CONTRACT REPORT
NASA CR 114399
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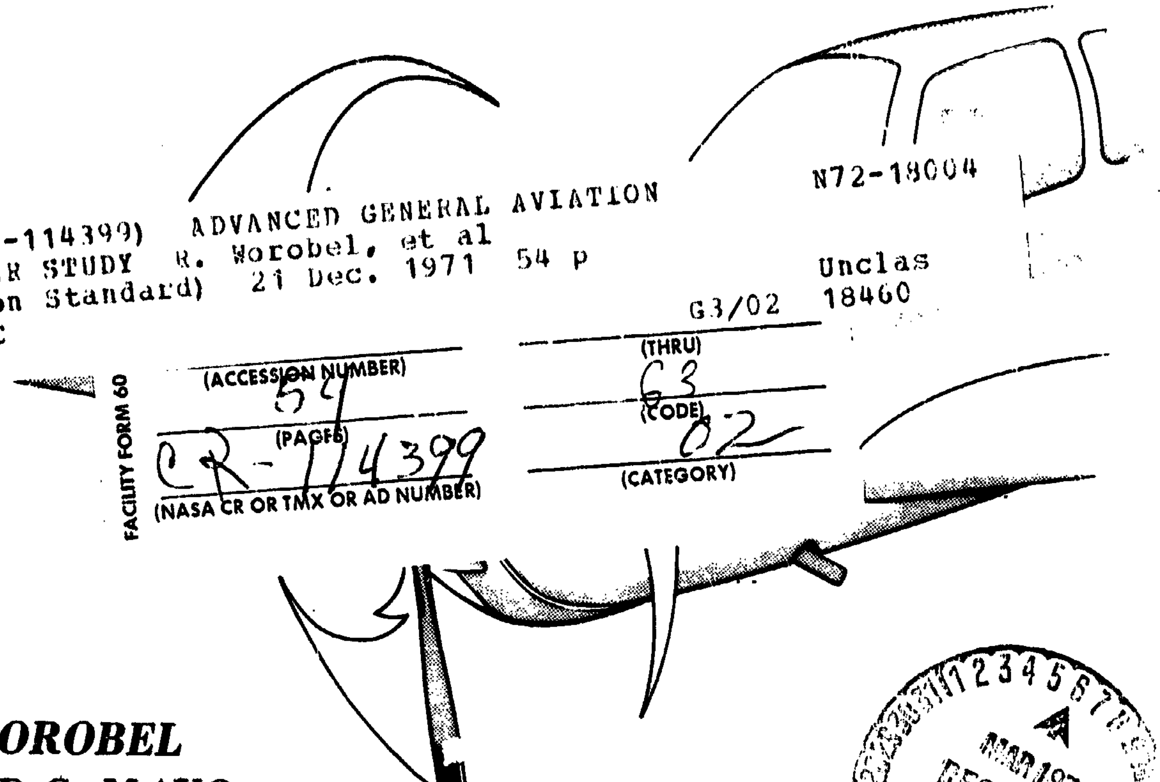
ADVANCED GENERAL AVIATION PROPELLER STUDY



BY
ROSE WOROBEL
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DECEMBER 21,1971

PREPARED UNDER CONTRACT NO. NAS2-6477 BY
HAMILTON STANDARD
DIVISION OF UNITED AIRCRAFT CORPORATION
WINDSOR LOCKS, CONNECTICUT
FOR
ADVANCED CONCEPTS AND MISSIONS DIVISION
OFFICE OF ADVANCED RESEARCH AND TECHNOLOGY
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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ABSTRACT

Under a previous NASA contract and reported in CR-114289 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. Under the present contract this basic program was refined to incorporate a method of including the blade shape parameter, integrated design lift coefficient. This method and a reverse thrust computational procedure were included in the computer program. The weight equation was refined and also incorporated in the computer program. A User's Manual which includes a complete listing of this computer program with detailed instructions on its use has been written and will be published as a NASA low number Contractor Report.

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FIGURES (Continued)

SUMMARY

A major outcome of the study sponsored by the Advanced Concept and mission Division, A.C.M.D. of NASA under Contract No. NAS2-5885 dated 30 January 1970 and reported in CR 114289 has been the development of a computer program for evaluating propeller performance, noise, weight and cost for general aviation aircraft propellers as a function of the prime geometric and aerodynamic variables. This program provides for changes in the activity factor per blade and number of blades, but it was limited to a single value of integrated design lift coefficient. This study, Contract No. NAS2-6477 dated 6 May 1971 and also sponsored by the A.C.M.D., extends this computer program to incorporate the integrated design lift coefficient as a propeller blade shape variable. Additional extensions to the computer program which are documented in this report are the capability of calculating propeller reverse thrust and the refinement of the propeller weight equation. A final requirement of Contract No. NAS2-6477 was to describe the complete computer program. This manual is reported in a separate low number NASA Contractor Report.

In this report the technology is developed for including the capability of varying integrated design lift coefficient. An existing reverse thrust method has been adapted for the general aviation aircraft application. The weights for 36 additional propellers over those used in the original study have been defined analytically and used in refining the weight equation. These technology additions and revisions are incorporated into the computer program.

INTRODUCTION

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

In view of this, a study was undertaken under NASA sponsorship to derive and computerize appropriate propeller performance, noise, weight and cost criteria to permit sensitivity studies of those factors to be made for advance propeller configurations designed for general aviation aircraft of the 1980 time period. The results of this study were presented in Contractor Report NASA CR 114289, "Advanced General Aviation Study" April 1971 (ref. 1). At NASA's request a contract study was undertaken to provide a User's Manual which includes a complete listing of this computer program with detailed instructions on its use. Furthermore the scope of the computer program has been extended to incorporate the following:

1. Method for varying integrated design lift coefficient (the only prime blade shape variable not included in the original program)

2. Method for computing reverse thrust

3. Refinement of the weight equation

Thus a reliable computer program has been developed for predicting propeller performance (static, flight and reverse), noise, weight and cost for the complete general aviation aircraft range.

A detailed discussion of the technology developments and incorporation into the computational procedures of the above extensions to the computer program are discussed in the following text. The User's Manual which includes FORTRAN IV listings and input/output instructions will be published under separate cover as a NASA low number Contractor Report.

SYMBOLS AND ABBREVIATIONS

AF — propeller blade activity factor, $\frac{100,000}{6} \int_{0.15}^{1.0} \left(\frac{b}{D}\right) x^3 \, dx$

b — blade section width, ft

B — number of blades

C_{L_D} — blade section design lift coefficient

C_{L_i} — propeller blade integrated design lift coefficient $4 \int_{0.15}^{1.0} C_{L_D} \, x^3 \, dx$

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

C_Q — torque coefficient for $J \leq 1.0$, $\frac{SHP\,(\rho_o/\rho)\,10^{11}}{4\pi\ N^3D^5}$

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

D — propeller diameter, ft

h — maximum blade section thickness

J — advance ratio, $\frac{101.4\ V_k}{ND}$

M — free stream Mach number

N — propeller speed, rpm

PNL — perceived noise level, PNdB

Q_C	torque coefficient for $J > 1.0$, $\dfrac{SHP(\rho_o/\rho)\ 10^{11}}{4\pi\ N^3D^5} \times \dfrac{1}{J^2}$
R	blade radius at propeller tip, ft
r	radius at blade element, ft
SHP	shaft horsepower
T	propeller thrust, pounds
T_C	thrust coefficient for $J > 1.0$, $\dfrac{1.514 \times 10^6\ T(\rho_o/\rho)}{N^2D^4} \times \dfrac{1}{J^2}$
V_K	freestream velocity, knots
x	fraction of propeller tip radius, r/R
$\beta 3/4$	propeller blade angle at 3/4 radius
ρ	density, lb sec^2/ft^4
ρ_o	density at sea level standard day, 0.002378 lb. sec^2/ft^4
ρ_o/ρ	θ/δ
θ	ratio of absolute temperature to absolute temperature at sea level, T/T_o
δ	ratio of static pressure to static pressure at sea level, P/P_o

TECHNOLOGY DEVELOPMENT

Method for Varying Integrated Design Lift Coefficient

In the original report (ref. 1), a performance method generalization was developed for predicting static and forward flight performance for general aviation aircraft propellers. 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:

$$C_P = \frac{SHP\,(\rho_0/\rho)\,10^{11}}{2N^3D^5}$$

$$C_T = \frac{1.514 \times 10^6 T\,(\rho_0/\rho)}{N^2D^4}$$

$$J = \frac{101.4\ V_K}{ND}$$

where:

SHP - shaft horsepower

ρ_0/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

Base curves were defined in this non-dimensional form presenting the performance of 2, 4, 6 and 8 bladed propellers referenced to an activity factor of 150 and 0.5 integrated design lift coefficient.

In order to minimize the number of curves and consequently the size and complexity of the computer program, the terms effective power coefficient, C_{P_E}, and effective thrust coefficient, C_{T_E} were introduced. The effective power coefficient and thrust coefficient are defined as follows:

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

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

where:

C_P - power coefficient

P_{AF} - activity factor adjustment to power coefficient (ref. 1, fig 3A)

$P_{C_{L_i}}$ - integrated design lift coefficient, C_{L_i} adjustment factor to power coefficient (described in subsequent text)

C_T - thrust coefficient

T_{AF} - activity factor adjustment factor to thrust coefficient (ref. 1, fig. 3A)

$T_{C_{L_i}}$ - integrated design lift coefficient, C_{L_i} adjustment factor to thrust coefficient (described in subsequent text)

In the original report, the base performance curves and the activity factor adjustment factors, P_{AF} and T_{AF} were developed and included in the computer program. Furthermore, a limited amount of work was done to establish the feasibility of generalizing the integrated design lift coefficient effect. Under the present study contract, the integrated design lift coefficient adjustment factor was developed for a range of $0.3 \leq C_{Li} \leq 0.8$. Blade camber distributions for this range of C_{L_i} are shown in figure 1. Thus, the base curves while referenced to a basic activity factor and integrated design lift coefficient, are applicable to the complete range of 2 to 8 blades, 80-200 activity factor and 0.3 to 0.8 integrated design lift coefficient.

Since it has been projected that general aviation aircraft will be operating at significantly higher speeds by the 1980 time period, a compressibility factor, F_t for the base curves of 0.5 integrated design lift coefficient was derived for use with the base plots presented in reference 1. The thrust is multiplied by the F_t to correct for compressibility losses. Under the present contract, the F_t correction was expanded to apply to the complete range of integrated design lift coefficient of 0.3 to 0.8.

The development of the integrated design lift coefficient adjustment factors, $P_{C_{L_i}}$ and $T_{C_{L_i}}$ and the compressibility correction, F_t, as well as their incorporation into the computational procedures are described in the following text

Integrated design lift coefficient adjustment factors - Using the propeller computational procedure based on the work of Goldstein as defined in reference 1, calculations were made for integrated design lift coefficient between 0.3 and 0.8, number of blades ranging from 2 to 8, and activity factor from 80 to 200. These calculations were utilized in deriving the adjustment factors, PCL_i and TCL_i for the power and thrust coefficients respectfully. These adjustment factors are dependent on advance ratio, number of blades, activity factor and integrated design lift coefficient. The detailed step-by-step procedure incorporated in the computer program is presented below for the case where thrust is calculated for a known shaft horsepower.

1. Cp_{E_1} - calculate = $Cp \times P_{AF}$ (P_{AF} - ref. 1, fig. 3A)
2. P_{BL} - read from figure 2 for the Cp_{E_1} of item 1 above and the proper number of blades
3. $PFCL_i$ - read from figure 3 for the appropriate J (revision of fig. 12A in ref. 1)
4. Cp_{E_2} - calculate = $Cp_{E_1} \times P_{BL} \times PFCL_i$
5. PCL_i - read from figure 4 for the Cp_{E_2} of item 4 and the C_{L_i} (expansion of fig. 13A in ref. 1)
6. Cp_E - calculate = $Cp_{E_1} \times PCL_i$

Now, the corresponding blade angle, $\beta 3/4$ and thrust coefficient, C_T are obtained as follows:

7. $\beta 3/4$ - read for Cp_E, J and appropriate number of blades (ref. 1, fig. 4A, 6A, 8A, 10A)
8. C_{T_E} - read for J and $\beta 3/4$ for the proper number of blades (ref. 1, fig. 5A, 7A, 9A, 11A)

The following iteration is required to define the thrust coefficient since $C_T = C_{T_E}/(T_{AF} \times TCL_i)$ and TCL_i is a function of C_T.

9. C_T - assume
10. $C_{T_{E_1}}$ - calculate = $C_T \times T_{AF}$ (TAF ref. 1, fig. 3A)

11. T_{BL} - read from figure 5 for $C_{T_{E_1}}$ and the appropriate number of blades

12. TFC_{L_i} - read from figure 3 for appropriate J (revision of fig. 12A in ref. 1)

13. $C_{T_{E_2}}$ - calculate $= C_{T_{E_1}} \times TFC_{L_i} \times T_{BL}$

14. TC_{L_i} - read from figure 6 for $C_{T_{E_2}}$ and C_{L_i} (expansion of fig. 14A in ref. 1)

15. C_{TE} - calculate $= C_{T_{E_1}} \times TC_{L_i}$

Items 9 through 15 are repeated until the C_{T_E} in item 15 equals the C_{T_E} in item 8. Compute the thrust corresponding to the final assumed C_T of item 9.

A similar procedure has been included in the computerization for the case where shaft horsepower is calculated for a known thrust with the iterative process required to define C_P and subsequently the corresponding SHP.

Compressibility factor. - The compressibility correction included in reference 1 was extended to span the complete integrated design lift coefficient range. The same computations as those used in developing the integrated design lift coefficient adjustment factor were used in developing the compressibility factor. A critical Mach number, M_{CRIT} for each value of advance ratio, J, has been defined as the limiting free stream Mach number at which no compressibility losses are encountered (fig. 7). Similar M_{CRIT} limits for J equals zero are shown on figure 8. If the free stream Mach number exceeds the critical Mach number, the compressibility factor, F_t is obtained (fig. 9). F_t has been derived as a function of C_T instead of C_P as defined originally (ref. 1) since it simplifies the computational procedures when the thrust input option is used. The compressibility factor, F_t is obtained as follows.

1. M - airplane Mach number, compute

$$M = \frac{\pi ND}{67,200} f_c \qquad J = 0$$

$$M = \frac{V_K f_c}{661.2} \qquad J > 0$$

where:

N - propeller rpm

D - propeller diameter, ft.

f_c - ratio of speed of sound at standard day sea level to speed of sound at operating condition

V_K - free stream velocity, knots true airspeed

2. M_{CRIT} - read from figure 7 for $J > 0$ and figure 8 for $J = 0$ for C_{L_i} (expansion of fig. 15A in ref. 1)

3. $\Delta(M-M_{CRIT})$ - calculate where M is the free stream Mach number

4. $C_{T_{E_3}}$ - calculate $= C_T \times T_{AF} \times T_{BL} \times TC_{L_i}$

5. F_t - read from figure 9 for $C_{T_{E_3}}$ and $\Delta(M-M_{CRIT})$

Method for Computing Reverse Thrust

Aircraft incorporating propellers with the reverse thrust feature have the capability to limit the landing ground run to significantly shorter distances than with wheel brakes alone. The propeller normally operates at a fixed reverse blade angle setting throughout the ground run operation and the reverse angle is selected to absorb normal rated power and speed at zero velocity. Occasionally, the reverse blade angle setting is based on a partial throttle setting instead of full throttle. Therefore, the option of computing reverse angle and the corresponding reverse thrust, horsepower and propeller speed for a range of velocities spanning the ground run speeds based on operating at several throttle settings is included in the computer program. With this data (fig. 10), the corresponding landing distances can be computed and accordingly the appropriate reverse angle and power setting can be obtained.

The analytical method for computing reverse thrust is based on an existing Hamilton Standard procedure which was obtained by generalizing all available propeller test data. The shaft horsepower, thrust, propeller rotational speed, velocity and diameter are included in the non-dimensional form of torque coefficient, C_Q or Q_C, thrust coefficient, C_T or T_C, and advance ratio, J defined as follows:

$$J = \frac{101.4\, V_K}{ND}$$

$$C_Q = \frac{SHP\,(\rho_o/\rho)\,10^{11}}{4\pi\, N^3 D^5} \qquad \text{for } J \leq 1.0$$

$$Q_C = \frac{SHP\ (\rho_o/\rho)\ 10^{11}}{4\pi\ N^3 D^5} \times \frac{1}{J^2} \qquad \text{for } J > 1.0$$

$$C_T = \frac{1.514 \times 10^6\ T\ (\rho_o/\rho)}{N^2 D^4} \qquad \text{for } J \leq 1.0$$

$$T_C = \frac{1.514 \times 10^6\ T\ (\rho_o/\rho)}{N^2 D^4} \times \frac{1}{J^2} \qquad \text{for } J > 1.0$$

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

Base curves have been defined in this manner for a 3 bladed, 100 activity factor, 0.4 integrated design lift coefficient propeller. The terms effective torque coefficient, C_{Q_E} or Q_{C_E}, and effective thrust coefficient, C_{T_E} or T_{C_E}, are used. As with the forward flight generalization, these base curves with appropriate adjustments for AF, C_{L_i} and number of blades can be used in predicting reverse thrust characteristics for the family of propellers spanning 2 to 8 number of blades, 80-200 AF, and 0.3 to 0.8 C_{L_i}. The effective torque coefficients and thrust coefficients are defined as follows:

$$C_{Q_E} = \left[C_Q \times (3/B)^{0.83} \times Q_{AF}\right] - \Delta C_{QE2}\ (PCR/100) \qquad \text{for } J \leq 1.0$$

$$Q_{C_E} = \left[Q_C \times (3/B)^{0.83} \times Q_{AF}\right] - \Delta Q_{C_{E2}}\ (PCR/100) \qquad \text{for } J > 1.0$$

$$C_{T_E} = \left[C_T \times (3/B)^{0.83} \times T_{AF}\right] - \Delta C_{T_{E2}}\ (PCR/100) \qquad \text{for } J \leq 1.0$$

$$T_{C_E} = \left[T_C \times (3/B)^{0.83} \times T_{AF}\right] - \Delta T_{C_{E2}}\ (PCR/100) \qquad \text{for } J > 1.0$$

where:

C_Q - torque coefficient for $J \leq 1.0$

$(3/B)^{0.83}$ - number of blades, B,adjustment

Q_{AF} - activity factor adjustment factor to torque (fig. 11)

$\Delta C_{Q_{E2}}$ - integrated design lift coefficient adjustment factor to torque for $J \leq 1.0$ (fig. 12)

PCR - percentage of integrated design lift coefficient adjustment factor to use (fig. 13)

Q_C - torque coefficient for $J \geq 1.0$

The base torque performance curves are shown on figure 14.

$\Delta Q_{C_{E2}}$ - integrated design lift coefficient adjustment factor to torque for $J > 1.0$ (fig. 15)

C_T - thrust coefficient for $J \leq 1.0$

The base thrust performance curve is shown on figure 16.

T_{AF} - activity factor adjustment factor to thrust (fig. 17)

$\Delta C_{T_{E2}}$ - integrated design lift coefficient adjustment factor to thrust for $J \leq 1.0$ (fig. 18)

T_C - thrust coefficient for $J > 1.0$

$\Delta T_{C_{E2}}$ - integrated design lift coefficient adjustment factor to thrust for $J > 1.0$ (fig. 18)

Computational procedure. - Using the method described above, the reverse angle is computed for zero velocity and a SHP and RPM corresponding to a specific throttle setting and the pressure and temperature condition associated with the airport. With the angle so defined, the SHP and RPM and the corresponding reverse thrusts are computed for the range of ground run velocities. It is reasonable to assume that for reciprocating engine installations SHP/N remains constant throughout the complete reverse range and that for power turbine installations, SHP remains constant for the turbine speed range encountered during landing.

For each throttle setting at zero velocity the following calculations are made to compute the corresponding reverse angle.

1. C_Q - calculate for given SHP and RPM
2. Q_{AF} - read from figure 11 for the specified AF and C_{L_i}
3. $(3/B)^{0.83}$ - number of blades, B adjustment, computed
4. $\Delta C_{Q_{E2}}$ - read from figure 12 for $J=0$ and specified C_{L_i}
5. PCR - 100 for $J = 0$
6. C_{Q_E} - calculate $(C_Q \times Q_{AF} \times (3/B)^{0.83}) - \Delta C_{Q_{E2}} \times (PCR/100)$
7. $\beta 3/4$ - read from figure 14 for C_{Q_E} and $J = 0$

For a range of J's the following calculations are made to define the RPM and power relationships over the landing run range.

8. J - advance ratio, assume a range of J's
9. C_{Q_E} or Q_{C_E} - if $J \leq 1.0$, read C_{Q_E} for J (item 8) and reverse $\beta 3/4$ (item 7) and if $J > 1.0$, Q_{C_E} from figure 14
10. $\Delta C_{Q_{E2}}$ or $\Delta Q_{C_{E2}}$ - if $J \leq 1.0$, read $\Delta C_{Q_{E2}}$ from figure 12 or $\Delta Q_{C_{E2}}$ from figure 15 if $J > 1.0$ for C_{L_i} and J
11. PCR - read from figure 13 for $\beta 3/4$ and $J \leq 0.9$; for $J > 0.9$, PCR $= 0$
12. C_Q - calculate where

$$C_Q = \frac{C_{Q_E} + \Delta C_{Q_{E2}} \times (PCR/100)}{Q_{AF} \times (3/B)^{0.83}} \quad \text{for } J \leq 1.0$$

noting that

$$C_Q = Q_C \times J^2$$

$$C_Q = \left(\frac{Q_{C_E} + \Delta Q_{C_{E2}} \times (PCR/100}{Q_{AF} \times (3/B)^{0.83}}\right) \quad \text{for } J > 1.0$$

For turbine engine installations, go to item 15. For aircraft with reciprocating engines, SHP/N remains approximately constant throughout the complete reversing range. Therefore,

13. N - propeller rpm is calculated $= RPM_1 \left(\frac{C_{Q1}}{C_{Q2}}\right)^{1/2}$

where subscription 1 refers to item 1 and subscript 2 to item 12

14. SHP - calculate $= \frac{SHP_1 \times RPM_2}{RPM_1}$

where subscript 1 refers to item 1 and subscript 2 to item 13. Go to item 17.

For aircraft with turbine engines, SHP remains approximately constant and therefore

15. N - propeller rpm is calculated $= RPM_1 \left(\frac{C_{Q1}}{C_{Q2}}\right)^{1/3}$

where the subscript 1 refers to item 1 and subscript 2 refers to item 12

16. SHP - same as used in item 1

The corresponding velocities and reverse thrusts are computed as follows:

17. V_K - forward speed velocity in knots $= \frac{J \times N \times D}{101.4}$

for J (item 8), N (item 13 for reciprocating engine and item 15 for turbine installations), and D is propeller diameter assumed in item 1.

18. C_{T_E} or T_{C_E} - if $J \leq 1.0$, read C_{T_E} for J (item 8) and reverse $\beta 3/4$ (item 7) and for $J > 1.0$, T_{C_E} from figure 16

19. T_{AF} - read from figure 17 for appropriate AF and C_{L_i}

20. $\Delta C_{T_{E2}}$ or $\Delta T_{C_{E2}}$ - if $J \leq 1.0$, read $\Delta C_{T_{E2}}$ and if $J > 1.0$, read $\Delta T_{C_{E2}}$ from figure 18 for C_{L_i}

21. C_T - calculate where

$$C_T = \frac{C_{T_E} + \Delta C_{T_{E2}} \times (PCR/100)}{T_{AF} \times (3/B)^{0.83}} \quad \text{for } J \leq 1.0$$

Noting that $C_T = T_C \times J^2$, then

$$C_T = \left(\frac{T_{C_E} + \Delta T_{C_{E2}} \times (PCR/100)}{T_{AF} \times (3/B)^{0.83}}\right) J^2 \quad \text{for } J \geq 1.0$$

22. Thrust - calculate $= \dfrac{0.661 \times 10^{-6} N^2 D^4 C_T}{\rho_0/\rho}$

Thus, from the computations described above, reverse thrust, propeller speed, the horsepower can be plotted versus ground run velocities for reverse angles corresponding to specific throttle settings similar to the plots on figure 10. Then, utilizing standard methods the corresponding landing runway distances can be computed and the appropriate reverse angle and throttle setting selected.

Refinement of Weight Generalization

The generalized weight equation used in the previous general aviation study (ref. 1) was derived using weights of current high tip speed propellers as a basis. Five classes of aircraft are defined in reference 1, and the propeller categories that correspond to each are as follows: category I - fixed pitch; category II - constant speed; category III - constant speed, full feather, deicing (for light twin engine aircraft); category IV - constant speed, full feather, deicing (for medium twin engine aircraft); category V - constant speed, full feather, deicing, reverse. Comparison of calculated design weights of a low tip speed 1980 technology propeller in each of categories II, IV and V with equation weights revealed sufficient discrepancy to make equation weight suspect over a wide tip speed range. As a result, this study was conducted to refine the generalized weight equation to provide reasonable accuracy for propellers encompassing a wide range of tip speeds.

Design weights were estimated for twelve 1980 technology propellers in each of categories II, IV and V for a total of thirty-six propellers. These propellers were selected to span tipspeed, activity factor and number of blades ranges shown in Table I. Propeller diameter, shaft horsepower and maximum flight Mach number were held constant for each category. Propeller weights were determined by calculating the weight of each sub-assembly using empirical equations and judgement based on experience with existing propeller families. The sub-assemblies included blades, blade retentions, barrel, pitch change dome and mechanism and fluid.

These propeller weights were plotted versus activity factor and tipspeed. The appropriate equation constants were modified to provide correlation of equation weights with the calculated weights within ten percent accuracy. The exponents generalized for the 1980 propellers are also applicable to the 1970 propellers with the difference in technology for the two eras being reflected in the constant. Constants were derived for categories I and III based on actual 1970 propeller weights and the generalizations for the other categories.

The modified generalized weight equation with variations in constants and exponents for the five aircraft categories is shown on Table II. The significant modifications to the equation are: (1) increased value of the activity factor exponent in categories I and II reflecting the greater proportion of blade weight in total weight of the simpler propellers, (2) decreased value of the tip speed exponent in all categories and (3) the addition of exponents to the counterweight equation for greater accuracy.

A comparison summary of representative 1970 actual propeller weights versus weights calculated from the generalized equation is shown in Table III. A summary of 1980 propeller calculated weights versus generalized equation weights is shown in Table I. It can be seen from Tables I and III that generally there is very good agreement between weights computed by the weight generalization equation and the actual weights.

The revised weight generalization deviates the furthest from the previous weight generalization for category II propellers since as was shown on Table X in reference 1, the generalization was the weakest for that classification. Therefore, the weights and consequently the costs for the sensitivity studies for category II (ref. 1) should be significantly higher. Furthermore, the weight and cost versus tipspeed curves should have less slope for all five categories.

In the previous study (ref. 1) a generalized cost equation was derived which is a function of propeller weight. Three propellers representative of the 1980 time period were design costed. A comparison of the costs based on those defined by the weight generalization and those on the design cost were made and tabulated on Table XIII (ref. 1). The agreement between the two sets of costs ranged from 6% low to 21% high. The costs based on the weight equation were recalculated due to the revised weight equation and a similar comparison was made. An inspection of Table IV shows that the costs computed with the generalized cost equation now agree from 7 to 15% low and thus the cost comparison has been significantly improved.

The refined generalized weight equation of Table II provides a useful tool for estimating propeller weight for any general aviation aircraft installation in this decade with reasonable accuracy. However it must be remembered that parameters other than the basic geometric and performance characteristics used in this equation effect propeller weights. These are variations in propeller environmental temperatures, type of control system and the degree to which individual manufacturers design for minimum weight.

Input/Output Additions to the Computer Program

It is not the intent to repeat the detailed input/output instructions for the computer program presented in reference 1 but to define the additional input required to use the extensions to the computer program developed under this contract and to present sample output sheets for demonstration purposes.

The following additional input is required to include the integrated design lift coefficient variation option.

1. Initial integrated design lift coefficient, C_{L_i}

2. Increment of C_{L_i} if a range of C_{L_i} is to be computed

3. Number of C_{L_i}'s

The input for the weight generalizations remain the same.

To use the option of computing reverse angle and reverse thrust, the following input is required

1. Option = 3

2. Specify engine - reciprocating or turbine

3. Option of including reverse angle or calculating it

4. SHP at zero velocity, full throttle setting

5. Reverse angle at 3/4 radius if this option is selected in 3

6. RPM at zero velocity, full throttle setting

7. Initial throttle setting

8. Increment of throttle setting if a range is to be calculated

9. Number of throttle settings

10. Landing touch down speed, knots

11. Temperatures, °F

12. Altitude, ft.

Specific input instructions are included in the User's Manual and will be discussed in the following section.

A sample output for a forward flight performance condition were integrated design lift coefficient, and tipspeed are varied is shown on figure 19. A typical reverse thrust computation for a range of throttle settings is presented on figure 20.

USER'S MANUAL

A User's Manual has been prepared for the computer program and will be published as a separate report (ref. 2). A summary of what is included in the User's Manual is presented below.

A brief description of the technology incorporated in the computer program for predicting propeller performance, noise, weight and cost is presented.

Detailed input and output instructions are given for making any of the following four available performance computations. First, for a given engine, the operating condition is defined with the horsepower and the corresponding thrust is computed. Second, for a given propeller thrust requirement, 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. Fourth, reverse pitch angle and the corresponding reverse thrusts for a range of landing ground roll velocities operating at the fixed reverse pitch angle are computed. The corresponding noise (PNL), weight and cost for the first three options are computed.

A complete listing of the computer program which has been coded in FORTRAN IV for the IBM System/370 is presented. Detailed input and output instructions are included as well as a list of error messages. Pertinent sample cases of input and output are shown.

CONCLUDING REMARKS

1. The integrated design lift coefficient variation was successfully developed.

2. A reverse thrust computational procedure was developed based on an existing computational procedure.

3. The weight equation was refined to predict propeller weights to an accuracy of $\pm$ 10%.

4. The accuracy of the estimate cost equation improves with the improvement in the weight equation.

5. The computer program was updated to include the above noted extensions.

6. A User's Manual which includes listings and detailed input/output instructions was written.

REFERENCES

1. Worobel, R. and Mayo, M.: Advanced General Aviation Propeller Study. NASA Report CR 114289, April 1971

2. Worobel, R.: Computer Program User's Manual for Advanced General Aviation Propeller Studies. To be published as a NASA low number Contractor Report.

TABLE I

WEIGHT SUMMARY OF PROPELLERS STUDIED FOR 1980

Class	Mach No.	No. Blades	Dia (Ft)	A. F.	SHP	RPM	Weight (Lbs) Est.	Equation
II	0.262	4	8	100	300	955	103	94
						1310	111	104
						1670	120	113
				150		955	134	134
						1310	148	150
						1670	167	163
				200		955	173	174
						1310	202	194
						1670	231	211
		3		150		955	109	110
						1310	122	123
						1670	136	133
IV	0.328	3	9	100	340	955	104	104
						1230	110	112
						1480	116	121
				150		955	143	148
						1230	151	159
						1480	159	169
				200		955	195	195
						1230	206	208
						1480	218	218
		4		150		955	189	184
						1230	200	197
						1480	211	208
V	0.368	4	10	100	650	860	171	164
						1190	180	180
						1525	193	195
				150		860	216	218
						1190	234	240
						1525	259	259
				200		860	263	267
						1190	287	294
						1525	318	317
		3		150		860	171	178
						1190	186	196
						1525	214	212

TABLE II

GENERAL AVIATION

Generalized Propeller Weight Equation:

$$W_T = K_W \left[\left(\frac{D}{10}\right)^{2} \left(\frac{B}{4}\right)^{0.7} \left(\frac{A.F.}{100}\right)^{u} \left(\frac{ND}{20,000}\right)^{v} \left(\frac{SHP}{10D^2}\right)^{0.12} (M+1)^{0.5} \right] + C_W$$

Where:

W_T = Prop. Wet Weight, lbs. (excludes spinner, deicing & 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)

$$C_W = y \left(\frac{D}{10}\right)^{2} (B) \left(\frac{A.F.}{100}\right)^{2} \left(\frac{20,000}{ND}\right)^{0.3} = \text{Counterweight Wt., lbs.}$$

K_W, C_W, u, v and y values for use in the weight equation are taken from table below:

Aircraft Class	Technology 1970	Technology 1980
I	(1)	(1)
II	(2)	(2)
III	(3)	(3)
IV	(3)	(4)
V	(3)	(5)

	K_W	u	v	y
(1)	170	0.9	0.35	0
(2)	200	0.9	0.35	0
(3)	220	0.7	0.40	5.0
(4)	190	0.7	0.40	3.5
(5)	190	0.7	0.30	0

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

(1) All fixed-pitch props

(2) Mc Cauley non-counterweighted, non-feathering, constant speed props

(3) All Hartzell, all Hamilton Standard small props, and feathering Mc Cauley

(4) Fiberglass-bladed, constant speed, counterweighted, full feathered

(5) Fiberglass-bladed, constant-speed, double-acting (non-counterweighted), full feathered, reverse

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.
Piper PA-28-235 Cherokee	I	170	PFA8069/1P235	2	Fixed	80.0	77.5	260	2700	38.0	37.0
---	I	---	IAI75/SFC 8640	2	Fixed	80.0	77.5	175	2400	33.0	33.0
Beech Bonanza V-35TC	II	190	3A32C76/82ND-2	3	No Cwt-No Fea.	80.0	90.5	285	2700	66.0	63.0
Cessna 210D, 206	II	190	D2A34C58/90-8	2	No Cwt-No Fea.	82.0	103.5	285	2700	55.0	61.0
Cessna 205, 210	II	175	D2A34C49/90A-8	2	No Cwt-No Fea.	82.0	103.5	260	2625	52.0	59.0
Cessna 180	II	130	2A34C50/90A-8	2	No Cwt-No Fea.	82.0	103.5	230	2600	52.0	57.0
Cessna 180	II	130	BHC-A2XF-1A/8433	2	Cwt-No Fea.	84.0	103.5	260	2625	62.0	61.0
Beech 35-33	II	160	HC-92ZK-1D1/8477	2	Cwt-No Fea.	84.0	103.5	240	2600	68.0	51.0
Cessna 32OE Twin Skyknight	III	210	3AF32C87/82NC-5.5	3	Cwt-Fea.	76.5	90.5	300	2700	75.0	78.0
Beech 95-55	III	210	2AF36C89/78BFS-0	2	Cwt-Fea.	78.0	103.5	260	2625	66.0	62.0
Cessna 336	III	180	D2AF34C46/76C-0	2	Cwt-Fea.	76.0	105.0	210	2800	54.0	60.0
Cessna 310	III	200	HC-A2XF-2-2B/8433-4	2	Cwt-Fea.	80.0	103.5	260	2625	65.0	67.0
Piper Comanche 250	III	180	HC-A2XK-1/8433-7	2	Cwt-No Fea.	77.0	105.0	250	2575	60.0	61.0

TABLE III (Continued)

TYPICAL 1970 PROPELLER WEIGHTS

Aircraft	Class	Speed (MPH)	Prop. Model	No. Blades	Prop. Type	Dia (in.)	A. F.	SHP	RPM	Weight Actual	Weight Calc.
Riley 310 Conversion	IV	---	HC-A3VK-2/V8433-4	3	Cwt-Fea	80.0	103.5	290	2600	87.0	93.0
Beech C50	IV	180	PHC-A3VF-4/V8433-2	3	No Cwt-No Fea.	82.0	103.5	285	2700	88.0	95.0
Aero Commander 560-A	IV	210	HC-A3X20-2/8433	3	Cwt-Fea.	84.0	103.5	280	2180	91.0	100.0
Twin Otter - Prototype	V	184	23LF-321	3	Cwt-Fea.	102.0	110	550	2200	149.0	160.0
Handley Page HP 137	V	200	23LF-329	3	Cwt-Fea.	102.0	110	800	1783	152.0	156.0
Handley Page HP 137	V	200	23LF-333	3	Cwt-Fea.	96.0	120	800	1783	144.0	146.0
Aero-Commander	V	250	33LF-307	3	Cwt-Fea.	84.0	109	575	2000	120.0	111.0
Aero-Commander	V	250	33LF-327	3	Cwt-Fea.	93.0	96	575	2000	120.0	118.0
1500 HP	V	305	1500 HP	3	Cwt-Fea.	132.0	133	1500	1563	355.0	341.0
1500 HP	V	305	1500 HP	3	Double-Acting Hyd - Feather	132.0	133	1500	1563	309.0	305.0
DHC-7	V	270	DHC-7	4	Solid Aluminum Blades/Cwt	135.0	116	1140	1210	377.0	344.0
DHC-7	V	270	DHC-7	4	Fiberglass Blades Cwt-Fea.	135.0	116	1140	1210	320.0	301.0

TABLE IV

O.E.M. SINGLE UNIT COST SUMMARY OF

REPRESENTATIVE PROPELLERS FOR 1980

Category	Generalized Equation Cost $/lb	Calculated Design Cost $/lb	Cost Variation %
II	27	29.1	+7
IV	35	38.5	+10
V	35	41.2	+15

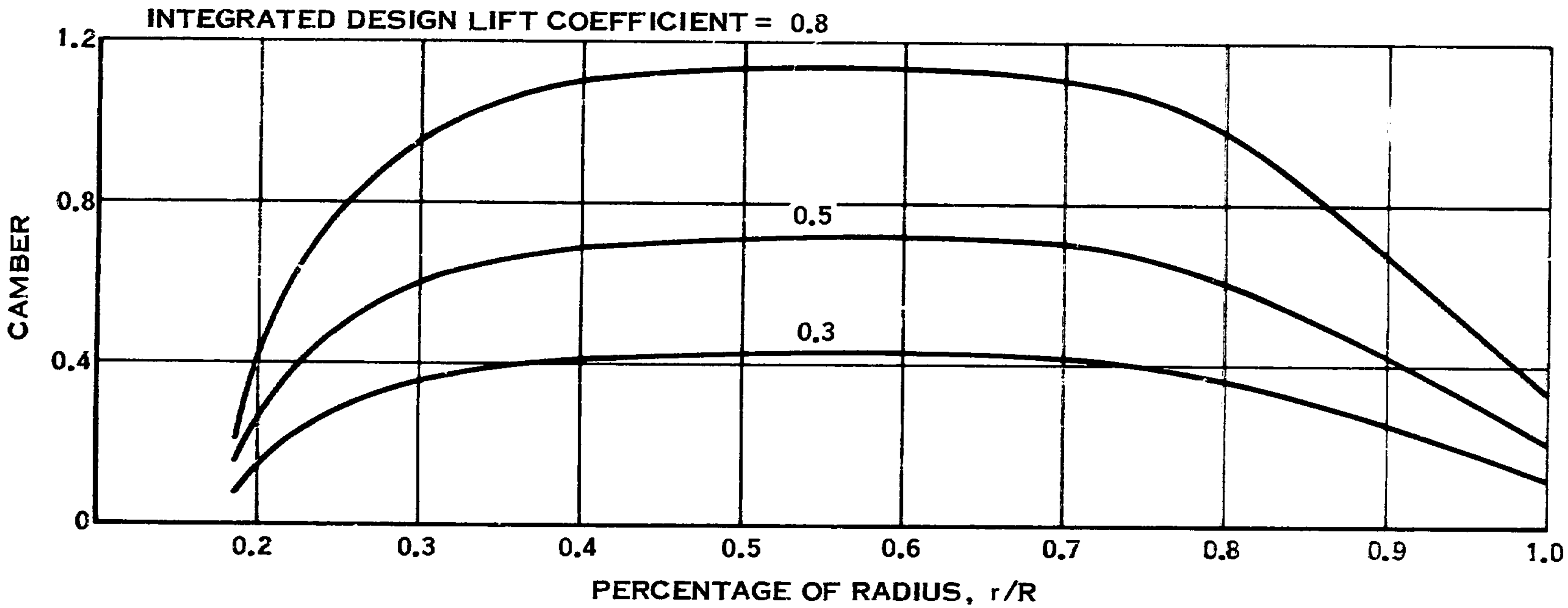

FIGURE 1. BLADE CAMBER DISTRIBUTION

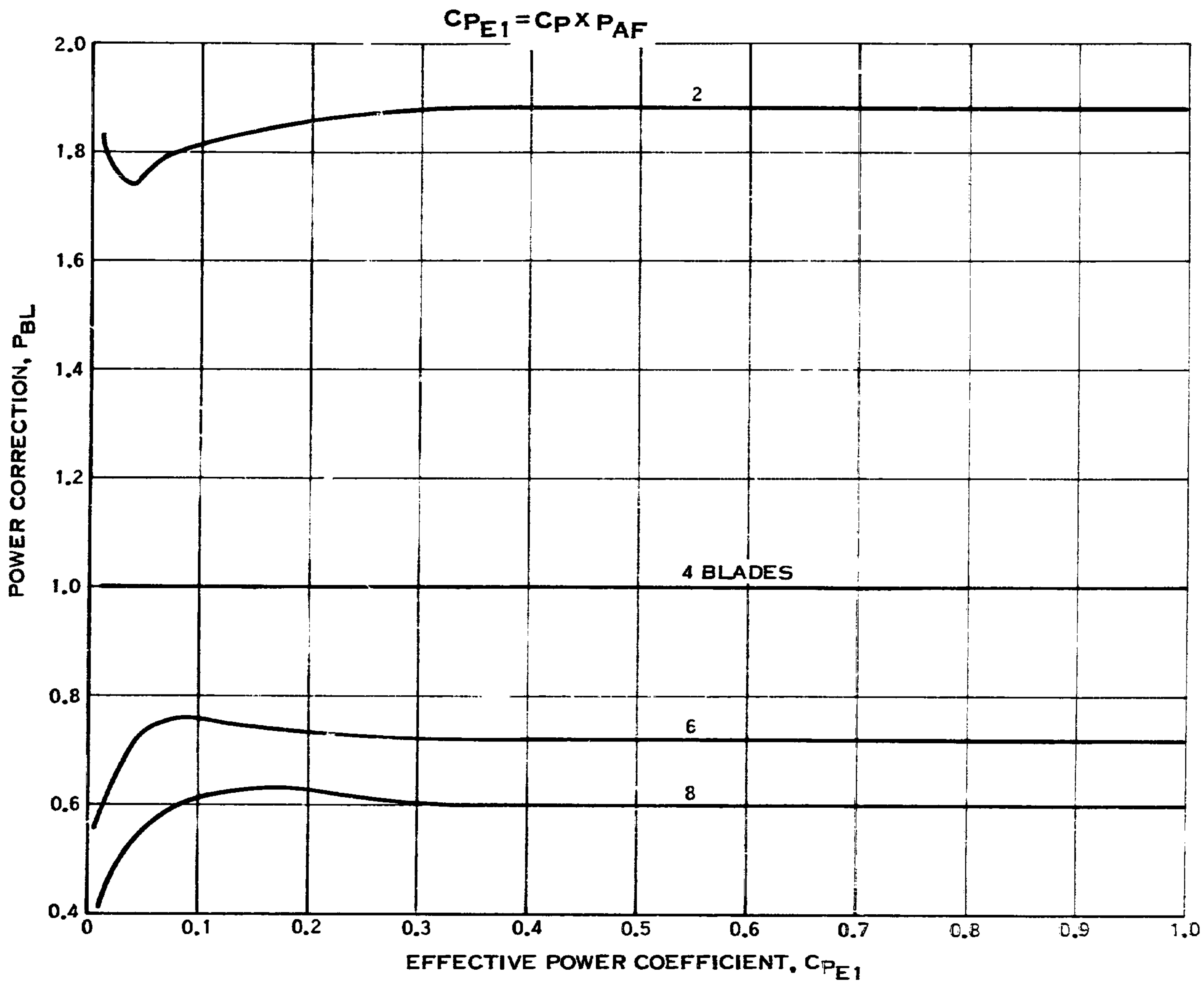

FIGURE 2. NUMBER OF BLADES CORRECTION FOR POWER COEFFICIENT

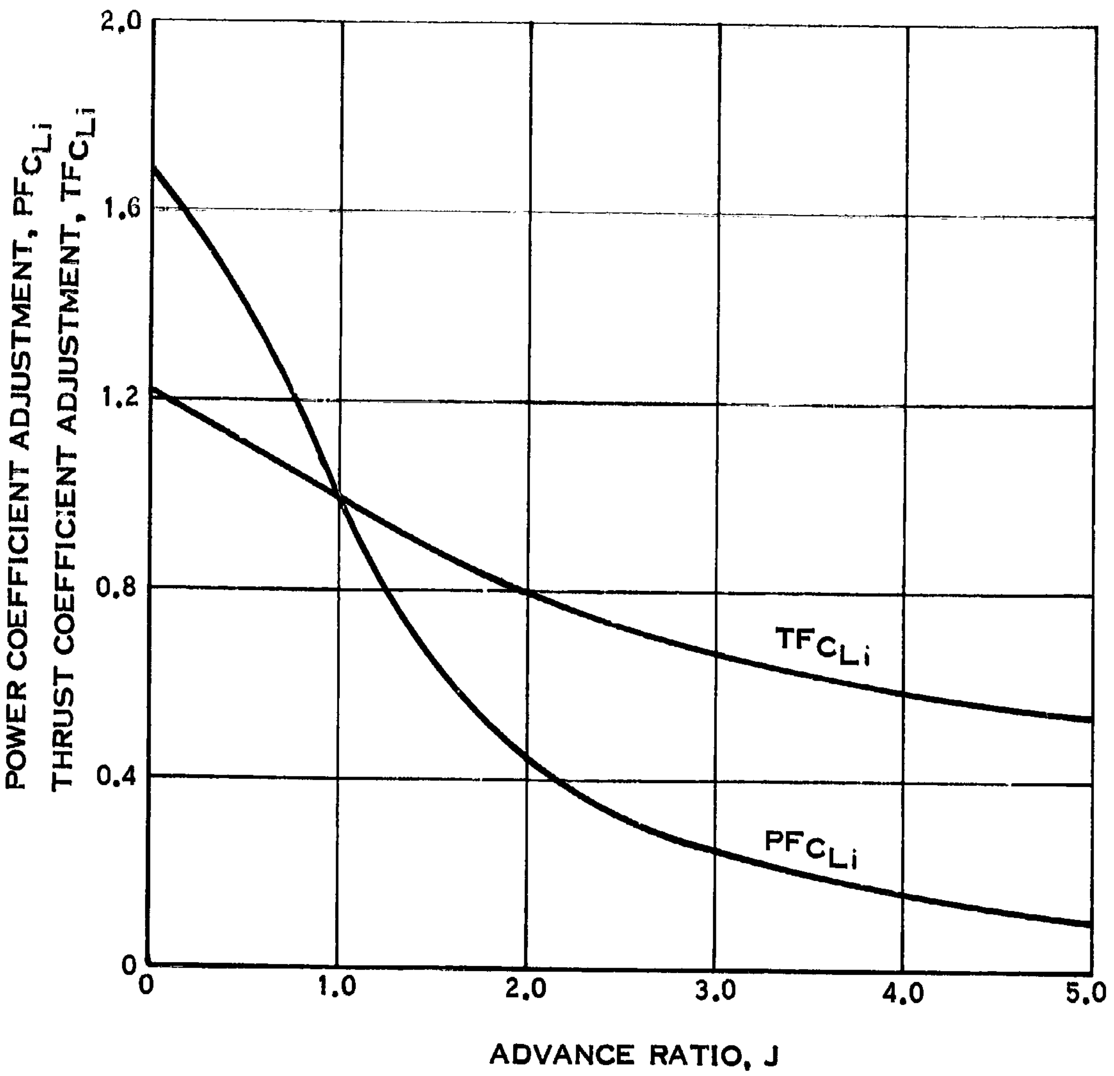

FIGURE 3. CAMBER FACTOR ADJUSTMENT FOR ADVANCE RATIO

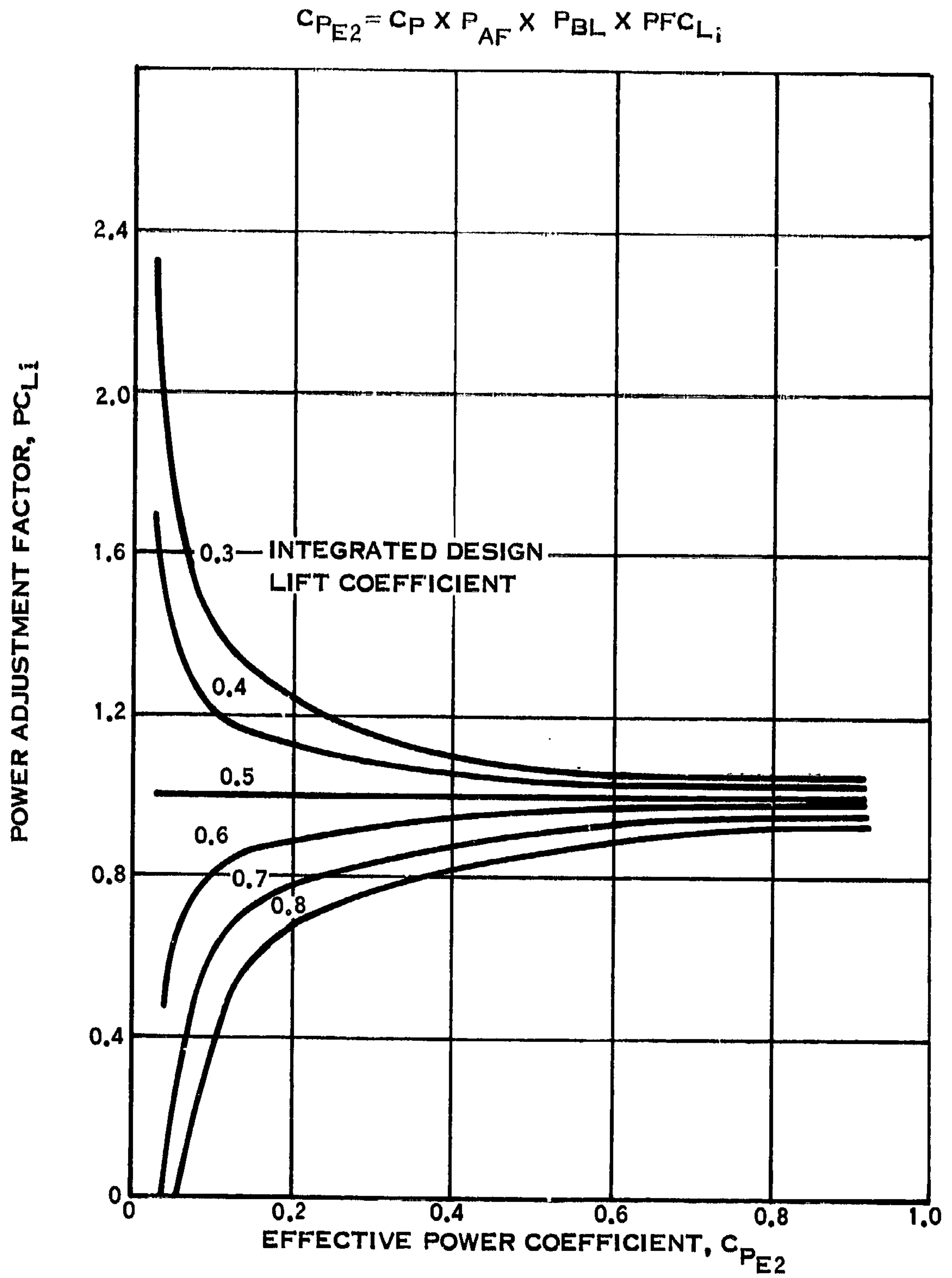

FIGURE 4. INTEGRATED DESIGN LIFT COEFFICIENT ADJUSTMENT TO POWER COEFFICIENT FOR 4—BLADED PROPELLERS

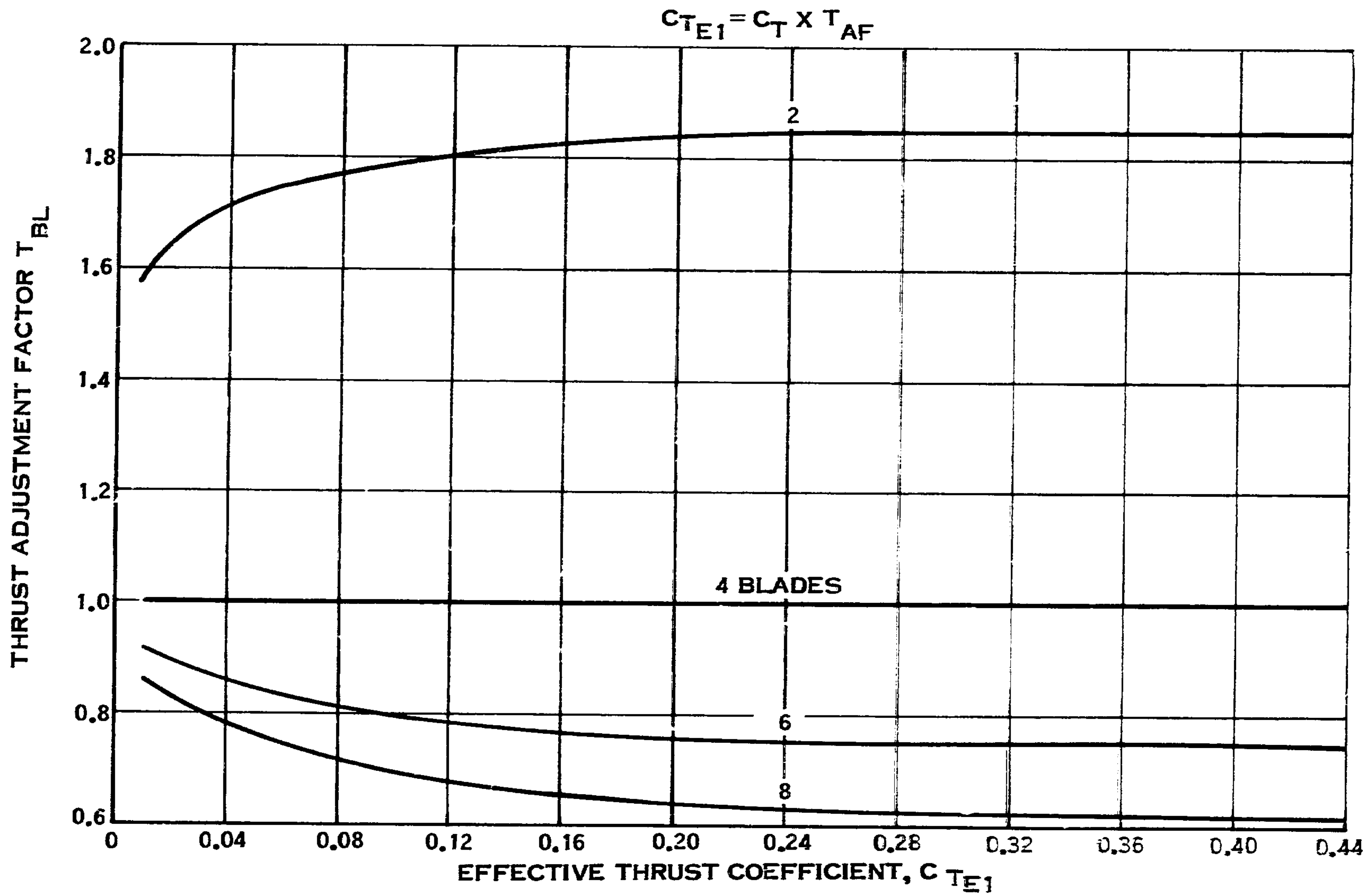

FIGURE 5. NUMBER OF BLADES CORRECTION FOR THRUST COEFFICIENT

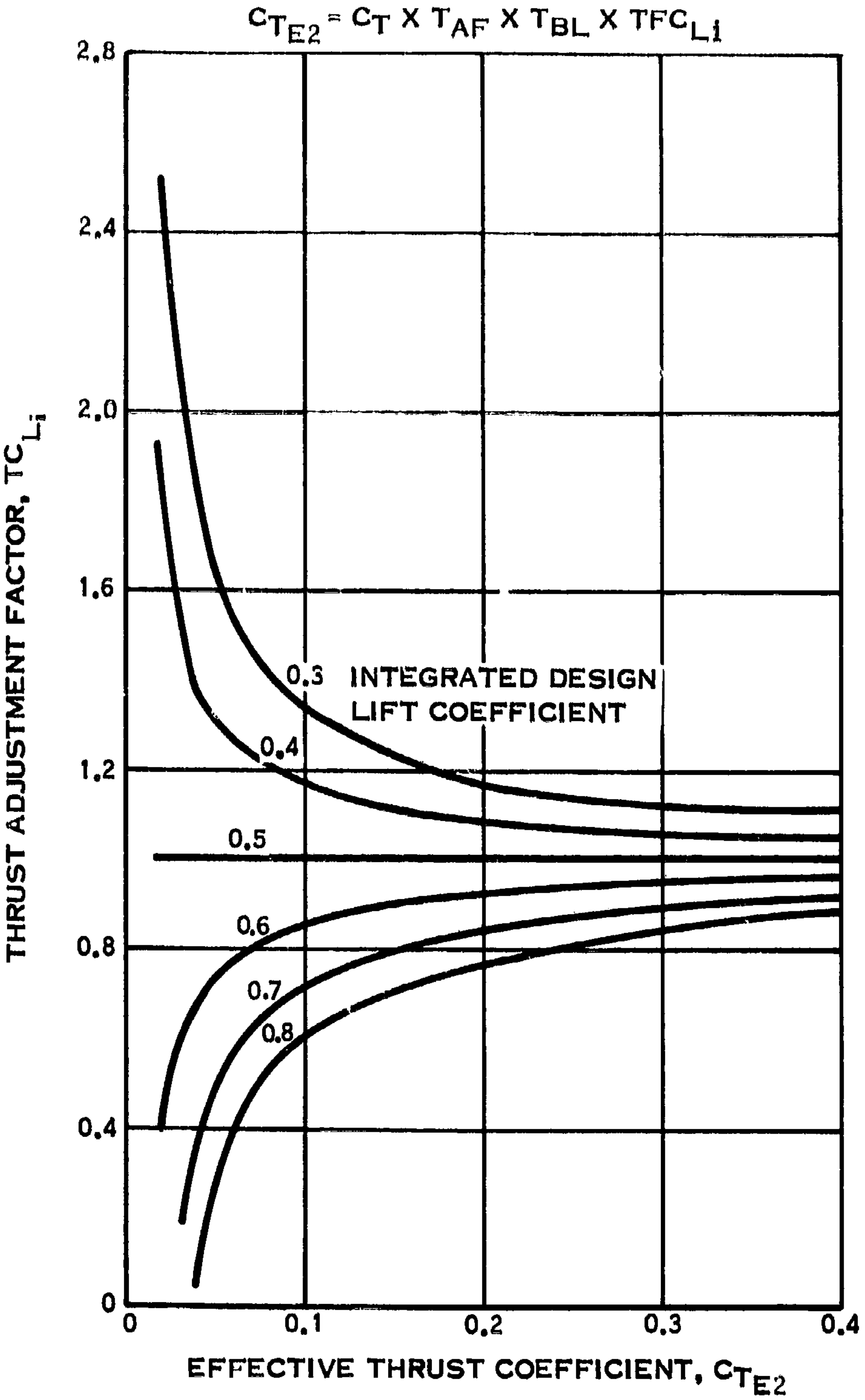

FIGURE 6. INTEGRATED DESIGN LIFT COEFFICIENT ADJUSTMENT TO THRUST COEFFICIENT FOR 4–BLADED PROPELLERS

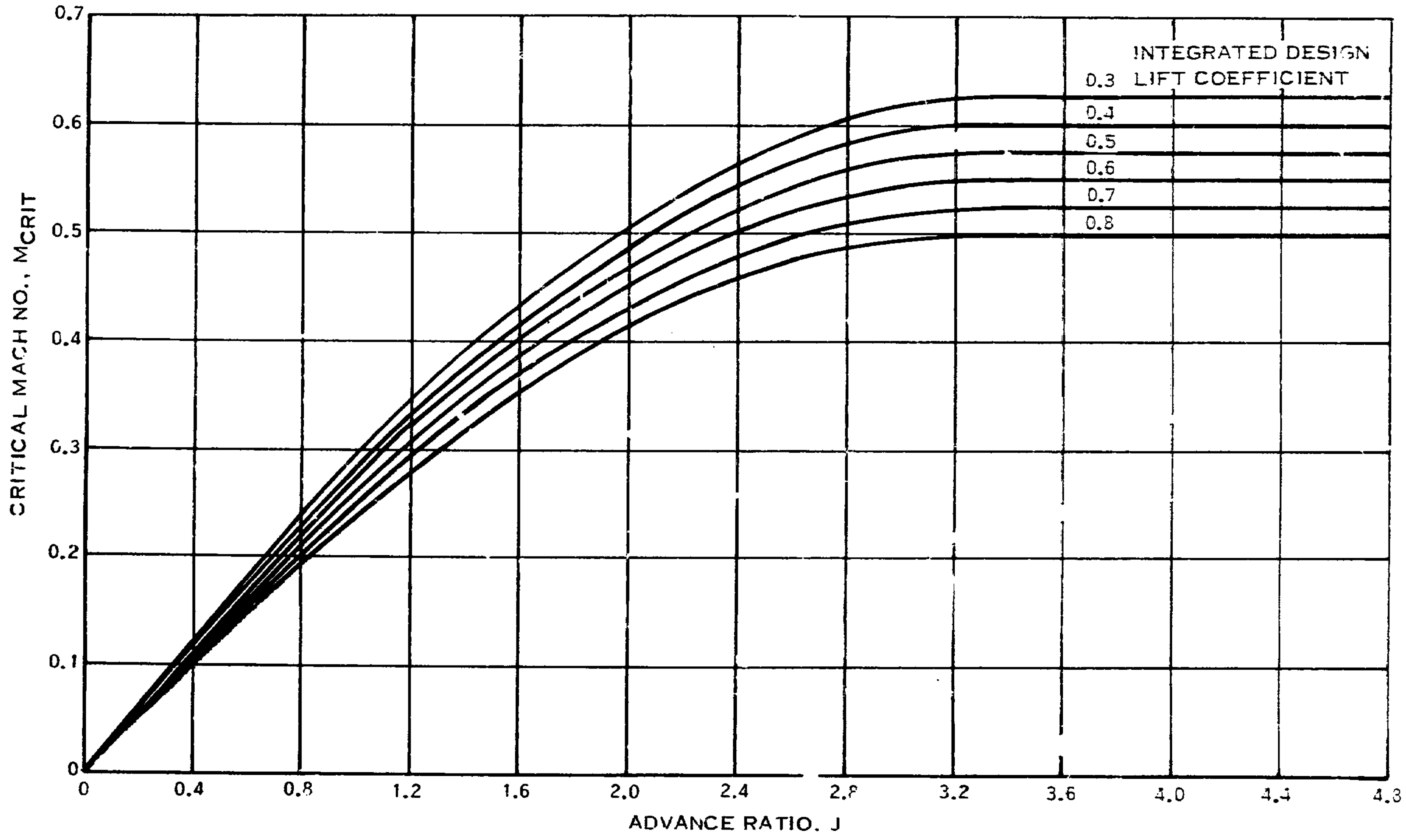

FIGURE 7. CRITICAL MACH NUMBER FOR ADVANCE RATIO GREATER THAN ZERO

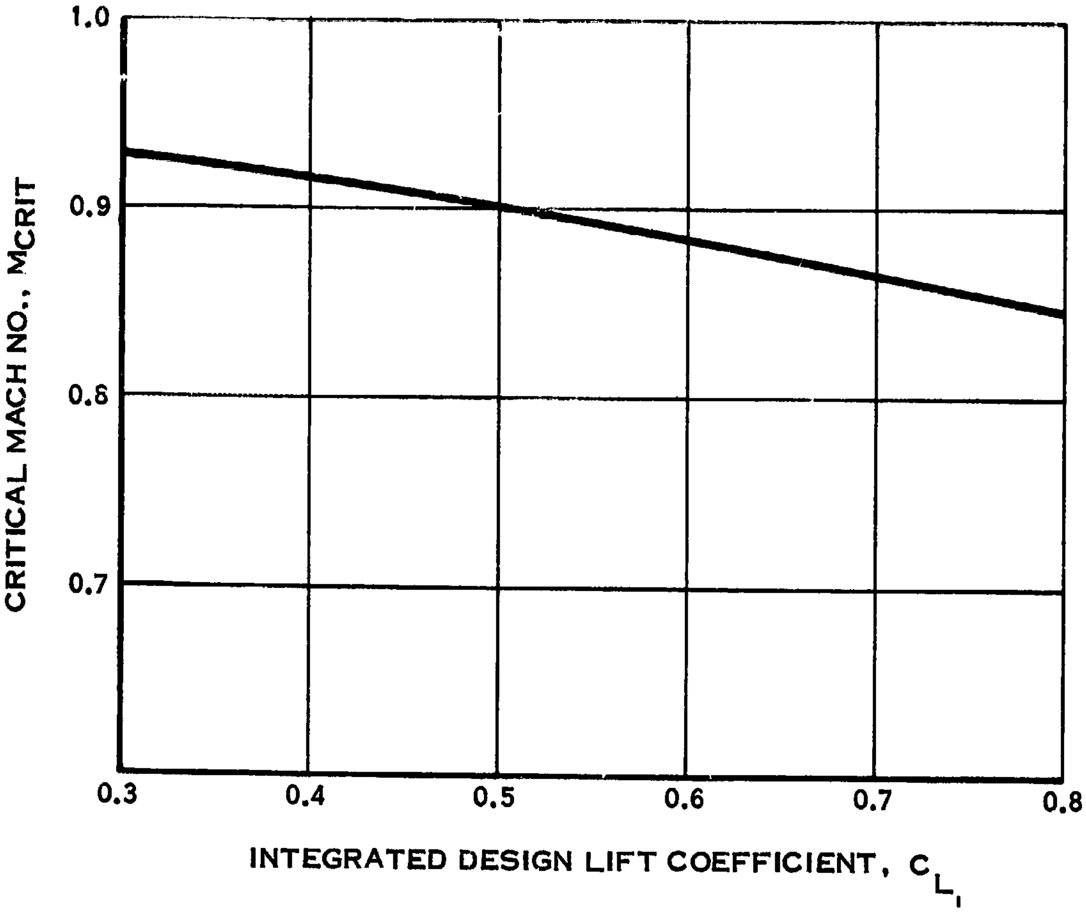

FIGURE 8. CRITICAL MACH NUMBER FOR ADVANCE RATIO EQUAL TO ZERO

$$C_{T_{E3}} = C_T \times T_{AF} \times T_{BL} \times TC_{L_i}$$

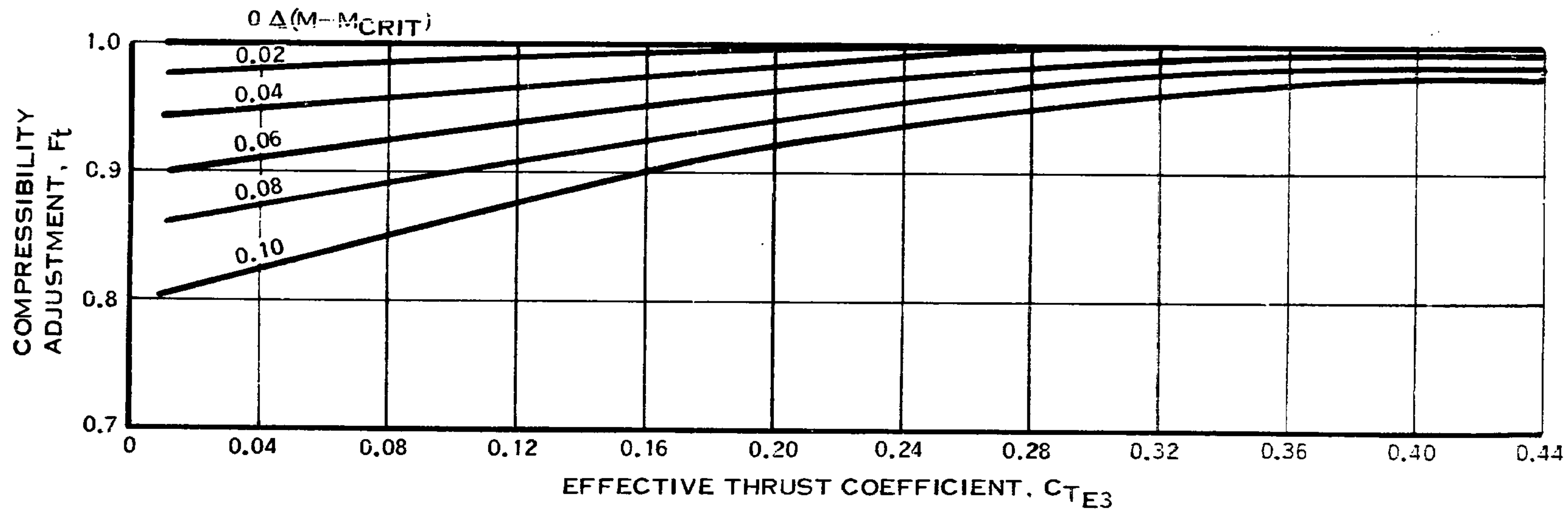

FIGURE 9. COMPRESSIBILITY ADJUSTMENT

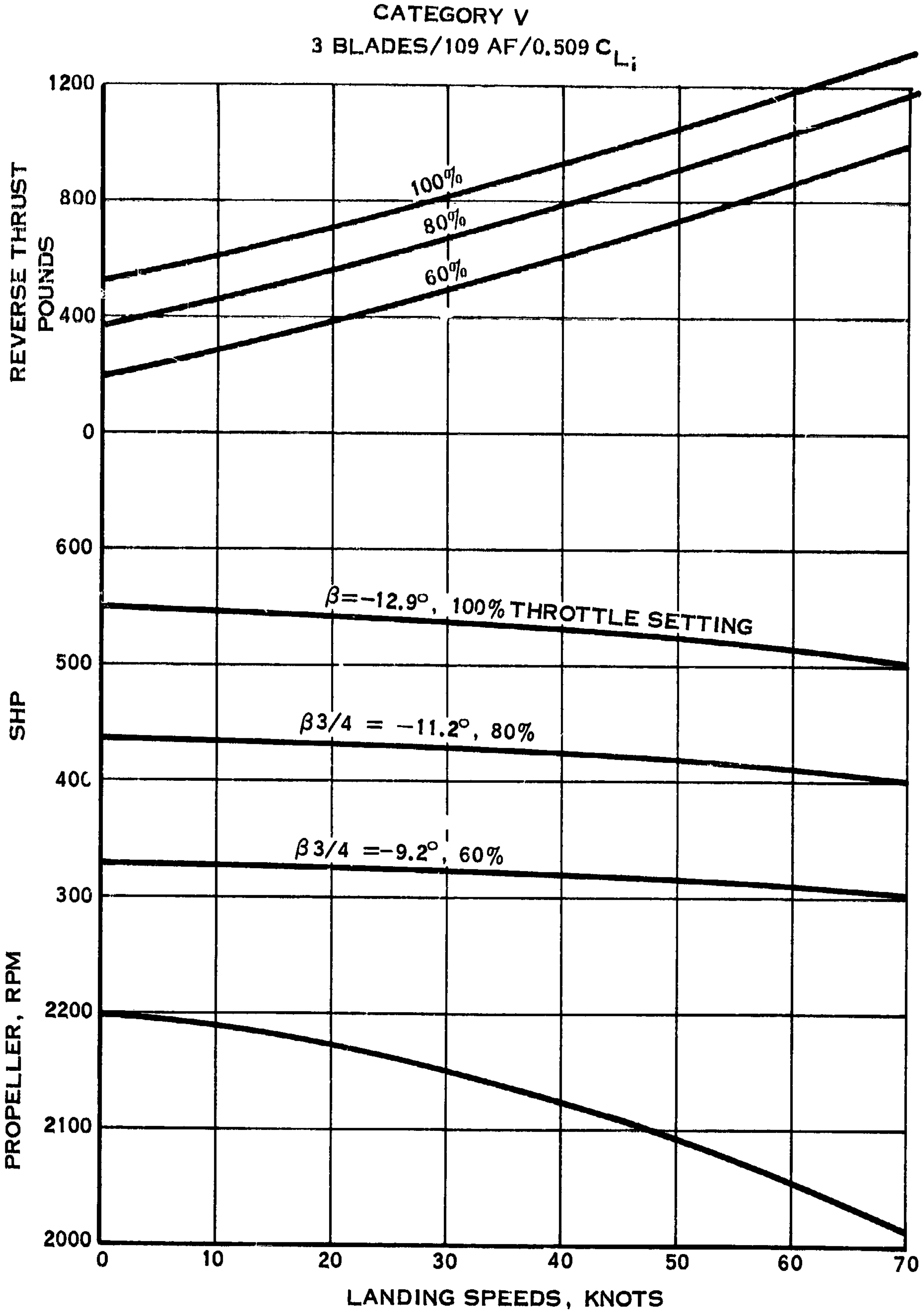

FIGURE 10. EXAMPLE REVERSE THRUST VARIATION WITH LANDING SPEED AND POWER SETTING

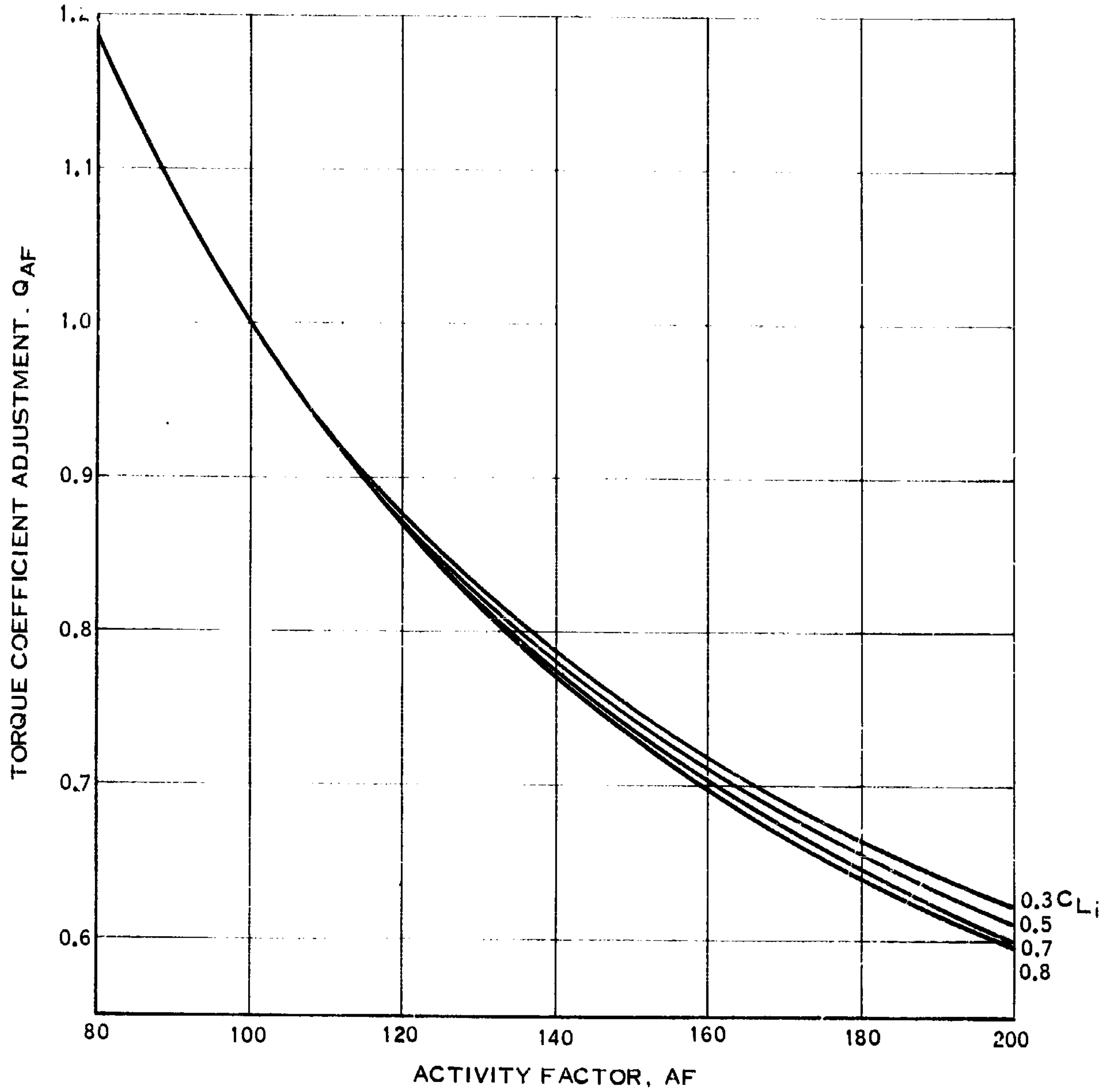

FIGURE 11. ACTIVITY FACTOR ADJUSTMENT TO TORQUE COEFFICIENT

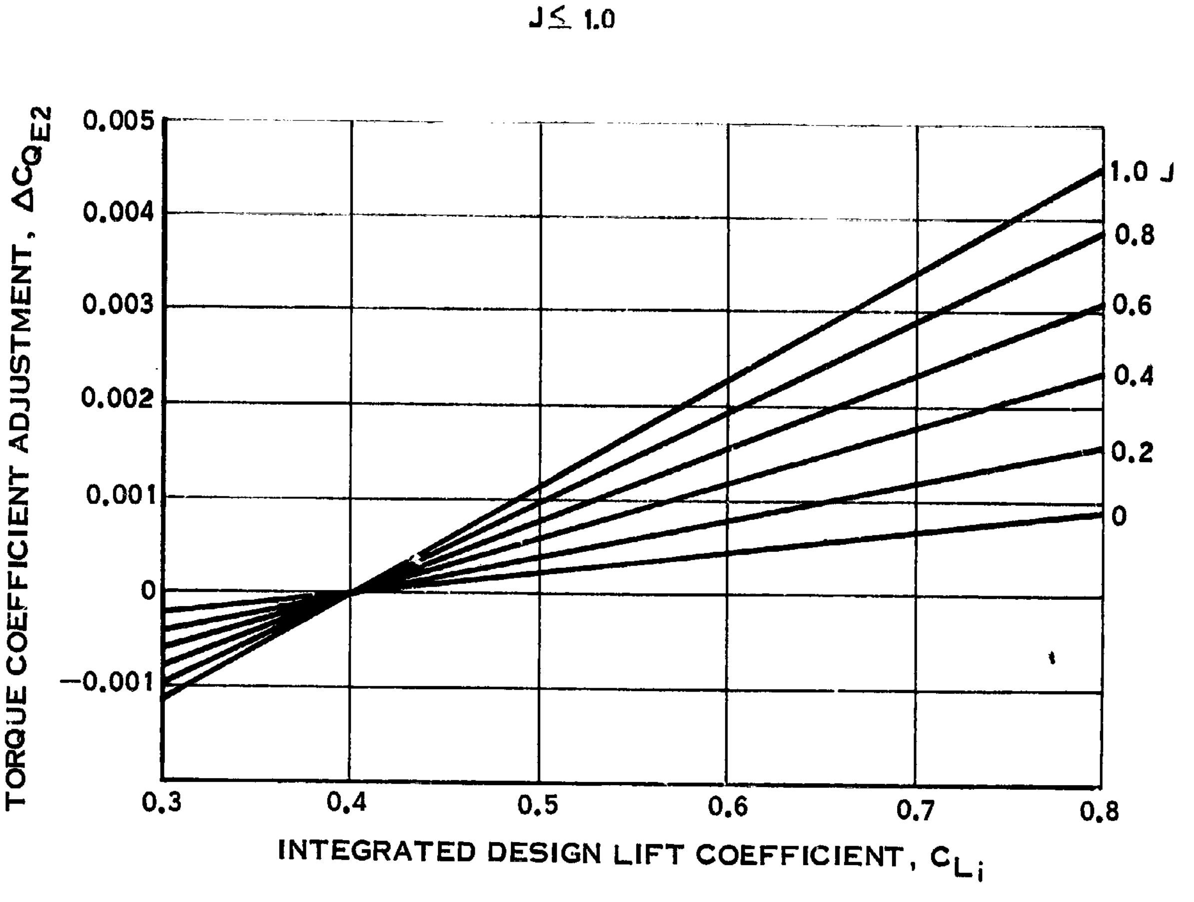

FIGURE 12. INTEGRATED DESIGN LIFT COEFFICIENT ADJUSTMENT TO TORQUE COEFFICIENT

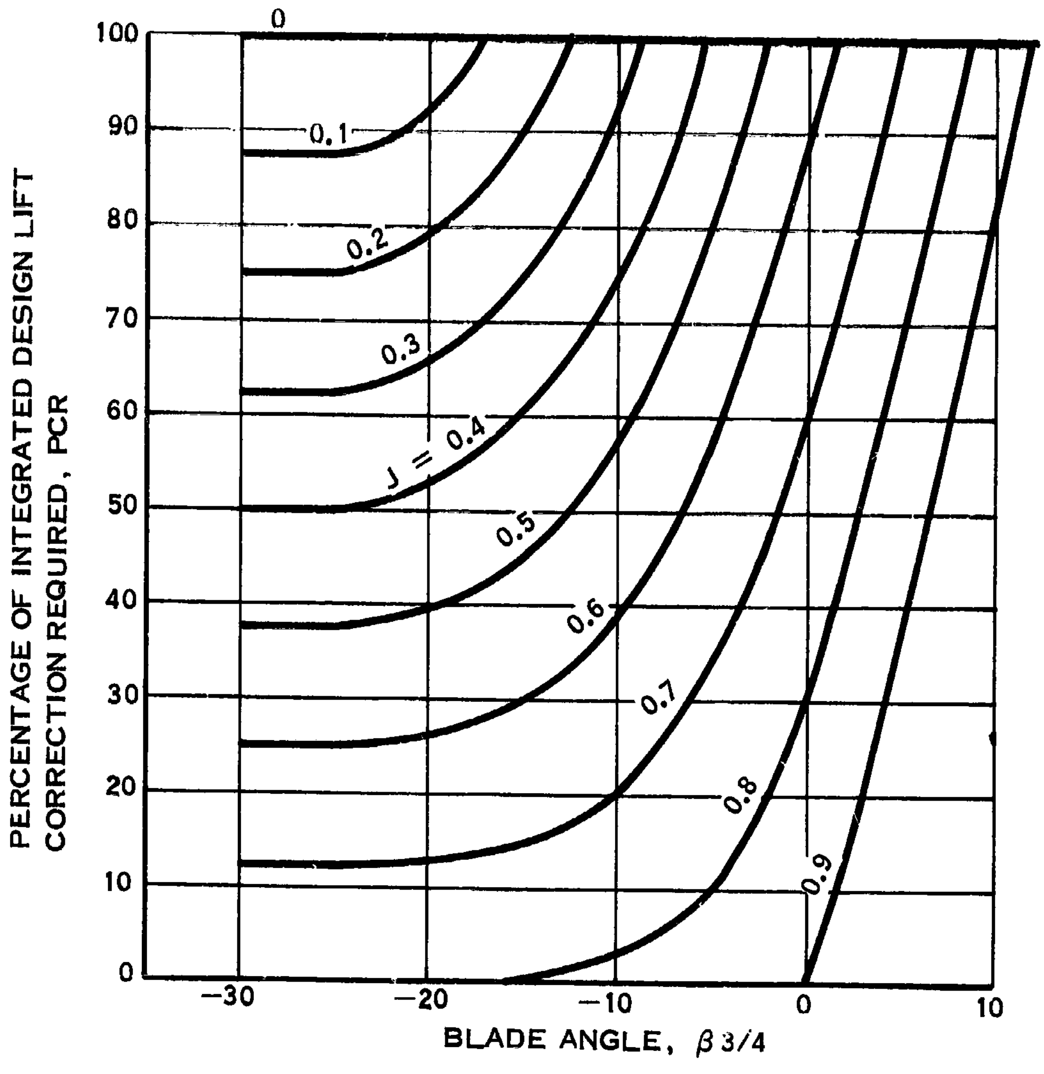

FIGURE 13. VARIATION OF PERCENTAGE OF INTEGRATED DESIGN LIFT COEFFICIENT CORRECTION REQUIRED FOR THRUST AND TORQUE

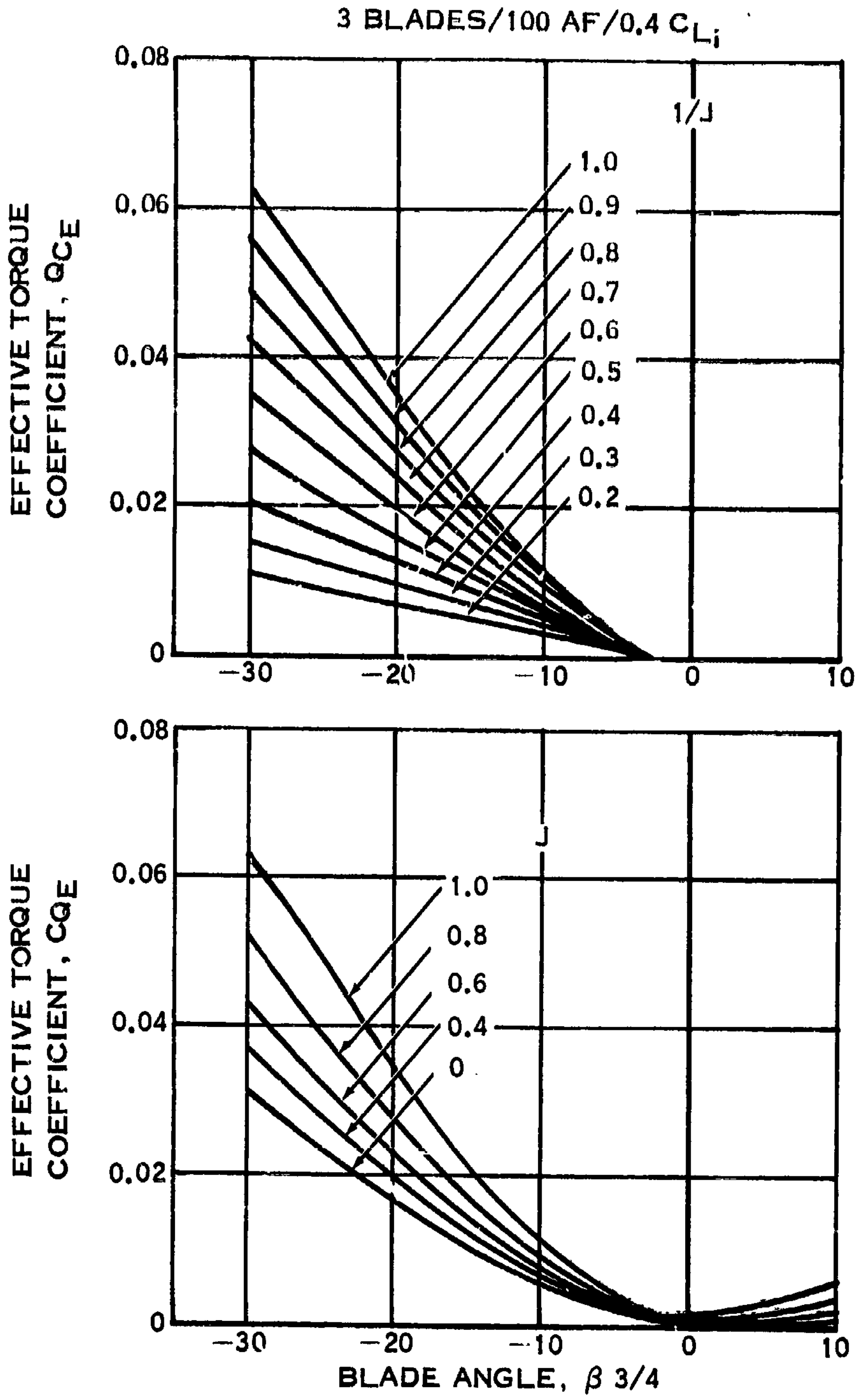

FIGURE 14. BASIC PERFORMANCE CURVE VARIATION OF EFFECTIVE TORQUE COEFFICIENT WITH ADVANCE RATIO & BLADE ANGLE

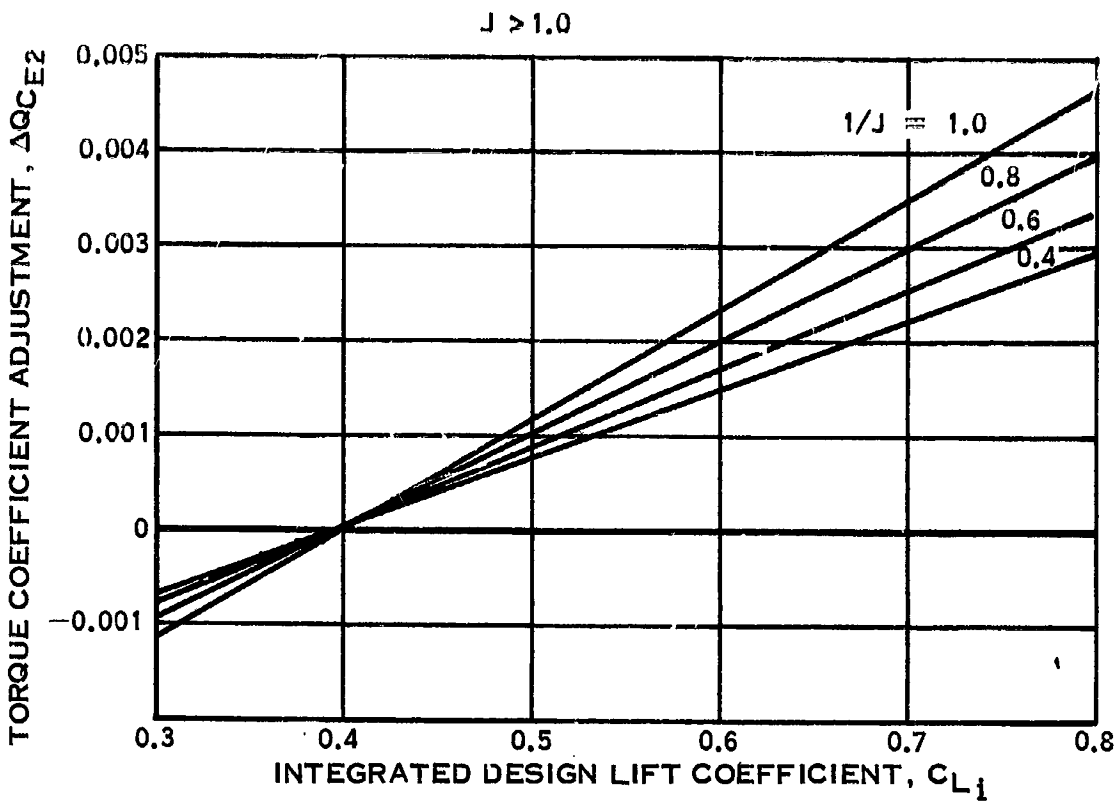

FIGURE 15. INTEGRATED DESIGN LIFT COEFFICIENT ADJUSTMENT TO TORQUE COEFFICIENT

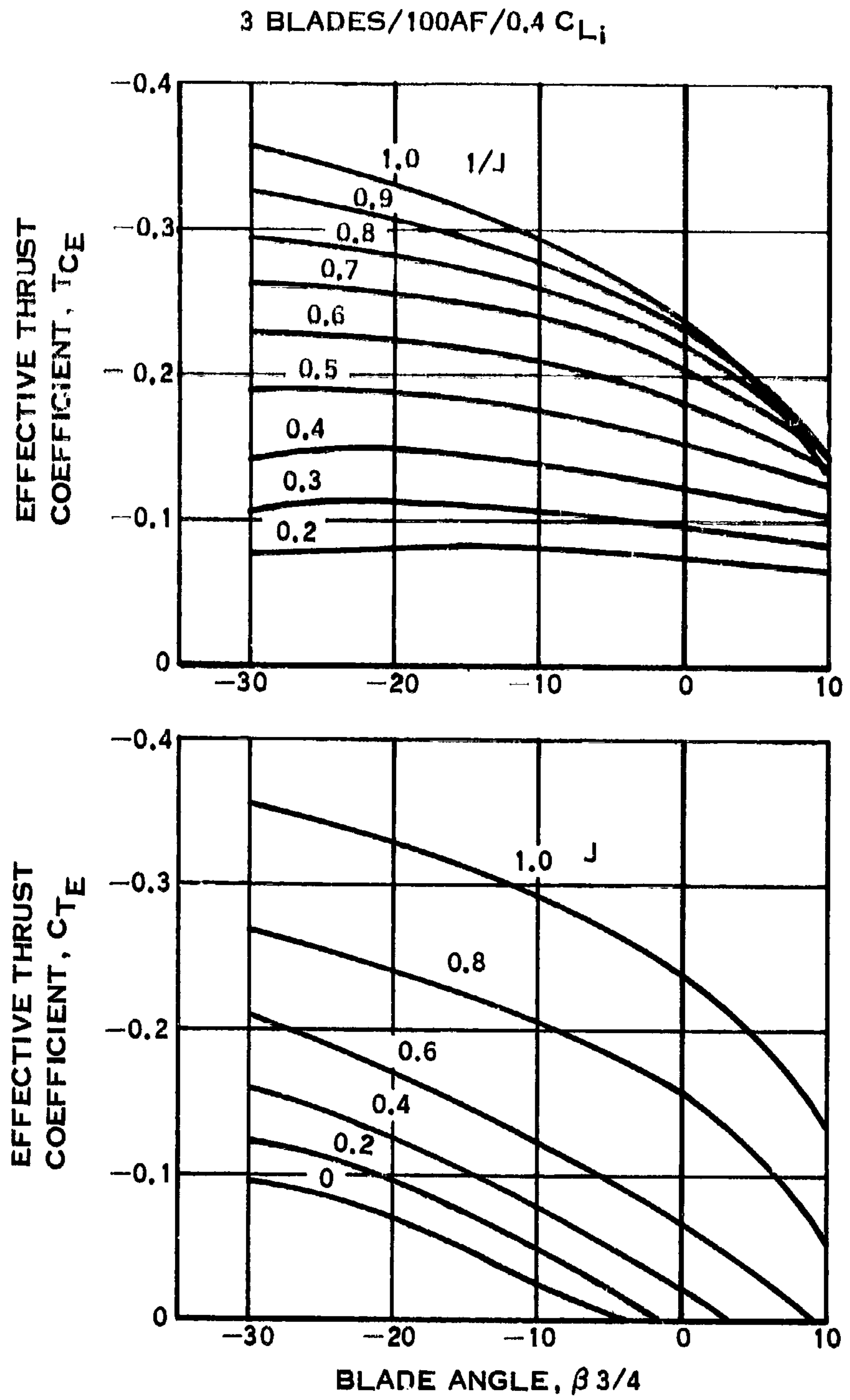

FIGURE 16. BASIC PERFORMANCE CURVE VARIATION OF EFFECTIVE THRUST COEFFICIENT WITH ADVANCE RATIO & BLADE ANGLE

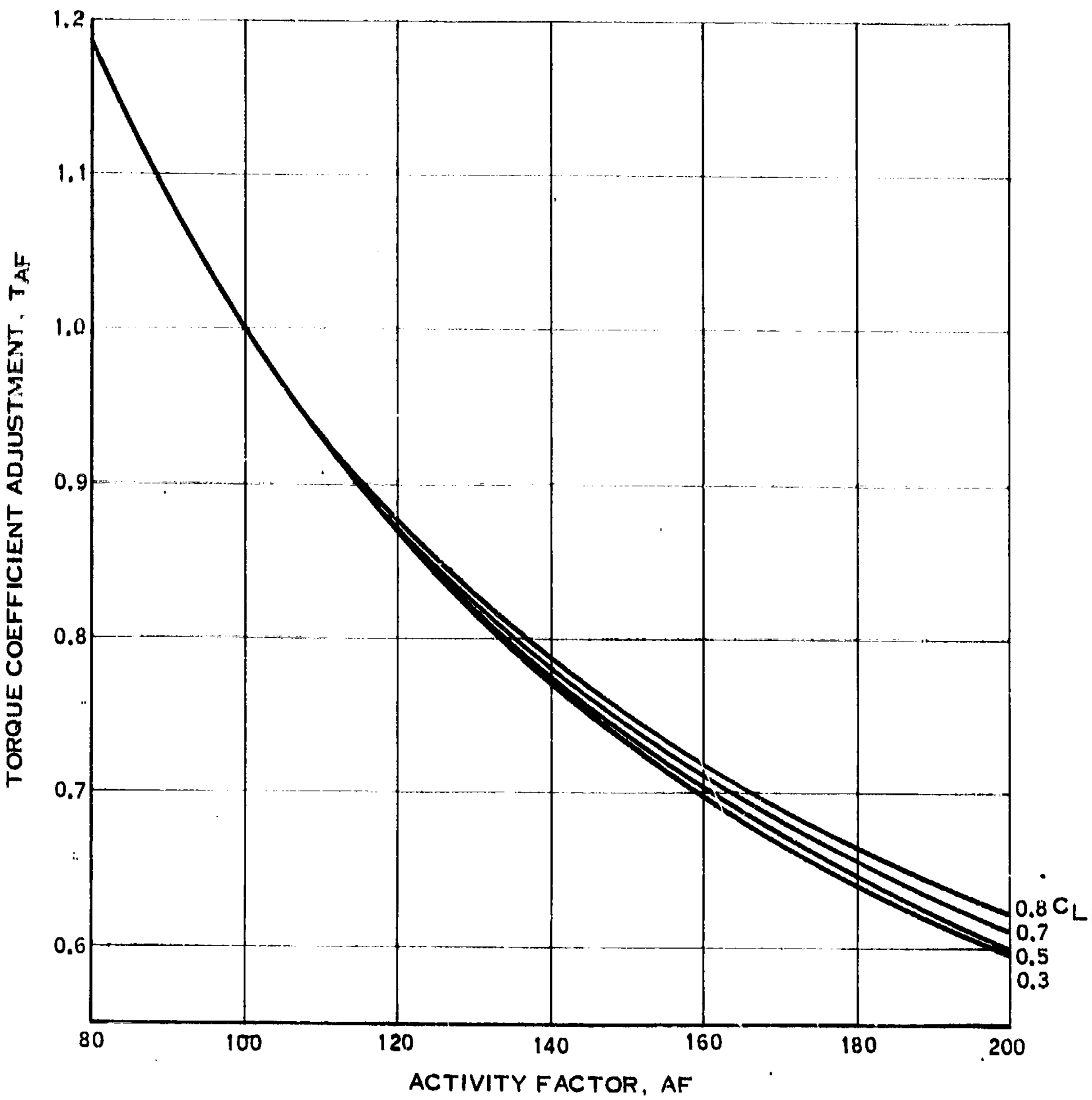

FIGURE 17. ACTIVITY FACTOR ADJUSTMENT TO THRUST COEFFICIENT

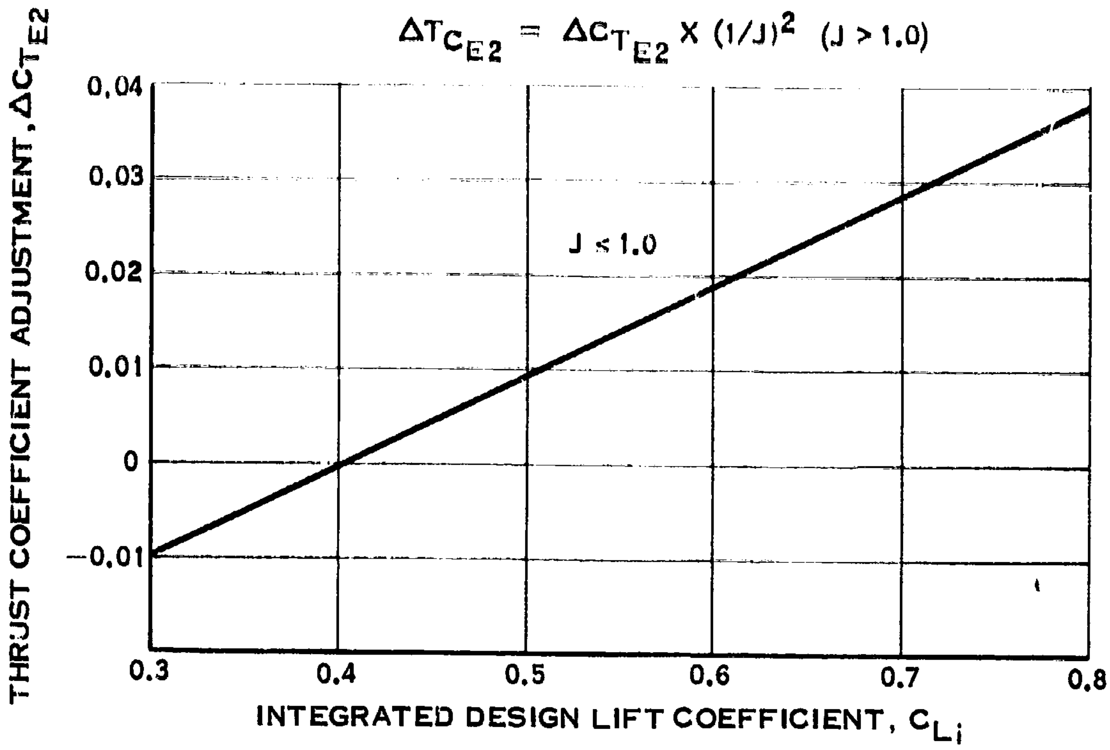

FIGURE 18. INTEGRATED DESIGN LIFT COEFFICIENT ADJUSTMENT TO THRUST COEFFICIENT

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

1 CLASSIFICATION 2 AIRPLANE SAMPLE CASE I

2 SHP INPUT-TIPSPEED AND DIAMETER VAR. - COST AND WEIGHT

OPERATING CONDITION

SHP =	300.	NO. OF ENGINES =	1.	UNIT FACTOR L.C.	= 3.22
ALT-FT =	0.	DESIGN FLIGHT M.=0.262		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. INTEGRATED DESIGN CL =.300

				*** 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
6.	750.	900.	94.	2810.	101.	1000.	5470.	101.	895.	21.6	1.000	0.1077	0.504	0.1418	0.1846
6.	650.	855.	90.	2810.	96.	951.	5470.	96.	852.	26.2	1.000	0.1077	0.582	0.2178	0.2335
6.	550.	749.	87.	2810.	91.	897.	5470.	91.	803.	32.6	1.000	0.1077	0.687	0.3595	0.2857
8.	750.	1046.	90.	2810.	168.	1659.	5470.	168.	1485.	17.5	1.000	0.1077	0.504	0.0798	0.1207
8.	650.	1015.	86.	2810.	160.	1578.	5470.	160.	1413.	21.1	1.000	0.1077	0.582	0.1225	0.1559
8.	550.	968.	82.	2810.	151.	1489.	5470.	151.	1333.	26.5	1.000	0.1077	0.687	0.2022	0.2077

NUMBER OF BLADES= 4. ACTIVITY FACTOR=150. INTEGRATED DESIGN CL =.500

				*** 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
6.	750.	891.	94.	2810.	101.	1000.	5470.	101.	895.	19.5	1.000	0.1077	0.504	0.1418	0.1828
6.	650.	882.	90.	2810.	96.	951.	5470.	96.	852.	24.6	1.000	0.1077	0.582	0.2178	0.2403
6.	550.	805.	87.	2810.	91.	897.	5470.	91.	803.	31.5	1.000	0.1077	0.687	0.3595	0.3071
8.	750.	960.	90.	2810.	168.	1659.	5470.	168.	1485.	15.0	1.000	0.1077	0.504	0.0798	0.1108
8.	650.	1000.	86.	2810.	160.	1578.	5470.	160.	1413.	19.1	1.000	0.1077	0.582	0.1225	0.1535
8.	550.	987.	82.	2810.	151.	1489.	5470.	151.	1333.	24.7	1.000	0.1077	0.687	0.2022	0.2117

NUMBER OF BLADES= 4. ACTIVITY FACTOR=150. INTEGRATED DESIGN CL =.700

				*** 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
6.	750.	879.	94.	2810.	101.	1000.	5470.	101.	895.	17.5	1.000	0.1077	0.504	0.1418	0.1803
6.	650.	874.	90.	2810.	96.	951.	5470.	96.	852.	22.6	1.000	0.1077	0.582	0.2178	0.2386
6.	550.	836.	87.	2810.	91.	897.	5470.	91.	803.	30.0	1.000	0.1077	0.687	0.3595	0.3187
8.	750.	726.	90.	2810.	168.	1659.	5470.	168.	1485.	11.8	1.000	0.1077	0.504	0.0756	0.0837
8.	650.	961.	86.	2810.	160.	1578.	5470.	160.	1413.	17.0	1.000	0.1077	0.582	0.1225	0.1476
8.	550.	973.	82.	2810.	151.	1489.	5470.	151.	1333.	22.7	1.000	0.1077	0.687	0.2022	0.2088

FIGURE 19. SAMPLE CASE 1 OF COMPUTER PROGRAM OUTPUT

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

1 CLASSIFICATION 5 AIRPLANE SAMPLE CASE II

2 REVERSE THRUST OPTION

REVERSE THRUST COMPUTATION

RECIPROCATING ENGINE

NORMAL RATED SHP = 550.
NORMAL RATED RPM = 2200.
TOUCH DOWN V-KNOTS = 72.

NUMBER OF BLADES= 3. ACTIVITY FACTOR=109. INTEGRATED DESIGN CL=.509

DIA.FT	THROTTLE SETTING	REVERSE ANGLE	V-KNOTS	REVERSE THRUST	SHP	RPM
8.5	100.	-12.9	0.0	524.	550.	2199.
			10.0	615.	547.	2188.
			20.0	714.	543.	2172.
			30.0	822.	538.	2151.
			40.0	938.	531.	2124.
			50.0	1059.	523.	2092.
			60.0	1179.	514.	2056.
			70.0	1313.	503.	2013.
			72.0	1342.	501.	2004.
8.5	80.	-11.2	0.0	380.	440.	2198.
			10.0	468.	437.	2187.
			20.0	565.	434.	2170.
			30.0	673.	430.	2149.
			40.0	790.	425.	2124.
			50.0	913.	419.	2093.
			60.0	1035.	412.	2059.
			70.0	1173.	404.	2019.
			72.0	1204.	402.	2010.
8.5	60.	-9.2	0.0	208.	330.	2200.
			10.0	293.	328.	2184.
			20.0	388.	325.	2165.
			30.0	495.	321.	2143.
			40.0	612.	318.	2117.
			50.0	737.	313.	2087.
			60.0	861.	308.	2054.
			70.0	1002.	303.	2018.
			72.0	1035.	302.	2010.

FIGURE 20. SAMPLE CASE II OF COMPUTER PROGRAM OUTPUT