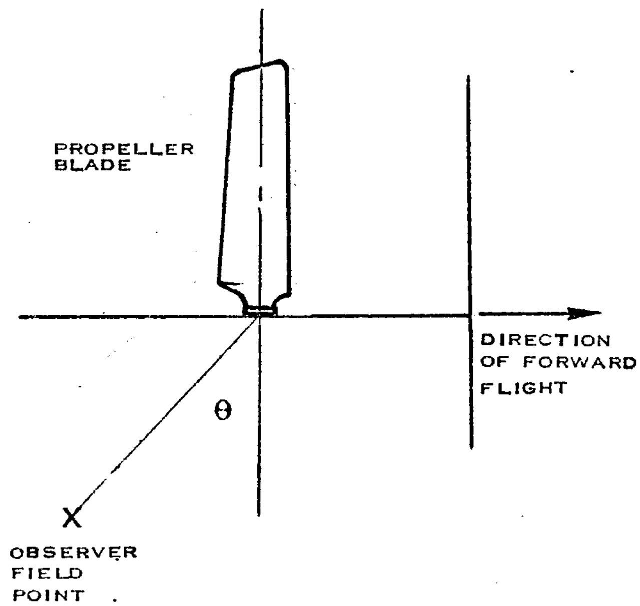


Figure 1B. Hamilton Standard Noise Computation

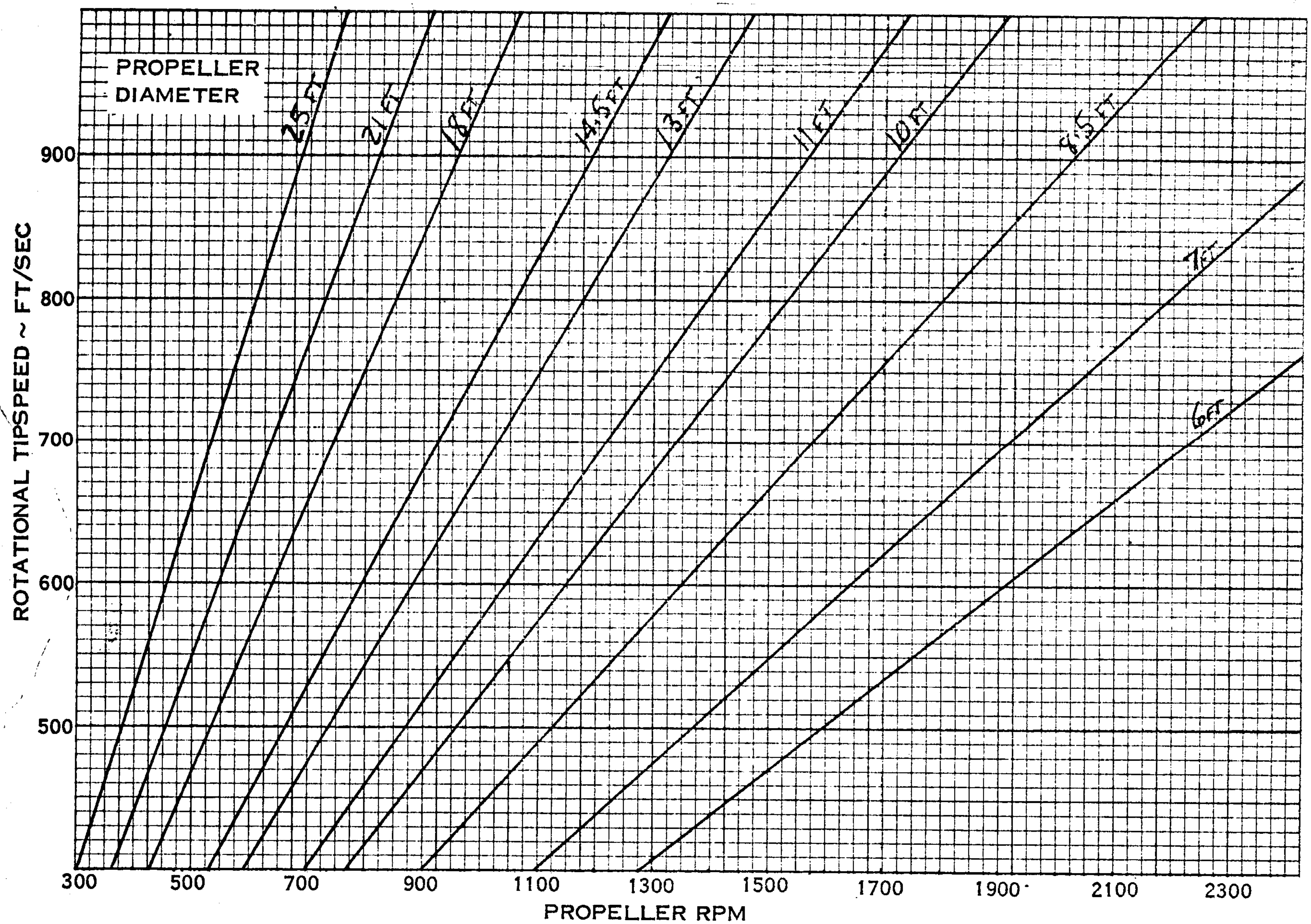


FIGURE 2B. PROPELLER ROTATIONAL TIPSPEED

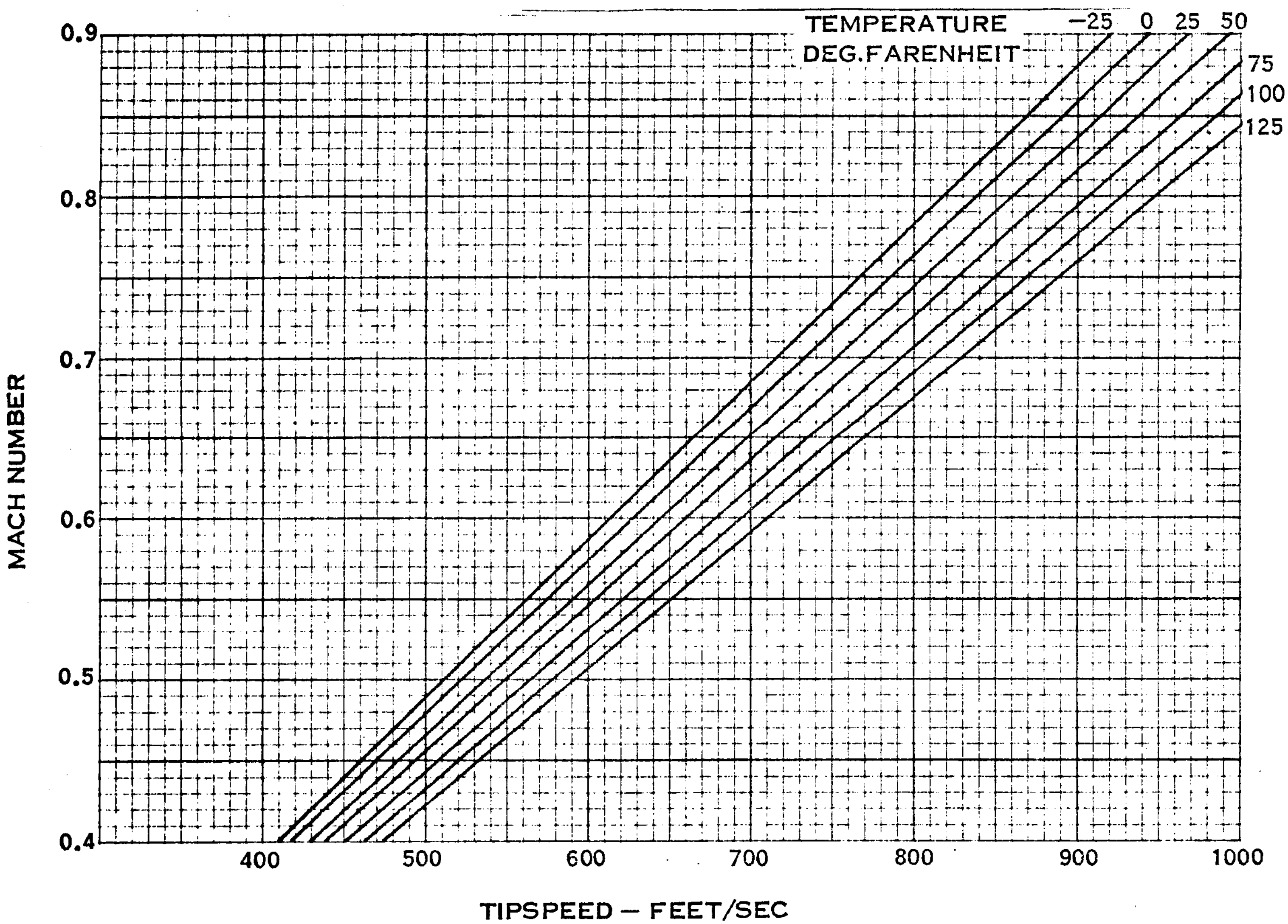


FIGURE 3B. PROPELLER TIP MACH NUMBER

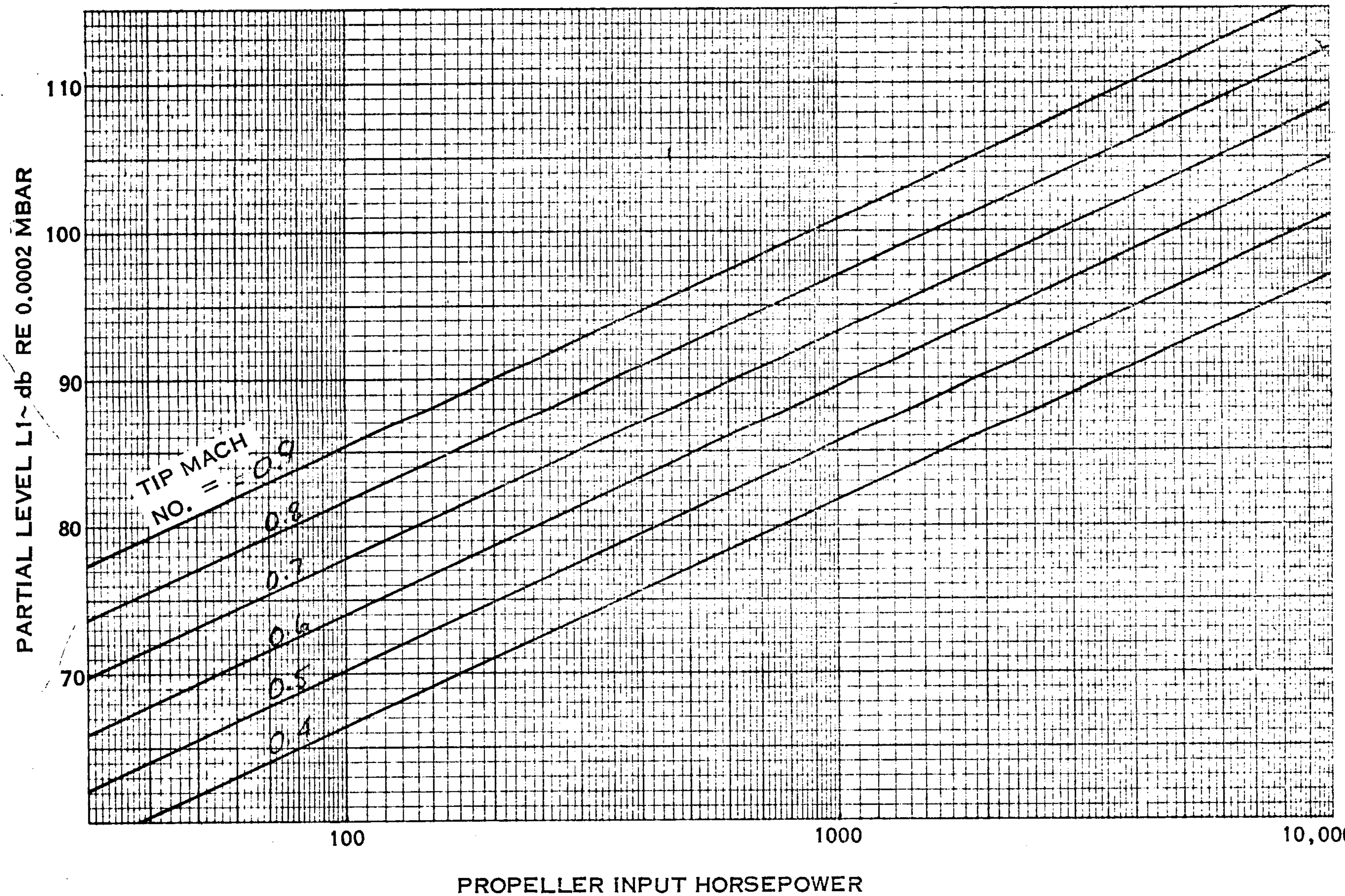


FIGURE 4B. PROPELLER TIP MACH NUMBER

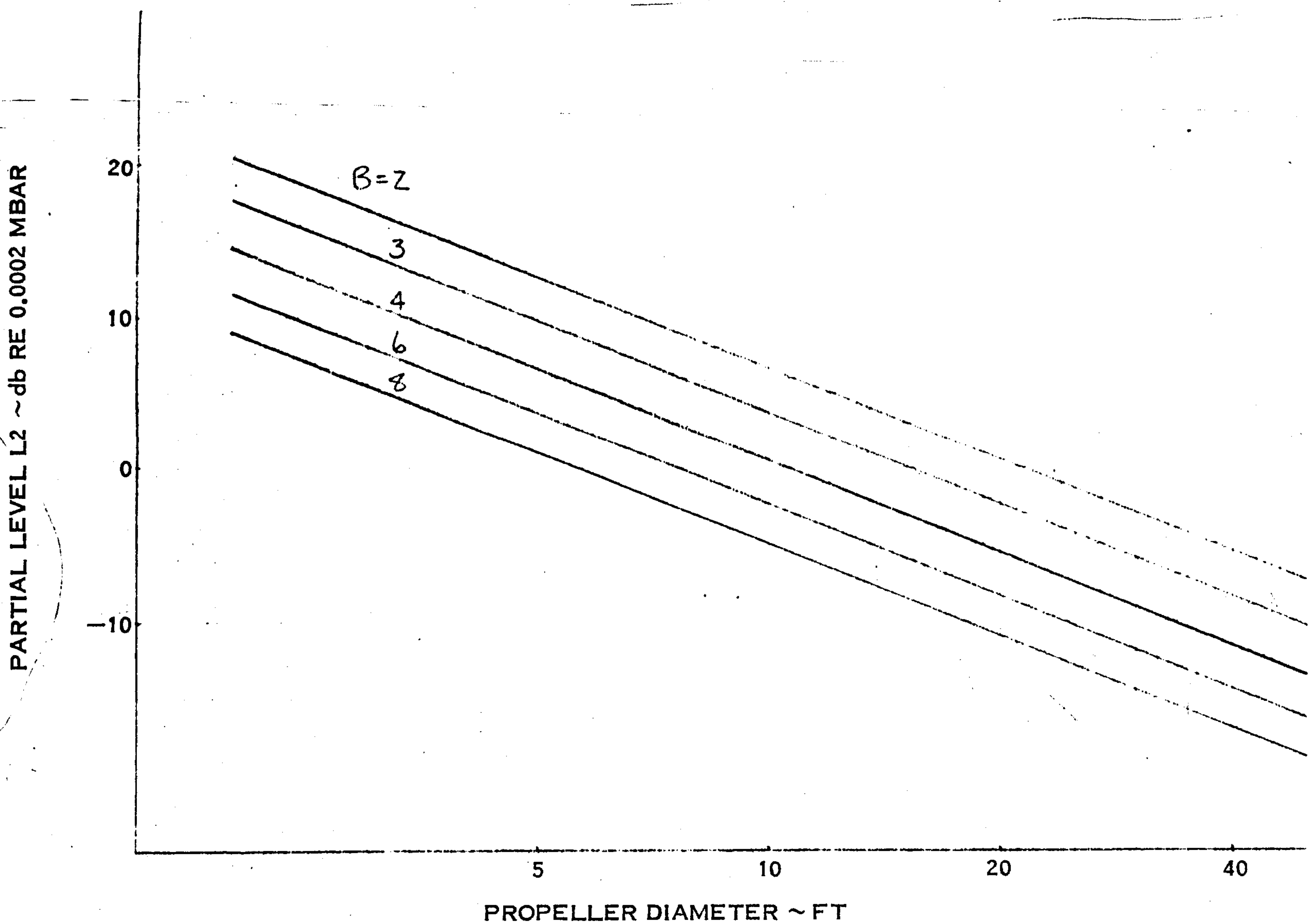


FIGURE 5B. PARTIAL NOISE LEVEL

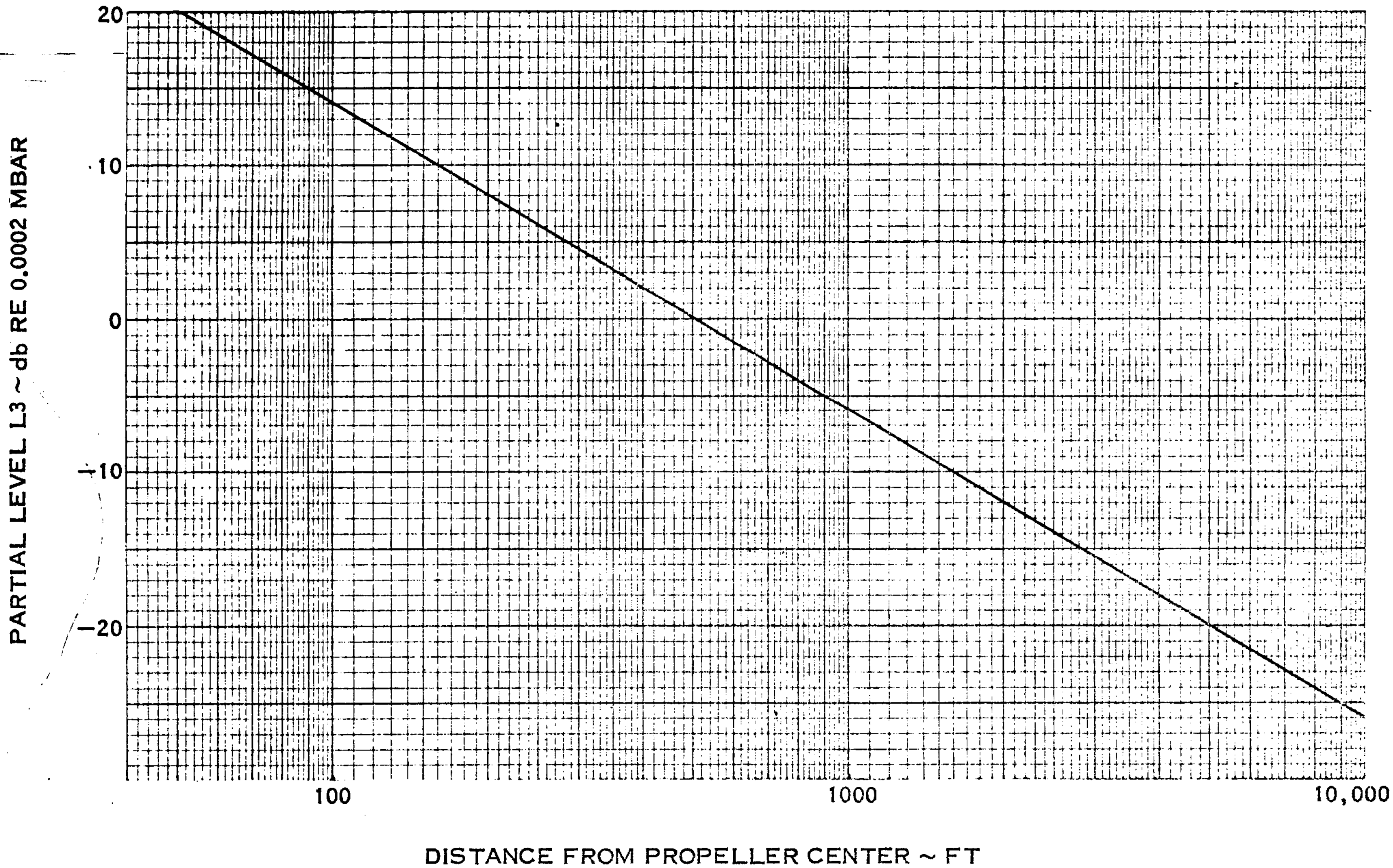


FIGURE 6B. SPHERICAL SPREADING OF SOUND

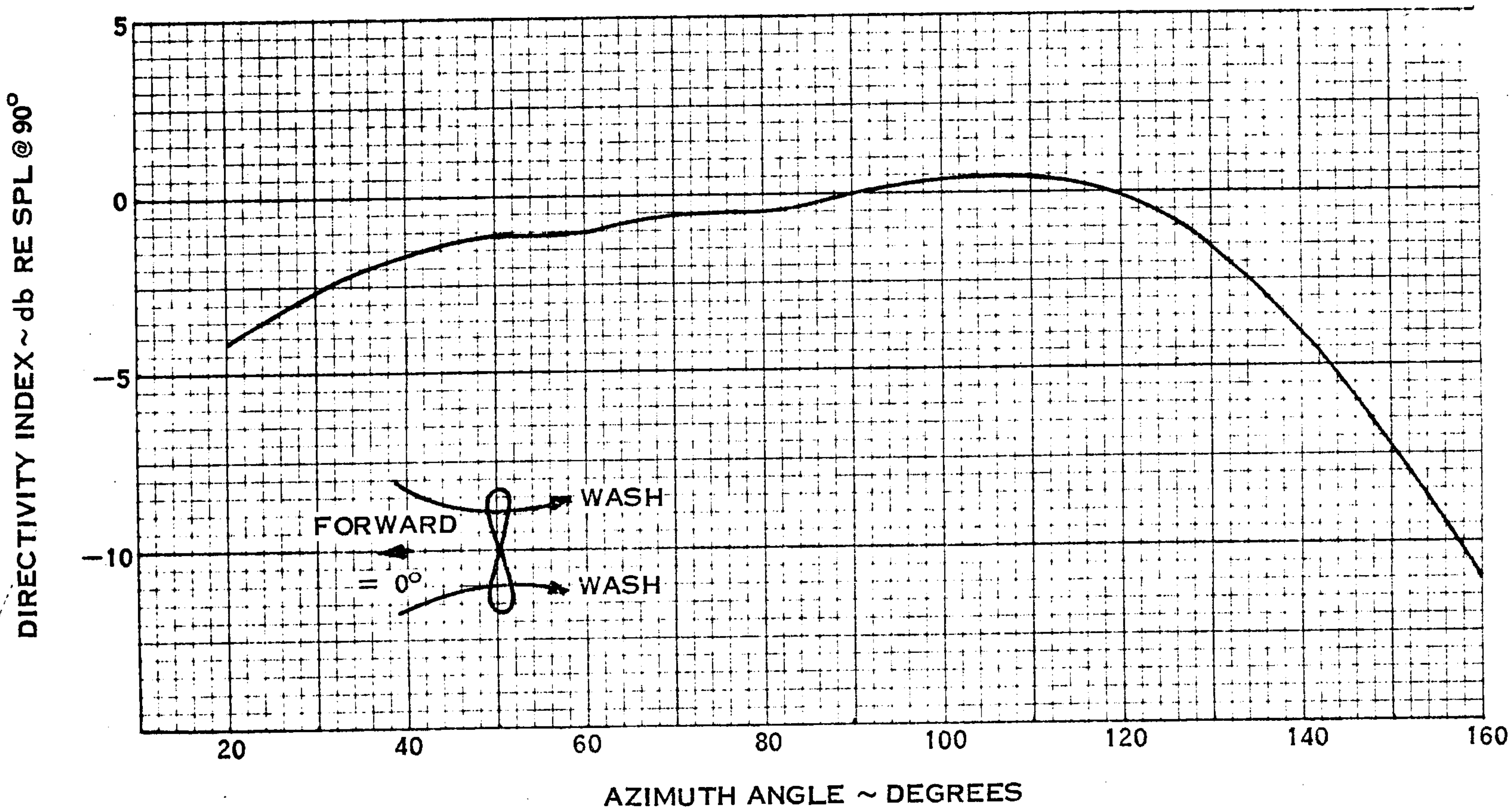


FIGURE 7B. DIRECTIVITY INDEX

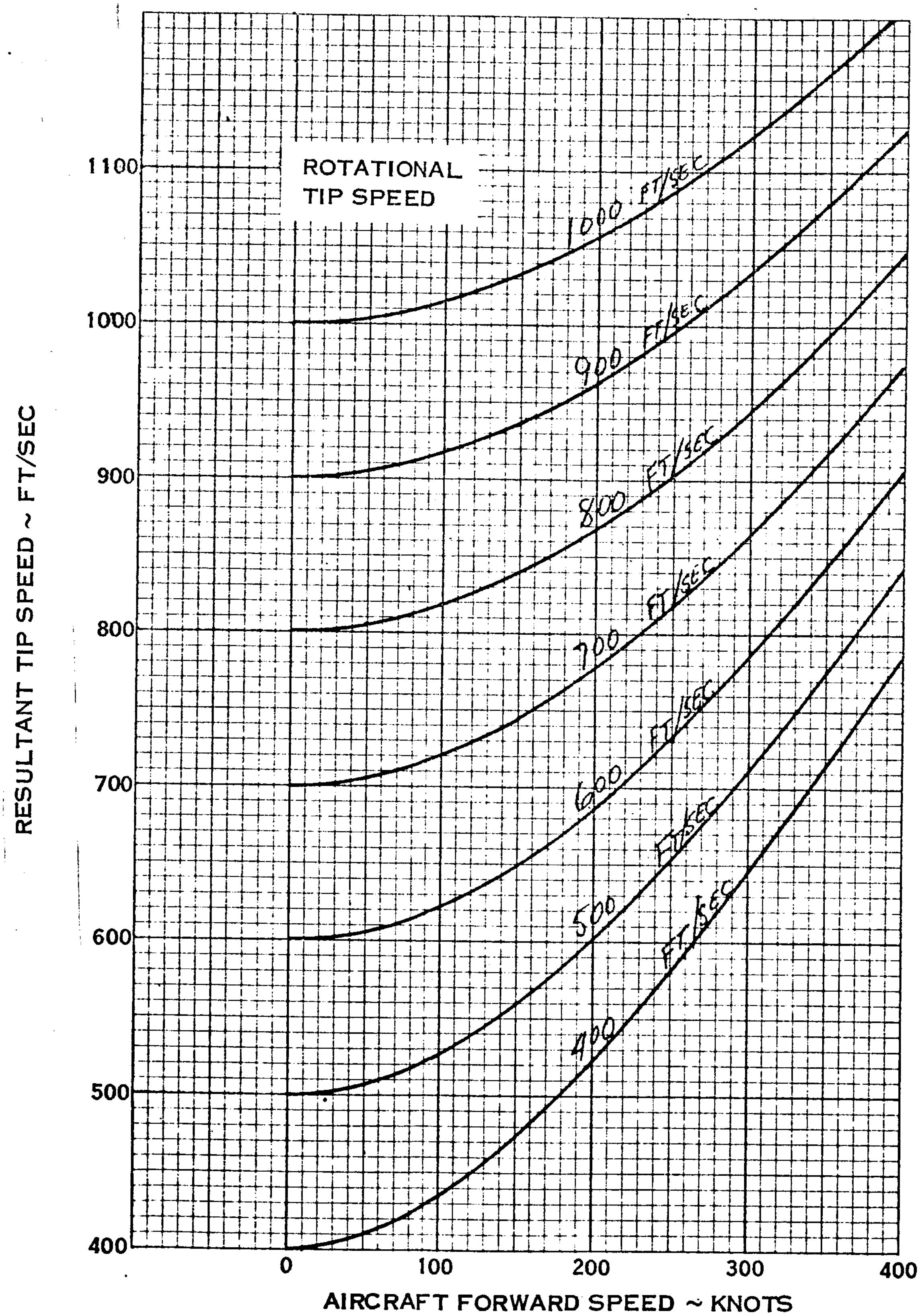


FIGURE 8B. PROPELLER RESULTANT TIPSPEED

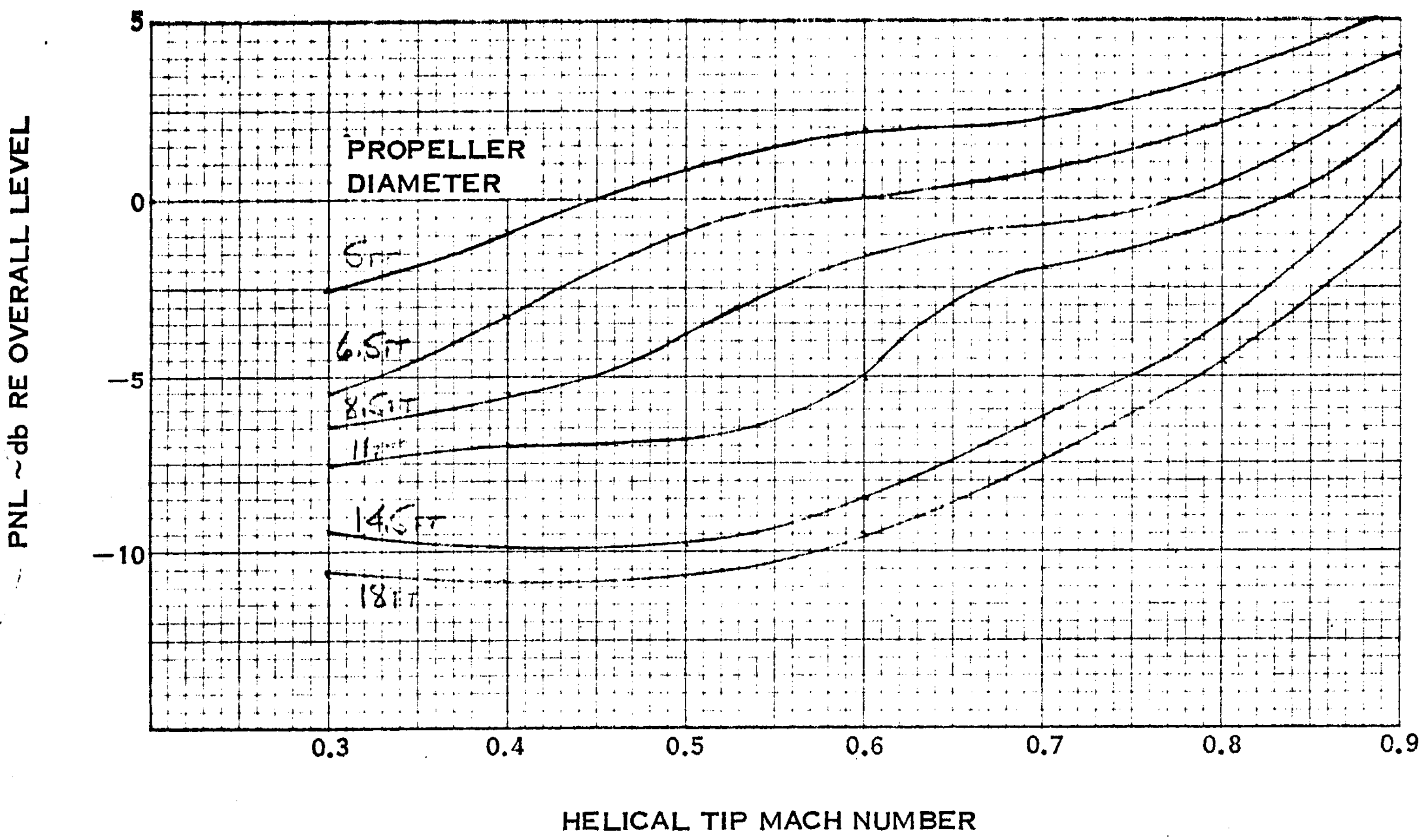


FIGURE 9B. PERCEIVED NOISE LEVEL ADJUSTMENT

2 BLADED PROPELLERS

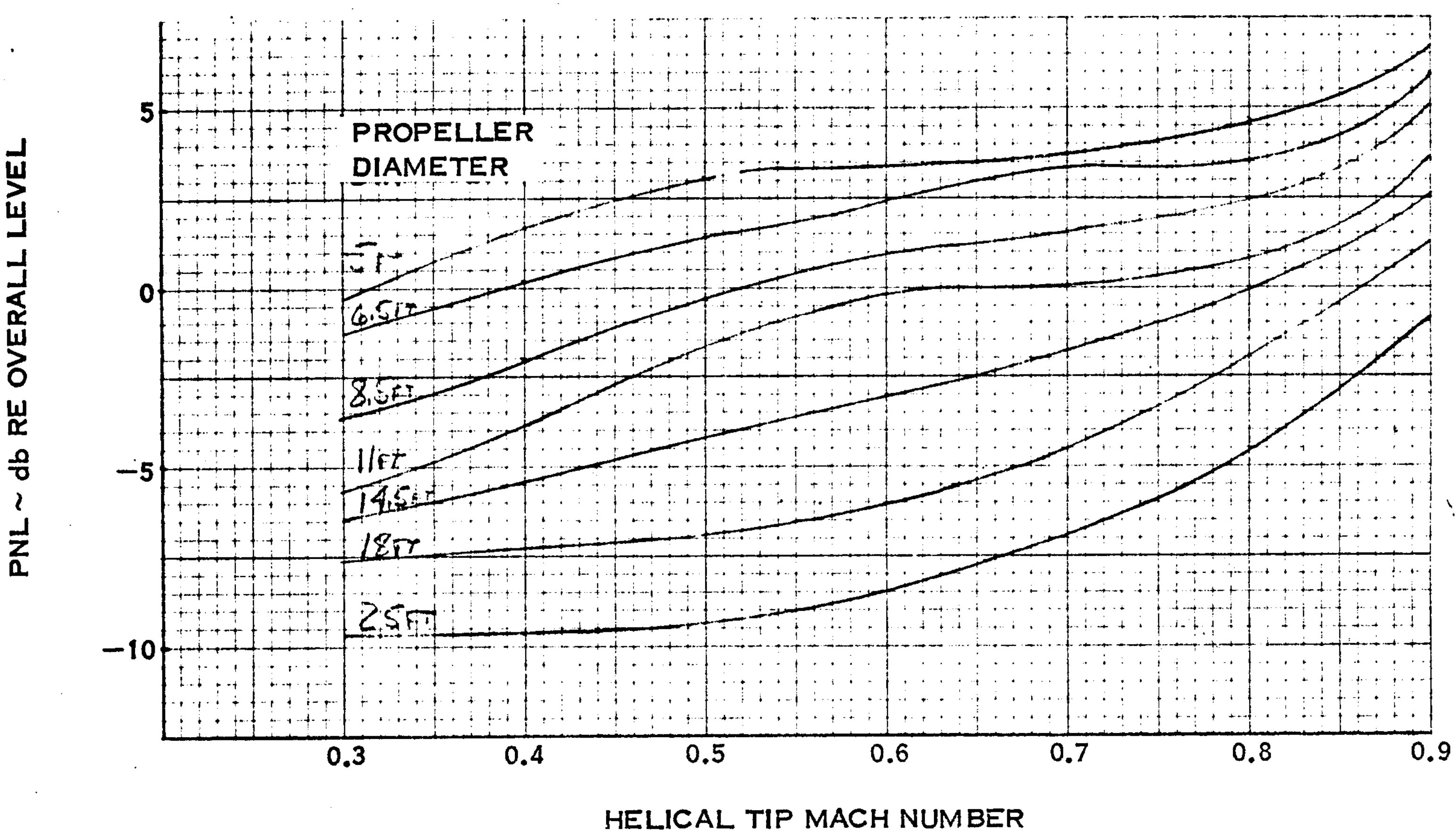


FIGURE 10B. PERCEIVED NOISE LEVEL ADJUSTMENT
3 BLADED PROPELLERS

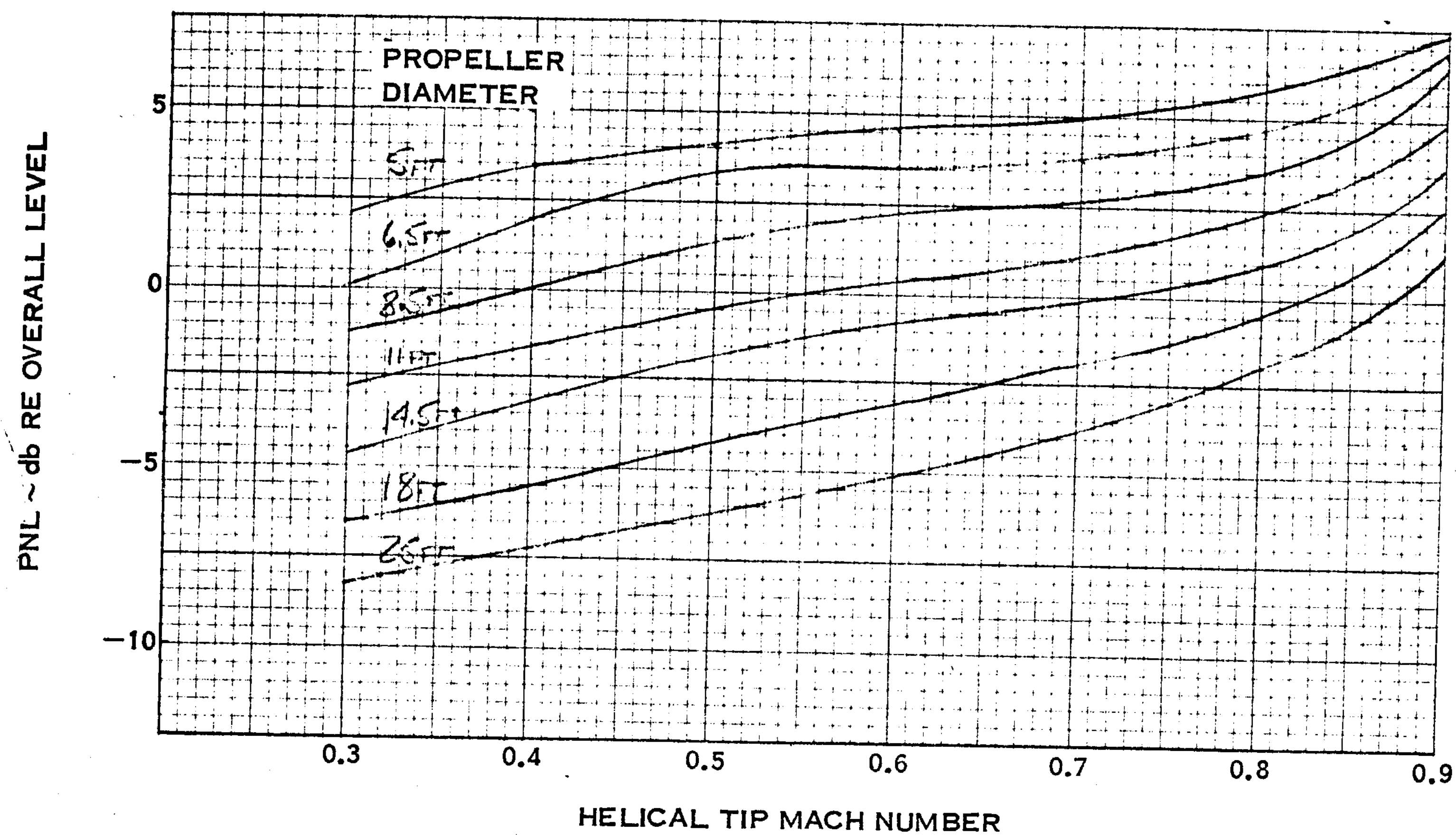


FIGURE 11B. PERCEIVED NOISE LEVEL ADJUSTMENT
4 BLADED PROPELLERS

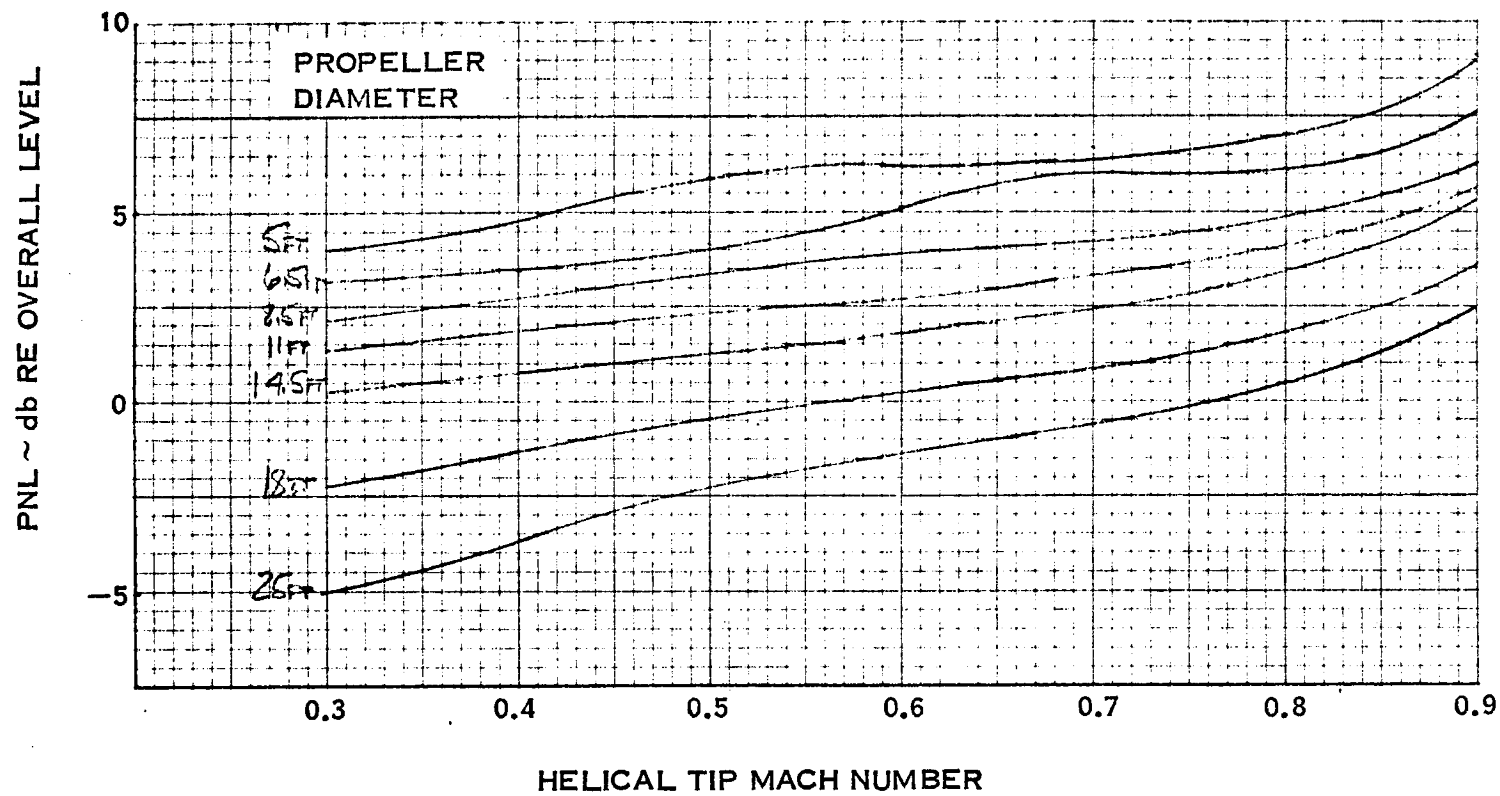


FIGURE 12B. PERCEIVED NOISE LEVEL ADJUSTMENT
6 & 8 BLADED PROPELLERS

APPENDIX C

PROPELLER MARKET SURVEY

Development of a generalized cost equation requires a forecast of the quantity of general aviation propellers that the industry will require in the 1980's and how many propellers a single manufacturer can be expected to sell.

To assist in the forecast, a report, "The Magnitude and Economic Impact of General Aviation," for Utility Aircraft Council, Aerospace Industries Association by R. Dixon Speas Associates (RDSA), July 1968, (ref. 1) was used. Various referenced sections of this report were utilized. The forecast of the 1980 aircraft population can be computed as follows and is shown in the table below:

$$Y = 1.08 \times (7.14 + 0.142 \times CGNP)$$

where Y = thousands of aircraft in fleet in year Z

CGNP = billions of current Gross National Product for the year (Z-1)

The current Gross National Product, CGNP predictions may be found in "The American Economy Prospects and Growth through 1982", McGraw Hill, (ref. 2).

Total Population of General Aviation of all Types[1]

Year Z	CGNP @ 2% Inflation (Z-1)	Population in Z
1968	833.6 Billion	-
1969	-	135,552
1979	1640.8 Billion	-
1980	-	259,344

The previous table shows the projection method used in the referenced report to determine the total fleet population. This population was divided into ten categories of which five were used in tables of this general aviation study. The categories include aircraft with gross weight less than 12,500 lbs. A comparison of the categories in the reference 1 RDSA Report and this Contractor's general aviation study is shown below:

[1] Reference 1, Section III, Figure 8

Category	RDSA Report	Hamilton Standard
I	Single Engine 1 - 3 seats	Single Engine 2 - 4 seats
II	Single Engine 4 + seats	Single Engine 4 + seats
III	Multi Engine 600 HP	Light Twin 300 HP
IV	Multi Engine 600 HP	Medium Twin 450 HP
V	Turboprop	Turboprop 1500 HP

Although these categories are not exactly comparable, there is sufficient compatibility for cost estimation purposes.

The following table was taken from the RDSA report, (reference 1):

Annual Sales of New General Aviation Aircraft - Total Fleet

Year	Domestic[2]	Export[3]	Total Units
1969	11, 250	3, 200	14, 450
1980	18, 990	5, 500	24, 490

Domestic annual sales is determined in RSDA Report by subtracting the total fleet population for successive years (not shown) times a factor for fleet retirements (approx. 30%). Export annual sales were based on 25% of domestic annual sales.

The breakdown of the total fleet population into the five categories for 1969 and 1980 was taken from the RDSA Report. The percent of the total fleet for each category was determined from it and factored into the total units for the 1969 and 1980 to arrive at the yearly units for each category. These results are shown in the following table:

[2]Reference 1, Section III, Figure 26

[3]Reference 1, Section III, Figure 28

Composition of General Aviation Aircraft Fleet Population

Category	I	II	III	IV	V	Total (5 Categories)
1969						
Total Units	46, 600	67, 100	12, 400	3, 510	765	129, 775[4]
% Total	35. 1	51. 91	9. 48	2. 71	0. 59	100
Yearly Units[5]	5, 100	7, 500	1, 370	393	86	14, 450
1980						
Total Units	58, 700	143, 900	26, 000	8, 700	4, 800	242, 100[4]
% Total	24. 3	59. 2	10. 8	3. 7	2. 0	100
Yearly Units[5]	5, 950	14, 600	2, 650	905	490	24, 490

The yearly units must be further broken down into the amount of units that a single manufacturer would produce in 1969 and 1980. Consequently, the final data from the RDSA Report shows the related investment of three aircraft companies which produce 75% of all general aircraft by value and 90% by volume.

Investment Ratios of Aircraft Companies

Company	1967	%
Beech	$ 1, 832, 687	12. 42
Cessna	9, 152, 975	62. 32
Piper	3, 709, 224	25. 26
Total	$14, 694, 000	100. 00

[4]About 95% of total fleet as established previously, so annual sales figures above used.

[5]Yearly Units = Total Annual Sales of New General Aviation Aircraft x % Total.

One propeller manufacturer contacted claimed that he manufactured all the propeller types used on Cessna reciprocating engine aircraft, and that he sells to Cessna 60% of the propellers for each of these aircraft. Therefore, a single major propeller manufacturer could, for example, produce a yearly quantity of propellers equal to 37.5% of any category, as seen by multiplying investment ratios of 62.3% from the previous table by 60% of the categories. Assuming this to be the case, Table 1C shows the number of propellers that a single manufacturer would produce in each category for 1969 and 1980. This table represents a probable upper limit to the fraction of the propeller market available to a single propeller manufacturer for both the current market and that projected for 1980.

TABLE 1C
1969 AND 1980 PROPELLER MANUFACTURE SUMMARY

	1969			1980		
Category	Aircraft/ Year	Props/ Year	Props/Mfr/[7] Year	Aircraft/ Year	Props/ Year	Props/Mfr/[7] Year
I	5100	5100	1910	5950	5950	2230
II	7500	7500	2810	14600	14600	5470
III[6]	1370	2740[7]	1030	2650	5300	1990
IV[6]	393	786[7]	295	905	1810	680
V[6]	86	172[7]	65	490	980	368

[6]Twin propeller aircraft

[7]Prop/Mfr/Year - Prop/Year x 0.375

REFERENCES

1. Anon: The Magnitude and Economic Impact of General Aviation for Utility Aircraft Council, Aerospace Industries. R. Dixon Speas Associates, July 1968

2. Anon: The American Economy Prospects and Growth through 1982, McGraw Hill

APPENDIX D

COMPUTER PROGRAM FOR GENERAL AVIATION AIRCRAFT PROPELLERS

Performance, noise, weight and cost generalizations based on the methodology discussed in the main text were computerized. With this computer program, sensitivity studies can be made which permit the evaluation of trade-offs among these factors for various propeller configurations. Variations in propeller diameter, activity factor (80-200), and number of blades (2-8) can be evaluated. The program is limited to 0.5 integrated design lift coefficient.

Specific cost criteria based on a unit cost factor, a learning curve and manufacture quantity is included as well as the option of inputting these quantities.

The computer deck is designated Hamilton Standard deck H432 and is programmed in FORTRAN V. The following are the pertinent input/output instructions.

Program Input

The first two cards include the card number in column 3 and any legal Hollerith punched in columns 4 through 80. The third card contains the following input data in a (I3, 3X, 10F6.0) format:

1. Card number
2. Number of engines
3. Airplane classification (Table ID)
4. Flight design Mach number

Items 5 through 11 include the various cost options. Code all of these items as zero if the cost criteria built into the computer program is to be used. It is defined as follows:

$$C = ZF\,(3B^{.75} + E)$$

$$C_1 = F\,(3B^{.75} + E)$$

Where:

- C - Average O.E.M. propeller cost for a number of units/year, \$/lb.
- C_1 - Single unit O.E.M. propeller cost, \$/lb.
- Z - $\frac{LF}{LF_1}$
- LF - Learning curve factor for a number of units/year
- LF_1 - Learning curve factor for a single unit
- B - Number of blades
- F - Single unit cost factor
- E - Empirical cost factor

The 89% slope learning curve is used and F, E and quantities are defined as follows:

	1970			1980		
Category	F	E	Quantity	F	E	Quantity
I	3.5	1.0	1910	3.5	1.0	2230
II	3.7	1.5	2810	3.7	1.5	5470
III	3.2	3.5	1030	3.2	3.5	1990
IV	2.6	3.5	295	3.5	3.5	680
V	2.0	3.5	65	3.4	3.5	368

If any deviations are required, the following additional information must be coded.

Learning Curve Variation: It is based on assuming that a learning curve is a straight line when plotted on log log paper. The learning curve is replaced as follows:

5. Learning curve factor for single unit
6. Learning curve factor for 1000 units

Unit Cost Factor, C_1: If a revision in unit cost is required, code as follows:

7. Unit cost for 1970, \$/lb.
8. Unit cost for 1980, \$/lb.

Quantities Variations: To investigate the effects of quantity changes on cost, code as follows:

9. Initial quantity to be used
10. Increment of quantity
11. Number of different quantities

The fourth card contains the following input data in a (2I3, 9F6. 0) format.

1. Card number
2. Number of operating conditions with a maximum of 10
3. Initial diameter
4. Increment in diameter if a range of diameters are to be computed
5. Number of diameters
6. Initial activity factor
7. Increment of activity factor if a range of AF is to be computed
8. Number of activity factors
9. Initial number of blades
10. Increment in number of blades if a range of blades is to be computed
11. Number of number of blades

Subsequent cards are coded as follows with (3X, I3, 10F6. 0) format for each operating condition. The number of these cards must be equal to the number specified in 2 on card 3.

1. Code 1 for defining condition with SHP Code 2 for defining condition with thrust
2. BHP or thrust per propeller
3. Altitude in ft.
4. Velocity in knots, true airspeed
5. Temperature in °F
6. Initial tipspeed, $\frac{\pi ND}{60}$, fps
7. Increment of tipspeed if a range of tipspeeds are to be computed
8. Number of tipspeeds.

9. Distance of field point at which noise is to be computed; directivity for peak noise is automatically used; the noise calculation should be made for takeoff conditions only; code = 0. when no noise calculation is to be made.

10. Code = 1. for computing the tipspeed corresponding to 50% stall. This should only be used for takeoff conditions.

11. Code = 1. if cost and weight are to be computed for the operating condition. This condition should be a takeoff condition.

For subsequent cases, repeat all the input data previously specified.

Program Output

The input data prints out initially and then the pertinent data under the following headings:

1. DIAM-FT - propeller diameter, ft.
2. T.S. FPS - tipspeed, fps
3. THRUST or SHP - dependent on which option selected
4. PNL - perceived noise in PNdB; value corresponds to the number of engines specified in the input.

The following cost and weight data prints out when computations are requested.

5. QUANTITY - number of units to be included in cost computation
6. WT-LBS - propeller weight, lbs
7. $COST - propeller cost in dollars

The weight and cost are included for both 1970 and 1980 technology.

8. ANGLE - propeller blade angle in degrees at 3/4 radius which is of particular interest in analyzing fixed pitch propellers.

The following data is included as additional information. For example, from an examination of these parameters, an indication of the presence and magnitude of compressibility losses and the blade loading characteristics may be established.

9. FT - compressibility correction
10. M - free stream Mach number

11. J - advance ratio = $\frac{101.4\ V_k}{ND}$

12. CP - power coefficient = $\frac{SHP\ (\rho_o/\rho)\ 10^{11}}{2N^3D^5}$

13. CT - thrust coefficient = $\frac{1.514T\ (\rho_o/\rho)}{N^2D^4}$

where V_k - velocity in knots, true airspeed

N - propeller speed, rpm

D - propeller diameter, ft.

SHP - horsepower

ρ_o/ρ - density ratio

T - propeller thrust, lbs.

For the option where tipspeed is varied, the calculations are made for the input ranges in the following order.

1. Tipspeed
2. Diameter
3. Number of blades
4. Activity factor
5. Operating condition

For the option where tipspeed for 50% stall is to be defined, the computations are made for the input ranges in the following order:

1. Diameter
2. Number of blades
3. Activity factor
4. Operating condition

The following warnings or messages print out.

1. 'INPUT ERROR IW=I2, IC=I2' - the input item specifying whether the horsepower or thrust option is required has been included as other than 1. or 2., the only options available

2. 'ILLEGAL ACTIVITY FACTOR = F8.1' - the input AF exceeds the permissible 80-200 AF range

3. 'ILLEGAL NUMBER OF BLADES = F8.1' - the input number of blades exceeds the permissible 2-8 blades

4. 'ADVANCE RATIO TOO HIGH' - check to see that input diameter, rpm, and velocity are correct. The advance ratio limits are 0 to 5.

5. 'FAILED STALL ITERATION' - problem encountered in defining tipspeed corresponding to 50% stall. If this message is encountered, check input for SHP, RPM, altitude, velocity, and diameter

6. ******* - print out under PNL indicates that the propeller is operating at a condition where it is more than 50% stalled

7. ******* - under SHP or THRUST indicates that this condition is off the limits of the performance curves

Sample Cases

Coding for three sample cases of the input are shown on figure 1D and the output presented as figures 2D through 4D respectively. The sample cases are presented in the following order:

1. The condition is defined by SHP, tipspeed variation and request for cost calculations based on the information included in the computer program.

2. The condition is defined by thrust and tipspeed variation.

3. The condition is defined by SHP, tipspeed requested for 50% stall and cost on the basis of a span of quantities.

Computer Deck

The flow chart for the computer program is shown on figure 5D and a listing is presented as figure 6D. The computer program has been run on a UNIVAC 1108. Approximately 2000 operating conditions are computed per minute.

ADVANCED GENERAL
AIRCRAF

	Aircraft Class	Seats	Cruise Vel., MPH	Engine Power	Propeller Typ
I.	Single Eng. Fixed Gear	2-4	100-160	100-200 Recip DD	Fixed Pitch 2 Blades
II.	Single Eng. Adv. Retract Gear IFR Equip.	4-6	120-250	150-300 Recip DD & Geared Some Small Turboprops	Constant Speed 2 Blades-Some 3 Bl
III.	Light Twins Retract Gear IFR Equip.	4-6	150-300	150-300 Recip DD & Geared Some Small Turboprops	Constant Speed 2 Blades-Some 3 Bl Full Feather, Deic
IV.	Medium Twins Retract Gear IFR Equip	6-11	150-300	250-450 Turboprops, Recip DD & Geared	Constant Speed Full Feather, Deic 3 Blades
V.	Heavy Twins Retract Gear IFR Equip.	11 & Up	175-400	600-1500 Turbines	Constant Speed Full Feather Deicing, Reverse 3 and 4 Blades

BLE ID
VIATION PROPELLER STUDY
CLASSIFICATION

	Application	Gross Weight, lbs.	Price Range	Example Aircraft
	Student, Private Rental, Aerobatic	1000-2500	$8-25K	CESSNA 150, 172, Skyhawk BEECH Musketeer A23-19 PIPER Super Cub, Cherokee
ades	Adv. Student Private (Family) Survey, Business	2000-4000	$20-50K	CESSNA Skywagon 180, 206, 207, 210 BEECH Bonanza, Musketeer Super 300 PIPER Comanche C, Cherokee Arrow MOONEY M20F
ades ing	Private (Family) Survey, Business	3500-6000	$40-120K	CESSNA Super Skymaster, 310Q BEECH Turbobaron, Baron 55 PIPER Twin Comanche C, Aztec D MOONEY Aerostar
ing	Executive Charter, Air Taxi	6000-8000	$100-200K	CESSNA 401B, 402B, 414, 421 BEECH Queen Air, Duke PIPER Navajo 300, Turbo Navajo NORTH AMERICAN ROCKWELL-Shrike Commander BRITTEN-NORMAN ISLANDER, Helio Twin Stallion
	Large Executive Charter, Third Tier Air Liners	8000-12,500	$400-600K	DEHAVILLAND Twin Otter MOONEY MU-2G NORTH AMERICAN ROCKWELL Hawk Commander BEECH King Air HANDLEY PAGE Jetstream

UAC CODING FORM # 3

ENGINEER: ROSE WOROBEL MAIL ADDRESS: AERODYNAMICS EXTENSION 306

TITLE GENERAL AVIATION PROPELLER STUDY ANALYST R. WOROBEL SHEET 1 OF 1

JOB NO. H432 ACCT. NO. 04302 W.O. NO. 123-W00-100A

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                       SAMPLE CASE #1

 1  CESSNA 210J AIRCRAFT CLASSIFICATION II             SAMPLE CASE I
 2  SHP INPUT- TIPSPEED VARIATION- COST BASED ON INITIAL COMPUTER DATA
 3  1.     2.     .262
 4 28.     1.     2.     150.   0.     1.     4.     0.     1.
   1300.   .0     71.2   0.     850.   -100.  4.     500.   0.     1.
   1214.   7500.  163.2  0.     650.   -100.  4.

                       SAMPLE CASE #2

 1  CESSNA 210J AIRCRAFT CLASSIFICATION II             SAMPLE CASE II
 2  THRUST INPUT-TIPSPEED VARIATION- NO COST CALC.
 3  1.     2.     .262
 4  18.    1.     2.     150.   0.     1.     2.     2.     3.
   2820.   .0     71.2   0.     750.   .0     .0     500.   0.     0.

                       SAMPLE CASE #3

 1  CESSNA 210J AIRCRAFT CLASSIFICATION II             SAMPLE CASE III
 2  SHP INPUT-CALC. TIPSPEED FOR 50 PERCENT STALL-COST FOR RANGE QUANT.
 3  1.     2.     .262   .0     .0     .0     .0     1.     1000.  5.
 4  18.    0.     1.     150.   0.     1.     2.     2.     3.
   1300.   .0     71.2   0.     850.   -100.  5.     500.   1.     1.
```

FIGURE 11

HAMILTON STANDARD COMPUTER DECK NO. H432
COMPUTES PERFORMANCE,NOISE,WEIGHT,AND COST FOR
GENERAL AVIATION PROPELLERS

1 CESSNA 210J AIRCRAFT CLASSIFICATION II SAMPLE CASE I

2 SHP INPUT- TIPSPEED VARIATION- COST BASED ON INITIAL COMPUTER DATA

OPERATING CONDITION

SHP = 300.
ALT-FT = 0.
V-KTAS = 71.2
TEMP R = 519.

NO. OF ENGINES = 1.
DESIGN FLIGHT M.= .262
CLASSIFICATION = 2.
FIELD POINT FT. = 500.

UNIT FACTOR L.C. = 3.22
1000 FACTOR L.C. = 1.02

NUMBER OF BLADES= 4. ACTIVITY FACTOR=150.

				*** 1970 TECHNOLOGY ***			*** 1980 TECHNOLOGY ***								
DIA.FT.	T.S.FPS	THRUST	PNL	QUANTITY	WT-LBS	$COST	QUANTITY	WT-LBS	$COST	ANGLE	FT	M	J	CP	CT
8.	850.	802.	94.	2810.	144.	1423.	5470.	144.	1274.	11.5	1.000	.1077	.445	.0548	.0721
8.	750.	960.	90.	2810.	136.	1337.	5470.	136.	1197.	15.0	1.000	.1077	.504	.0798	.1108
8.	650.	999.	86.	2810.	126.	1244.	5470.	126.	1114.	19.1	1.000	.1077	.582	.1225	.1535
8.	550.	987.	82.	2810.	116.	1145.	5470.	116.	1025.	24.7	1.000	.1077	.667	.2022	.2117
8.	450.	905.	78.	2810.	105.	1035.	5470.	105.	927.	32.9	1.000	.1077	.840	.3692	.2901
8.	350.	***********	*****	2810.	93.	913.	5470.	93.	817.	45.8	1.000	.1077	1.080	.7847	.3618
9.	850.	676.	93.	2810.	178.	1751.	5470.	178.	1567.	9.9	1.000	.1077	.445	.0433	.0480
9.	750.	898.	89.	2810.	167.	1645.	5470.	167.	1472.	13.2	1.000	.1077	.504	.0630	.0819
9.	650.	1038.	85.	2810.	155.	1531.	5470.	155.	1371.	17.5	1.000	.1077	.582	.0968	.1260
9.	550.	1031.	81.	2810.	143.	1408.	5470.	143.	1261.	22.4	1.000	.1077	.687	.1598	.1745
9.	450.	983.	76.	2810.	129.	1274.	5470.	129.	1140.	29.9	1.000	.1077	.840	.2917	.2488
9.	350.	*********	71.	2810.	114.	1124.	5470.	114.	1006.	42.3	1.000	.1077	1.080	.6200	.3540

OPERATING CONDITION

SHP = 214.
ALT-FT = 7500.
V-KTAS = 163.2
TEMP R = 492.

NO. OF ENGINES = 1.
DESIGN FLIGHT M.= .262
CLASSIFICATION = 2.
FIELD POINT FT = -0.

NUMBER OF BLADES= 4. ACTIVITY FACTOR=150.

DIA.FT.	T.S.FPS	THRUST	PNL	ANGLE	FT	M	J	CP	CT
8.00	850.	319.	0.	21.7	1.000	.2534	1.019	.0489	.0359
8.00	750.	372.	0.	25.2	1.000	.2534	1.155	.0712	.0538
8.00	650.	374.	0.	29.2	1.000	.2534	1.333	.1094	.0719
8.00	550.	375.	0.	34.5	1.000	.2534	1.575	.1805	.1008
8.00	450.	380.	0.	41.6	1.000	.2534	1.925	.3296	.1525
8.00	350.	369.	0.	51.2	1.000	.2534	2.476	.7006	.2447
9.00	850.	220.	0.	20.9	1.000	.2534	1.019	.0386	.0195
9.00	750.	339.	0.	24.5	1.000	.2534	1.155	.0563	.0387
9.00	650.	365.	0.	28.5	1.000	.2534	1.333	.0864	.0555
9.00	550.	376.	0.	33.7	1.000	.2534	1.575	.1425	.0797
9.00	450.	382.	0.	40.3	1.000	.2534	1.925	.2604	.1210
9.00	350.	376.	0.	49.3	1.000	.2534	2.476	.5535	.1968

FIGURE 2D. SAMPLE CASE I OF COMPUTER PRINTOUT

HAMILTON STANDARD COMPUTER DECK NO. H432
COMPUTES PERFORMANCE,NOISE,WEIGHT,AND COST FOR
GENERAL AVIATION PROPELLERS

1 CESSNA 210J AIRCRAFT CLASSIFICATION II SAMPLE CASE II

2 THRUST INPUT-TIPSPEED VARIATION- NO COST CALC.

OPERATING CONDITION

THRUST =	820.	NO. OF ENGINES =	1.
ALT-FT =	0.	DESIGN FLIGHT M.=	.262
V-KTAS =	71.2	CLASSIFICATION =	2.
TEMP R =	519.	FIELD POINT FT =	500.

NUMBER OF BLADES= 2. ACTIVITY FACTOR=150.

DIA.FT.	T.S.FPS	SHP	PNL	ANGLE	FT	M	J	CP	CT
8.00	750.	245.	91.	17.6	1.000	.1077	.504	.0651	.0946
9.00	750.	238.	90.	15.7	1.000	.1077	.504	.0500	.0747

NUMBER OF BLADES= 4. ACTIVITY FACTOR=150.

DIA.FT.	T.S.FPS	SHP	PNL	ANGLE	FT	M	J	CP	CT
8.00	750.	260.	89.	14.0	1.000	.1077	.504	.0690	.0946
9.00	750.	273.	88.	12.8	1.000	.1077	.504	.0574	.0747

NUMBER OF BLADES= 6. ACTIVITY FACTOR=150.

DIA.FT.	T.S.FPS	SHP	PNL	ANGLE	FT	M	J	CP	CT
8.00	750.	295.	88.	12.9	1.000	.1077	.504	.0783	.0946
9.00	750.	323.	87.	11.9	1.000	.1077	.504	.0679	.0747

FIGURE 3D. SAMPLE CASE II OF COMPUTER PRINTOUT

HAMILTON STANDARD COMPUTER DECK NO. H432
COMPUTES PERFORMANCE,NOISE,WEIGHT,AND COST FOR
GENERAL AVIATION PROPELLERS

1 CESSNA 210J AIRCRAFT CLASSIFICATION II SAMPLE CASE III

2 SHP INPUT-CALC. TIPSPEED FOR 50PERCENT STALL-COST FOR RANGE QUANT.

OPERATING CONDITION

SHP = 300.	NO. OF ENGINES = 1.	UNIT FACTOR L.C. = 3.22
ALT-FT = 0.	DESIGN FLIGHT M.= .262	1000 FACTOR L.C. = 1.02
V-KTAS = 71.2	CLASSIFICATION = 2.	
TEMP R = 519.	FIELD POINT FT. = 500.	

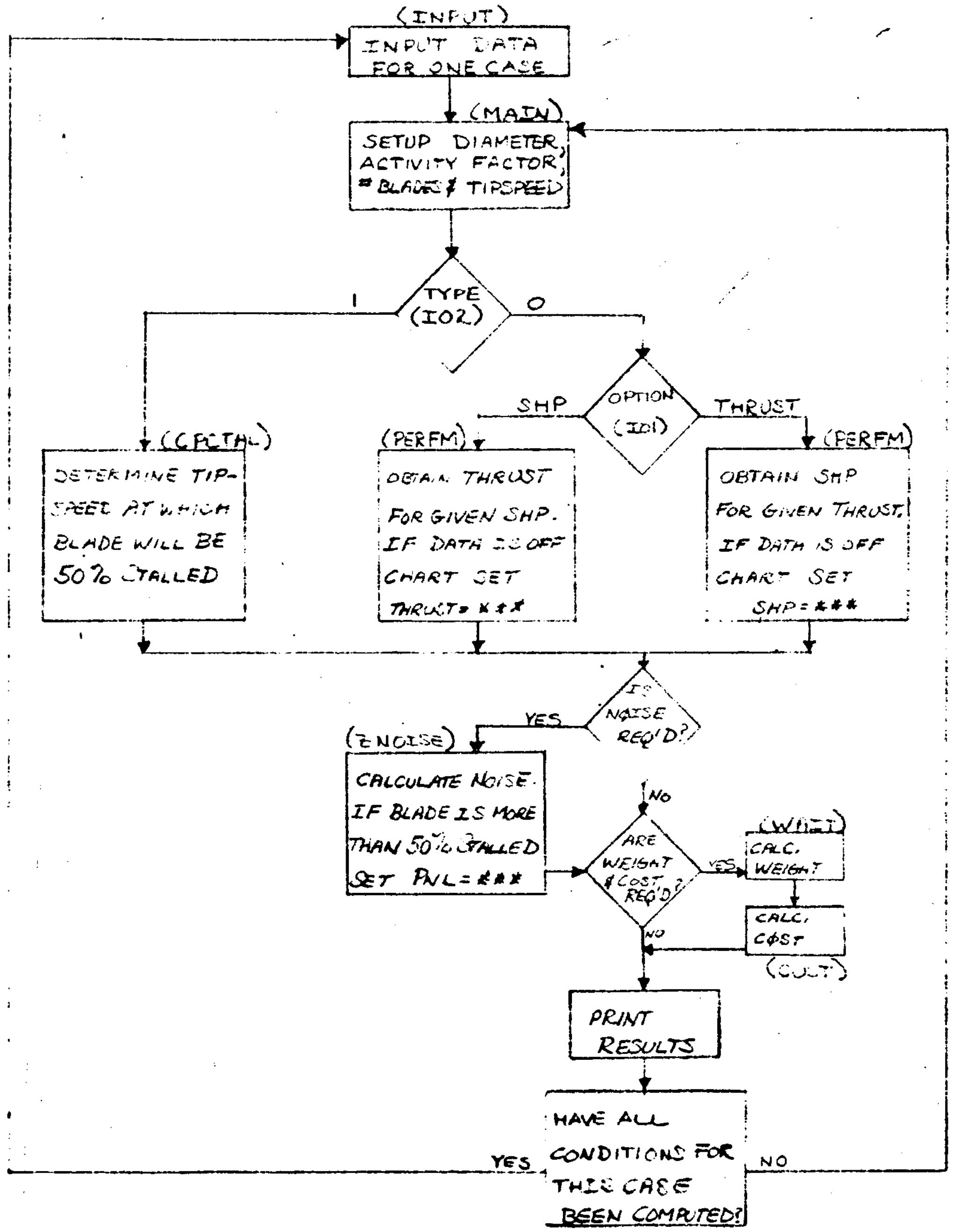
NUMBER OF BLADES= 2. ACTIVITY FACTOR=150.

				*** 1970 TECHNOLOGY ***			*** 1980 TECHNOLOGY ***								
DIA.FT.	T.S.FPS	THRUST	PNL	QUANTITY	WT-LBS	$COST	QUANTITY	WT-LBS	$COST	ANGLE	FT	M	J	CP	CT
8.	570.	827.	85.	1.	73.	1761.	1.	73.	1761.	11.9	1.000	.1077	.664	.1821	.1655
				1001.	73.	558.	1001.	73.	558.						
				2001.	73.	497.	2001.	73.	497.						
				3001.	73.	465.	3001.	73.	465.						
				4001.	73.	443.	4001.	73.	443.						

NUMBER OF BLADES= 4. ACTIVITY FACTOR=150.

				*** 1970 TECHNOLOGY ***			*** 1980 TECHNOLOGY ***								
DIA.FT.	T.S.FPS	THRUST	PNL	QUANTITY	WT-LBS	$COST	QUANTITY	WT-LBS	$COST	ANGLE	FT	M	J	CP	CT
8.	381.	799.	75.	1.	97.	3571.	1.	97.	3571.	11.9	1.000	.1077	.991	.6066	.3564
				1001.	97.	1132.	1001.	97.	1132.						
				2001.	97.	1009.	2001.	97.	1009.						
				3001.	97.	943.	3001.	97.	943.						
				4001.	97.	899.	4001.	97.	899.						

FIGURE 4D. SAMPLE CASE III OF COMPUTER PRINTOUT



( ) INDICATE NAMES OF PROGRAM SUBROUTINES

FIGURE 5D. FLOW CHART FOR H.S. DECK H432

```
*IP FOR MAIN
      COMMON/AFCOR/AFCPE,AFCTE,XFT
      COMMON/ASTRK/CPAST,CTAST
      COMMON/CPECTE/CPE,CTE,BLLLL
      DIMENSION FC(10),ALTPR(11),PRESSR(11),RORO(10)
      DIMENSION DIST(10),CQUAN(2,11),COST70(10),COST80(10)
      COMMON /ZINPUT/ BHP(10),THRUST(10),ALT(10),VKTAS(10),T(10),TS(10)
     1,IWIC(10),NOF,D,DD,ND,AF,DAF,NAF,BLADN,DBLAD, NBL,DTS(10),NDTS(10)
     2,DIST,XNOE,WTCON,ZMWT,STALIT(10),CLF1,CLF,CK70,CK80,CAMT,DAMT,NAMT
     3,DCOST(10)
      DATA (ALTPR(I),I=1,11)/0.,10000.,20000.,30000.,40000.,50000.,
     X60000.,70000.,80000.,90000.,100000./
      DATA (PRESSR(I),I=1,11)/1.0,.6877,.4595,.2970,.1851,.1145,.07078,
     X.04419,.02741,.01699,.01054/
      DATA/BLANK/6H       /
  701 CONTINUE
      WRITE (6,1)
    1 FORMAT ('1',19X'HAMILTON STANDARD COMPUTER DECK NO. H432'/17X'COMP
     1UTES PERFORMANCE,NOISE,WEIGHT,AND COST FOR'/26X'GENERAL AVIATION P
     2ROPELLERS')
      CALL INPUT
      DO 700 IC=1,NOF
      NCOST=DCOST(IC)+.01
      IF (STALIT(IC).LE..50) GO TO 710
      NDTS(IC)=10
      DTS(IC)=0.0
  710 CONTINUE
      IW= IWIC(IC)
C IW=1    HP INPUT
C IW=2    THRUST INPUT
      IF (IW.EQ.1.OR.IW.EQ.2) GO TO 3
      WRITE (6,2) IW,IC
    2 FORMAT( ' INPUT ERROR, IW = 'I2,' IC = ' I2 )
      GO TO 700
    3 CONTINUE
C     COMPUTATION OF DENSITY RATIO
      IF(T(IC))100,100,160
  100 IF(ALT(IC)-36000.)120,120,140
  120 T(IC)=518.688-.00356*ALT(IC)
      GO TO 180
  140 T(IC)=389.988
      GO TO 180
  160 T(I)=T(IC)+459.69
  180 TO=518.69
      TOT=TO/T(IC)
      FC(IC)=SQRT(TOT)
      CALL UNINT (11,ALTPR,PRESSR,ALT(IC),POP,LIMIT)
      RORO(IC)=1.0/(POP*TOT)
C     AF LOOP
      AFT=AF-DAF
      WRITE (6,706)
  706 FORMAT ('0',18X'OPERATING CONDITION'/)
      IF(NCOST-1)290,200,290
  200 IENT=1
      CALL COST (WTCON,BLADT,CLF1,CLF,CK70,CK80,CAMT,DAMT,NAMT,CQUAN(1,1
     1),WT70,WT80,COST70,COST80,CCLF1,CCLF,CCK70,CCK80,IENT)
      GO TO (210,230),IW
  210 WRITE (6,220) BHP(IC),XNOE,CCLF1
  220 FORMAT(' SHP     =',F7.0,9X'NO. OF ENGINES   =',F5.0,9X'UNIT FACTOR
     1L.C.     ='F5.2)
```

FIGURE 6D. LISTING OF ADVANCED GENERAL AVIATION PROPELLER PROGRAM (PAGE 1 OF 14)

```
      GO TO 250
  240 FORMAT(' THRUST =',F7.0,9X'NO. OF ENGINES  =',F5.0,9X'UNIT FACTOR
     1L.C.    =' F5.2)
  230 WRITE (6,240)THRUST(IC),XNOE,CCLF1
  250 IF(CK70.GT.0..OR.CK80.GT.0.) GO TO 255
      WRITE (6,252) ALT(IC),ZMWT,CCLF,VKTAS(IC),WTCON,T(IC),DIST(IC)
  252 FORMAT(' ALT-FT =',F7.0,9X'DESIGN FLIGHT M.='F5.3,9X,'1000 FACTOR
     1L.C.    ='F5.2/' V-KTAS =',F7.1,9X'CLASSIFICATION  ='F5.0/' TEMP R
     2=',F7.0,9X'FIELD POINT FT. ='F5.0)
      GO TO 270
  255 WRITE (6,260) ALT(IC),ZMWT    ,CCLF,VKTAS(IC),WTCON, CK70,T(IC),
     1DIST(IC), CK80
  260 FORMAT(  ' ALT-FT =',F7.0,9X'DESIGN FLIGHT M.='F5.3,9X'1000 FACTOR
     1 L.C.   ='F5.2/' V-KTAS =',F7.1,9X'CLASSIFICATION  ='F5.0,9X'UNIT
     2COST 1970      =' ,F5.1/' TEMP R =',F7.0,9X'FIELD POINT FT. ='F5.0,
     39X'UNIT COST 1980      ='F5.1)
      GO TO 270
  290 GO TO (10,12),IW
   10 WRITE (6,11) SHP(IC),XNOE
   11 FORMAT(     ' SHP     =' ,F7.0,23X'NO. OF ENGINES  =',F5.0)
      GO TO 14
   12 WRITE (6,13) THRUST(IC),XNOE
   13 FORMAT(     ' THRUST =',F7.0,22X'NO. OF ENGINES  =',F5.0)
   14 WRITE (6,15) ALT(IC),ZMWT,VKTAS(IC),WTCON,T(IC),DIST(IC)
   15 FORMAT(' ALT-FT =',F7.0,23X'DESIGN FLIGHT M.=',F5.3/' V-KTAS =',
     1F7.1,23X'CLASSIFICATION  =',F5.0/' TEMP R =',F7.0,23X'FIELD POINT
     2 FT =',F5.0)
  270 DO 1200 IAF=1,NAF
      AFT=AFT+DAF
      IF(AFT.LE.200..AND.AFT.GE.80.) GO TO 182
      WRITE(6,181) AFT
  181 FORMAT( ' ILLEGAL ACTIVITY FACTOR = ',F8.1)
      GO TO 1200
  182 CONTINUE
C     NO. OF BLADES LOOP
      BLADT=BLADN-DBLAD
      DO 1000 IB=1,NBL
      BLADT=BLADT+DBLAD
      IF(BLADT.LE.8..AND.BLADT.GE.2.) GO TO 888
      WRITE(6,887) BLADT
  887 FORMAT(' ILLEGAL NO. OF BLADES = ',F8.1)
      GO TO 1000
  888 CONTINUE
C PRINT APPROPIATE HEADING
      WRITE (6,20) BLADT,AFT
   20 FORMAT('0',' NUMBER OF BLADES=',F3.0,18X'ACTIVITY FACTOR=',F4.0)
      IF(NCOST.EQ.1) GO TO 500
      GO TO (21,24),IW
   21 WRITE (6,22)
   22 FORMAT('0',' DIA.FT. T.S.FPS THRUST  PNL   ANGLE    FT       M
     1 J       CP       CT'/)
      GO TO 30
   24 WRITE(6,25)
   25 FORMAT('0',' DIA.FT. T.S.FPS    SHP    PNL   ANGLE    FT       M
     1 J       CP       CT'/)
      GO TO 30
  500 GO TO (510,550),IW
  510 WRITE (6,520)
  520 FORMAT('0',30X'*** 1970 TECHNOLOGY ***   *** 1980 TECHNOLOGY ***'/
     1' DIA.FT. T.S.FPS THRUST  PNL  QUANTITY  WT-LBS  $COST   QUANTITY
```

FIGURE 6D. LISTING OF ADVANCED GENERAL AVIATION PROPELLER PROGRAM (PAGE 2 OF 14)

```
     2 WT-LBS   $COST   ANGLE    FT      M        J        CP        CT'/)
       GO TO 30
   550 WRITE (6,560)
   560 FORMAT('0',30X'*** 1970 TECHNOLOGY ***   *** 1980 TECHNOLOGY XXX'/
      1' DIA.FT. T.S.FPS  SHP    PNL  QUANTITY  WT-LBS  $COST   QUANTITY
      2 WT-LBS   $COST   ANGLE    FT      M        J        CP        CT'/)
    30 CONTINUE
       ILINE=ILINE+6
C      DIAMETER LOOP
       DIA=D-DD
       DO 800 ID=1,ND
       DIA=DIA+DD
C      TIPSPEED LOOP
       TIPSPD=TS(IC)-DTS(IC)
       NTS=NDTS(IC)
       DO 600 ITS=1,NTS
       CTAST=BLANK
       CPAST=BLANK
       TIPSPD=TIPSPD+DTS(IC)
C      MACH NUMBER CALCULATION AND ADVANCE RATIO J
       IF (VKTAS(IC))300,320,300
   300 ZMS=.001512*VKTAS(IC)*FC(IC)
       GO TO 340
   320 ZMS=TIPSPD*FC(IC)/1120.
   340 ZJI=5.309*VKTAS(IC)/TIPSPD
       IF(ZJI.LE.5.0) GO TO 342
       WRITE(6,341) ZJI
   341 FORMAT(' ADVANCE RATIO TOO HIGH = ', F8.4)
       GO TO 600
   342 CONTINUE
C   ITERATION ON CT OR CP TO GET 50 PERCENT STALL TIPSPEED
       IFIN=0
       IF (STALIT(IC).LE..50) GO TO 399
       CALL CPCTAL (ISTALL,ZJI,BLADT,CPSTL,CTSTL)
       GO TO (711,712),IW
   711 CONTINUE
       CP=BHP(IC)*10.E10*RORO(IC)/(2.0*TIPSPD**3*DIA**2*6966.)
       CALL PERFM(1,CP,ZJI,AFT,BLADT,CT,ZMS,7710)
   421 CT=CTSTL/AFCTE
       CPSTL=CPSTL/AFCPE
       THRUST(IC)=CT*TIPSPD**2*DIA**2/(1.515E06*RORO(IC))*364.76
       IF (ABS(CP -CPSTL).LE..005*CP) GO TO 713
       TIPSPD= CBRT(BHP(IC)*10.E10*RORO(IC)/(2.*DIA**2*6966.*CPSTL))
       GO TO 709
   712 CONTINUE
       CT=THRUST(IC)*1.515E06*RORO(IC)/(TIPSPD**2*DIA**2*364.76)
       CALL PERFM(1,CP,ZJI,AFT,BLADT,CT,ZMS,7710)
   451 CP=CPSTL/AFCPE
       CTSTL=CTSTL/AFCTE
       BHP(IC)=CP*2.0*TIPSPD**3*DIA**2/(10.E10*RORO(IC))*6966.
       IF (ABS(CT -CTSTL).LE..005*CT) GO TO 713
       TIPSPD= SQRT(THRUST(IC)*1.515E06*RORO(IC)/(DIA**2*364.76*CTSTL))
   709 IF (NTS.NE.ITS) GO TO 600
       WRITE (6,598) CPE,CPSTL,CTE,CTSTL
   598 FORMAT ( ' FAILED STALL ITERATION     CPE    CPSTL      CTE    CTSTL'
      1 /  .    '                            ',  4F8.4)
   713 IFIN=7710
       GO TO 720
C    END OF TIPSPD ITERATION 50 PERCENT STALL
C      CALCULATION OF REQUIRED CP OR CT
```

FIGURE 6D. LISTING OF ADVANCED GENERAL AVIATION PROPELLER PROGRAM (PAGE 3 OF 14)

```
399 IF(IW-1)400,400,430
400 CP=BHP(IC)*10.E10*RORO(IC)/(2.0*TIPSPD**3*DIA**2*6966.)
    CALL             PERFM (1,CP,ZJI,AFT,BLADT,CT,ZMS,LIMIT)
420 THRUST(IC)=CT*TIPSPD**2*DIA**2/(1.515E06*RORO(IC))*364.76
    IF(CTAST.NE.BLANK) THRUST(IC)=99999999999999.
    GO TO 460
430 CT=THRUST(IC)*1.515E06*RORO(IC)/(TIPSPD**2*DIA**2*364.76)
    CALL             PERFM (2,CP,ZJI,AFT,BLADT,CT,ZMS,LIMIT)
450 BHP(IC)=CP*2.0*TIPSPD**3*DIA**2/(10.E10*RORO(IC))*6966.
    IF(CPAST.NE.BLANK) BHP(IC)=99999999999999.
460 CONTINUE
720 CONTINUE
    PNL=0.0
    ISTALL=0
    IF(DIST(IC).LE.0.) GO TO 461
    CALL ZNOISE (BLADT,DIA,TIPSPD,VKTAS(IC),BHP(IC),DIST(IC),PNL,
   1FC(IC),XNOE)
    CALL CPCTAL (ISTALL,ZJI,BLADT,CPSTL,CTSTL)
    IF(ISTALL.EQ. 2) PNL=99999999.
461 CONTINUE
    WT70=99999.
    WT80=99999.
    COST70(1)=99999.
    COST80(1)=99999.
    IF (NCOST-1) 730,725,730
725  IF(NCOST.EQ.1)CALL WAIT(WTCON,ZMWT,BHP(IC),DIA,AFT,BLADT,TIPSPD,
   1WT70,WT80)
    IENT=2
    CALL COST (WTCON,BLADT,CLF1,CLF,CK70,CK80,CAMT,DAMT,NAMT,CQUAN(1,1
   1),WT70,WT80,COST70,COST80,CCLF1,CCLF,CCK70,CCK80,IENT)
    GO TO (570,580),IW
570 WRITE (6,575)DIA,TIPSPD,THRUST(IC),PNL,CQUAN(1,1),WT70,COST70(1),
   1CQUAN(2,1),WT80,COST80(1),BLLLL,XFT,ZMS,ZJI,CP,CT
575 FORMAT(2F7.0,F9.0,F6.0,2F8.0,F9.0,2F8.0,F9.0,F9.1,F6.3,F7.4,F8.3,
   12F8.4)
    GO TO 585
580 WRITE (6,575) DIA,TIPSPD,BHP(IC),PNL,CQUAN(1,1),WT70,COST70(1),
   1CQUAN(2,1),WT80,COST80(1),BLLLL,XFT,ZMS,ZJI,CP,CT
585 IF(NAMT-1) 40,40,586
586 DO 588 I=2,NAMT
    WRITE(6,587) CQUAN(1,I),WT70,COST70(I),CQUAN(2,I),WT80,COST80(I)
587 FORMAT (29X,2F8.0,F9.0,2F8.0,F9.0)
588  CONTINUE
    GO TO 40
730  GO TO (31,34),IW
31   WRITE(6,32) DIA,TIPSPD,THRUST(IC),PNL,BLLLL,XFT,ZMS,ZJI,CP,CT
32  FORMAT(F7.2,F7.0,F9.0,F6.0,F6.1,F8.3,F7.4,F8.3,2F8.4)
    GO TO 40
34   WRITE(6,32) DIA,TIPSPD,BHP(IC),PNL,BLLLL,XFT,ZMS,ZJI,CP,CT
40  CONTINUE
    IF(ISTALL.EQ. 2) GO TO 800
    IF(IFIN.EQ.7710) GO TO 800
600 CONTINUE
800 CONTINUE
1000 CONTINUE
1200 CONTINUE
700 CONTINUE
    GO TO 701
    END
'IP FOR COST
```

FIGURE 6D. LISTING OF ADVANCED GENERAL AVIATION PROPELLER PROGRAM (PAGE 4 OF 14)

```
      SUBROUTINE COST (WTCON,BLADT,CLF1,CLF,CK70,CK80,CAMT,DAMT,NAMT,
     1CQUAN      ,WT70,WT80,COST70,COST80,CCLF1,CCLF,CCK70,CCK80,IENT)
      DIMENSION CQUAN(2,11),COST70(10),COST80(10),ZFFAC(2,5),ZQUAN(2,5),
     1ZEFAC(5)
      DATA (ZFFAC(1,I),I=1,5)/3.5,3.7,3.2,2.6,2.0/
      DATA (ZFFAC(2,I),I=1,5)/3.5,3.7,3.2,3.5,3.4/
      DATA (ZEFAC(I),I=1,5)/1.0,1.5,3.5,3.5,3.5/
      DATA (ZQUAN(1,I),I=1,5)/1910.,2810.,1030.,295.,65./
      DATA (ZQUAN(2,I),I=1,5)/2230.,5470.,1990.,680.,368./
      ICON=WTCON +.01
      GO TO (5,100),IENT
    5 IF(CLF1)10,10,20
   10 CCLF1=3.2178
      CCLF=1.02
      GO TO 1000
   20 CCLF1=CLF1
      CCLF=CLF
      GO TO 1000
  100 IF(CK70)40,40,50
   40 CCK70=ZFFAC(1,ICON)*(3.0*BLADT**.75+ZEFAC(ICON))
      GO TO 60
   50 CCK70=CK70
   60 IF(CK80)70,70,90
   70 CCK80=ZFFAC(2,ICON)*(3.0*BLADT**.75+ZEFAC(ICON))
      GO TO 110
   90 CCK80=CK80
  110 IF(CAMT)120,120,130
  120 CQUAN(1,1)=ZQUAN(1,ICON)
      CQUAN(2,1)=ZQUAN(2,ICON)
      GO TO 140
  130 CQUAN(1,1)=CAMT
      CQUAN(2,1)=CAMT
  140 XLN=(ALOG(CCLF)-ALOG(CCLF1))/6.90775527
      DO 200 I=1,NAMT
      COST70(I)=CCK70*EXP(ALOG(CQUAN(1,I))*XLN+ALOG(CCLF1))*WT70/CCLF1
      COST80(I)=CCK80*EXP(ALOG(CQUAN(2,I))*XLN+ALOG(CCLF1))*WT80/CCLF1
      CQUAN (1,I+1)=CQUAN (1,I)+DAMT
      CQUAN (2,I+1)=CQUAN (2,I)+DAMT
  200 CONTINUE
 1000 RETURN
      END
'IP FOR WAIT
      SUBROUTINE WAIT (WTCON,ZMWT,BHP,DIA,AFT,BLADT,TIPSPD,WT70,WT80)
      IF(WTCON.LE.0.) RETURN
      ZND=TIPSPD*60./3.14159
      ZN=ZND/DIA
      ZK2=(DIA/10.)**2
      ZK3=(BLADT/4.)**.7
      ZK4=(AFT/100.)**.75
      ZK5=(ZND/20000.)**.5
      ZK6=(BHP/10./DIA**2)**.12
      ZK7=(ZMWT+1.0)**.5
      WTFAC=ZK2*ZK3*ZK4*ZK5*ZK6*ZK7
C     WTCON DEFINES AIRPLANE CATEGORY
      IWTCON=WTCON
      ZC=2.5*BHP/ZN*ZMWT/DIA*AFT*BLADT
      GO TO (10,20,30,40,50),IWTCON
   10 WT70=170.*WTFAC
      WT80=WT70
      GO TO 60
```

FIGURE 6D. LISTING OF ADVANCED GENERAL AVIATION PROPELLER PROGRAM (PAGE 5 OF 14)

```
   20 WT70=180.*WTFAC
      WT80=WT70
      GO TO 60
   30 WT70=240.*WTFAC+ZC
      WT80=WT70
      GO TO 60
   40 WT70=240.*WTFAC+ZC
      WT80=210.*WTFAC+ZC
      GO TO 60
   50 WT70=240.*WTFAC+ZC
      WT80=195.*WTFAC
   60 RETURN
      END
'IP FOR INPUT
      SUBROUTINE INPUT
      DIMENSION DIST(10)
      DIMENSION  TITLE(14)
      COMMON /ZINPUT/ BHP(10),THRUST(10),ALT(10),VKTAS(10),T(10),TS(10)
     1,IWIC(10),NOF,D,DD,ND,AF,DAF,NAF,BLADN,DBLAD,NBL,DTS(10),NDTS(10)
     2,DIST,XNOE,WTCON,ZMWT,STALIT(10),CLF1,CLF,CK70,CK80,CAMT,DAMT,NAMT
     3,DCOST(10)
      DO 3 I=1,2
      READ (5,1) TITLE
    1 FORMAT (13A6,A2)
      WRITE(6,2) TITLE
    2 FORMAT ('0',13A6,A2)
    3 CONTINUE
      READ (5,4) IDUM,XNOE,WTCON,ZMWT,CLF1,CLF,CK70,CK80,CAMT,DAMT,CNAMT
      READ (5,4) NOF,D,DD,ZND,AF,DAF,ZAF,BLADN,DBLAD,ZNBL
    4 FORMAT(3XI3,12F6.1)
      ND = ZND+.01
      NAF= ZAF+.01
      NBL= ZNBL+.01
      NAMT=CNAMT+.01
      DO 6  IC=1,NOF
      READ(5,4) IWIC(IC),BHP(IC),ALT(IC),VKTAS(IC),T(IC), TS(IC),
     1DTS(IC),ZNDTS,DIST(IC),STALIT(IC),DCOST(IC)
      NDTS(IC)= ZNDTS
      IF(IWIC(IC).EQ.1) GO TO 5
      THRUST(IC)= BHP(IC)
      BHP(IC)= 0.0
    5 CONTINUE
    6 CONTINUE
      RETURN
      END
'IP FOR ZNOISE
      SUBROUTINE ZNOISE (BLADT,DIA,TIPSPD,VKTAS     ,BHP     ,DIST    ,SPL,
     1FC     ,XNOE)
      DIMENSION                    PNLA(20),PNLB(10),PNLC(13,7,4),DIAM(20),
     1BBL(4),TMTH(20)
      DATA (TMTH(I),I=1,13)/.3,.35,.4,.45,.5,.55,.6,.65,.7,.75,.8,.85,.9
     X/
      DATA (PNLC(I,1,1),I=1,13)/-2.5,-1.8,-1.0,.0,.8,1.4,1.8,2.0,2.25,
     X2.75,3.5,4.3,5.3/
      DATA (PNLC(I,2,1),I=1,13)/-5.5,-4.5,-3.3,-2.0,-.9,-.2,.0,.3,.75,
     X1.3,2.1,3.0,4.0/
      DATA (PNLC(I,3,1),I=1,13)/-6.5,-6.1,-5.6,-4.99,-3.8,-2.6,-1.6,-1.,
     X-.75,-.4,.4,1.6,3.1/
      DATA (PNLC(I,4,1),I=1,13)/-7.5,-7.25,-7.,-6.9,-6.8,-6.3,-5.0,-2.9,
     X-1.9,-1.4,-.6,.4,2.1/
```

FIGURE 6D. LISTING OF ADVANCED GENERAL AVIATION PROPELLER PROGRAM (PAGE 6 OF 14)

```
      DATA (PNLC(I,5,1),I=1,13)/-9.4,-9.75,-9.9,-9.9,-9.75,-9.3,-8.5,
     X-7.4,-6.3,-5.0,-3.5,-1.5,.9/
      DATA (PNLC(I,6,1),I=1,13)/-10.6,-10.8,-10.9,-10.9,-10.6,-10.3,-9.6
     X,-8.6,-7.5,-6.2,-4.6,-2.8,-.8/
      DATA (PNLC(I,7,1),I=1,13)/-11.4,-11.6,-11.7,-11.7,-11.5,-11.2,
     X-10.4,-9.4,-8.3,-7.0,-5.4,-3.6,-1.6/
      DATA (PNLC(I,1,2),I=1,13)/-.25,.70,1.7,2.45,3.0,3.3,3.3,3.5,3.7,
     X4.1,4.6,5.3,6.7/
      DATA (PNLC(I,2,2),I=1,13)/-1.3,-.6,.2,.8,1.4,1.7,2.4,3.0,3.4,3.4,
     X3.5,4.3,6.0/
      DATA (PNLC(I,3,2),I=1,13)/-3.6,-3.0,-2.1,-1.2,-.3,.4,.95,1.3,1.5,
     X1.9,2.4,3.7,5.0/
      DATA (PNLC(I,4,2),I=1,13)/-5.7,-4.8,-3.8,-2.7,-1.7,-.8,-.2,.0,.1,
     X.3,.8,1.7,2.6/
      DATA (PNLC(I,5,2),I=1,13)/-6.5,-6.0,-5.4,-4.8,-4.3,-3.6,-3.1,-2.5,
     X-1.8,-1.0,-.1,1.1,2.6/
      DATA (PNLC(I,6,2),I=1,13)/-7.6,-7.4,-7.3,-7.2,-6.9,-6.6,-6.1,-5.4,
     X-4.5,-3.3,-2.0,-.4,1.3/
      DATA (PNLC(I,7,2),I=1,13)/-9.7,-9.7,-9.7,-9.5,-9.4,-9.0,-8.5,-7.8,
     X-6.9,-5.9,-4.6,-2.9,-.8/
      DATA (PNLC(I,1,3),I=1,13)/2.1,2.8,3.4,3.7,4.1,4.4,4.6,4.75,5.0,
     X5.3,5.8,6.5,7.3/
      DATA (PNLC(I,2,3),I=1,13)/.2,1.0,2.0,2.7,3.4,3.5,3.5,3.6,3.8,4.2,
     X4.7,5.5,6.9/
      DATA (PNLC(I,3,3),I=1,13)/-1.2,-.7,.1, .75,1.4,1.8,2.3,2.5,2.6,
     X3.0,3.5,4.5,6.4/
      DATA (PNLC(I,4,3),I=1,13)/-2.8,-2.2,-1.6,-1.0,-.5,.0,.4,.7,1.1,
     X1.7,2.4,3.7,4.8/
      DATA (PNLC(I,5,3),I=1,13)/-4.7,-3.9,-3.2,-2.5,-1.8,-1.3,-.7,-.5,
     X-.2,.3,1.0,2.0,3.6/
      DATA (PNLC(I,6,3),I=1,13)/-6.5,-6.1,-5.5,-4.9,-4.2,-3.7,-3.1,-2.5,
     X-1.9,-1.3,-.5,.7,2.5/
      DATA (PNLC(I,7,3),I=1,13)/-8.3,-7.7,-7.3,-6.8,-6.3,-5.7,-5.1,-4.5,
     X-3.8,-3.0,-2.0,-.7,1.3/
      DATA (PNLC(I,1,4),I=1,13)/4.0,4.3,4.7,5.4,5.9,6.3,6.3,6.3,6.4,6.6,
     X7.0,7.6,9.0/
      DATA (PNLC(I,2,4),I=1,13)/3.2,3.3,3.5,3.6,4.0,4.5,5.1,5.7,6.0,6.0,
     X6.1,6.6,7.6/
      DATA(PNLC(I,3,4),I=1,13)/2.1,2.4,2.7,3.0,3.3,3.7,3.9,4.0,4.2,4.5,
     X4.8,5.4,6.3/
      DATA (PNLC(I,4,4),I=1,13)/1.3,1.6,1.8,2.1,2.3,2.5,2.7,3.0,3.3,3.6,
     X4.1,4.7,5.6/
      DATA (PNLC(I,5,4),I=1,13)/.25,.5,.75,1.0,1.3,1.5,1.8,2.1,2.4,2.8,
     X3.4,4.2,5.4/
      DATA (PNLC(I,6,4),I=1,13)/-2.3,-1.8,-1.3,-.8,-.5,-.1,.3,.5,.8,1.2,
     X1.8,2.5,3.6/
      DATA (PNLC(I,7,4),I=1,13)/-5.0,-4.5,-3.7,-2.8,-2.3,-1.8,-1.4,-1.0,
     X-.7,-.2,.5,1.3,2.5/
      DATA (DIAM(I),I=1,7)/5.0,6.5,8.5,11.,14.5,18.,25./
      DATA  BBL /2.,3.,4.,6./
      TMT= SQRT(TIPSPD**2+(VKTAS    /.5925)**2)/1120.*FC
      NBB=1
      IB=BLADT-1.0+.001
      GO TO (2,2,2,5,6,6,6),IB
    2 KK=IB
      GO TO 7
    5 NBB=4
      KK=1
      GO TO 7
    6 KK=4
```

FIGURE 6D. LISTING OF ADVANCED GENERAL AVIATION PROPELLER PROGRAM (PAGE 7 OF 14)

```
      NBB=4
    7 CONTINUE
      DO 8 K=KK,NBB
      DO 9  I=1,7
    9 CALL UNINT (13,TMTH(1),PNLC(1,I,K),TMT, PNLA(I)   ,LIMIT)
    8 CALL UNINT ( 7,DIAM(1),PNLA(1),DIA, PNLB(K),LIMIT )
      PNLD = PNLB(KK)
      IF (IB.EQ.5) CALL UNINT(4,BBL(1),PNLB(1),BLADT,PNLD,LIMIT)
      RMT = TIPSPD/1120.
      SPL = 1(7.7+ 6.69*ALOG(BHP     )-4.34*ALOG(BLADT**2*DIA**2*DIST**2/
     XXNOE) + 38.1* RMT + PNLD
      IF(LIMIT.NE.0) SPL=999999.
      RETURN
      END
*IP  FOR CPCTAL
      SUBROUTINE CPCTAL (ISTALL,ZJI,BLADT,CPSTL,CTSTL)
      COMMON/CPECTE/CPE,CTE
      DIMENSION CTSTAL(16,4),CTSLL(4)
      DIMENSION CPSTAL(16,4),ZJSTAL(16),CPSLL(4),B(4)
      DATA (CTSTAL(I,1),I=1,9)/.125,.151,.172,.187,.204,.218,.233,.243,
     1.249/
      DATA (CTSTAL(I,2),I=1,9)/.268,.309,.343,.369,.387,.404,.420,.435,
     1.451/
      DATA (CTSTAL(I,3),I=1,9)/.401,.457,.497,.529,.557,.582,.605,.639,
     1.651/
      DATA (CTSTAL(I,4),I=1,9)/.496,.577,.628,.665,.695,.720,.742,.764,
     1.785/
      DATA(CPSTAL(I,1),I=1,9)/.05,.12,.22,.35,.49,.65,.82,1.01,1.19/
      DATA(CPSTAL(I,2),I=1,9)/.16,.29,.49,.75,1.05,1.37,1.74,2.13,2.53/
      DATA(CPSTAL(I,3),I=1,9)/.30,.47,.75,1.1,1.51,1.96,2.41,2.86,3.30/
      DATA(CPSTAL(I,4),I=1,9)/.45,.71,1.03,1.40,1.89,2.45,3.06,3.45,4.1/
      DATA B/2.,4.,6.,8./
      DATA (ZJSTAL(I),I=1,9)/0.,.4,.8,1.2,1.6,2.0,2.4,2.8,3.2/
      ISTALL=0
      IB=BLADT
      IBT=MOD(IB,2)+1
      GO TO (1,2),IBT
    1 KK=IB/2
      NBB=KK
      GO TO 3
    2 KK=1
      NBB=4
    3 DO 4  I=KK,NBB
      CALL UNINT (9,ZJSTAL,CTSTAL(1,  I),ZJI,CTSLL( I),LIMIT )
    4 CALL UNINT(9,ZJSTAL,CPSTAL(1,  I),ZJI,CPSLL( I),LIMIT)
      CPSTL =CPSLL (KK)
      CTSTL =CTSLL (KK)
      CPST=CPSLL(KK)
      IF(NBB-KK) 5,5,6
    6 CALL UNINT(NBB,B,CPSLL,BLADT,CPST,LIMIT)
      CALL UNINT (NBB,B,CTSLL,BLADT,CTST,LIMIT)
      CTSTL = CTST
      CPSTL = CPST
    5 CONTINUE
      CPST=CPST*1.10
      IF(CPE.GT.CPST) ISTALL=2
      RETURN
      END
*IP FOR PERFM
      SUBROUTINE  PERFM (IW,CP,ZJI,AFT,BLADT,CT,ZMS,KIMIT)
```

FIGURE 6D. LISTING OF ADVANCED GENERAL AVIATION PROPELLER PROGRAM (PAGE 8 OF 14)

```
 COMMON/AFCOR/AFCPE,AFCTE,XFT
 COMMON/CPECTE/CPE,CTE,BLLLL
 COMMON/ASTRK/CPAST,CTAST
 DIMENSION  AFVAL(6),AFCPC(6,2),AFCTC(6,2),AFCP(7),AFCT(7),XLB(4),
X          INN(7),ZJJ(7),CTT(7),CPP(7),CTTT(4),CPPP(4),CPANG(10,7,4),
XCTANG(10,7,4),BLDANG(10,7),NJ(7),BLL(7),BLLL(7)
X,ZJCL(8),ZMCRL(8),CPEC(14),BLDCR(14,4),ZMMMC(5),CPEEL(15),
XZFT(15,5),XFFT(5)
 DATA/ASTERK/6H******/
 DATA (BLDANG (I,1),I=1,10)/0.,2.,4.,6.,10.,14.,18.,22.,26.,30./
 DATA (BLDANG (I,2),I=1,6)/10.,15.,20.,25.,30.,35./
 DATA (BLDANG (I,3),I=1,8)/10.,15.,20.,25.,30.,35.,40.,45./
 DATA (BLDANG (I,4),I=1,8)/20.,25.,30.,35.,40.,45.,50.,55./
 DATA (BLDANG (I,5),I=1,7)/30.,35.,40.,45.,50.,55.,60./
 DATA (BLDANG (I,6),I=1,10)/45.,47.5,50.,52.5,55.,57.5,60.,62.5,65.
X,67.5/
 DATA (BLDANG (I,7),I=1,6)/57.5,60.,62.5,65.,67.5,70./
 DATA (CPANG  (I,1,1),I=1,10)/.0165,.0165,.0188,.0230,.0369,.0588,
X.0914,.1340,.1816,.2273/
 DATA (CPANG  (I,2,1),I=1,6)/.0215,.0459,.0829,.1305,.1906,.2554/
 DATA (CPANG  (I,3,1),I=1,8)/-.0149,-.0088,.0173,.0744,.1414,.2177,
X.3011,.3803/
 DATA (CPANG (I,4,1),I=1,8)/-.0670,-.0385,.0285,.1304,.2376,.3536,
X.4624,.5535/
 DATA (CPANG  (I,5,1),I=1,7)/-.1150,-.0281,.1086,.2646,.4213,.5860,
X.7091/
 DATA (CPANG  (I,6,1),I=1,10)/-.1151,.0070,.1436,.2910,.4345,.5744,
X.7142,.8506,.9870,1.1175/
 DATA(CPANG(I,7,1),I=1,6)/-.2427,.0782,.4242,.7770,1.1164,1.4443/
 DATA (CPANG  (I,1,2),I=1,10)/.0311,.0320,.0360,.0434,.0691,.1074,
X.1560,.2249,.3108,.4026/
 DATA (CPANG  (I,2,2),I=1,6)/.0380,.0800,.1494,.2364,.3486,.4760/
 DATA (CPANG  (I,3,2),I=1,8)/-.0228,-.0109,.0324,.1326,.2578,.399,
X.5664,.7227/
 DATA (CPANG (I,4,2),I=1,8)/-.1252,-.0661,.0535,.2388,.4396,.6554,
X.8916,1.0753/
 DATA (CPANG  (I,5,2),I=1,7)/-.2113,-.0480,.1993,.4901,.7884,1.099,
X1.3707/
 DATA (CPANG  (I,6,2),I=1,10)/-.2077,.0153,.2657,.5387,.8107,1.075,
X1.3418,1.5989,1.8697,2.1238/
 DATA (CPANG  (I,7,2),I=1,6)/-.4508,.1426,.7858,1.448,2.0899,2.713/
 DATA (CPANG  (I,1,3),I=1,10)/.0450,.0461,.0511,.0602,.0943,.1475,
X.2138,.2969,.4015,.5237/
 DATA (CPANG  (I,2,3),I=1,6)/.0520,.1065,.2019,.3230,.4774,.5607/
 DATA (CPANG  (I,3,3),I=1,8)/-.0168,-.0085,.0457,.1774,.3520,.5506,
X.7833,1.0236/
 DATA (CPANG (I,4,3),I=1,8)/-.1678,-.0840,.0752,.3262,.6085,.9127,
X1.2449,1.5430/
 DATA (CPANG  (I,5,3),I=1,7)/-.2903,-.0603,.2746,.6803,1.0989,
X1.5353,1.9747/
 DATA (CPANG  (I,6,3),I=1,10)/-.2783,.0259,.3665,.7413,1.1215,
X1.4923,1.8655,2.2375,2.6058,2.9831/
 DATA (CPANG  (I,7,3),I=1,6)/-.6181,.1946,1.0758,1.9951,2.8977,
X3.7748/
 DATA (CPANG  (I,1,4),I=1,10)/.0577,.0591,.0648,.0751,.1141,.1783,
X.2599,.3551,.4682,.5952/
 DATA (CPANG  (I,2,4),I=1,6)/.0650,.1277,.2441,.3947,.5803,.8063/
 DATA (CPANG  (I,3,4),I=1,8)/-.0079,-.0025,.0595,.2134,.4266,.6708,
X.9519,1.2706/
 DATA (CPANG (I,4,4),I=1,8)/-.1894,-.0908,.0956,.3942,.7416,1.1207,
```

FIGURE 6D. LISTING OF ADVANCED GENERAL AVIATION PROPELLER PROGRAM (PAGE 9 OF 14)

```
X1.5308,1.9459/
 DATA (CPANG   (I,5,4),I=1,7)/-.3390,-.0632,.3350,.8315,1.3494,
X1.890,2.4565/
 DATA (CPANG   (I,6,4),I=1,10)/-.3267,.0404,.4520,.9088,1.3783,
X1.8424,2.306,2.7782,3.2292,3.7058/
 DATA (CPANG   (I,7,4),I=1,6)/-.7508,.2395,1.315,2.4469,3.5711,
X4.6638/
 DATA (CTANG   (I,1,1),I=1,10)/.0303,.0444,.0586,.0743,.1065,.1369,
X.1608,.1767,.1848,.1856/
 DATA (CTANG   (I,2,1),I=1,6)/.0205,.0691,.1141,.1529,.1765,.1780/
 DATA (CTANG   (I,3,1),I=1,8)/-.0976,-.0566,.0055,.0645,.1156,.1589,
X.1864,.1841/
 DATA (CTANG (I,4,1),I=1,8)/-.1133,-.0624,.0111,.0772,.1329,.1776,
X.202,.1881/
 DATA (CTANG   (I,5,1),I=1,7)/-.1132,-.0356,.0479,.1161,.1711,.2111,
X.2061/
 DATA (CTANG   (I,6,1),I=1,10)/-.0776,-.0159,.0391,.0868,.1279,.1646
X,.1964,.2213,.2414,.2505/
 DATA (CTANG   (I,7,1),I=1,6)/-.1228,-.0221,.0633,.1309,.1858,.2314/
 DATA (CTANG   (I,1,2),I=1,10)/.0426,.0633,.0853,.1101,.1649,.2204,
X.2678,.3071,.3318,.3416/
 DATA (CTANG   (I,2,2),I=1,6)/.0318,.1116,.1909,.2650,.3241,.3423/
 DATA (CTANG   (I,3,2),I=1,8)/-.1761,-.0960,.0083,.1114,.2032,.2834,
X.3487,.3596/
 DATA (CTANG (I,4,2),I=1,8)/-.2155,-.1129,.0188,.1385,.2401,.3231,
X.3850,.3690/
 DATA (CTANG   (I,5,2),I=1,7)/-.2137,-.0657,.0859,.2108,.3141,.3894,
X.4095/
 DATA (CTANG (I,6,2),I=1,10)/-.1447,-.0314,.0698,.1577,.2342,.3013,
X.3611,.4067,.4457,.4681/
 DATA (CTANG (I,7,2),I=1,6)/-.2338,-.0471,.1108,.2357,.3357,.4174/
 DATA (CTANG (I,1,3),I=1,10)/.0488,.0732,.0999,.1301,.2005,.2731,
X.3398,.3982,.4427,.4648/
 DATA (CTANG (I,2,3),I=1,6)/.0375,.1393,.2448,.3457,.4356,.4931/
 DATA (CTANG (I,3,3),I=1,8)/-.2295,-.1240,.0087,.1443,.2687,.3808,
X.4739,.5256/
 DATA (CTANG (I,4,3),I=1,8)/-.2999,-.1527,.0235,.1853,.3246,.4410,
X.5290,.5467/
 DATA (CTANG (I,5,3),I=1,7)/-.3019,-.0907,.1154,.2871,.429,.5338,
X.5954/
 DATA (CTANG (I,6,3),I=1,10)/-.2012,-.0461,.0922,.2125,.3174,.4083,
X.4891,.5549,.6043,.6415/
 DATA (CTANG (I,7,3),I=1,6)/-.3307,-.0749,.1411,.3118,.4466,.5548/
 DATA (CTANG (I,1,4),I=1,10)/.0534,.0795,.1084,.1421,.2221,.3054,
X.3831,.4508,.5035,.5392/
 DATA (CTANG (I,2,4),I=1,6)/.0423,.1588,.2841,.4056,.5157,.6042/
 DATA (CTANG (I,3,4),I=1,8)/-.2606,-.1416,.0097,.1685,.3172,.4526,
X.5655,.6536/
 DATA (CTANG (I,4,4),I=1,8)/-.3615,-.1804,.0267,.2193,.3870,.5312,
X.6410,.7032/
 DATA (CTANG (I,5,4),I=1,7)/-.3674,-.1096,.1369,.3447,.5165,.6454,
X.7308/
 DATA (CTANG (I,6,4),I=1,10)/-.2473,-.0594,.1086,.2552,.3830,.4933,
X.5899,.6722,.7302,.7761/
 DATA (CTANG (I,7,4),I=1,6)/-.4165,-.1040,.1597,.3671,.5289,.6556/
 DATA (AFVAL(I),I=1,6)/80.,100.,125.,150.,175.,200./
 DATA (AFCPC(I,1),I=1,6)/1.67,1.37,1.165,1.0,.881,.81/
 DATA (AFCPC(I,2),I=1,6)/1.55,1.33,1.149,1.,.890,.82/
 DATA (AFCTC(I,1),I=1,6)/1.39,1.27,1.123,1.0,.915,.865/
 DATA (AFCTC(I,2),I=1,6)/1.46,1.29,1.143,1.0,.890,.84/
```

FIGURE 6D. LISTING OF ADVANCED GENERAL AVIATION PROPELLER PROGRAM (PAGE 10 OF 14)

```
      DATA(XLB(I),I=1,4)/2.,4.,6.,8./
      DATA(ZJJ(I),I=1,7)/0.,.5,1.,1.5,2.,3.,5./
      DATA(INN(I),I=1,7)/10,6,8,8,7,10,6/
      DATA (NJ(I),I=1,7)/1,2,3,4,5,6,7/
      DATA (ZJCL(I),I=1,8)/.0,.5,1.,1.5,2.,2.5,3.,3.5/
      DATA (ZMCRL(I),I=1,8)/.0,.132,.261,.371,.461,.526,.571,.599/
      DATA (CPEC(I),I=1,14)/.01,.02,.03,.04,.05,.06,.08,.10,.15,.20,.25,
     1.30,.35,.40/
      DATA (BLDCR(I,1),I=1,14)/1.84,1.775,1.75,1.74,1.76,1.78,1.80,1.81,
     11.835,1.85,1.865,1.875,1.88,1.88/
      DATA (BLDCR(I,2),I=1,14)/1.,1.,1.,1.,1.,1.,1.,1.,1.,1.,1.,1.,1.,1.
     1/
      DATA (BLDCR(I,3),I=1,14)/.585,.635,.675,.710,.738,.745,.758,.755,
     1.705,.735,.710,.725,.725,.725/
      DATA (BLDCR(I,4),I=1,14)/.415,.460,.505,.535,.560,.575,.600,.610,
     1.630,.630,.610,.605,.600,.600/
      DATA (CPEEL(I),I=1,15)/.01,.02,.03,.04,.05,.06,.08,.10,.15,.20,.3,
     1.4,.5,.6,.7/
      DATA (ZMMMC(I),I=1,5)/.0,.02,.04,.06,.08/
      DATA (ZFT(I,1),I=1,15)/1.,1.,1.,1.,1.,1.,1.,1.,1.,1.,1.,1.,1.,1.,
     X1./
      DATA (ZFT(I,2),I=1,15)/.95,.975,.984,.987,.99,.991,.992,.993,.994,
     1.995,.997,.999,1.,1.,1./
      DATA (ZFT(I,3),I=1,15)/.915,.945,.962,.968,.973,.976,.979,.980,
     1.982,.984,.987,.990,.993,.996,.999/
      DATA (ZFT(I,4),I=1,15)/.869,.902,.924,.937,.945,.950,.955,.960,
     1.966,.971,.977,.983,.986,.989,.991/
      DATA (ZFT(I,5),I=1,15)/.775,.820,.854,.878,.898,.912,.929,.937,
     1.946,.953,.963,.971,.978,.984,.988/
      KK=1
C     AN ADJUSTMENT FOR CP AND CT FOR AF
      DO 120 K=1,2
      CALL UNINT (6,AFVAL(1),AFCPC(1,K),AFT,AFCP(K),LIMIT)
      CALL UNINT (6,AFVAL(1),AFCTC(1,K),AFT,AFCT(K),LIMIT)
  120 CONTINUE
      DO 100  K=3,7
      AFCP(K)=AFCP(2)
  100 AFCT(K)=AFCT(2)
      CALL UNINT(7,ZJJ,AFCP,ZJI,AFCPE,LIMIT)
      CALL UNINT(7,ZJJ,AFCT,ZJI,AFCTE,LIMIT)
      IF(KIMIT.EQ.7710) GO TO 600
      ILIM=0
      ITEST=0
  119 CONTINUE
      NB= BLADT+.1
      LMOD=MOD(NB,2)+1
      GO TO (160,180),LMOD
  160 NBB=1
      L=BLADT/2.+.1
      GO TO 200
  180 NBB=4
      L=1
  200 DO 500 IBB=1,NBB
C     J INTERPOLATION
      DO 300 K=1,7
  208 IF(IW-1) 210,210,250
  210 CPE=CP*AFCP(K)
      CALL UNINT (INN(K),CPANG(1,K,L),CTANG(1,K,L),CPE,CTT(K),LIMIT)
      CALL UNINT (INN(K),CPANG(1,K,L),BLDANG(1,K),CPE,BLL(K),LIMIT)
      IF(LIMIT.EQ.0) GO TO 211
```

FIGURE 6D. LISTING OF ADVANCED GENERAL AVIATION PROPELLER PROGRAM (PAGE 11 OF 14)

```
      ILIM=99
      IF(ITEST.EQ.7710) CTT(K)=99999.
  211 CONTINUE
      CTT(K)=CTT(K)/AFCT(K)
      GO TO 300
  250 CTE=CT*AFCT(K)
      CALL UNINT(INN(K),CTANG(1,K,L),CPANG(1,K,L),CTE,CPP(K),LIMIT)
      CALL UNINT(INN(K),CTANG(1,K,L),BLDANG(1,K),CTE,BLL(K),LIMIT)
      IF(LIMIT.EQ.0) GO TO 251
      ILIM=99
      IF(ITEST.EQ.7710) CPP(K)=99999.
  251 CONTINUE
      CPP(K)=CPP(K)/AFCP(K)
  300 CONTINUE
      CALL UNINT (7,ZJJ(1),BLL(1),ZJI,BLLL(IBB),LIMIT)
      BLLLL=BLLL(IBB)
      IF(IW-1)310,310,350
  310 CALL UNINT (7,ZJJ(1),CTT(1),ZJI,CTTT(IBB),LIMIT)
      CT=CTTT(IBB)
      GO TO 360
  350 CALL UNINT (7,ZJJ(1),CPP(1),ZJI,CPPP(IBB),LIMIT)
      CP=CPPP(IBB)
  360 L=L+1
C     COMPRESSIBILITY CORRECTION
      CALL UNINT (8,ZJCL(1),ZMCRL(1),ZJI,ZMCRT,LIMIT)
      DMN=ZMS-ZMCRT
      IF (DMN) 460,460,410
  410 IF(IW-1)440,420,440
  420 LK=L-1
      CALL UNINT (14,CPEC(1),BLDCR(1,LK),CPE,PBL,IMIT1)
      CPEE=CPE*PBL
      DO 430 IK=1,5
      CALL UNINT (15,CPEEL(1),ZFT(1,IK),CPEE,XFFT(IK),IMIT2)
  430 CONTINUE
      CALL UNINT(5,ZMMMC(1),XFFT(1),DMN,XFT,LIMIT)
      CT=CT*XFT
      GO TO 500
  440 WRITE (6,450)
  450 FORMAT ( ' NO COMPRESSIBILITY ADJUSTMENT FOR THRUST INPUT OPTION
     XAT PRESENT ' )
  460 XFT=1.0
  500 CONTINUE
      IF(NBB-1) 510,590,510
  510 CALL UNINT (4,XLB(1),BLLL(1),BLADT,BLLLL,LIMIT)
      IF(IW-1)520,520,530
  520 CALL UNINT (4,XLB(1),CTTT(1),BLADT,CT,LIMIT)
      GO TO 590
  530 CALL UNINT (4,XLB(1),CPPP(1),BLADT,CP,LIMIT)
  590 CONTINUE
      IF(ILIM.NE.99) GO TO 600
      IF(ITEST.EQ.7710)  GO TO 591
      ITEST=7710
      SAVCP=CP
      SAVCT=CT
      GO TO 119
  591 CONTINUE
      IF(ABS(SAVCP/CP-1.0).LT..001) GO TO 592
      CPAST=ASTERK
  592 IF(ABS(SAVCT/CT-1.0).LT..001) GO TO 593
      CTAST=ASTERK
```

FIGURE 6D. LISTING OF ADVANCED GENERAL AVIATION PROPELLER PROGRAM (PAGE 12 OF 14)

```
593 CONTINUE
    CP=SAVCP
    CT=SAVCT
600 CONTINUE
    CPE=CP*AFCPE
    CTE=CT*AFCTE
    RETURN
    END
*I FOR UNINT
      SUBROUTINE UNINT ( N, XA, YA, X , Y, L)
C
C     THIS ROUTINE INTERPOLATES OVER A 4 POINT INTERVAL USING A
C     VARIATION OF 2ND DEGREE INTERPOLATION TO PRODUCE A CONTINUITY
C     OF SLOPE BETWEEN ADJACENT INTERVALS.
C
      DIMENSION  XA(1), YA(1), D(4), P(5)
      L=0
      I=1
C     TEST FOR OFF LOW END    NO   =   YES
        IF ( XA(1)-X )    100, 150,   10
 10   L=1
        GO TO 150
 100    DO 120 I=2,N
        IF ( XA(I)-X)  120, 150, 200
 120  CONTINUE
C     OFF HIGH END
      I = N
      L= 2
 150  Y= YA(I)
        GO TO 999
C     TEST FOR FIRST INTERVAL
 200    IF(I-2) 240,220,240
C     FIRST INTERVAL
 220  JX1 = 1
      RA = 1.
        GO TO 400
C     TEST FOR LAST INTERVAL
 240    IF(I-N) 300, 250, 300
C     LAST INTERVAL
 250  JX1 = N-3
      RA = 0.
        GO TO 400
 300  JX1 = I-2
      RA = (XA(I)-X) /(XA(I)-XA(I-1) )
 400  RB = 1. - RA
C
C     GET COEFFICIENTS AND RESULTS
      J = JX1
        DO 500 I=1,3
      P(I) = XA(J+1) - XA(J)
      D(I) = X - XA(J)
 500  J = J+1
      D(4) = X - XA(J)
      P(4) = P(1) + P(2)
      P(5) = P(2) + P(3)
C     RESULT
      Y = YA(JX1) * RA/P(1) * D(2)/P(4) * D(3) +
     1  YA(JX1+1) * (-RA/P(1) * D(1)/P(2) * D(3) + RB/P(2) * D(3)/P(5)
     2  *D(4)) + YA(JX1+2) *(RA/P(2) * D(1)/P(4) * D(2) - RB/P(2)
     3  * D(2)/P(3) * D(4)) + YA(JX1+3) * RB/P(5) * D(2)/P(3) * D(3)
```

FIGURE 6D. LISTING OF ADVANCED GENERAL AVIATION PROPELLER PROGRAM (PAGE 13 OF 14)

```
999     RETURN
        END
```

FIGURE 6D. LISTING OF ADVANCED GENERAL AVIATION PROPELLER PROGRAM
(PAGE 14 OF 14)

APPENDIX E

ADVANCED BLADE SHELL MATERIAL SYSTEM CONCEPTS

The current process for fabrication of fiberglass cloth reinforced epoxy resin blade shell cover stock for use in lightweight blade construction consists of the following individual time-consuming steps:

The required glass cloth reinforcement and resin binder are initially combined via a wet layup technique on an airfoil tool mandrel. Final part fabrication is then accomplished via a vacuum pressure bag method. The semi-finished glass/resin composite is then subjected to a post-cure, followed by post-fabrication machining and subsequent preparation for adhesive bonding to the metal structural spar member.

The advantage of this method of blade shell cover stock fabrication is the one-piece airfoil construction which requires adhesive bonding only at the tip and trailing edges to form the final airfoil shape which is accomplished concurrently with bonding the shell to the spar.

When assessed on the basis of cost and technical considerations, the present cover stock fabrication method has the following disadvantages which are directly related to the manual, wet layup aspects of the cover stock material system (#181 glass cloth/ERL-2256-Tonox) used:

1. Cost - Because of the tight weave of #181 style cloth, excessive time and labor are expended in uniformly wetting the fabric with resin.

2. Technical - Because of the individual operator skill factor involved in the wet layup phase, the time required and the resultant glass/resin ratio achieved in final part fabrication varies.

With this in mind, it becomes apparent that significant cost reductions in lightweight propeller blade fabrication can only be realized if changes in shell cover stock preparation can be made. It is believed that segmentation of shell cover stock into two halves is possible, making available a range of material systems which are readily adaptable to automated fabrication methods (fig. 1E). Segmentation of the blade shell into two components immediately suggests that a glass cloth/resin prepreg system could be used with matched die molds to eliminate the manual wet layup process. Table 1D lists several other material systems presently available for use in developing a low-cost blade shell for 1980. These include bulk molding compounds available in sheet form with oriented reinforcement fibers which can be easily compression molded in matched dies. Prepreg and preform systems are also listed as being applicable to shell fabrication.

These systems require development programs to orient the reinforcement fibers in a direction to offer maximum strength in the direction of stresses in the shell.

To further reduce process time and cost, it would be desirable to use stamping processes, similar to sheet metal forming, to fabricate reinforced plastic blade shell components. Allied Chemical Company offers a new thermoset-thermoplastic laminate that can be readily cold formed to deep drawn configurations in a stamping press then subjected to an oven cure to complete the part. 3M Corporation offers a high temperature thermoplastic resin (aromatic polysulfate ester) which can be readily formed at 700°F in seconds in a matched die mold then bonded to the aluminum blade core. These stamp forming materials are relatively new and costly at this time, but by 1980 costs are expected to be reduced to levels that coupled with simple automated forming techniques will result in lowest cost shell components.

Current manufacturing methods for the solid aluminum blade core (chemical-milled forgings) represent the lowest costs for 1980 as well.

TABLE 1E

MATERIAL SYSTEMS AND PROCESSES AVAILABLE FOR 1980 BLADE SHELL FABRICATION

A. Bulk Molding Compounds

(High Pressure Compression Molding Process)

Compound	Source	Reinforcement	Resin
GEMON 3010	General Electric Co.	Chopped glass (3/8" length)	Polyimide
FM 7074	Fiberite Corp.	Chopped glass (3/8" length)	Phenolic
T7-1100	3M	Chopped glass (3/8" length)	Epoxy
T7-XP212	3M	Chopped glass (3/8" length)	Epoxy-Novalac
GEMON DP-3	General Electric Co.	Chopped graphite (Hi-strength, Hi-modulus)	Polyimide
GEMON DP-5	General Electric Co.	Chopped graphite and glass	Polyimide
HYE-5001	Fiberite Corp.	Chopped graphite	Epoxy

B. Prepreged Glass Reinforced Materials

(Vacuum Bag, Autoclave, Compression Molding Processes)

Compound	Source	Reinforcement	Resin
F-150	Cost Mfg. & Supply Co.	Woven glass cloth	Epoxy
GEMON L	General Electric Co.	Woven glass cloth	Polyimide
Scotch Ply 1002	3M	Non-woven glass cloth	Epoxy
GEMON L	General Electric Co.	Woven hi-strength, hi-modulus graphite cloth	Polyimide

TABLE 1E (CONT)

C. Preform Glass Reinforced Plastics

(Low Pressure Compression Molding Process)

Both polyester and epoxy based glass (1 1/2" to 2" length) reinforced preformed plastic components are available at Hamilton Standard (i.e., HS Spec. 798, Type 18)

D. New Materials

1. Thermoset-thermoplastic composite (Allied Chemical Co.). Cold form the composite to the desired shape, followed by curing of the thermoset (glass reinforced epoxy) core material. Cold forming operation similar to metal stamping.

2. Glass cloth reinforced hi-temperature thermoplastic composite (i.e., Polymer 360 from 3M). High pressure, high temperature molding to shape (similar to a metal hot stamping operation). No additional processing required.

MATERIALS	MOLDING PROCESS
GLASS FIBER/EPOXY GLASS FIBER/PHENOLIC GLASS FIBER / HI MOD. GRAPHITE / EPOXY OR PHENOLIC	COMPRESSION INJECTION OR PREFORM MATCH MOLDING
PREPREG GLASS CLOTH	VACUUM BAG MOLD

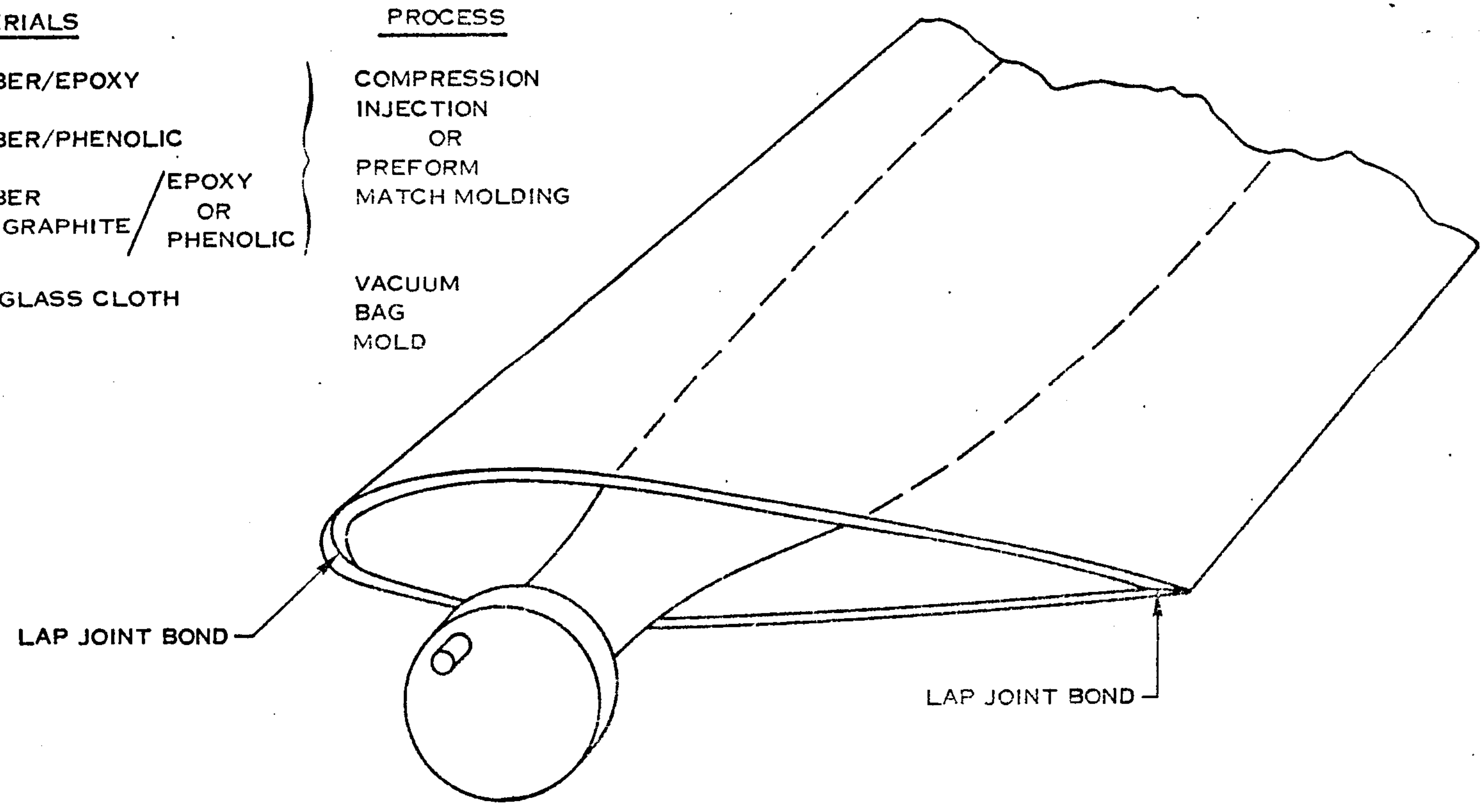


FIGURE 1E. PROPOSED BLADE SHELL SEGMENTATION, MATERIALS AND PROCESSES