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RESEARCH REQUIREMENTS FOR DEVELOPMENT OF IMPROVED HELICOPTER ROTOR EFFICIENCY

By
S. Jon Davis

Prepared under Contract No. NAS1-13624
By
Boeing Vertol Company
Philadelphia, Pennsylvania

for

National Aeronautics and
Space Administration

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ABSTRACT

This report documents the research requirements for developing an improved-efficiency rotor for a civil helicopter. The various design parameters affecting the hover and cruise efficiency of a rotor are surveyed and the parameters capable of producing the greatest potential improvement are identified. Research and development programs to achieve these improvements are defined and estimated costs and schedules are presented. Interaction of the improved-efficiency rotor with other technological goals for an advanced civil helicopter is noted, including its impact on engine noise, hover and cruise performance, one-engine-inoperative hover capability, and maintenance and reliability.

FOREWORD

This report was prepared by the Boeing Vertol Company for the National Aeronautics and Space Administration, Langley Research Center, under NASA Contract NAS1-13624. William Snyder was technical monitor for this work. The Boeing Vertol Project Manager was Wayne Wiesner.

SUMMARY

In order to improve the performance capability of future civil helicopters, the goals of a 9.3-percent improvement in hover efficiency and a 20-percent improvement in cruise efficiency by 1985 have been established.

The improvement in hover efficiency is to be obtained by concentrating on a reduction in the induced power. Cruise efficiency is to be increased by reducing the cruise profile-power component.

Technological gaps have been identified in the areas of presently available rotor test data which reflects the effect of variations in rotor design parameters on rotor efficiency and analytical performance-prediction capability in both flight regimes.

Therefore, research and development programs involving considerable model-rotor testing in both hover and cruise flight are recommended, leading to the eventual design and test of a full-scale, improved-efficiency rotor.

The improved-efficiency rotor:

- Results in a 2.9-percent increase in cruising speed, a 15-percent increase in specific range, and a 12.9-percent decrease in fuel consumption.
- Produces a reduction in empty weight of 3.83 percent.
- Results in smaller engines being sized by the HOEI requirement.
- Produces a 4.42-percent reduction in flyaway cost and a 6.75-percent reduction in direct operating cost.

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LIST OF SYMBOLS

Btu	British thermal unit (1 Btu (mean) = 1055.87 J)
$\bar{c}_d$	average blade-profile-drag coefficient, $\bar{c}_d = \dfrac{8\,P_{PRO}}{\sigma\pi R^2 \rho V_T^3}$
$\bar{c}_\ell$	average blade-lift coefficient, $\bar{c}_\ell = 6\,C_T/\sigma$
C_L	blade-element lift coefficient
C_{m_o}	blade aerodynamic pitching-moment coefficient
C_P	rotor power coefficient, $C_P = P/\rho\pi R^2 V_T^3$
C_T	rotor thrust coefficient, $C_T = T/\rho\pi R^2 V_{TIP}^2$
$dC_{D/dM}$	rate of increase of airfoil-section profile drag with increasing Mach number
DOC	direct operating cost, \$/seat-km
EI	energy intensity, J/passenger-km
EW/GW	structural empty-to-gross weight ratio
F_e	equivalent flat-plate drag area, m^2
FM	helicopter rotor figure of merit, $0.707\,C_T^{3/2}/C_P$
HOEI	hover, one engine inoperative
K_{IND}	hovering-rotor induced-power factor
L/D_E	rotor lift-to-effective drag ratio
M	Mach number
$M_{1(90)}$	advancing-blade-tip Mach number
M_{DD}	drag-divergence Mach number
P_{PRO}	profile-power component of rotor cruise power, kw

P_{IND}	induced-power component of rotor cruise power, kw
R	rotor blade radius, m
R&D	research and development
RDT&E	research, development, test and engineering
Re	Reynolds number
sfc	specific fuel consumption, kg/hr/kw
T	thrust, N
V_{TIP}	rotor tip speed, m/s
V	forward speed, kph
α_{TPP}	rotor tip-path-plane angle, deg
θ_{TWIST}	rotor-blade twist, deg
μ	advance ratio, V/V_{TIP}
ρ	atmospheric density, kg/m^3
σ	rotor solidity, $bc/\pi R$

1.0 INTRODUCTION

Previous studies have shown that, on the basis of fuel efficiency, helicopters can be competitive with other forms of transportation for some missions. Current energy-consumption levels can be reduced, however, through the infusion of advanced technology into the design process.

The studies of reference 1 examined five technological areas that promise to reduce helicopter energy consumption. These are sfc reduction, increased rotor figure of merit and cruise L/D_E, parasite-drag reduction, and reduced empty weight through the application of advanced-composite materials.

Preliminary estimates were made of the development programs required to achieve specified goals. The percentage of energy reduction for each technological area was also estimated and presented as development cost per unit energy intensity saved.

These results, shown in Figures 1 and 2, show that improving rotor efficiency (figure of merit and cruise L/D_E) offers large payoffs in energy reduction at minimum cost.

This report documents the research requirements for developing such an improved-efficiency rotor for a civil helicopter. The various design parameters affecting the hover and cruise efficiency of a rotor are surveyed and the parameters capable of producing the greatest potential improvement are identified. Research and development programs to achieve these improvements are defined and estimated costs and schedules are presented. Interaction of the improved efficiency rotor with other technological goals for an advanced civil helicopter is noted, including its impact on engine noise, hover and cruise performance, one-engine-inoperative hover capability, and maintenance and reliability.

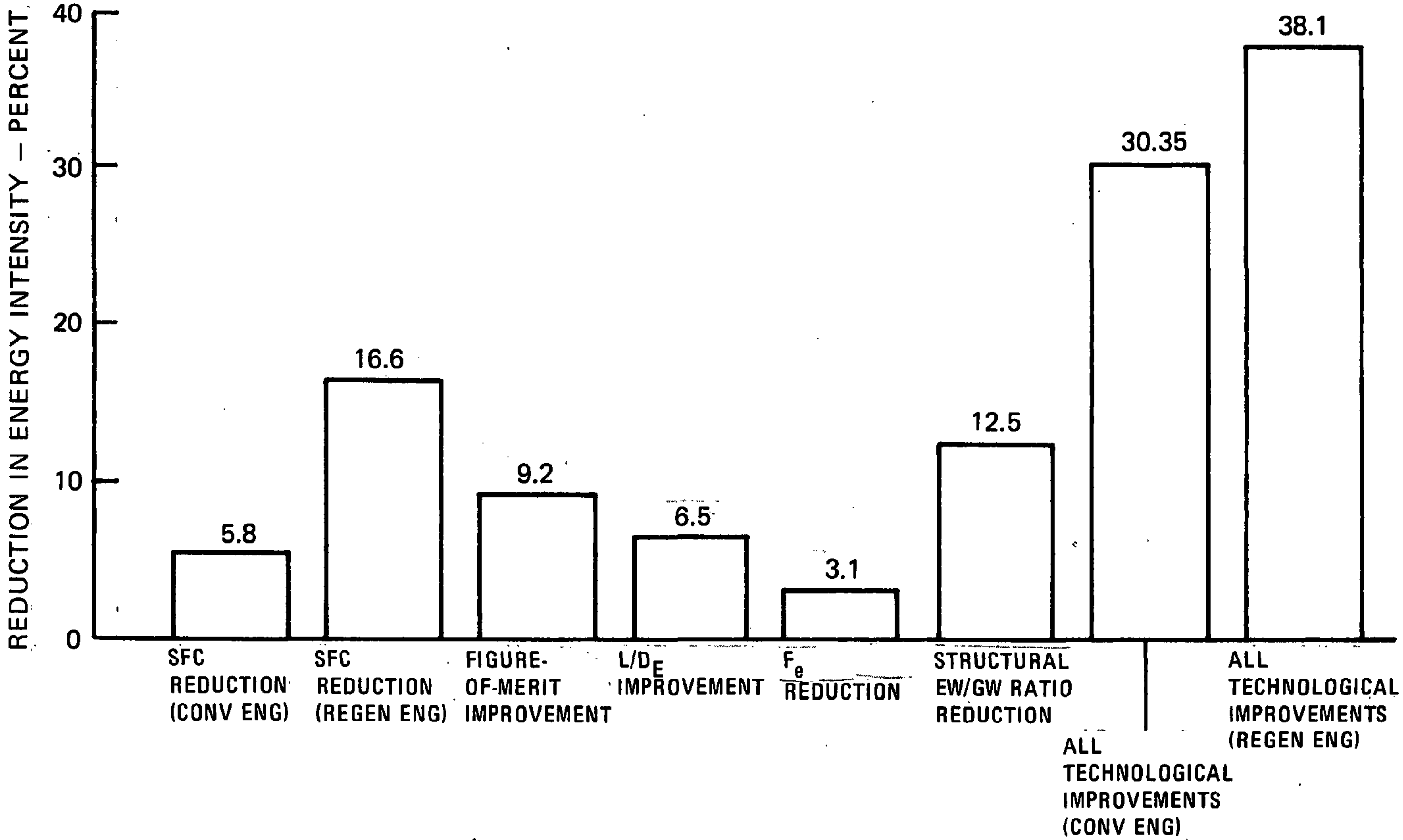

Figure 1. Comparison of reduction in energy intensity for the compromise design mission

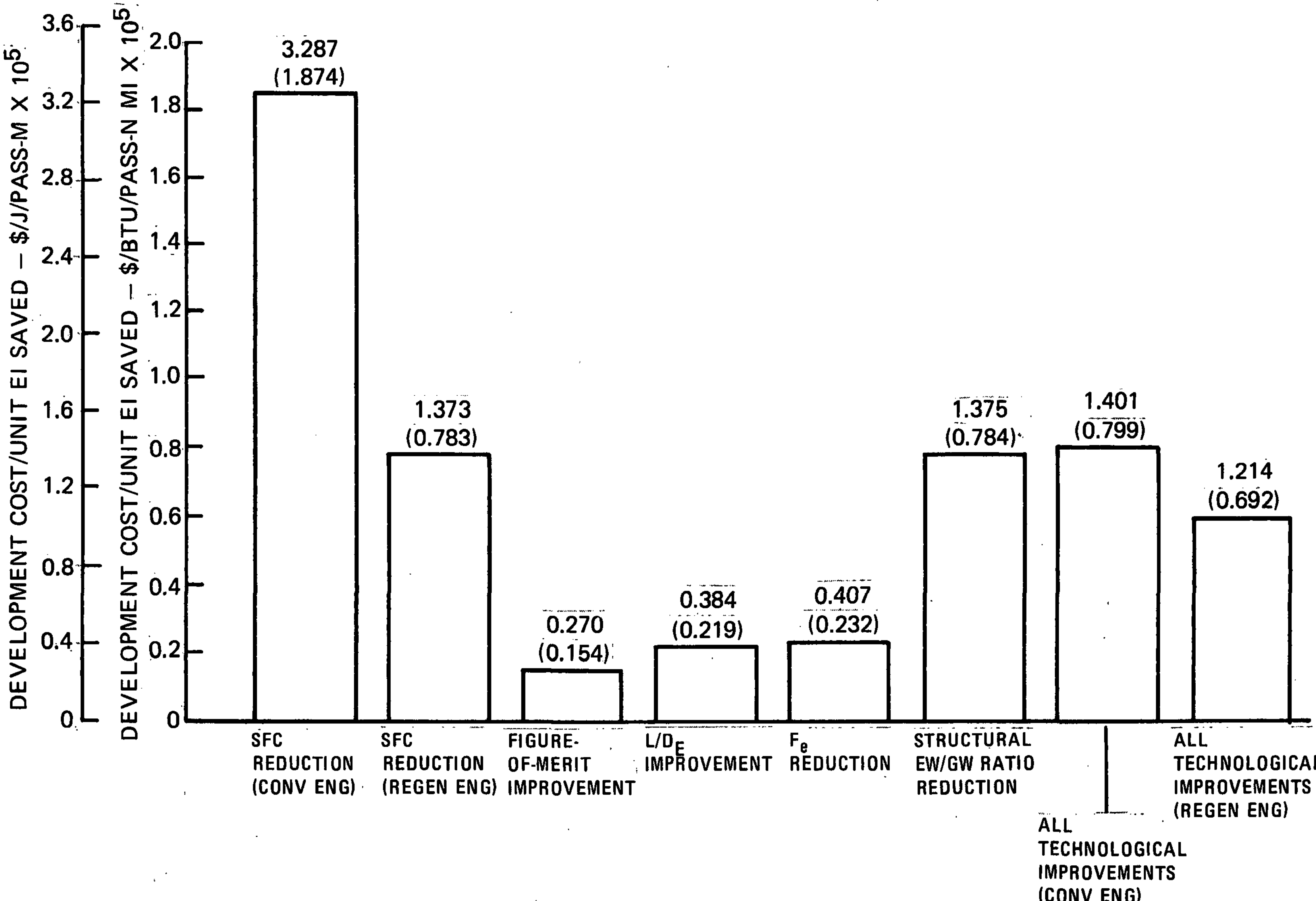

Figure 2. Comparison of technological development in terms of cost/unit EI saved for the compromise design mission

2.0 FACTORS AFFECTING ROTOR EFFICIENCY

The following paragraphs provide some insight into the overall factors governing the improvement of rotor efficiency in hover and cruise.

2.1 Improvement in Figure of Merit

The two major components of figure of merit which have to be improved are the induced and profile powers. The induced power is the theoretical power used to generate lift in the absence of any airfoil profile drag. Momentum theory shows that the induced drag is minimized when a uniform distribution of perpendicular induced or downwash velocity is achieved through the rotor. Increasing the number of blades and/or having nonlinear values of twist result in more-uniform induced velocities with the associated increase in figure of merit.

The other major component of actual hover power, the profile power, is dependent on the best obtainable lift-to-drag ratio. This is a function of local Mach number. For the airfoils in use today, blade sections would have to operate at $C_L = 0.8 \div 0.9$ to achieve the highest lift-to-drag ratio.

In order to visualize the relative importance of the induced- and profile-power components to figure of merit, a simplified analysis (ref. 2) is presented where:

$$FM = \frac{1}{\left[K_{IND} + \frac{2.5984}{\sqrt{\sigma}(\bar{c}_\ell^{3/2}/\bar{c}_d)}\right]}$$

and

K_{IND} = induced-power component

$\frac{2.5984}{\sqrt{\sigma}(\bar{c}_\ell^{3/2}/\bar{c}_d)}$ = profile-power component.

The previous equation is the result of rearranging the basic rotor hover-efficiency relationship,

$$FM = 0.707 \frac{C_T^{3/2}}{C_{P_{IND}} + C_{P_{PRO}}},$$

into the form,

$$FM = \frac{1}{K_{IND} + \frac{C_{P_{PRO}}}{0.707\, C_T^{3/2}}},$$

where

$$C_{P_{IND}} = \frac{\sqrt{2}}{2} K_{IND} C_T^{3/2}$$

$$C_{P_{PRO}} = \frac{\bar{c}_d \sigma}{8} .$$

The profile-power component can be further rationalized into the format of reference 2 by combining the basic rotary-wing definitions of

$$\bar{c}_d = \frac{8}{\sigma} C_{P_{PRO}}$$

$$\bar{c}_\ell = 6 (C_T/\sigma)$$

into the parameter $\bar{c}_\ell^{3/2}/c_d$ (which is analogous to $C_L^{3/2}/C_D$ in fixed-wing performance) so that:

$$\frac{\bar{c}_\ell^{3/2}}{\bar{c}_d} = \frac{1.8371 C_T^{3/2}}{\sqrt{\sigma}\, C_{P_{PRO}}}$$

or

$$C_{P_{PRO}} = \frac{1.8371\, C_T^{3/2}}{\sqrt{\sigma}\, (\bar{c}_\ell^{3/2}/\bar{c}_d)} .$$

This can be substituted into the profile-power component of the simplified hover-efficiency equation to obtain:

$$\frac{C_{P_{PRO}}}{0.707 C_T^{3/2}} = \frac{2.5984}{\sqrt{\sigma}\, (\bar{c}_\ell^{3/2}/\bar{c}_d)} .$$

The factor K_{IND}, or induced-power factor, is the ratio of actual rotor-induced power to the ideal rotor-induced power (assuming a uniform downwash distribution). It can be minimized by optimizing blade chord, twist distribution, and blade number. $\bar{c}_\ell^{3/2}/\bar{c}_d$, the profile-power factor, is influenced by improved airfoil-section characteristics, etc.

Figure 3 is a plot of the required values of K_{IND} and $\bar{c}_\ell^{3/2}/\bar{c}_d$ for given values of FM, assuming $\sigma = 0.10$ as typical of contemporary rotor designs. Superimposed on the plot are typical $(\bar{c}_\ell^{3/2}/\bar{c}_d)_{max}$ levels for symmetrical (NACA 0012) and cambered (V23010-1.58) airfoil sections. Note that the integrated or total blade values of $(\bar{c}_\ell^{3/2}/\bar{c}_d)$ for a rotor employing those sections will be less than the levels illustrated.

Reference 3 defines a maximum or upper limit to the practical amount of improvement in induced power that can be achieved. Figure 4 illustrates this minimum value of K_{IND} as a

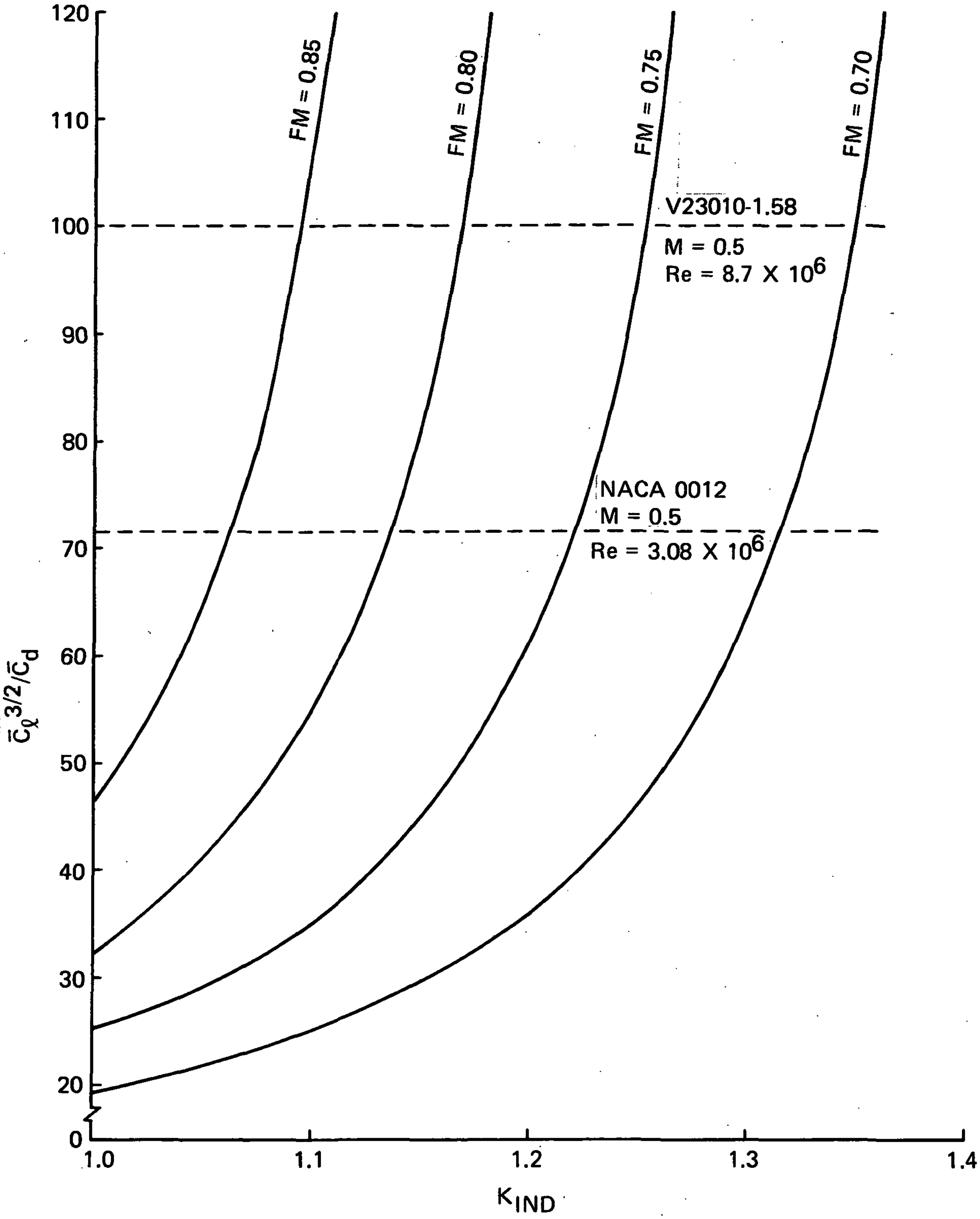

Figure 3. Required values of $\bar{C}_\ell^{3/2}/\bar{C}_d$ and K_{IND} for given values of figure of merit

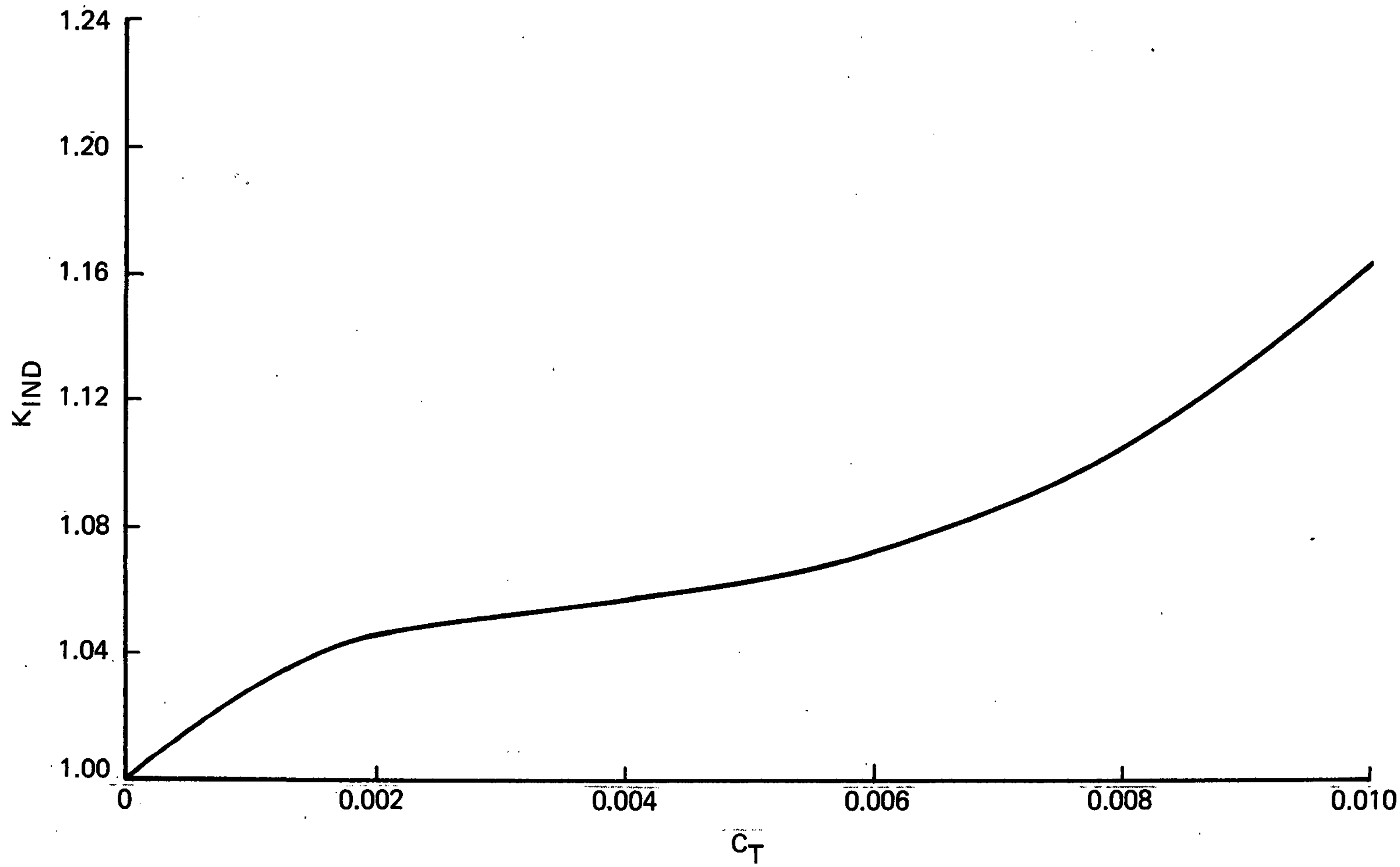

Figure 4. Minimum obtainable induced-power factor, K_{IND}

function of C_T for a 4-bladed rotor. If we assume for purposes of illustration that an integrated value of $(\bar{c}_\ell^{3/2}/\bar{c}_d) = 100$ is obtainable and use that value in combination with the values of K_{IND} defined in Figure 4, we get the maximum FM curve illustrated in Figure 5.

Figure 6 illustrates the different options available for improving rotor efficiency in hover. Point E is representative of a current, 1975-technology, square-tip rotor blade. For purposes of illustration, a desired improved FM level, in this case 0.80, is selected and vectors AE and BE are drawn. Vector AE represents an improvement in FM obtained purely through a reduction in induced power (K_{IND}), while vector BE achieves an FM = 0.80 through improved airfoil characteristics with no change in induced power. It should be noted, however, that vector AE assumes no limit to the amount of induced-power reduction achievable. If such a limit (as defined in Figure 4) is imposed, vector AE is replaced by vector CE.

2.2 Improvement in L/D_E

Forward-flight power required can be divided into profile-, induced-, and parasite-power components.

Profile power is defined as the power required to overcome the profile or frictional losses incurred by the rotor as it turns. As in hover, the basic profile drag is dependent on the lift/drag characteristics of the airfoil sections employed, the surface roughness of the blade, and its operating Reynolds number range. Also included are the profile-drag increments due to compressibility effects on the advancing blade and stall effects on the retreating blade.

Induced power, as in the case of hover, is defined as the power required to generate lift in the absence of airfoil profile drag.

Parasite power is defined as the power required to provide propulsive thrust equivalent to the total parasite drag of the helicopter.

Figure 7 illustrates a typical rotor power-component split with forward speed. Note the reduction in importance of induced power to the total power required as forward speed increases.

For purposes of evaluating the relative efficiency of a rotor in producing lift in forward flight, the profile and induced power can be combined and expressed as an equivalent rotor lift-to-drag ratio, where:

$$L/D_E = \frac{L}{3600\,(P_{PRO} + P_{IND})/V}$$

and L = rotor lift force, N

P_{PRO} = rotor profile-power component, kw

P_{IND} = rotor induced-power component, kw

V = forward speed, kph.

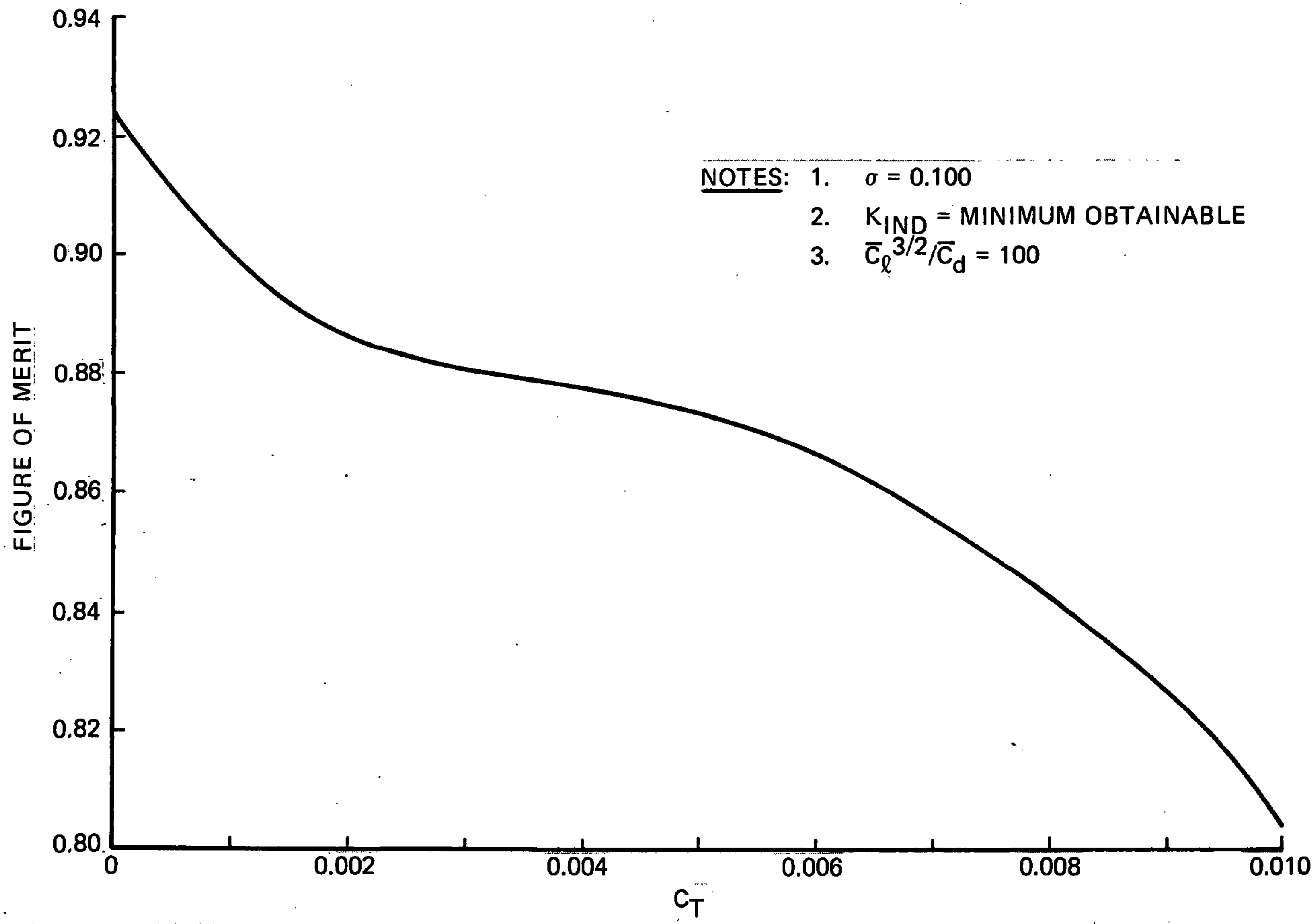

Figure 5. Maximum obtainable hover efficiency

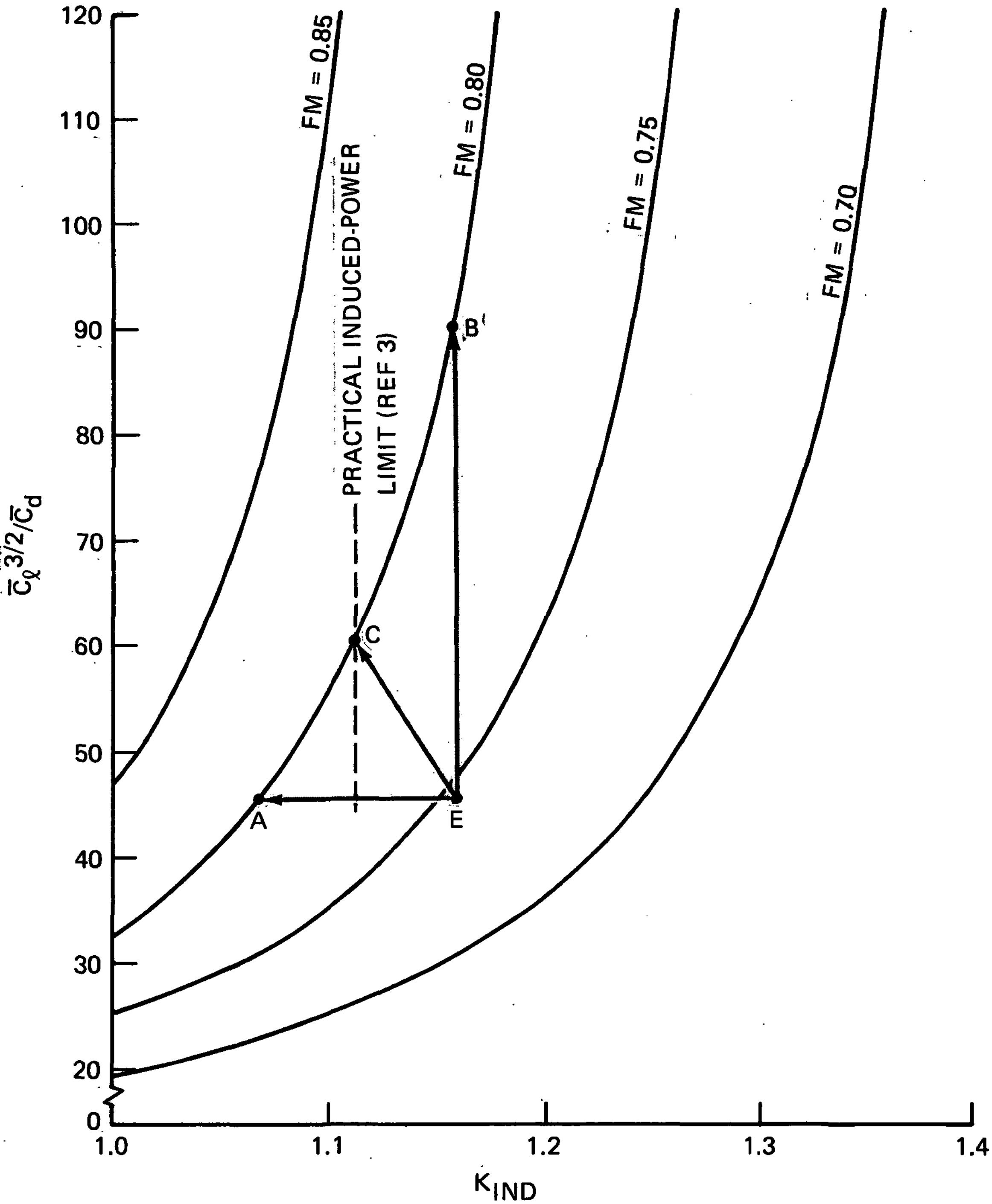

Figure 6. Typical improvement vectors for figure of merit

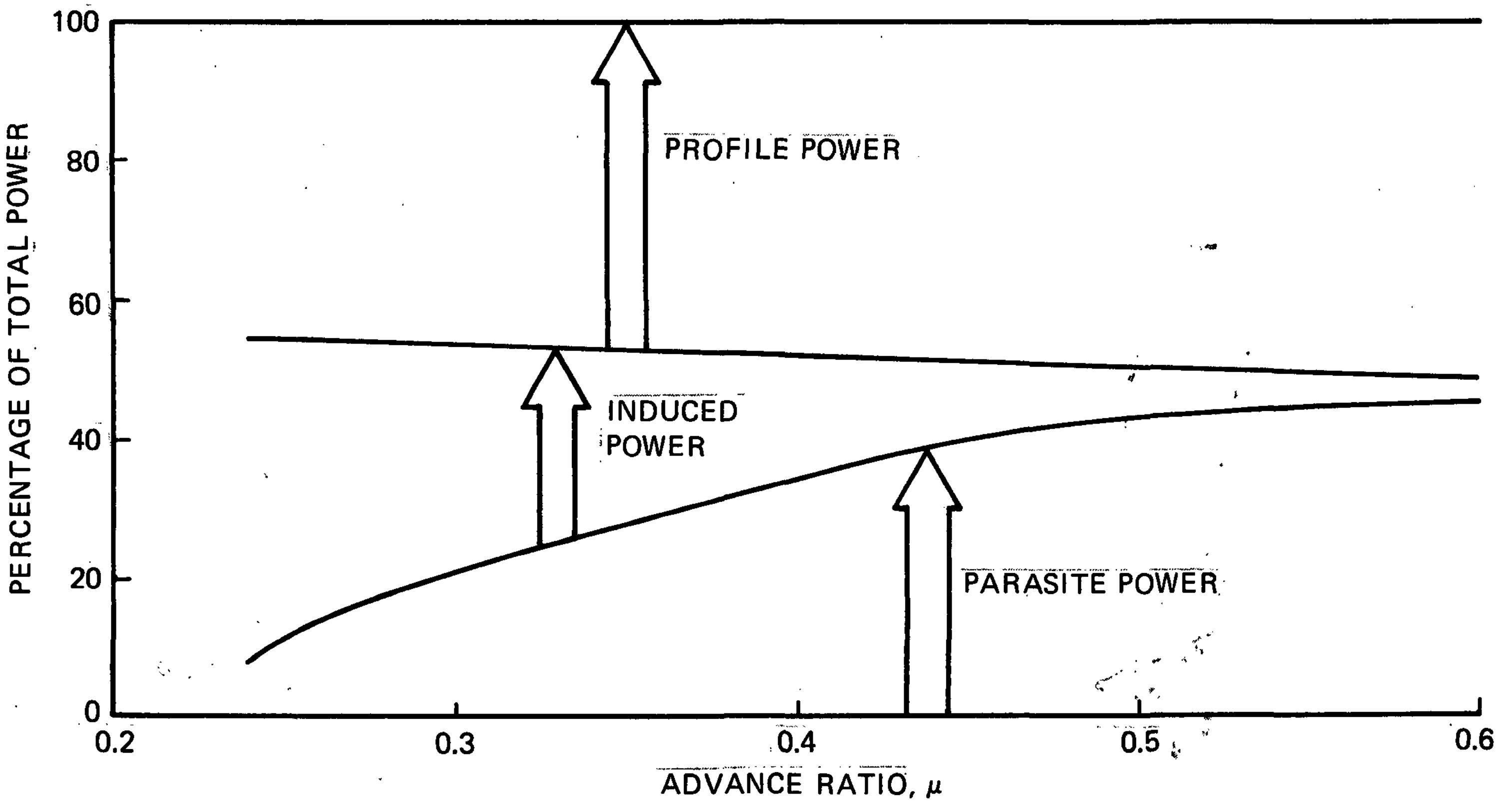

Figure 7. Power-required split in cruising flight

As can be seen from Figure 7, profile power comprises a much greater share of the total power required and therefore presents a greater potential area for L/D_E improvement than induced power.

Figure 8 shows a split of the profile-power component of Figure 7 into its subcomponents.

Figure 9 illustrates the effect on rotor L/D_E of the various individual profile-power components identified in Figure 8. Line ① corresponds to the rotor L/D_E with the profile-power component consisting only of the basic profile-drag subcomponent. The region between lines ① and ② illustrates the reduction in L/D_E resulting from the addition of the advancing-rotor-blade compressibility subcomponent of profile power to line ①. The further addition of the retreating-blade-stall subcomponent to line ② results in line ③.

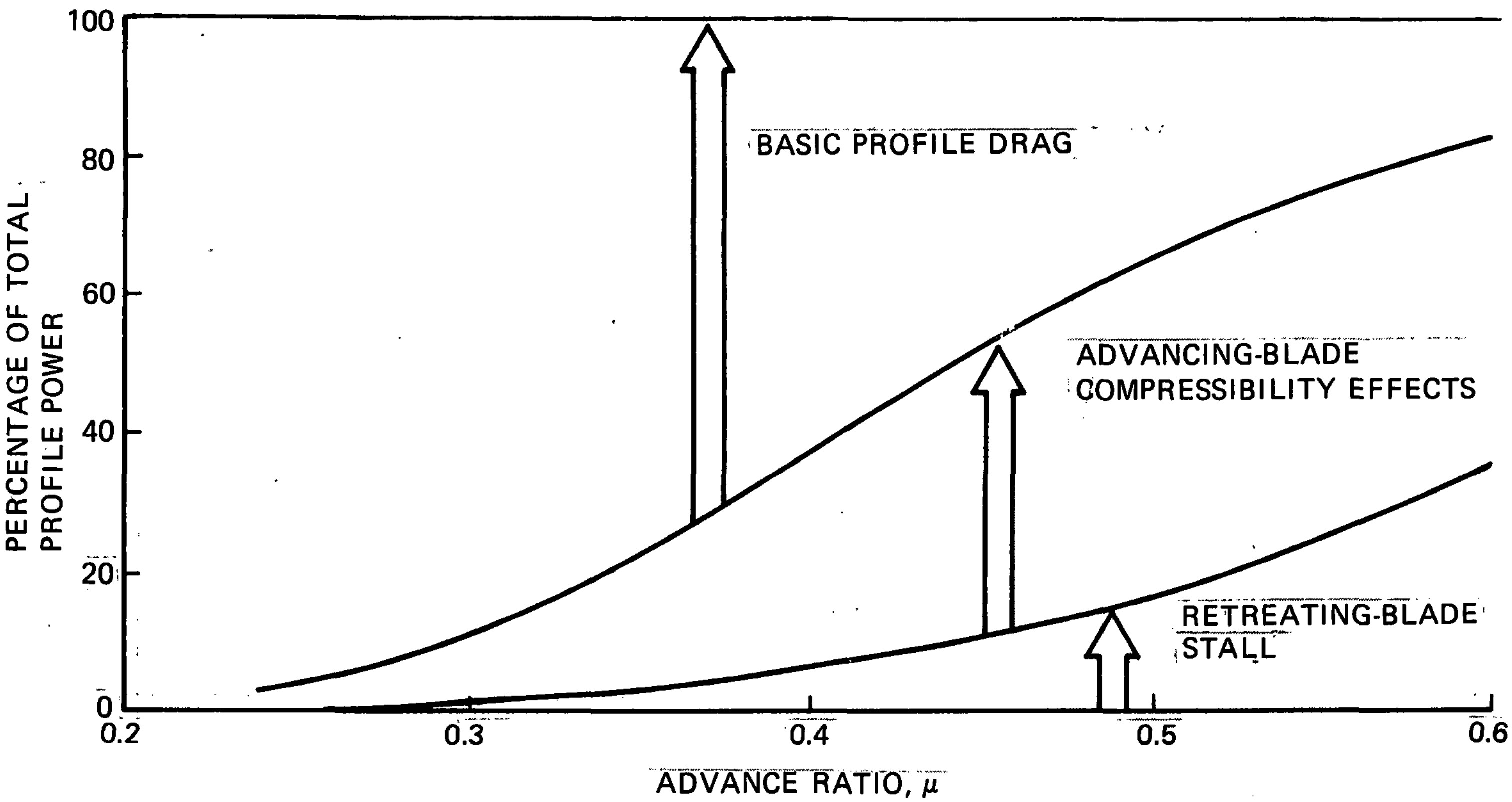

Figure 8. Profile-power-required split in cruising flight

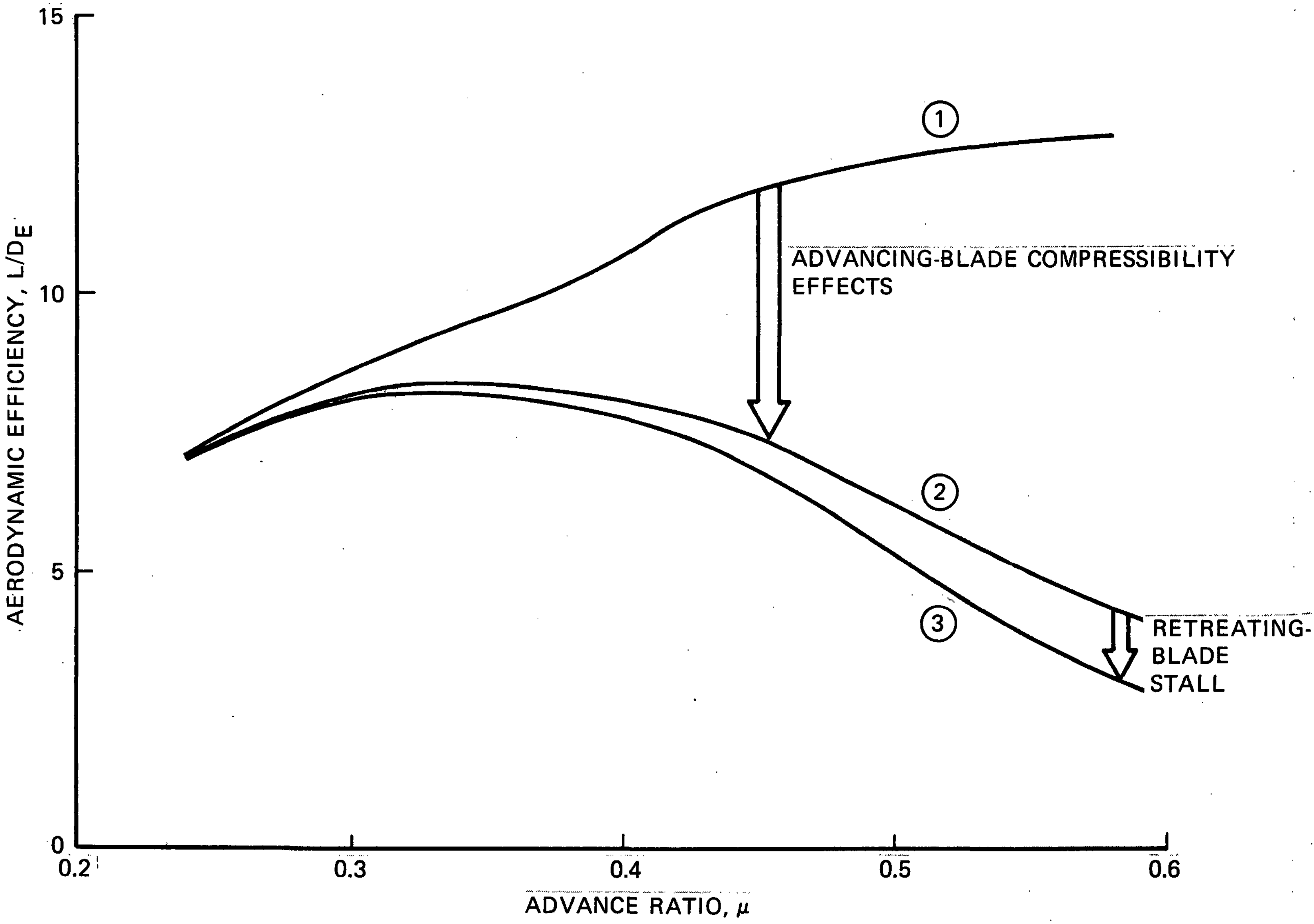

Figure 9. Rotor lift/effective drag

3.0 DISCUSSION OF THE EFFECTS OF DESIGN PARAMETERS ON ROTOR EFFICIENCY

3.1 Factors That Influence Hover Efficiency

As pointed out in section 2.1, the two components of rotor hover power are induced and profile power. For a given number of blades, induced power is influenced very strongly by blade planform and tip shape (spanwise chord distribution) and twist. Profile power is affected by the choice and distribution of airfoil sections, the surface roughness of the blade, and the operating Reynolds number of the blade.

3.1.1 Tip shape. – Induced power is reduced by a more-uniform spanwise distribution of induced velocity across the blade. This induced-velocity distribution is controlled by the spanwise-lift distribution, which can be changed by either twisting the blade or modifying its chord distribution.

Vector DE in Figure 10 is an example of the improvement in induced power possible simply by modifications in the tip-chord distribution of a rotor blade. The reduction in K_{IND} shown was obtained by changing the outer 7.5-percent radius of a square-tip blade to a modified elliptical-chord distribution. Note also the improvement in $\bar{c}_{\ell}^{\,3/2}/\bar{c}_d$ obtained as a result of overall operation of the blade sections at a more-optimum lift distribution.

Figure 11 illustrates the K_{IND} reduction obtained by progressively increasing the percentage radius of the outer portions of the rotor blade changed to a modified elliptical-chord distribution. Note how K_{IND} versus span/radius modified becomes asymptotic to the limiting value of K_{IND} identified by the results of reference 3.

3.1.2 Twist. – Figure 12 illustrates the effect on figure of merit and K_{IND} of twisting a square-tipped, constant-chord blade with a linearly varying twist. Use of a nonlinear twist distribution would result in still greater reductions in K_{IND}.

3.1.3 Airfoil section. – Figure 13 illustrates the effects of airfoil-section type (camber and thickness/chord variations) on hovering efficiency. The upper plot shows the difference in performance between a rotor blade with uncambered and slightly cambered airfoil sections. Note that the cambered blade exhibits improved FM due to increased section L/D values. Note also that as tip Mach number increases, the cambered blade is affected by compressibility-drag increases more than the uncambered blade.

The lower plot shows a comparison in FM between the cambered rotor from above and a rotor with an airfoil section of reduced thickness/chord ratio and less camber. Note that the resulting rotor exhibits higher overall hover efficiency than the uncambered, thicker-section rotor in the upper plot. This is due to the increase in section L/D caused by the camber combined with the improved compressibility characteristics resulting from the thinner airfoil section.

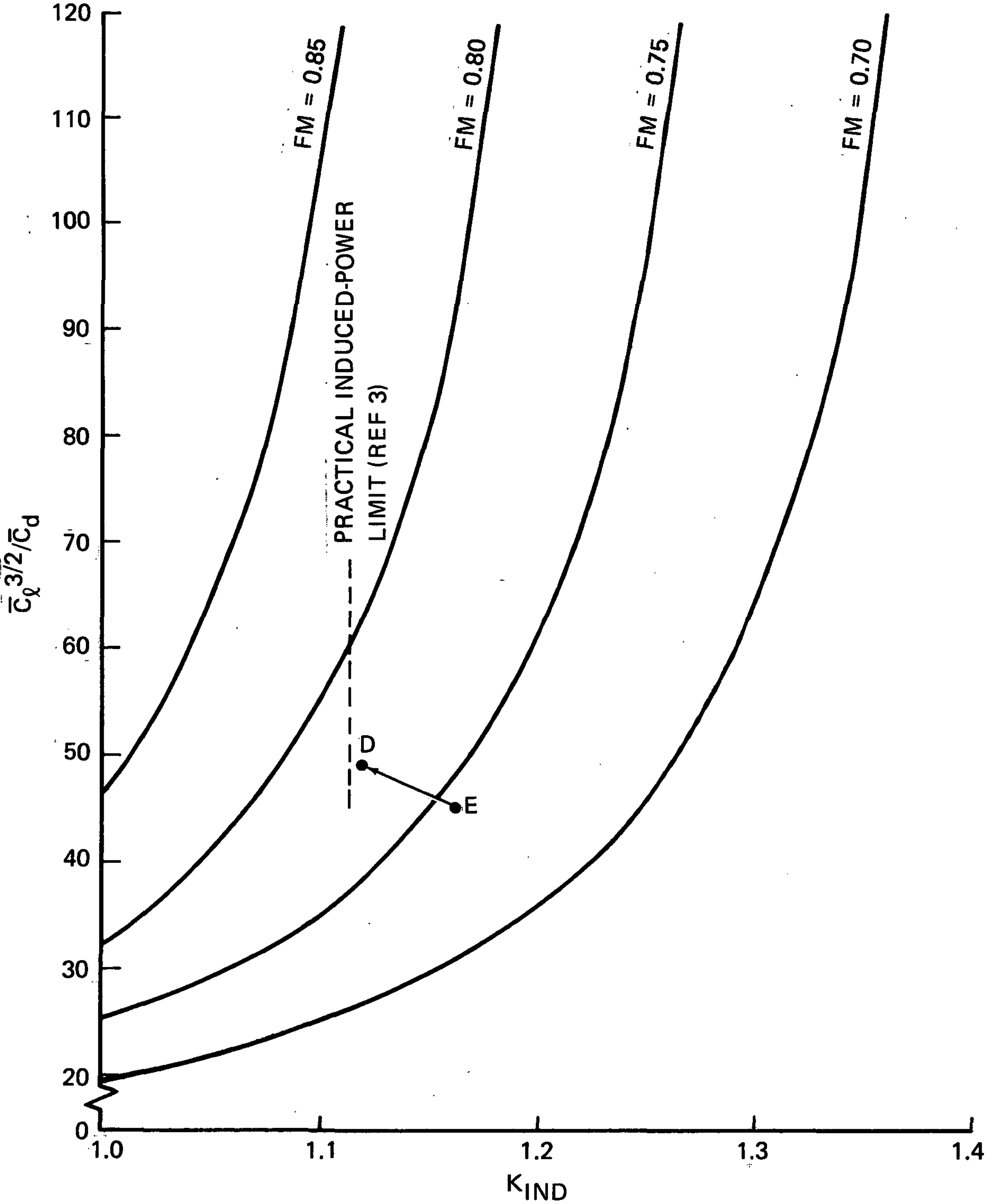

Figure 10. Improvement vectors for figure of merit with elliptical-planform blade tip

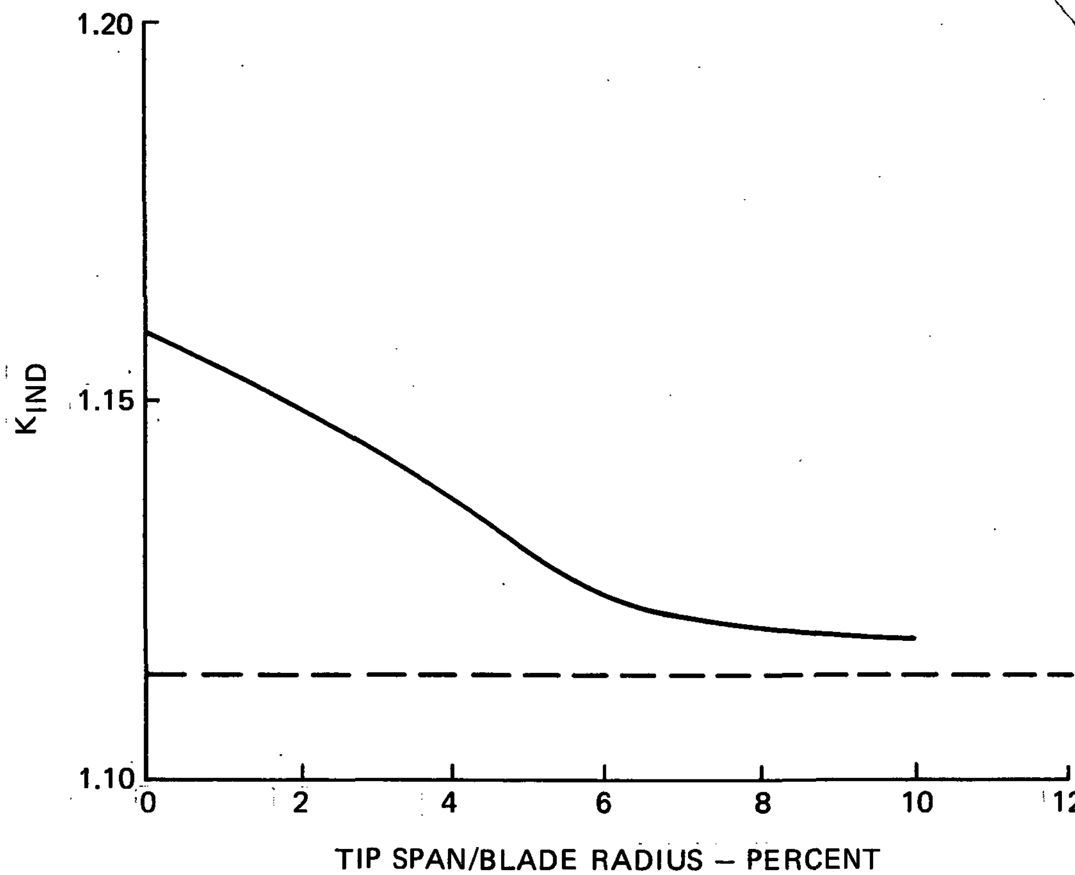

Figure 11. Effect of tip shape on rotor induced-power factor

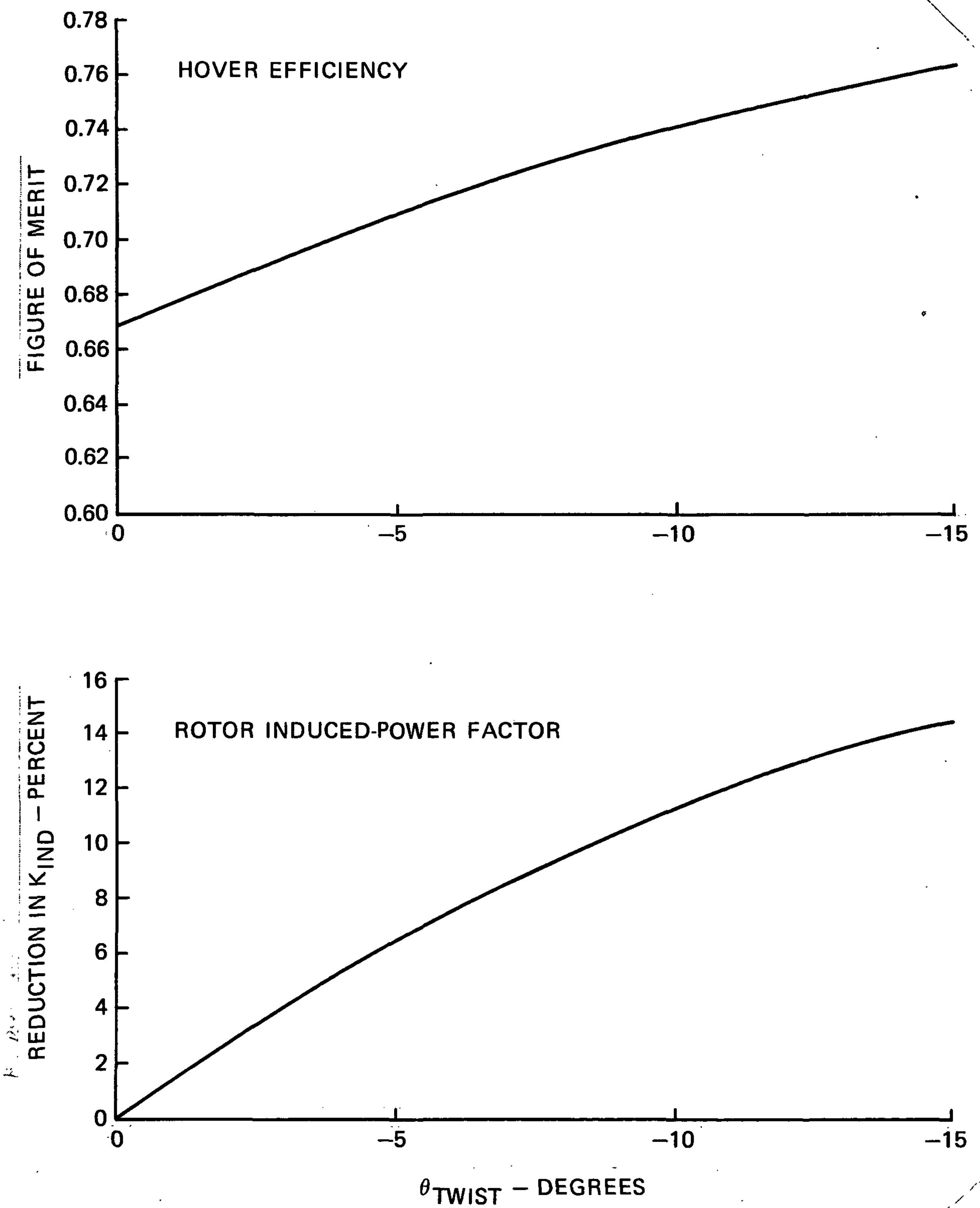

Figure 12. Effect of twist on hover efficiency and on rotor induced-power factor

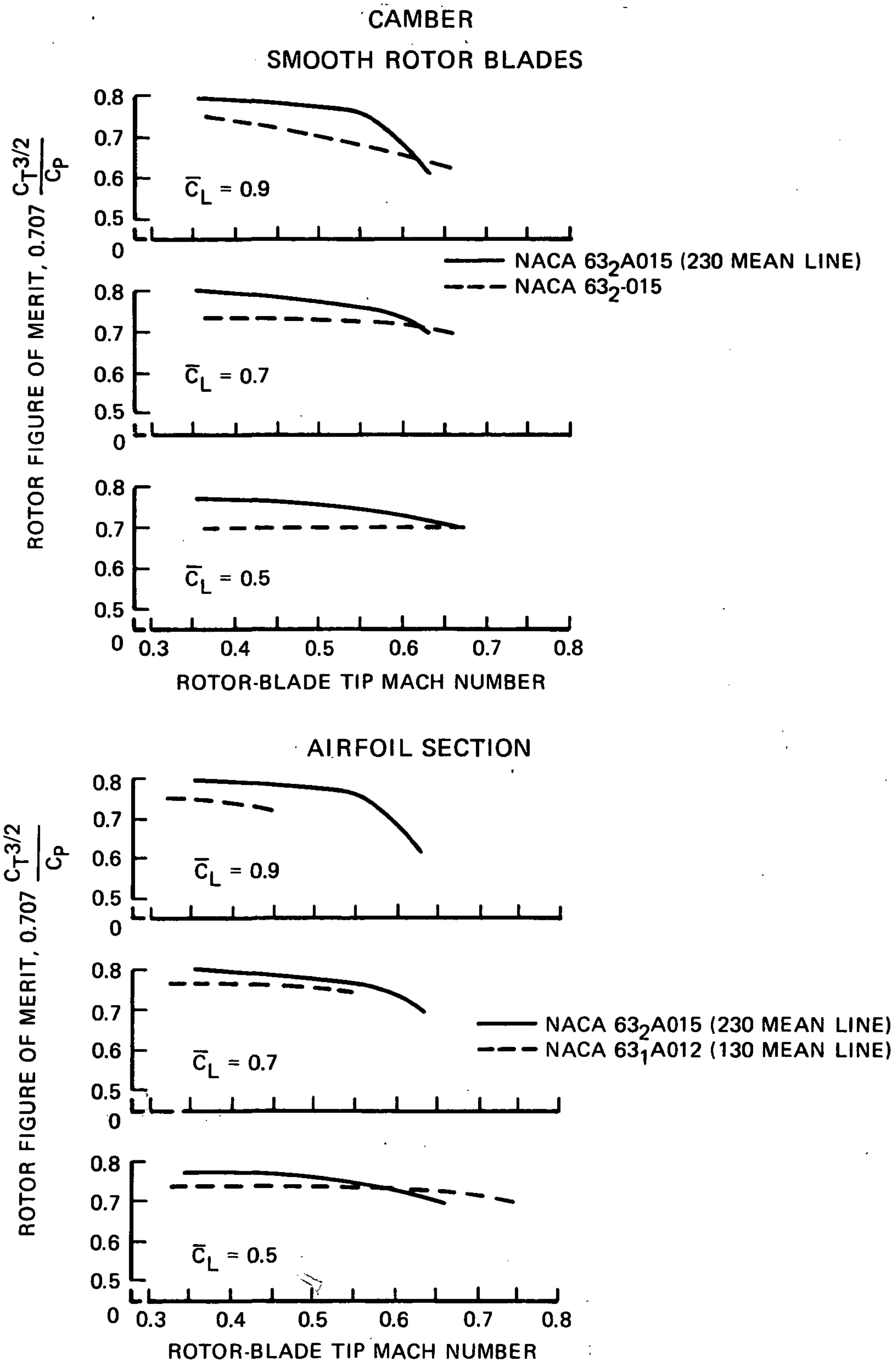

Figure 13. Effect of camber and airfoil section on rotor hovering efficiency

3.1.4 Surface roughness. – Figure 14 illustrates the importance of maintaining relatively smooth surface conditions on the leading edge of a rotor. Note that the standard-roughness condition results in a much more severe degradation in hover performance compared to the slightly roughened leading-edge surface also shown. This is because the standard-roughness condition corresponds to actual grit affixed to the blade surface, rather than the surface waviness of the latter. Obviously the former results in much more turbulent skin-friction drag than the latter.

3.1.5 Reynolds number. – Figure 15 illustrates the effect of Reynolds number on airfoil-section profile-drag coefficient. Reynolds numbers which occur operationally in hover can range from 4×10^5 for model-scale blades to 2×10^7 for full-scale, wide-chord blades operating at moderately high tipspeeds. Note that at the Reynolds numbers associated with full-scale rotors, the minimum C_D obtainable corresponds to the flat-plate turbulent skin-friction-drag trend line. Note also that the variation in Reynolds number referred to above results in a 47-percent variation in profile C_D. Obviously, it is of great importance to have airfoil-section data available over a wide range of Reynolds numbers for use in correcting model-scale results to full-scale conditions and for analytically accounting for the rapid variations in blade chord associated with planform modifications such as those noted in section 3.1.1.

3.2 Factors That Influence Cruise Efficiency

As noted earlier in section 2.2, rotor cruise efficiency, or L/D_E, is a function of both induced and profile effects. The induced component depends primarily on twist and blade planform. The profile component is dependent on blade planform, airfoil-section characteristics, blade-surface roughness, and Reynolds number. System or configuration variables which can be applied to modify rotor L/D_E include higher-harmonic control and lift offset. As seen from Figure 7 in section 2.2, induced effects account for a substantially smaller portion of cruise power than profile effects. Thus, the greatest potential for L/D_E improvement lies in reducing the profile-power component.

3.2.1 Rotor variables. –

3.2.1.1 Twist: In forward flight, since the effect of induced power on overall performance is small, the effect of twist on overall performance is correspondingly small. In fact, the large amounts of static design twist which are desirable from the point of view of increased hover efficiency prove to be a disadvantage in forward flight, producing higher blade stresses and more vibrations than a lower twist. Live, or aerodynamically adaptive twist, offers the possibility of designing a rotor with a large amount of static twist for improved hover efficiency that is automatically reduced in cruise flight, lowering both blade stresses and vibration.

Figure 16 illustrates the almost negligible effect such a twist change has on the cruise L/D_E of a rotor. The data shown was obtained by inducing a nose-up pitching moment on a model rotor, thus tending to unwind it.

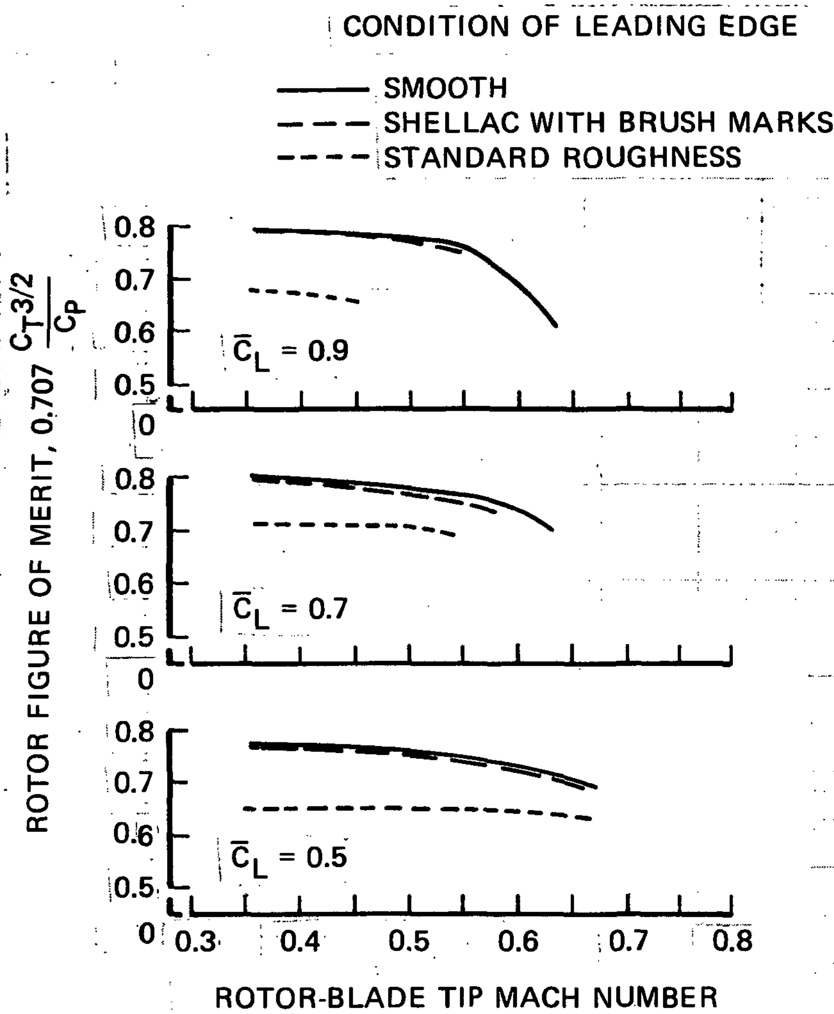

Figure 14. Effect of roughness on rotor hovering efficiency

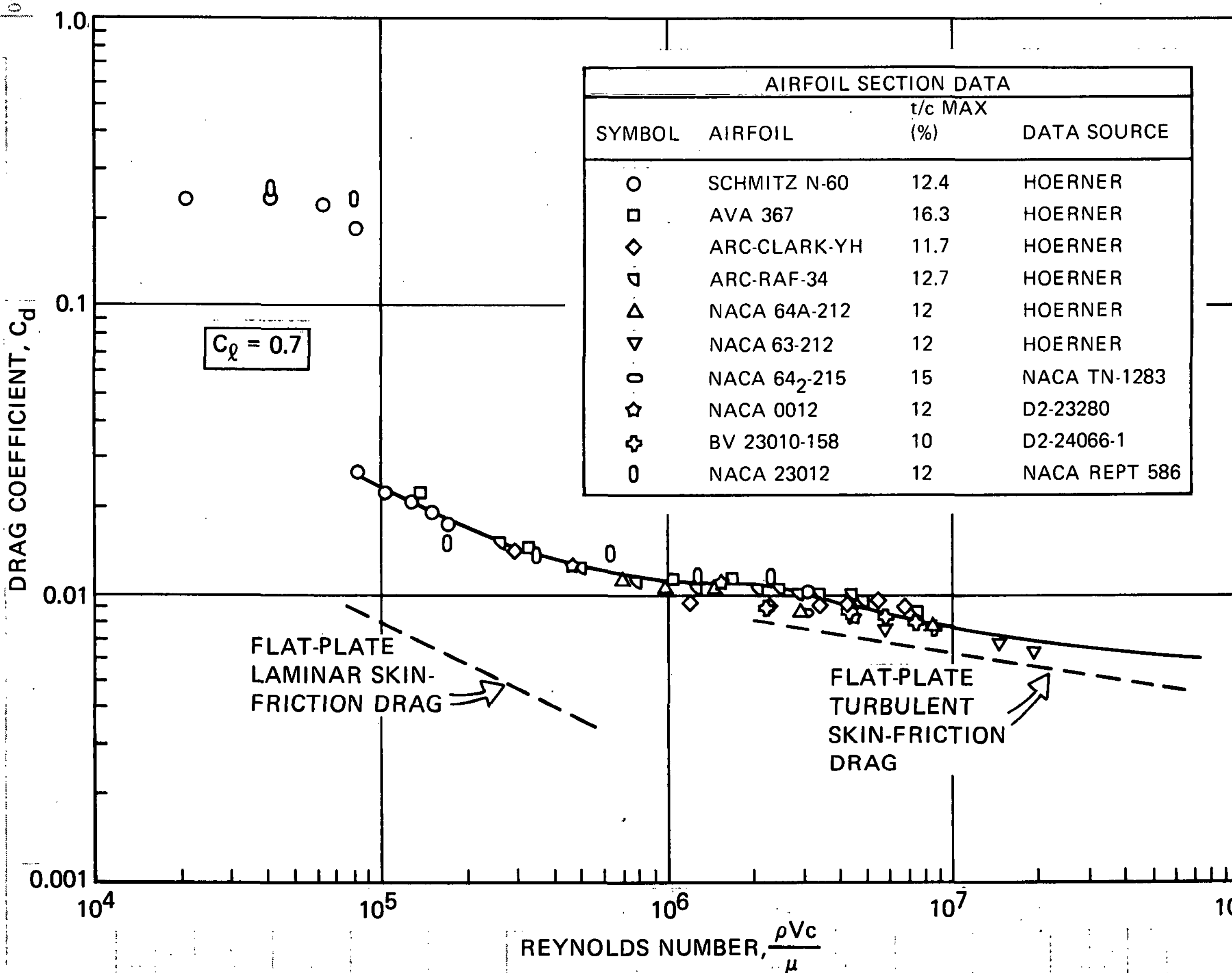

Figure 15. Effect of Reynolds number on coefficient of drag

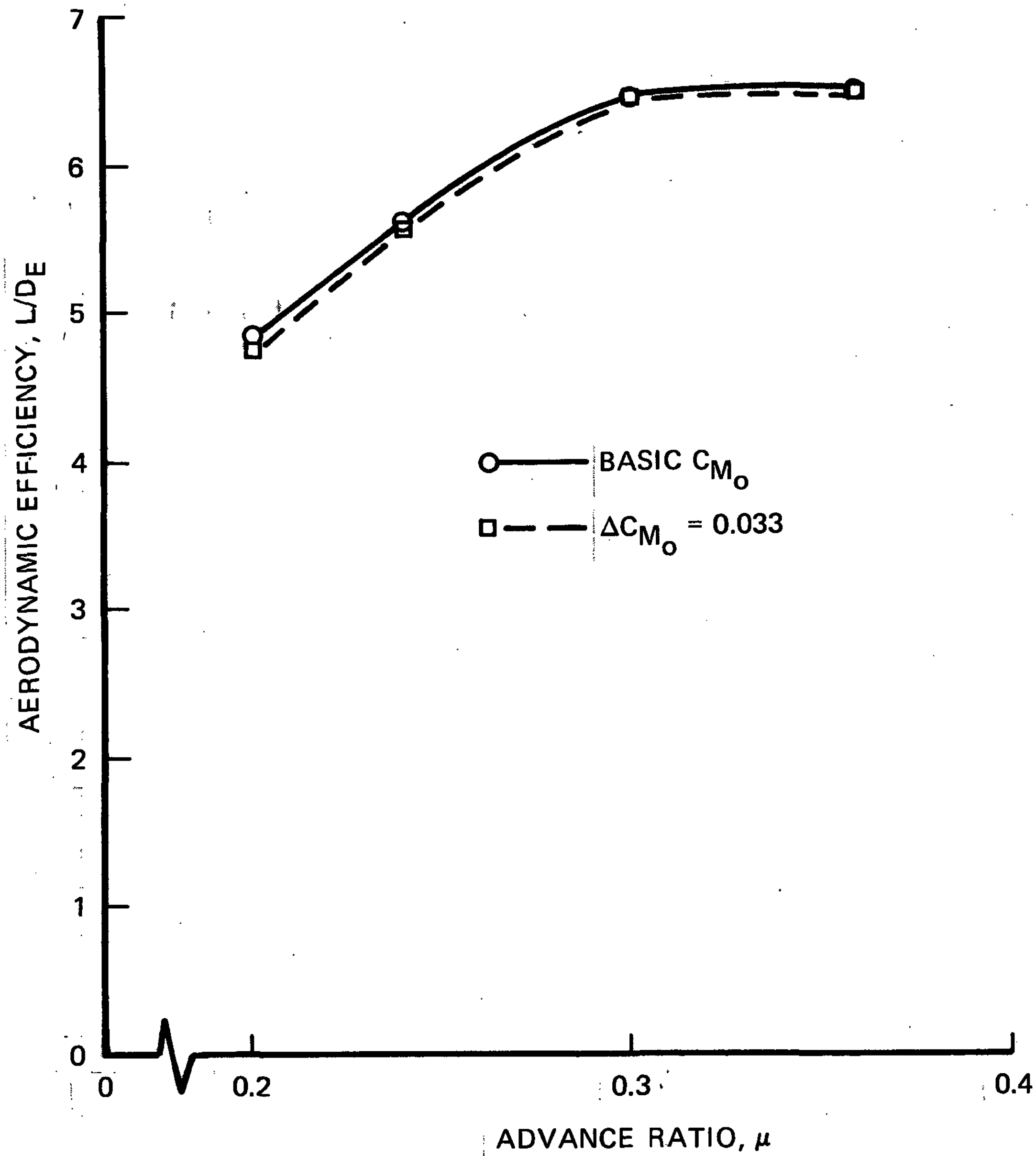

Figure 16. Effect of change in blade twist on aerodynamic efficiency

3.2.1.2 Blade planform and tip shape: The primary effect of blade planform, or tip-shape modification, on a rotor in forward flight is the redistribution of the lift in a more efficient manner, allowing operation at more-optimum section C_L's and thus reducing the section profile drag (and therefore rotor profile power). Table 1 shows the improvement in cruise L/D_E obtained by revising the outboard 10 percent of a square-tip rotor blade to a modified elliptical-chord distribution.

TABLE 1. EFFECT OF CHANGE IN BLADE-TIP PLANFORM ON AERODYNAMIC EFFICIENCY

Advance Ratio, μ	Percentage Improvement in Rotor L/D_E Due To Elliptical-Planform Tip
0.180	10.86
0.260	10.64
0.333	7.64
0.380	5.62

3.2.1.3 Airfoil-section characteristics, surface roughness, and Reynolds number: Airfoil-section drag characteristics in cruise flight influence profile power in the same manner as in hover. For example, increased camber results in higher section L/D_E's with a resultant profile-drag reduction and an overall rotor L/D_E increase. However, this increase in L/D_E is likewise accompanied by increased vibration and blade stresses due to the increased section C_M. For this reason, large values of camber, with their resultant performance benefits, are generally avoided in rotor-blade design. Also, as in hover, the surface roughness and operational Reynolds number are important in determining section profile-drag level, and therefore rotor profile power.

Of critical importance, however, are the section-compressibility characteristics of the airfoil such as drag-divergence Mach number and the rate of increase of C_D with increasing Mach number (dC_D/dM). Improvements in this technological area are of benefit to both hover and cruise flight. However, as evidenced by the increasing dominance of the advancing-blade compressibility effects on total profile power as displayed in Figure 8 of section 2.2, such improvements are of paramount importance in cruise flight.

Traditionally, high-drag-divergence Mach numbers have been obtained by using relatively thin airfoil sections; but with the recent advances in supercritical and transonic airfoil technology, it should be possible to design moderately thick airfoil sections with favorable compressibility characteristics which, at the same time, do not compromise the low-speed high-lift characteristics excessively.

3.2.2 Rotor-system and configuration variables. –

3.2.2.1 Higher-harmonic rotor-system control: As noted in the previous section, advancing-blade compressibility effects represent a sizable proportion of the rotor profile power at higher flight speeds. Instead of tailoring airfoil sections to obtain more-favorable compressibility characteristics, an alternative approach is to lower the rotor tipspeed in forward flight, thus reducing the advancing-blade Mach number.

This tipspeed reduction, however, increases the rotor advance ratio at a given forward speed, resulting in increased amounts of retreating-blade stall and an enlarged reverse-flow region. Thus, by simply reducing tipspeed, we have replaced advancing-blade-compressibility problems with retreating-blade-stall problems. It is possible, of course, to relieve retreating-blade stall simply by unloading the rotor with a wing; i.e., compounding the helicopter.

The other recourse is to use higher-harmonic control in a reverse-velocity-rotor system, obtaining substantial lift in the reverse-flow region and redistributing the rest of the lift between the advancing and the fore-and-aft sections of the rotor disk in order to obtain a substantial rotor L/D_E increase. Figure 17 illustrates the L/D_E's to be expected from such a configuration. The upper L/D_E trend reflects rotor operation with no attempt at trimming out rotor-blade flapping. Application of control power to eliminate blade flapping results in the lower L/D_E line illustrated. The L/D_E levels achieved are particularly noteworthy, considering that current-technology rotors are operating at L/D_E's of about 6 at advance ratios on the order of 0.4. The main disadvantages of such a system are the complexity of the hub and control systems and the requirement to operate at or near autorotation, with auxiliary propulsion being needed.

3.2.2.2 Lift-offset-rotor configurations: A second approach to the reduction of advancing-blade-compressibility effects is in the use of the highly lift-offset rotor. In this concept, rotor tipspeed is reduced with the attendant increase in advance ratio (and inherent potential for retreating-blade-stall problems), and retreating-blade stall is dealt with by dumping lift on the retreating side of the rotor and increasing the lift by a like amount on the advancing side. The proportion of lift reduction on the retreating side to lift addition on the advancing side results in a given fraction of lateral lift offset relative to the rotor center of rotation. Figure 18 illustrates a typical trend of L/D_E and lift as a function of percentage of lateral lift offset. The major disadvantages of this type of system are in the large aerodynamic rolling moment generated by the lift offset and the necessity, as in the RVR concept, for auxiliary propulsion at higher speeds. The rolling moment can, however, be dealt with by various configuration approaches. Four such configurations are:

1. The coaxial superposition of two counterrotating, highly lift-offset rotors (as in the Sikorsky ABC concept).

2. Two oppositely rotating, highly lift-offset rotors in a tandem configuration.

3. Two oppositely rotating, highly lift-offset rotors in a lateral (side-by-side) configuration.

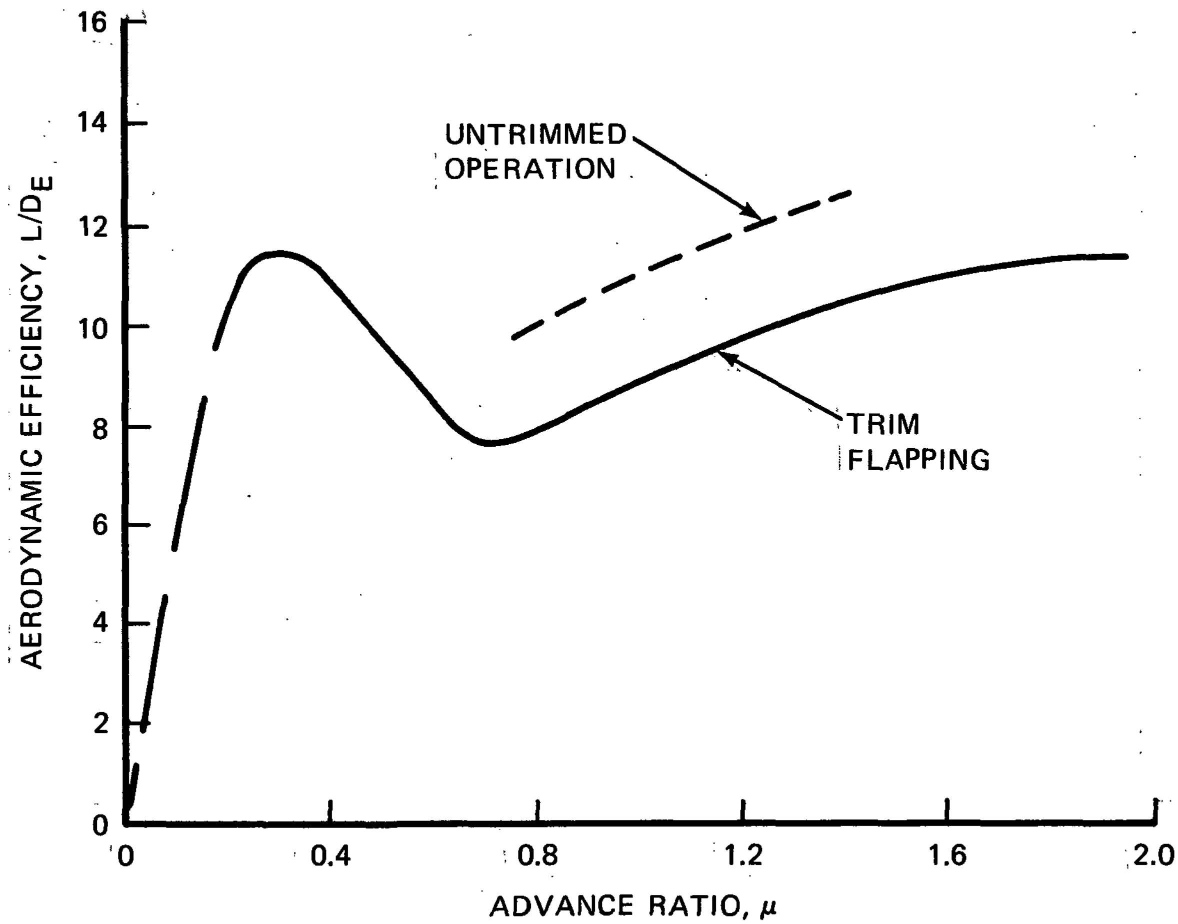

Figure 17. Estimated aerodynamic efficiency of the full-scale reverse-velocity rotor

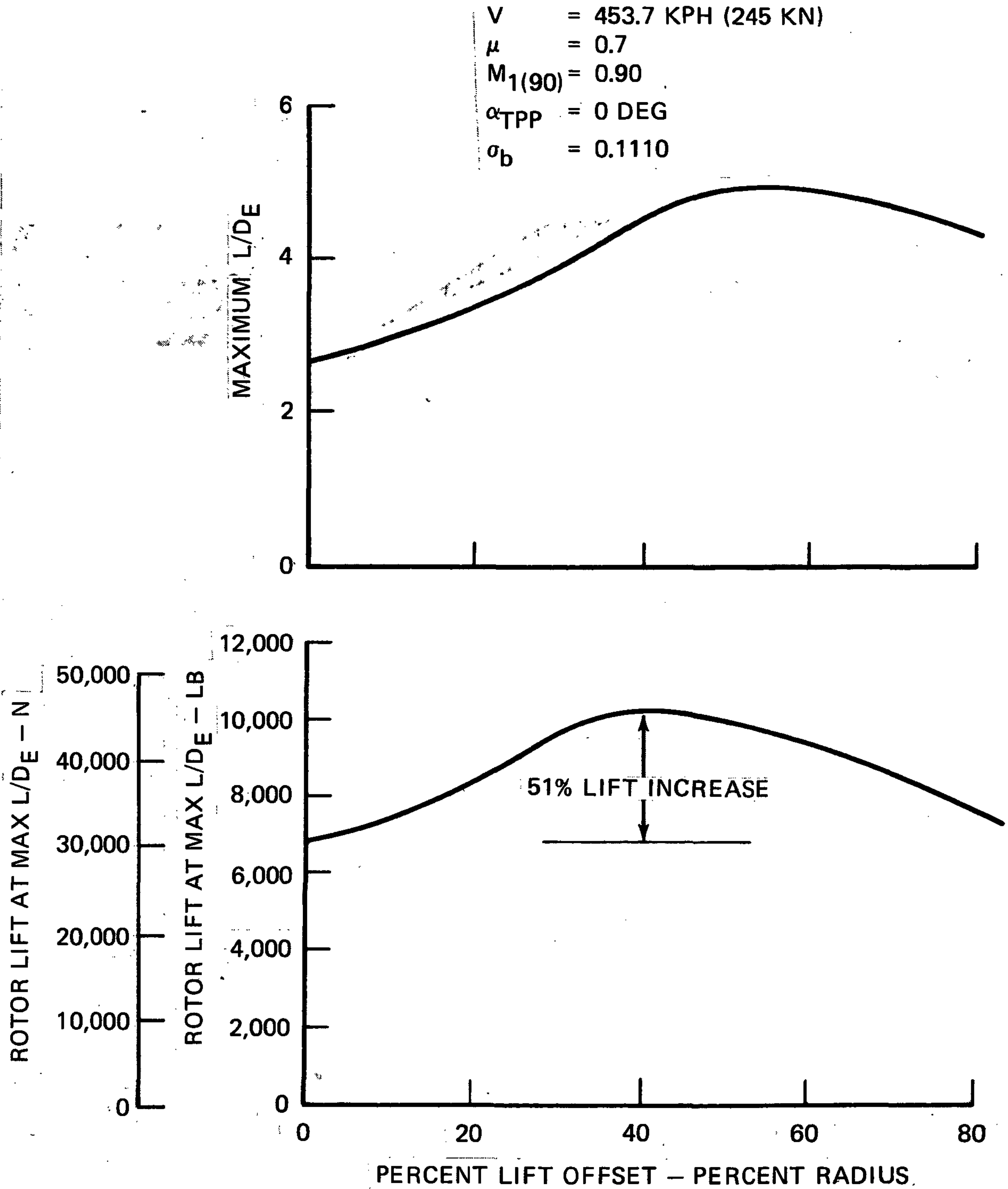

Figure 18. Trend of lift and aerodynamic efficiency with percent lift offset

4. Use of a single, highly lift-offset rotor in a geometrically asymetrical single-main-rotor with tail-rotor configuration.

The potential disadvantages of these various configurations can be summarized as follows:

Approach 1 results in a relatively heavy rotor mast and complex control system due to the need to provide rotor-blade clearances and differential-pitch inputs to the counterrotating coaxial rotors and to absorb the rolling moment in the rotor mast.

Approach 2 results in a heavy fuselage structure since the portion of the fuselage between the rotor masts must absorb the opposing rolling moments, in essence converting the fuselage into a large torque tube.

Approach 3 results in a configuration which takes up a lot of space due to its basic geometry and has a heavy wing and strut structure since the rotor lift is concentrated at the tips of the wing/strut and the major portion of the vehicle weight is at its center. Thus the wing/strut structure must absorb tip-lift forces, the concentrated vehicle weight, and opposing aerodynamic rolling moments.

Approach 4 requires extremely careful design and careful control of the center of gravity and weight and balance.

4.0 CURRENT TECHNOLOGY

4.1 Previous Research and Development

4.1.1 Improvement in Rotor Figure of Merit. – During the first 30 years after the first successful helicopter flights in the 1930's, figure of merit had only increased in percentage from the high 60's to the low 70's. But in the last few years, motivated by the U.S. Army to develop the lifting capability of cargo-carrying helicopters, the slope of figure-of-merit improvement versus time has been increasing.

Limited investigations in the past have been carried out to determine the effect of variations in airfoil-section camber and thickness on hover efficiency (ref. 4). Current interest at Boeing Vertol revolves around investigations into the effect of tailoring the tip-chord geometry to increase hover efficiency by reducing the induced-power component (ref. 5).

4.1.2 Improvement in Rotor L/D_E. – Work is in progress in industry, NASA, and the Army to increase the L/D_E (presently near 6) to values approaching 7 or 8. The most interesting of this work is that variable twist changes the span and azimuthal loading of the rotor and decreases the blade cyclic loads. With variable twist, both the aerodynamic and structural speed limits of rotors as well as increased L/D_E at a given airspeed can be obtained. The variable twist can be put in mechanically (Kaman) or through blade aeroelastic features of such nature as to favorably redistribute the loadings over the rotor disk (Boeing, ref. 6).

Experiments and analyses are also being conducted (Boeing/Army) to extend efficient L/D_E values to higher advance ratios ($\mu \rightarrow 0.6$). Results of preliminary tests show that rotor propulsive forces with adequate lift and L/D_E's of 7.5 can be developed by conventional rotors at forward speeds up to 463 kph (250 knots) by the use of high values of cyclic pitch.

Limited testing has also been conducted to determine the effects of blade-tip-planform modifications on rotor cruise efficiency (ref. 7).

4.2 Technological Gaps and Problem Areas

Existing gaps and problem areas in the technology of rotor hover and cruise performance have been identified as follows.

4.2.1 Hover Performance. – There is no broad base of low-Reynolds-number airfoil-section data for use in rotor hover-performance analyses.

- There is no one rotor hover-performance analysis which easily and accurately reflects the effect of blade-tip-planform shape on hover performance.

- There is no extensive base of rotor test data (either model or full-scale) which reflects the interplay of various combinations of twist, planform, blade-tip geometry, and airfoil sections on hover performance.

4.2.2 Cruise Performance. – There is no one rotor cruise-performance analysis which easily and accurately reflects the effect of blade-tip-planform shape on cruise performance.

- There is no extensive base of model or full-scale rotor test data which shows the effect of blade parameters such as tip shape and airfoil sections on rotor profile and induced power (and therefore L/D_E).

- There is a lack of detailed knowledge on the interaction of aeroelastic and dynamic effects on areas such as retreating-blade stall and their subsequent effects on rotor profile power (and therefore rotor L/D_E).

5.0 RESEARCH AND DEVELOPMENT REQUIREMENTS

Rotor technological gaps and problem areas are defined in section 4.2. The following represents a summary of the actions which must be taken in order to realize the goals set forth in reference 1.

5.1 Improvement in Hover Efficiency (Figure of Merit)

As indicated by Figure 6 in section 2.1, reducing induced power is a more powerful means for improving the hover efficiency of current rotors than reducing profile power. Accordingly, the primary emphasis should be placed on gaining a better understanding of the interaction of blade design parameters and induced-power effects, and a secondary emphasis placed on improving and developing new airfoil sections.

This can be accomplished by:

- Considerable model-rotor hover testing of various combinations of planform, tip shape, twist, and airfoil sections to obtain a broad range of both induced- and profile-power data.
- Development of improved analytical techniques for accurate hover-performance prediction of rotor blades designed to benefit from the technological data base obtained in the first step. Such techniques must be capable of dealing with rotor blades having spanwise chord variations and nonlinear twist and operating at high thrust coefficients.
- Considerable airfoil-section testing at low Reynolds numbers to build up a data base for use in the hover-performance prediction of various planform and tip-shape blades with the improved analytical tools noted above.
- Additional airfoil-section development work concentrated in the area of improving compressibility-drag-rise characteristics such as drag-divergence Mach number (M_{DD}) and dC_D/dM.
- Employment of the rotor-optimization trends obtained from the broad model-rotor test program in conjunction with the improved analytic performance and design techniques to produce a full-scale optimum hovering rotor.

5.2 Improvement in Cruise Efficiency (L/D_E)

As discussed in section 3.2, the reduction of profile power in cruise flight is of the utmost importance in increasing rotor L/D_E. Such a reduction can be achieved by concentrating on obtaining a better understanding of the mechanisms inherent in both the retreating-blade-stall and advancing-blade-compressibility components of profile power and using both rotor design parameters and vehicle configuration approaches to reduce their effects.

This can be accomplished by:

- Considerable model-rotor testing (wind-tunnel) of various combinations of planform, tip shape, twist, and airfoil sections to obtain a broad understanding of the effect of these blade design parameters on rotor L/D_E.
- Development of improved analytical cruise-flight performance-prediction techniques which can accurately reflect the interaction of the blade design parameters specified above on rotor forward-flight cruise performance.
- Development of airfoil sections with improved compressibility characteristics such as increased drag-divergence Mach number (M_{DD}).
- Investigation of the interactions of blade aeroelastic/dynamic effects on areas such as retreating-blade stall and determination of the value of concepts such as live twist and higher-harmonic control in both reducing blade stresses and vibrations and increasing rotor L/D_E by reducing the effect of the retreating-blade-stall component of profile power.
- Further study of advanced rotor-system concepts such as the reverse-velocity rotor and configuration approaches such as the highly lift-offset rotor as means of reducing the retreating-blade-stall component of profile power.

5.3 Integration of Rotor Design Parameters

Some of the approaches to be investigated for improving rotor efficiencies are compatible with both flight regimes; for example, improvements in airfoil-section compressibility characteristics can be of benefit to both hover and cruise efficiencies. Some are not; the RVR system uses a double-ended airfoil section for obtaining lift in the reverse-flow region in forward flight, thus increasing L/D_E. This type of airfoil section, however, penalizes the rotor hover performance compared to a more conventional section. Thus, in developing an optimum rotor, care must be exercised in the integration of the rotor design parameters to obtain this combination for maximum efficiency in hover and cruise.

5.4 Schedules and Estimated R&D Costs for Improvement of Rotor Efficiency in Hover and Cruise

Figures 19 and 21 are the schedule and estimated R&D costs for programs to improve rotor hover and cruise efficiency.

Figures 20 and 22 are plots of program expenditures and improvements in figure of merit and cruise efficiency as a function of time.

ITEM	PROGRAM YEAR 1	2	3	4	5	6	7	COST ($)
HOVER TESTS (MODEL) TO ISOLATE GEOMETRY EFFECTS	■		■					200,000
AIRFOIL TESTS TO OBTAIN CHARACTERISTICS AT SAME REYNOLDS NUMBER AS HOVER-MODEL TESTS	■							50,000
DEVELOP COMPUTER MODEL THAT PREDICTS EFFECT OF TIP SHAPE, TWIST, PLANFORM, AND AIRFOIL	■	■						75,000
ASSESS THE LOADS AND PERFORMANCE OF THE HIGH-FIGURE-OF-MERIT ROTOR IN HIGH-SPEED FORWARD FLIGHT BY COMPUTER ANALYSES		■	■					100,000
DESIGN AND CONSTRUCT ROTOR MODEL THAT CONTAINS THE BEST BLADE SHAPES AND AIRFOILS FOR HOVER AND CRUISE			■	■				200,000
CONDUCT MODEL TEST AND WRITE REPORT				■	■			200,000
DESIGN AND CONSTRUCT OPTIMUM FULL-SCALE ROTOR FOR RSRA				■	■			4,000,000
INSTALL, TEST, AND EVALUATE OPTIMUM ROTOR ON RSRA						■	■	3,000,000
WRITE GUIDELINES							■	150,000

Figure 19. Program schedule and estimated research and development costs for increased figure of merit

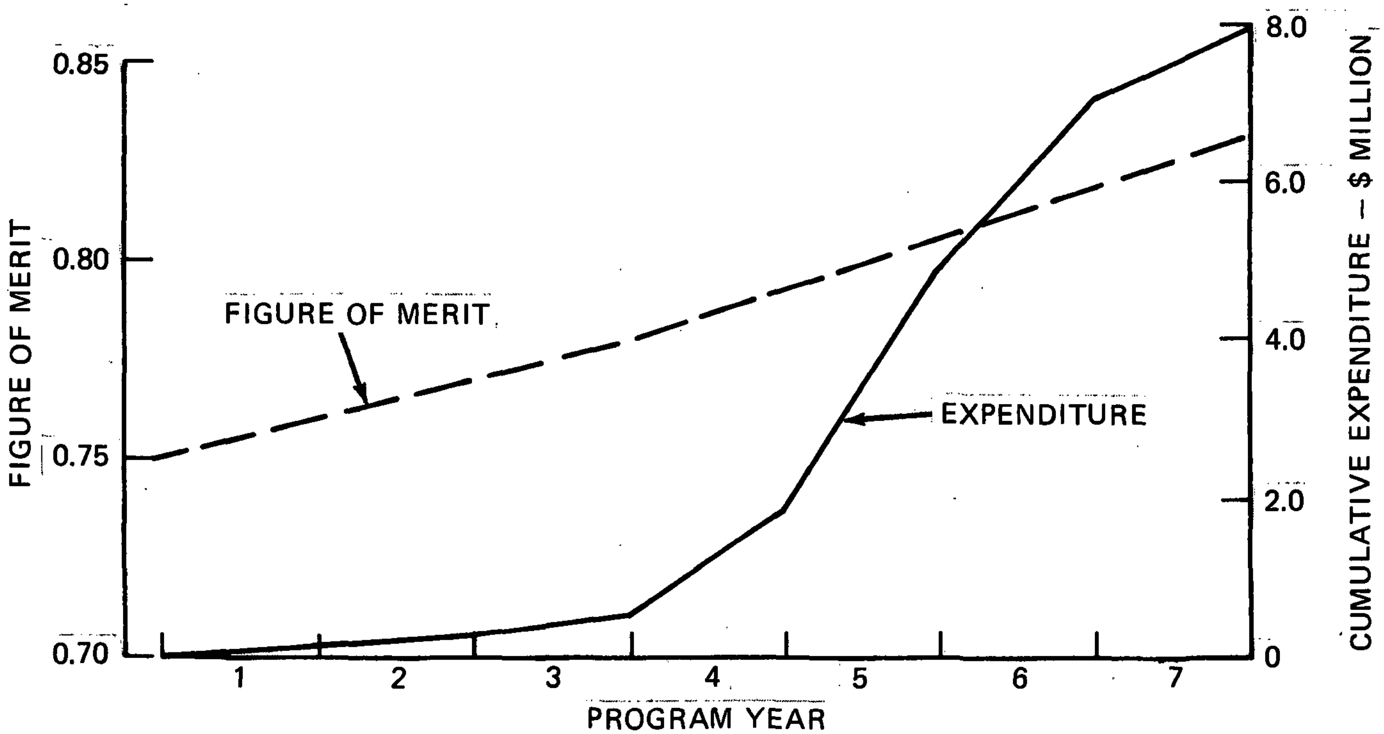

Figure 20. Improvement of figure of merit and expenditure as a function of time

ITEM	PROGRAM YEAR 1	2	3	4	5	6	7	COST ($)
PREPARE COMPUTER PERFORMANCE PROGRAM TO CONTAIN LIVE-TWIST ROTOR CHARACTERISTICS COUPLED WITH HIGH FORWARD TILT AND CYCLIC PITCH								200,000
DESIGN, BUILD, AND TEST WIND-TUNNEL MODEL FOR OPTIMUM PERFORMANCE AND LOADS								150,000
REVISE COMPUTER PROGRAM								50,000
CONDUCT FURTHER WIND-TUNNEL TESTS TO EVALUATE EFFECTS OF AEROELASTIC ADAPTIVITY ON OPTIMUM SOLIDITY, AIRFOIL CRITERIA, ETC								300,000
REVISE COMPUTER PROGRAM								175,000
DESIGN, BUILD, AND TEST FULL-SCALE ROTOR FOR RSRA TO VERIFY PERFORMANCE AND HANDLING QUALITIES								7,000,000
PREPARE DESIGN GUIDELINES BASED ON FULL-SCALE TESTS AND ANALYSES								150,000

Figure 21. Program schedule and estimated research and development costs for increased rotor aerodynamic efficiency (L/D_E)

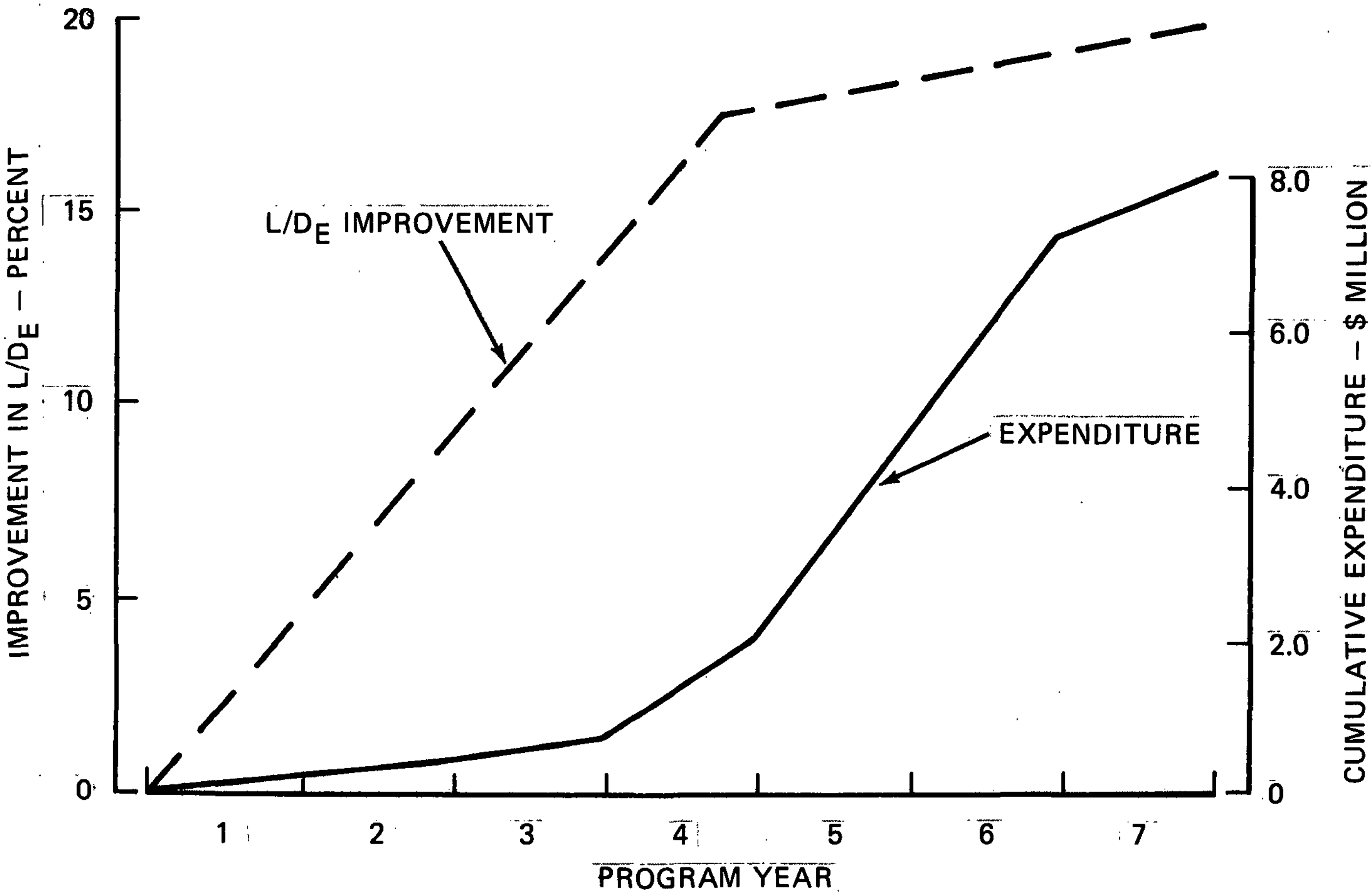

Figure 22. Improvement of rotor aerodynamic efficiency and expenditure as a function of time

6.0 TECHNOLOGY AND DESIGN INTERACTIONS

The impact of rotor hover and cruise efficiency improvement on interacting technological areas and systems is discussed in the paragraphs which follow.

6.1 Helicopter Noise Generation

6.1.1 Main-rotor noise. – Table 2 shows how various rotor design parameters are related to different types of noise. Some of the more important effects can be summarized as follows:

- Airfoils such as the Boeing Vertol VR-7 reduce low-speed slap because their shock-stall characteristics are better than the NACA 23000 series.
- Planform taper and twist reduce rotational noise because they move the blade-span loading toward the center of rotation.
- An increase in disk loading increases the rotational noise due to the higher strength of the vortices.
- Airfoil thickness ratio has a great effect on high-speed slap.
- Planform shape, especially tip planform shape, has a great effect on low-speed slap (0 to 30 knots) since its shape will affect the structure of the blade tip vortex.

All of these effects on rotor noise must be given careful consideration when varying the rotor design parameters to increase rotor efficiency.

6.1.2 Main/tail-rotor interaction noise. –Very little is known about the noise increase due to interaction between the main and tail rotors. It is known that tail-rotor noise is always higher in the presence of the main rotor than when alone. Under certain conditions, as when the helicopter is flying away from the observer, a pounding noise at the main-rotor-blade passage frequency is measured. It is postulated that such pounding is tail-rotor noise being modulated by the passage of the main-rotor-blade tip vortices through the tail rotor. This is an area that should be further researched so that such effects can be quantified and applied to the design of advanced rotors.

6.1.3 Engine noise. – Improved rotor efficiency will have very little effect on engine-noise level. The increase in figure of merit will decrease required installed power by 11.4 percent. Such a reduction in the size of the powerplant is estimated to decrease the sound-pressure level of engine noise by one decibel; thus engine noise will not be reduced to any measurable extent by more efficient rotors.

TABLE 2. EFFECT OF ROTOR PARAMETERS ON ROTOR NOISE

Rotor Parameter	Type of Rotor Noise Affected: Rotational	High-Speed Slap	Broadband	Low-Speed Slap
Total Blade Area			X	
Planform Taper	X			X
Twist	X			
Tipspeed	(X)	(X)	(X)	X
Airfoil Type				(X)
Planform Tip Shape		X		X
Surface Finish		X	X	
Disk Loading	X			
Blade-Span Load Distribution	X			X
Airfoil Thickness Ratio		(X)	X	
Design C_L		X	X	X
No. of Blades	X Freq only			X
Thrust	(X)		(X)	
Chord			X	
Radius			X	
Aircraft Velocity		X		X

(X) Items having major effect on noise

6.2 Performance

Improved rotor efficiency affects overall vehicle performance in several ways. The increased hover efficiency results in a lower hover-power requirement, with a resultant saving in installed power. Compared to the 1975-technology-baseline compromise helicopter of reference 1, the improved-efficiency-rotor helicopter exhibits a reduction in installed power of 11.4 percent. This reduction in engine size is important because it lowers the overall absolute value of the fuel-consumption rate, improves specific fuel consumption at partial-power throttle settings, and increases vehicle specific range. The improved-rotor L/D_E results in a lower power required for a given speed (and therefore lower fuel consumption) and a higher cruising-speed capability. Overall, when compared to the 1975-technology-baseline helicopter (ref. 1), the improved rotor results in a 2.9-percent increase in cruising speed at normal rated power, a 15.1-percent increase in specific range, and a 12.9-percent decrease in fuel (and therefore, energy) consumed.

6.3 Empty Weight

Because of the performance improvements noted in section 6.2 with the resultant savings in fuel, and the iterative nature of the sizing process, the helicopter with the improved rotor exhibits a 3.83-percent decrease in empty weight. The EW/GW fraction remains unchanged.

6.4 Drive-System Efficiency and Weight

The improved-efficiency rotor should have no impact on helicopter drive-system efficiency. Drive-system weight will be reduced because of the reduction in installed power.

6.5 Hover With One Engine Inoperative (HOEI)

The increased rotor efficiency in hover will result in a lower hover-power requirement, thus insuring smaller engines. The ratio of hover-power required to installed power will remain unchanged.

6.6 Reliability and Maintainability

The maintenance of advanced rotor blades and hubs should be the same as, if not better than, present rotors because better materials and methods of fabrication will be used, along with a reduction in number of parts. If higher-harmonic control is used to obtain higher speeds, the control-system design should be carefully surveyed for the effect of many more load cycles applied during the life of the aircraft.

Control-system maintenance will probably increase during the initial use of advanced rotors. However, since rotor-system (including upper controls) maintenance costs are only 15 percent of total maintenance costs, small increases in upper-controls maintenance should not materially affect the overall cost of maintenance.

Control rods to the main rotor will probably be routed through the center of the rotor shaft to decrease drag. Therefore, maintenance considerations should be given to such internal configurations and the effects on transmission design arrangement.

6.7 Production

The advanced rotor blades that will evolve should be no more costly to produce than present blades, even though they may have more complex planform and twist shaping, because they will be constructed of composite-type fiber materials. Filament-winding techniques may even reduce cost. However, protection of the leading edge will require a complex formed-metal cap which can add to production cost. Research should be conducted to find methods for manufacturing these caps.

The upper-control system may be more expensive due to the higher loads and greater number of load cycles if higher-harmonic control is used.

Bearingless hubs will be used. This type of hub should reduce production costs through the use of less-expensive material and fewer parts.

6.8 Rotor-Blade and Control-System Loads

Control-system loads will be higher and the necessary static and fatigue strength must be designed into the parts carrying such loads. If higher-harmonic pitch is used, coupled with high once-per-rev cyclic, the control loads may double from present loads. Both the control system and the blade design must consider such loading and research will be required to minimize such loads.

6.9 Vibration

The vibration level in the fuselage of helicopters equipped with advanced rotors will be low, approaching that of fixed-wing aircraft. This low level of vibration will come from the use of higher-harmonic control to reduce rotor vibratory loads at the source (i.e., on the blade) and from the use of vibration absorbers between the fuselage and rotor. Gust-alleviation systems will further improve the ride quality. All three of these areas need more research and applied operational experience.

7.0 IMPACT ON INITIAL COSTS AND OPERATING COSTS

The cost impact of improving both rotor hover efficiency (FM) and cruise efficiency (L/D_E) has been determined for the following categories:

- Initial costs
  - Research, development, test, and engineering (RDT&E)
  - Initial investment
- Direct operating cost

Reference 1 lists the RDT&E costs required to bring the rotor technologies up to the point where they can be applied to an advanced helicopter as:

Hover-Efficiency Improvement	$7,975,000
Cruise-Efficiency Improvement	$8,025,000
Total Improvement	$16,000,000

These costs are not included in the initial-investment (flyaway) costs of the vehicle. The flyaway costs reflect only the labor and material costs required to produce the vehicle after the desired level of technology has been achieved.

Compared to the baseline helicopter (ref. 1), the initial-investment (flyaway) costs are 4.42 percent less. This is a result of the reduction in size and weight due to the more efficient rotor system.

Direct operating cost (DOC) is reduced 6.75 percent from the baseline value. One of the major factors contributing to this reduction is a 12.85-percent decrease in fuel costs due to the more efficient energy-consumption characteristics of this helicopter.

It is estimated that by 1990 22,000 helicopters of all sizes will be in operation in the United States and Canada. These aircraft will have a total capital (initial) cost of $4.15 billion and will burn $325 million worth of fuel per year (see Table 3).

If the cited savings in investment and fuel are conservatively applied to only one-tenth of these 22,000 helicopters, the initial-cost savings can be (0.10) x (0.044) x (4,150,000,000) = $18,343,000, and the fuel-cost savings can be (0.10) x (0.128) x (325,000,000) = $4,160,000 per year. Thus, the savings in capital costs alone can return the research costs, while the fuel-cost savings over 10 years (in the 1990's) will amount to three times the research costs. This is a very good payoff considering only these two cost items. The value of increased productivity and smoother ride will show up as wider acceptance and increased usage of helicopters.

TABLE 3. ECONOMICS OF EXISTING AND FUTURE HELICOPTER FLEETS IN THE UNITED STATES AND CANADA

Item	Present Fleet	1990 Fleet*
No. of Aircraft	5,500	22,000
Fuel/Yr, gal	107,000,000	430,000,000
Fuel Cost/Yr, $/yr	80,000,000	325,000,000
Total Structural Weight, lb	4,600,000	18,000,000
Capital Cost, $	1,036,000,000	4,150,000,000
Rental Price/Yr, $	1,141,000,000	4,500,000,000
Place-Miles Available	2,143,000,000	8,600,000,000
Income/Aircraft, $/yr	200,000	200,000
Rent/Place-Mile, ¢	50	50
Maintenance Cost, $	103,000,000	410,000,000

*No inflation, no improvements

8.0 CONCLUSIONS

The improvement of rotor hover and cruise efficiencies and the R&D programs required to achieve them are summarized in the following paragraphs.

8.1 Improvement in Hover Efficiency

The hover-efficiency improvement of current rotors depends primarily on the reduction of the induced-power component. This reduction can be achieved by concentration of research in the areas defined in Table 4, carried out in conjunction with the development of the following:

- An improved rotor hover-performance analysis (computer program)
- Design, construction, and test of a full-scale optimum hovering rotor
- Documentation of guidelines for the design of an optimum hovering rotor.

8.2 Improvement in Cruise Efficiency

The cruise-efficiency improvement of current rotors depends primarily on the reduction of the profile-power component. This reduction can be obtained by concentration of research in the areas defined in Table 5, conducted in conjunction with the development of the following:

- An improved rotor cruise-performance analysis (computer program)
- Design, construction, and test of a full-scale rotor optimized for cruise
- Documentation of guidelines for the design of a rotor optimized for cruise.

TABLE 4. SUMMARY OF RESEARCH RECOMMENDED FOR IMPROVED ROTOR EFFICIENCY (HOVER FIGURE OF MERIT)

Research Item	Research Recommendation	Priority	Size Applicability	Payoff
Blade Tip Shape	Yes	High	All	High
Blade Planform/ Taper Ratio	Yes	Medium	All	Medium
Twist	Yes	High	All	High
Airfoil Sections with Improved Compressibility Characteristics	Yes	Medium	All	Medium
Airfoil Sections Operating at Low Reynolds Numbers	Yes	Medium	All	Medium

TABLE 5. SUMMARY OF RESEARCH RECOMMENDED FOR IMPROVED ROTOR EFFICIENCY (ROTOR L/D_E)

Research Item	Research Recommendation	Priority	Size Applicability	Payoff
Blade Tip Shape	Yes	High	All	High
Blade Planform/ Taper Ratio	Yes	Medium	All	Medium
Airfoil Sections with Improved Compressibility Characteristics	Yes	Medium	All	Medium
Aeroelastic Adaptivity (Live Twist) Effect on Retreating-Blade Stall, etc	Yes	High	All	High
Higher-Harmonic Control	Yes	High	All	High
RVR Rotor System	Yes	Low	All	Low
Highly Lift-Offset Rotor System	Yes	Low	All	Low

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