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FACTORS SHAPING CONCEPTUAL DESIGN OF ROTARY-WING AIRCRAFT

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ABSTRACT

Of the many factors involved in shaping conceptual designs of rotary-wing aircraft, attention is first briefly focused on powerplants. Then, principal design parameters of helicopters and new rotary-wing concepts are investigated, and generalized performance levels shown. This is done by examining ten actual and four hypothetical helicopters belonging to the Soviet school of design, and fourteen helicopters plus four new concepts representing the Western approach. The Soviets appear to depart from their past design philosophies, as witnessed by Mi-24, and especially, Mi-26 types. Following the path blazed by their hypothetical helicopters, they now approach the design parameter values and performance levels established in the West. Competitive position of new concepts with respect to conventional helicopters is also briefly assessed.

List of Symbols

C_T	thrust coefficient
$\bar{c}_d$	avg. blade profile drag coefficient
$\bar{c}_\ell$	avg blade-lift coefficient
D_e	equivalent helicopter drag; lb
f	equivalent flat-plate area; sq.ft
$\overline{FF}$	relative fuel flow: lb/unit of weight and time, or distance
FM_{oa}	helicopter overall figure of merit
k_{ind}	rotor induced power coefficient
k_v	download coefficient
ℓ	distance; n.mi
M	Mach number
n	number
PI	productivity index; lb-kn/lb-hr
R	rotor radius; ft
RP	rotor power: ft-lb/sec, or hp
SHP	shaft horsepower; hp
SP	shaft power; ft-lb/sec, or hp
sfc	specific fuel consumption; lb/hr-hp
V	speed of flight; kn
V_t	rotor tip speed; fps
W	weight; lb
w	disc, and area loading; psf
η_{oa}	overall rotor-power transmission efficiency: RP/SP
λ	relative engine power lapse rate
μ	rotor advance ratio
ρ	air density; slugs/cu.ft
σ	rotor solidity

Subscripts

av	available
cr	cruise
e	empty
f	forward
fp	flat plate
gr	gross
H	altitude
h	hovering
id	ideal
ind	induced
ℓ	at distance ℓ
mr	main rotor
o	initial value
pl	payload
R	rotor
req	required
TO	takeoff
v	at speed of flight V
w	gross weight

FACTORS SHAPING CONCEPTUAL DESIGN OF ROTARY-WING AIRCRAFT

by

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1. INTRODUCTION

It is obvious that there are many factors which influence the basic design formulation process of all engineering products. With respect to helicopters and other VTOL vehicles, it is enough to cite such factors as those either directly spelled out by the potential customer, or as anticipated by designer requirements regarding performance, flying qualities, maintainability, general technology, materials, maximum system cost, direct operating costs, and environmental restrictions (i.e. noise). In other words the whole spectrum of technical, energy, economic, and environmental aspects exerts some bearing on the formulation of the design concept. Furthermore, the importance and hence, the influence, of any one of these factors may vary with time, customer, and anticipated geographic and climatic operational conditions.

I have already discussed some of these factors before this audience. For instance, at the Third European Forum, I talked about the influence of energy aspects[1], and at the Fifth Forum, L. H. Sloan and I together looked at the importance of economic factors, as reflected in operating costs, on design optimization of helicopters[2]. Consequently, these two subjects will not be considered in detail in this presentation. Because of time limitations on the oral, and space restrictions on written presentations, environmommental aspects will also be excluded. One's attention will be focused on the most important design parameter value trends as exhibited by the foremost design schools represented by the Soviet Union and the Western nations. A review of various generalized performance items will permit one to judge the degree of success resulting from the application of the two design philosophies.

In addition to pure helicopters of various configurations, a few new rotary-wing concepts as the tilt rotor, ABC, and the X-wing are included so that their competitive positions with respect to classical helicopters can be assessed.

2. CONSIDERED AIRCRAFT

2.1 Soviet Helicopters

With the exception of the Mi-2, Mi-24, and Mi-26, the Soviet helicopters shown in Table 1 represent traditional Soviet design philosophy, as demonstrated by thousands of production aircraft. The Mi-2 with Allison 250-C20B engines reflects the desire of Polish engineers to develop their own approach to helicopter concept formulation. The Mi-24 and Mi-26 are examples of the new Soviet design philosophy adopted by the Tishchenko design team; formerly headed by the late Dr. Mil.

A glance at the current thinking of this particular group was obtained from a book authored by Tishchenko and his associates[3], wherein studies of helicopters of various configurations and design gross weights ranging from 12 to 52 metric-tons were performed. It will be shown later that the so-called hypothetical helicopters included in the referenced study represented a considerable departure from their predecessors with respect to their basic design parameters and performance expectations.

As shown in Table 1, four of the considered hypothetical helicopters selected for this comparative study are: the 15 and 24 metric-ton single-rotor machines represented by Fig. 1; plus two 52 metric-ton machines, one of the side-by-side and another, of the single-rotor configuration (Figs 2 and 3a respectively).

It should also be noted from circulars and data obtained at the 1981 Paris Air Show that the Mi-26 (Fig. 3b) bears a close similarity to the hypothetical 52-ton single-rotor helicopter, and that many of the design goals set for the hypothetical design have been met.

2.2 Western Rotary-Wing Aircraft

The Western rotorcraft selected for this comparative study include single-rotor and tandem helicopters ranging in maximum gross weights from about 5000 to almost 150,000 pounds (Table 2). In addition, there are some interesting newcomers to the rotary-wing field deserving a quick look prior to a discussion of their basic design parameters and performance aspects.

The extremely valuable real-life flight-test data in the tilt-rotor category being acquired by the Bell XV-15 flight research aircraft[4,5] should enhance the confidence of the designers in extending this configuration to such commercially-feasible concepts as that of the 30-passenger D326 (Fig. 4).

With respect to the Sikorsky ABC concept[6], the situation is somewhat similar, as there is an operational flight research aircraft, again providing a realistic basis for such future developments as the Navy HSX[7] ASW project (Fig. 5).

Finally, the X-wing[8,9], a concept that has been pursued for almost a decade by the Navy under the guidance of Bob Williams, is now undergoing detailed design studies by Boeing-Vertol and Sikorsky. The Boeing-Vertol version is shown in Fig. 6.

3. POWERPLANTS

The state of the art of powerplants has always exerted, and still exerts, an important influence on design concepts of rotary-wing aircraft. The basic differences in such engine characteristics as specific weitht (Fig. 7) and sfc (Fig. 8) that existed between Western and Soviet engines have, undoubtedly, contributed to the differences in the design philosophies represented by these two schools. In addition, current Soviet helicopter engines are much bulkier than their Western counterparts. However, this disadvantage is supposedly compensated by greater ruggedness of the powerplants and sufficiency of unskilled maintenance personnel. On the other hand, it should be noted that for the hypothetical engines postulated in Tishchenko's studies of future helicopters, specific weights and specific fuel consumption are assumed to lie on the optimal boundary of the Western powerplants. Furthermore, it appears that in the new Lotarev, over 11,000 hp, D-136 turboshaft powering the Mi-26 helicopter, their ambitious goals regarding specific weight and sfc have been achieved. While variations of sfc with partial-power settings (Fig. 9) appear, in general, to be similar to those of the West, the curves representing the D-136, and even the hypothetical engines, appear to be less flat than the curves of the most advanced Western helicopter powerplants.

In concluding this brief review of powerplant aspects, it should be pointed out that the relative lapse rate (Fig. 10) of Soviet helicopter engines (especially for the larger ones) is different from those of their Western counterparts. The shapes of these relative lapse curves indicate that the thermal capacity of Soviet engines is higher than actually utilized at sea level. Whether this design philosophy of the past has been retained in the D-136 turboshaft is not known to this writer; but his personal opinion is that it has probably changed, and the relative lapse rate of this newest Soviet helicopter powerplant is similar to those in the West.

4. PRINCIPAL DESIGN PARAMETERS

4.1 Selection of Parameters

With respect to the principal design parameters, the following quantities were selected for comparison: (1) disc loading; (2) installed power loading; (3) tip speed; (4) advancing tip Mach number and advance ratio; (5) average blade-lift coefficient (C_T/σ), and average blade profile drag coefficient; and (6) equivalent flat-plate area loading. Except for the equivalent flat-plate area loading and average blade profile drag coefficient, these parameters can usually be directly obtained from data published in standard rotary-wing descriptions.

4.2 Disc Loading

It can be seen from Fig. 11 that the trends in disc loading values increase with gross weight and, for the largest Western single-rotor helicopter, reach a level of 15 psf at its maximum flying gross weight. The disc loadings of Western tandems also increase with gross weight but, in general, are below those of single-rotor machines. While Soviet production helicopters, regardless of configuration, have lower disc loadings than their Western counterparts, the Mi-24D and hypothetical machines are closer to the Western upper limits. The disc loadings of the Mi-26 and the 52-ton hypothetical single-rotor helicopters are almost identical. It should also be noted that the disc loadings of such new concepts as the tilt-rotor, ABC, and the X-wing are at the upper limits of classical helicopters.

4.3 Power Loading

A study of installed power loading (Fig. 12) clearly indicates that the values of this design parameter for Soviet production helicopters are, in general, above those adopted by Western designers. Levels of the installed power loadings of the so-called hypothetical helicopters seem to indicate a future trend in Soviet designs toward values similar to those of the West. Indeed, this new trend is confirmed in the power-loading levels of the Mi-24D and Mi-26 helicopters.

4.4 Tip Speed

With respect to tip speed (Fig. 13), both Soviet and Western designers seem to agree that about 700 fps represents a desirable value. Exceptions can be found in the tilt-rotor in the airplane configuration, and ABC in cruise, where the tip speed is reduced to approximately 600 and 500 fps, respectively.

4.5 Advancing Blade-Tip Mach Number and Advance Ratio Barrier

It can be seen from Fig. 14) that conventional helicopters – regardless of their national origin – still encounter the old $M_T - \mu$ barrier. During fast cruise, the advancing tip Mach number does not usually go above the $M = 0.9$ level, while almost all of the advance ratio values appear to be included within the 0.3 to 0.4 band. Exceptions are encountered in the ABC configuration where, in fast cruise, the advance ratio and the advanced tip Mach number are both equal to 0.85, and in the X-wing where the stopped rotor represents an infinite advance ratio value.

4.6 $(SHP/W_{gr}) = f(V)$ Relationship

As previously mentioned, the two remaining design parameters; namely, the equivalent flat-plate area loading and average blade-lift coefficient must be indirectly deduced from such data as SHP vs. speed of flight curve which, for the known gross weight can be presented under the form of the $(SHP/W_{gr}) = f(V)$ relationship (Fig. 15). Simplified analytical expressions for this relationship can be derived, for instance, from Eqs. (3.106) and (3.107) of Ref. 10, and written as follows:

$$(SHP/W_{gr}) = \left[2.413\rho\,\frac{V^3}{w_{fp}} + 0.296\,\frac{k_{v_f}k_{ind_f}w}{\rho V} + 0.75\left(1 + 4.7\mu^2\right)\left(\frac{\bar{c}_d}{\bar{c}_\ell}\right)V_t\right] \Big/ 550\eta_{oa} \qquad (1)$$

where V is the flight speed in knots; k_{v_f} is the download factor; k_{ind_f} is the induced power factor; w is the disc loading in psf; $w_{fp} \equiv W_{gr}/f$ is the equivalent flat plate area (f) loading in psf; $\mu \equiv 1.69V/V_t$ is the advance ratio; V_t is the tip speed in fps; ρ is the flight air density in slugs/cu.ft; $(\bar{c}_d/\bar{c}_\ell)$ is the ratio of the average profile drag to the average lift coefficient in flight; and η_{oa} is the overall rotor power transmission efficiency representing the ratio of the rotor to shaft power.

There are five unknowns in Eq. (1): k_{v_f}, k_{ind_f}, η_{oa}, $\bar{c}_d$, and w_{fp}; the last two of which are the sought design parameters. In principle, hence, having a reliable (say, based on flight tests) $SHP/W_{gr} = f(V)$ relationship between the minimum power required and V_{max} points, five points along the curve can be selected, yielding 5 linear algebraic equations from which values of the unknowns can be found. However, values of such quantities as the k_{v_f} and η_{oa} can probably be better estimated separately. Also, in this approach, values of the induced power coefficients were assumed rather than calculated; thus, only w_{fp} and $\bar{c}_d$ were computed from the two equations corresponding to the two pairs of the (*SHP, V*) values which often can be obtained from the usually published performance data.

We know that either the maximum continuous or the transmission limited power, and the corresponding V_{max} value represent the high-speed pair of the *SHP* (i.e., SHP/W_{gr}) and *V* values. From the known maximum rate of climb in forward flight, and takeoff (or transmission-limited) power available, the approximate SHP_{min} can be estimated. The approximate speed of flight can also be computed, thus providing the second necessary pair of *SHP* (SHP/W_{gr}) and *V* values.

4.7 Equivalent Flat-Plate Area Loading

The two-point technique described above was used to determine the w_{fp} values shown in Fig. 16. The absolute quantities indicated here may be somewhat conservative as they may, to some extent, reflect both compressibility and incipient stall effects encountered under the high advancing tip Mach number and μ conditions; but the general trend should be correct, as well as the relative ranking of the compared helicopters regarding their aerodynamic cleanness. As may be expected, this aerodynamic cleanness improves with size (gross weight) of the helicopters, but still remains disappointingly low for the production machines when compared with fixed-wing aircraft. It should also be noted that, in their new designs, the Soviet designers hope to achieve much higher w_{fp} values than those representing the current state of the art.

Unfortunately, at this time, it is impossible to evaluate the extent to which the goals of aerodynamic cleanness set up for the hypothetical machines have been achieved in the actual design represented by the Mi-26 helicopter, as there is no reliable available information regarding the *SHP* at V_{max}. The $w_{fp} = 627$ psf value shown in Fig. 16 has been computed from rather uncertain inputs, and should be judged as conservative. Nevertheless, it appears that the ambitious goal of $w_{fp} = 1460$ psf shown for the Hypo 52-SR has not been approached.

4.8 Average Blade Lift and Profile Drag Coefficients

The average blade lift coefficients (C_T/σ) are shown in Fig. 17. It is apparent that the $\bar{c}_\ell$ (C_T/σ) values exhibited by Soviet production helicopters are, in general higher than those of the Western counterparts. Again, as far as the hypothetical helicopters are concerned, their $\bar{c}_\ell$'s are more in line with those of the West, and the Mi-26 helicopter seems to follow the trend established by the hypothetical machines.

The $\bar{c}_d$'s are evaluated from the known $\bar{c}_\ell$, and ($\bar{c}_d/\bar{c}_\ell$) values computed from Eq. (1). It can be seen from the lower part of Fig. 17 that the so-obtained $\bar{c}_d$ level appears to be quite uniformly close to the 0.01 mark for all the considered helicopters.

5. WEIGHT ASPECTS

5.1 Selection of Reference Weight

In establishing criteria for the comparison of various designs, it is obvious that from the point of view of their weight effectiveness, selection of the proper reference gross weight is all important. Since the so-called normal gross weight is a somewhat elusive quantity depending, to large extent, on the postulated mission, the maximum flying gross weight (symbolized by the inverted triangle), as specified by the manufacturer of each aircraft, was selected whenever possible. In such cases as the hypothetical helicopters, it was arbitrarily assumed that the maximum flying gross weight is identical to the gross weight corresponding to hovering OGE at SL, ISA.

5.2 Weight-Empty and Zero-Range Payload to Gross-Weight Ratios

Using the above approach, the weight-empty to gross-weight ratios are shown in Fig. 18, and the zero-range payload to gross-weight ratios are given in Fig. 19. Looking at both figures, one would see that weight-wise, the Soviet production helicopters are generally less efficient than their Western counterparts.

But, judging from the trends established by the hypothetical machines, they expected to have their new designs on the optimal boundary of the Western helicopters. On noting the points representing the Mi-26 on these figures, one would see that, indeed, they came very close to their goals.

As expected, the new concepts appear to be less efficient than pure helicopters from a weight point of view. However, it should be noted that the comparison is not complete at this point since, with the exception of the Bell XV-15, the maximum flying gross weights of the new configurations were not available. Assuming, for instance, that the maximum flying gross weight of the Bell D326 was 44,000 pounds, the corresponding relative weight figures would be as follows: $W_e/W_{gr} = 0.56$ and $W_{pl_o}/W_{gr} = 0.43$.

6. HOVERING

6.1 Overall Figure of Merit

In reviewing the hover performance of rotary-wing aircraft, the overall figure of merit

$$FM_{oa} = RP_{id}/SP \qquad (2)$$

defined as a ratio of the ideal power required to hover OGE to the shaft power actually needed, can serve as a yardstick to measure the designer's success in providing an efficient lifting rotor or rotors, the most effective rotor-torque compensating arrangement, and the lowest download. Furthermore, using the overall figure of merit, very simple relationships may be established for calculating such quantities as maximum hovering weight at various altitudes and vertical rates of climb (see Appendix).

It can be seen from Fig. 20 that all twin-rotor configurations (i.e., coaxial, side-by-side, and tandem) exhibit the highest overall figures of merit, generally in excess of the 0.6 level. The single-rotor helicopters show lower values of the overall figure of merit, with noticeable scatter. As far as the comparison of Soviet and Western helicopters is concerned, there seems to be no established pattern of differences.

6.2 Power per Pound of Gross Weight Required to Hover OGE at SL, ISA

Figure 21 indicates that the SHP per pound of gross weight required to hover OGE at SL, ISA increases as the size, with the corresponding disc loading, becomes larger. Older Soviet and Western designs seem to form the lower boundary of the hovering power required per unit of gross weight, while in more recent designs of both schools, this expenditure of power becomes higher. The expenditure of power by the new concepts is also on the high side, because of their elevated disc loadings.

6.3 Ratio of OGE at SL, ISA Hovering Gross Weight to Maximum Flying Weight

It is interesting to take a look at the relationship of the maximum OGE hovering gross weights at SL, ISA, and the maximum flying gross weights specified by the manufacturers. Looking at Fig. 22, one can clearly see that definite differences exist between Soviet and Western production helicopters. In the latter case – in contrast to the Soviet approach – the SL maximum hovering weight is almost always higher than the permissible maximum flying weight. For the Soviet hypothetical machines, this ratio is one since, as previously mentioned, the maximum flying gross weight used in this presentation was arbitrarily established as that corresponding to hover OGE at SL, ISA. For the Mi-26, this ratio is also close to one (1.007). Judging from the fact that this ratio is quite high for the Mi-24D at its normal gross weight (about 1.24), it may be expected that at its maximum flying gross weight, the ratio would exceed the value of 1.0.

7. FORWARD FLIGHT

7.1 $(SHP/W_{gr}) = f(V)$ at SL, ISA

Plots of the shaft horsepower required per pound of gross weight versus speed in horizontal flight at SL, ISA were prepared in order to provide a common denominator for all the compared rotary-wing aircraft with respect to their performance in forward flight.

Looking at the rotary-wing aircraft weighing up to 12,000 pounds (Fig. 23), and between 12,000 and 30,000-pound gross-weight classes (Fig. 24), one can see that in the low-speed range, the Soviet helicopters of both classes exhibit lower power requirements than their Western counterparts. It should also be noted that gross weight to the equivalent drag ratios of all helicopters are disappointingly low, with only one helicopter reaching the $(W_{gr}/D_e) = 5$ value. In this respect, the tilt-rotor flight research aircraft in the airplane configuration performs much better.

In the higher gross-weight classes, the following should be noted: in the 30,000 to 100,000-pound gross-weight class (Fig. 25), the Mi-6 appears to exhibit higher (W_{gr}/D_e) than the compared Western helicopters, as well as relatively low power requirements throughout the whole range of flight speeds. The Soviet designers expect to improve the high-speed power requirements for the hypothetical 15 and 25-ton helicopters over those of the Mi-6. In the cruise regime of flight, the advanced ABC helicopter usually shows lower unit power requirements and higher (W_{gr}/D_e) values than classical helicopters. However, the largest gains in high-speed unit power requirements and (W_{gr}/D_e) values are exhibited by the projected tilt-rotor aircraft.

As far as the heavy-lift class ($W_{gr} \geqslant 100{,}000$ lb) is concerned (Fig. 26), it can be judged from the $(SHP/W_{gr}) = f(V)$ relationships of the hypothetical helicopters that Soviet designers expected to achieve very significant gains in their high-speed power required and maximum (W/D_e) values. This is especially apparent in the hypothetical single-rotor configuration. However, on the basis of the Mi-26 data presently available, it appears that they were not as successful as they were in reaching their weight and hovering performance goals. Looking at this figure, one would note that in the low-speed regime, the $(SHP/W_{gr}) = f(V)$ curve very closely follows the hypothetical trend, but at $V > 50$ kn, it begins to deviate from that trend, and approaches values representing the USA tandem heavy-lift helicopter.

7.2 Maximum Gross-Weight to Equivalent-Drag Ratios

The $(W_{gr}/D_e)_{max}$ values are summarized once more in Fig. 27. It may be recalled at this point that the maximal values of (W_{gr}/D_e) can be expressed as follows[2]:

$$(W_{gr}/D_e)_{max} \approx \frac{\eta_{oa}}{k_{v_f}\sqrt{k_{ind}\, w/w_{fp}} + \tfrac{3}{4}\mu(1 + 4.7\mu^2)(\bar{c}_d/\bar{c}_\ell)} \qquad (3)$$

Looking at all of the design parameters appearing in this formula, one realizes that minimization of the w/w_{fp} ratio would have the greatest effect as far as betterment of maximum weight to the equivalent drag ratio is concerned. But going too far down with respect to the disc loading is not very practical because of the weight empty and overall aircraft dimensional aspects. Greatly improved aerodynamic cleanness of design — as represented by the high equivalent flat-plate area loadings — seems to be the most profitable way of improving the $(W_{gr}/D_e)_{max}$ ratio. It may be recalled from Fig. 16 and the accompanying discussion that the Soviet designers intend to follow the line of high w_{fp} values (as reflected in their hypothetical helicopters), but have not met with much success so far.

7.3 Fast Cruise

It can be seen from Fig. 28 that fast cruise is usually performed at about 140 kn for most Western helicopters; as well as for the large production and hypothetical Soviet helicopters. Small Soviet helicopters, especially the coaxial configurations, appear to have fast cruise speeds much lower than their Western counterparts. New concepts such as the ABC, tilt-rotors, and especially, the X-wing, represent a quantum jump as far as fast cruise capability is concerned.

7.4 Ideal Absolute, and Relative Productivities

Assuming the fast cruise values just shown, the ideal absolute productivity, defined here as

$$P = (W_{pl})_{id} \times V_{cr_{max}} \qquad \text{in lb-n.mi/hr} \tag{4}$$

was computed for payloads corresponding to the 100 n.mile range (Fig. 29). Here, it can be seen that the ideal absolute productivity of production Soviet helicopters remains below that of the corresponding Western machines.

The tilt-rotor of the future appears quite promising in that respect since, even at its normal gross weight, its productivity points for cruise at SL, and especially, at 20,000 feet, are located above the optimal helicopter trend at their maximum flying weights.

The ideal relative productivity (also called Productivity Index $-PI$) is defined as follows

$$PI_{id} = (W_{pl})_{id} V_{cr_{max}} / W_e \qquad \text{in lb-n.mi/hr-lb} \tag{5}$$

The PI_{id} for 100 n.mile range are shown in Fig. 30, and it can be seen that using this criterion, the Soviet production helicopters are considerably below the optimal boundary of the Western counterparts, while smaller hypothetical machines are on, and large hypothetical machines close to this boundary. Spotting the Mi-26 point, one notes that it is very close to that of the hypothetical single-rotor heavy-lift helicopter. At its normal gross weight, the tilt-rotor is somewhat below the optimal boundary.

7.5 Ideal Ferry Range

To complete the picture of forward flight aspects, the ideal ferry range in nautical miles, expressed in a form similar to the classic Breguet formula (see Appendix) is examined.

$$\ell_{id} = \frac{100}{\overline{FF}_{w_{opt}}} \, \ell n \, \frac{1}{1 - (W_{pl_o}/W_{gr_{max}})} \approx \frac{100(W_{pl_o}/W_{gr_{max}})}{\overline{FF}_{w_{opt}}[1 - \frac{1}{2}(W_{pl_o}/W_{gr_{max}})]} \tag{6}$$

A considerable gap between the optimal boundaries of Western and Soviet production helicopters is shown in Fig. 31. One can find an explanation of this gap in Eq. (6). It has already been shown that zero-range payload to gross-weight ratios of Western helicopters are, in general, higher than those of the Soviet production counterparts. It will be shown later that the fuel required per pound of gross weight and 100 n.miles (symbol $\overline{FF}_{w_{opt}}$ in the formula) is also more favorable for Western rotorcraft.

With respect to hypothetical Soviet helicopters, here also, their ideal ferry range is expected to be as good or better than, that represented by the optimal boundary of the West. Furthermore, it appears that they came very close to that goal in their Mi-26.

As for the tilt-rotor, it appears that its ideal ferry range (cruise at 20,000 ft) at normal gross weight is right on the optimal boundary. It is obvious that at maximum flying gross weight, it would be way above the trend curve.

8. ENERGY ASPECTS

8.1 Fuel Required per Hour and Pound of Gross Weight and Payload

Energy consumption per pound of gross weight and hour in hover can be guaged by the following expression:

$$\overline{FF}_{w_h} = \frac{sfc\sqrt{w/2\rho'}}{550\, FM_{oa}} \tag{7}$$

and the fuel required per pound of payload and hour would be:

$$\overline{FF}_{pl_h} = \frac{sfc\sqrt{w/2\rho}}{550\,FM_{oa}(W_{pl_o}/W_{gr})} \tag{8}$$

The factors in Eq. (7) contributing to the betterment of fuel required per pound of gross weight and hour are: (1) low sfc of the engines; (2) low disc loading – although this may be in conflict with other requirements; and (3) high overall figure of merit. In the case of minimizing fuel per pound of payload and hour, as shown in Eq. (8), a new factor appears under the form of high payload to gross-weight ratio.

Fig. 32 clearly indicates that while the band of fuel required per pound of gross weight and hour is relatively narrow for all the considered helicopters, this fuel consumption, when referred to pound of payload becomes highly scattered. Here, advanced Western and Soviet hypothetical helicopters gravitate toward the lower boundary of this band, while Soviet production helicopters and the new concepts (high disc loading and low payload to gross-weight ratios) are grouped toward the upper limit. It is interesting to note that in spite of its high disc loading, the hovering fuel consumption of the Mi-26, when referred to payload, is close to the optimal boundary.

8.2 Fuel Required per 100 N.Miles and Pound of Gross Weight and Payload

The energy consumption aspects of rotary-wing aircraft in forward flight compared with other vehicles was considered in detail in Ref. 1. However, here, only the direct energy consumption referred to say, 100 n.miles and pound of gross weight for all types of powered vehicles, is considered:

$$\overline{FF}_{w_f} = \frac{(sfc)_V}{3.25\,(W_{gr}/D_e)_V} \tag{9}$$

where $(sfc)_V$ and $(W_{gr}/D_e)_V$ respectively, signify the engine specific fuel consumption, and the gross weight to the equivalent drag ratio at speed of flight V.

When the reference base is changed to pound of payload and 100 n.miles, the corresponding fuel consumption equation for cargo vehicles becomes:

$$\overline{FF}_{pl_f} = \frac{(sfc)_V}{3.25(W_{gr}/D_e)_V(W_{pl}/W_{gr})} \tag{10}$$

A glance at the above expression indicates that the requirement for favorable energy consumption is governed by a low sfc, high gross-weight to the equivalent-drag ratio, and a payload to gross-weight ratio as high as possible.

Optimal fuel requirements per 100 n.miles, and pound of gross weight and zero payload of actual and hypothetical helicopters, as well as some of the new concepts, can be judged from Fig. 33. In this figure, one may note a picture somewhat similar to that in hover. Here, also, the band of fuel requirements referred to a unit of gross weight is relatively narrow for all considered helicopters. It should also be noted that the ABC appears at the lower limit of the band, while the projected tilt-rotor configuration is noticeably below that limit.

When optimal fuel consumption per 100 n.miles is referred to pound of the zero-range payload, the band containing points representing actual helicopters becomes somewhat broader; but for the Western helicopters, still indicates a definite level of this quantity decreasing with the increasing size of the rotorcraft. The new ABC and tilt-rotor configurations (at their normal gross weights) are within the boundaries established by Western helicopters. Some of the Soviet production helicopters appear within, and some above those boundaries, while the points representing hypothetical concepts appear at the bottom of the Western trend, where one would also find a point representing the Mi-26.

8.3 Variation of Payload to Gross-Weight Ratio with Flight Distance

To complete the picture of energy aspects in forward flight, the variation with distance of the payload to gross-weight ratio is shown in Fig. 34. Here, it can be seen that Soviet production helicopters form the lower, and the hypothetical helicopters, the upper boundary of that spectrum. The Mi-26 is represented by a separately marked line to indicate that apparently, in this case, the goal established through the hypothetical helicopters has been met.

Slopes of such new concepts as the ABC and especially, the tilt rotor, are less steep than for conventional helicopters, although at their normal gross weights, the zero range values are lower than those for most helicopters.

9. CONCLUDING REMARKS

Under the influence of political, economic, geographic, climatic, and technological factors, two schools representing distinctly different design philosophies of rotary-wing aircraft have evolved: Soviet vs. Western. In addition to these 'generic' factors, for many years the Soviet designers have had to cope with utilization of greatly inferior powerplants in the areas of specific weights and sfc, when compared to those of the West.

Concentrating their efforts chiefly on classic helicopters – mostly of single-rotor and coaxial configurations – they developed a series of traditional designs where, in order to optimize their helicopters around inferior powerplants, they had to use values of such basic parameters as disc and power loadings plus average blade-lift coefficients different from those of the West. The Soviet designers were rather successful in such areas as power required per unit of gross weight, both in hover and in forward flight; where values similar to, or even better than those of their Western counterparts have been obtained. By contrast, with respect to weight aspects and various criteria of energy consumption referred to payload and, in general, level of vertical flight performance (hovering ceilings and rates of climb), they remained behind the West.

However, by following the path indicated in studies of the hypothetical powerplants and rotary-wing aircraft, such new engines as the Lotarev 136-D, and new helicopters as the Mil Mi-24 and Mi-26 have been developed. Specific weight and sfc characteristics of this engine are on the Western level, while the basic design parameters of those two new helicopters become similar to those of their Western counterparts, and weight and performance aspects appear to be on the Western level.

Within the Western School, new rotary-wing concepts are being developed, which contain a potential for broadening the field of application of VTOL aircraft.

APPENDIX

Hovering Weight at Given Altitude (H)

SHP required to hover at an altitude H, where the air density is ρ_H, by a rotorcraft having n_R rotors can be expressed as follows:

$$(SHP_H)_{req} = W_{gr}\sqrt{W_{gr}/2\pi n_R R^2_{mr}\rho_H}\Big/550\,FM_{oa} \tag{A.1}$$

On the other hand, knowing the relative engine lapse rate, λ_H, the expression for SHP available becomes

$$(SHP_H)_{av} = \lambda_H (SHP_{TO})_o \tag{A.2}$$

Equating the right sides of Eqs. (A.1) and (A.2), and solving for W_{gr}, the sought hovering weight OGE at altitude H is obtained:

$$(W_{gr})_{hH} = 123.86\sqrt[3]{n_R\,\rho_H}\,[\,(SHP_{TO})_o\,\lambda_H\,R_{mr}\,FM_{oa}\,]^{2/3} \tag{A.3}$$

Ideal Ferry Range

Elementary decrease of inflight gross weight due to the burnt fuel is

$$dW_{gr} = -\overline{\overline{FF}}_w W_{gr} d\ell/100 \tag{A.4}$$

Assuming that $\overline{\overline{FF}}_w$ remains constant and equal to its optimal value, Eq (A.4) can be integrated within limits of the initial gross weight ($W_{gr_o} = W_{gr_{max}}$) and also that after flying distance ℓ when the ideal maximum fuel available (W_{pl_o}) is used, $W_{gr_\ell} = W_{gr_{max}} - W_{pl_o}$. The resulting ideal ferry range (no fuel reserve, and no weight or drag penalties for additional tankage) thus becomes:

$$\ell_{id} = \frac{100}{\overline{\overline{FF}}_{w_{opt}}} \ell n \frac{1}{1 - (W_{pl_o}/W_{gr_{max}})} \approx \frac{100(W_{pl_o}/W_{gr_{max}})}{\overline{\overline{FF}}_{w_{opt}}[1 - ½(W_{pl_o}/W_{gr_{max}})]} \tag{A.5}$$

Acknowledgements

The author wishes to acknowledge with gratitude his indebtedness to the U.S. Army Aviation Research and Technology Laboratories for permission to use figures and other material from his Comparative Study of Soviet vs. Western helicopters performed under contract to USAARTL. Also my sincere thanks to Boeing Vertol Company for their help in reducing the figures and tables, and to MBB for their kind offer to reproduce the preprints. The text of this paper was set by Mrs. W. L. Metz of ITA, who also assisted with editorial aspects.

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ACTUAL HELICOPTERS	APPROX. MAX. GW (LB)	SYMBOLS	
		MAX. GW	NORM. GW
KAMOV Ka-26	7,150	▼	●
Mil Mi-2 W/ Allison Engines	7,800	▼	
Mil Mi-2	8,150		
KAMOV Ka-25	16,100	▼	
Mil Mi-24D	22,000 (NGW)	—	
Mil-8	26,450	▼	
Mil Mi-10K	83,600		
Mil Mi-6 W/Wings	93,700	▼	
Mil Mi-26	123,480	▼	

HYPOTHETICAL HELICOPTERS	NGW/MAX. GW (LB)	SYMBOLS	
		MAX. GW	NORM. GW
S.R. 15 M.Ton	33,060/[37,800]	▽	◑
S.R. 24 M.Ton	52,900/[58,700]		
S.R. 52 M.Ton	114,700/[131,350]		
S.B.S. 52 M.Ton	114,700/[129,200]	▽	◑

TABLE 1. Soviet production and hypothetical helicopters.

HELICOPTERS	APPROX. MAX. GW (LB)	SYMBOLS	
		MAX. GW	NORM. GW
MBB Bo-105CB	5,100		○
BELL 222	7,850	▽	
AEROSPATIALE SA-365N	8,500		
BELL UH-1H	9,500		
SIKORSKY S-76	10,000		
AEROSPATIALE SA-330Y	16,300		
BOEING-VERTOL YUH-61A	19,700		
SIKORSKY UH-60A	20,250		
SIKORSKY CH-3E	22,050		
BOEING-VERTOL CH-46E	23,300	▽	
SIKORSKY CH-53D	42,000	▽	
BOEING VERTOL CH-57D	50,000	▽	
SIKORSKY CH-53E	73,500	▽	
BOEING VERTOL XCH-62A	148,000	▽	

NEW CONCEPTS	APPROX. MAX. OR NGW (LB)	SYMBOLS	
		MAX. GW	NORM. GW
BELL TILT-ROTOR XV-15	15,000	▽	○
BELL TILT-ROTOR D326	37,000 (NGW)	—	○
SIKORSKY ABC HSX	37,000 (NGW)	—	○
X-WING, B–V STUDY	30,000 (NGW)	—	○

TABLE 2. Western helicopters and new rotary-wing concepts.

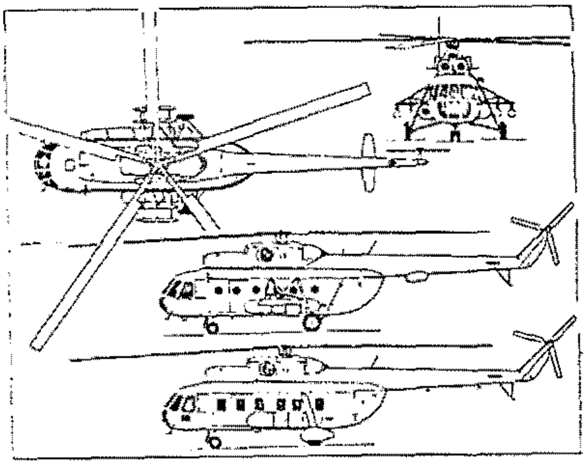

Figure 1. General configuration of the hypothetical 15 and 24 metric-ton helicopters (similar to the Mi-8).

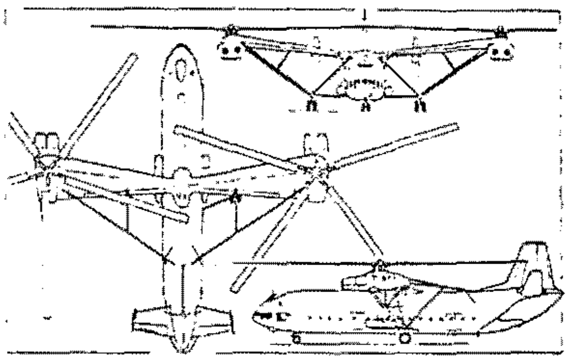

Figure 2. General configuration of the hypothetical 52 m.ton side-by-side helicopter (similar to the Mi-V-12).

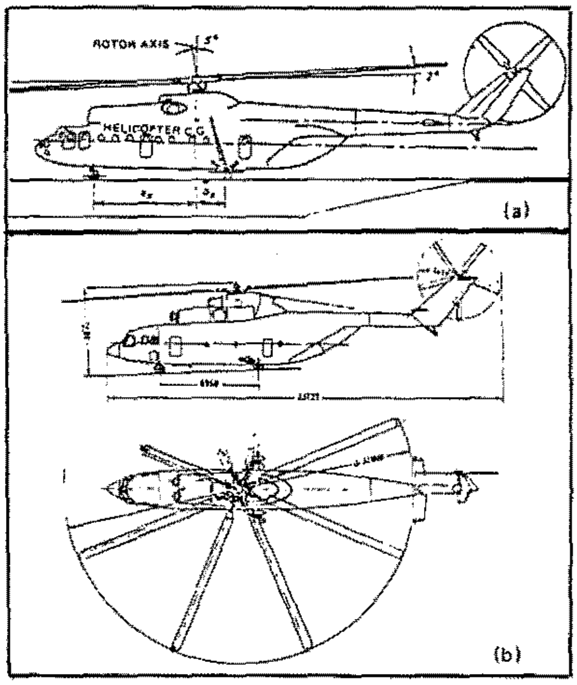

Figure 3. (a) Side view of the hypothetical 52 m.ton, single-rotor helicopter (similar to the Mi-6); (b) Mil Mi-26 heavy-lift helicopter.

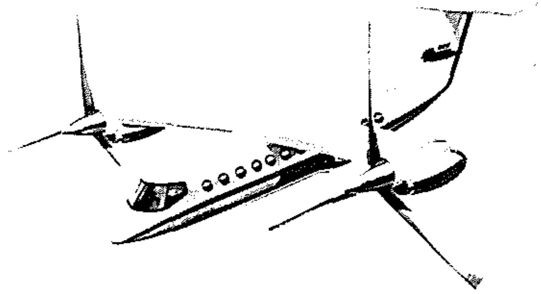

Figure 4 Artist's concept of the Bell 30-passenger tilt-rotor transport, D-326

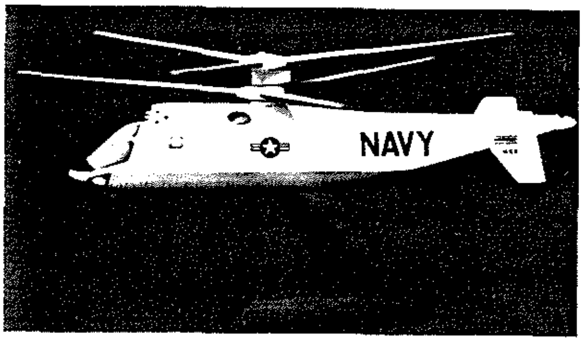

Figure 5 Model of Sikorsky ABC ASW project

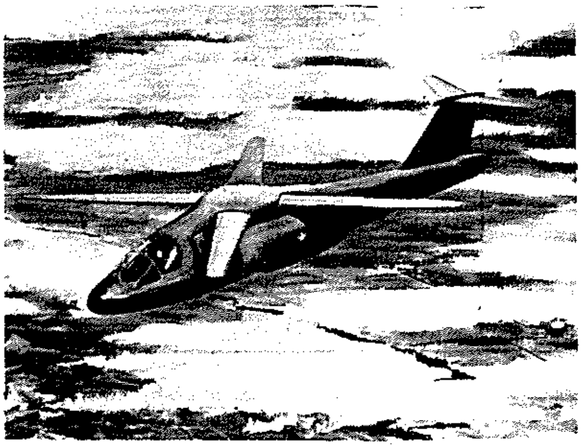

Figure 6. Artist's concept of Boeing-Vertol version of the X-Wing.

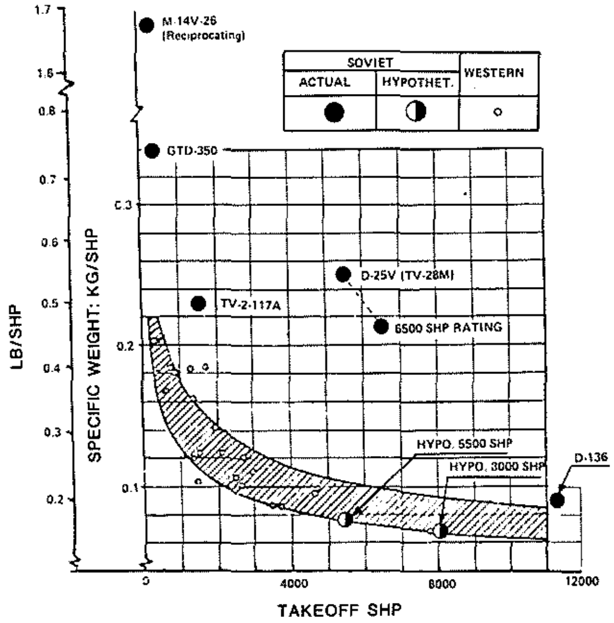

Figure 7. Specific engine weights

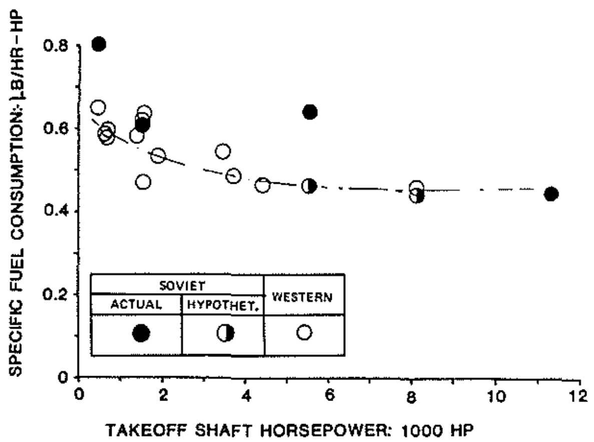

Figure 8. Takeoff sfc vs. engine power rating.

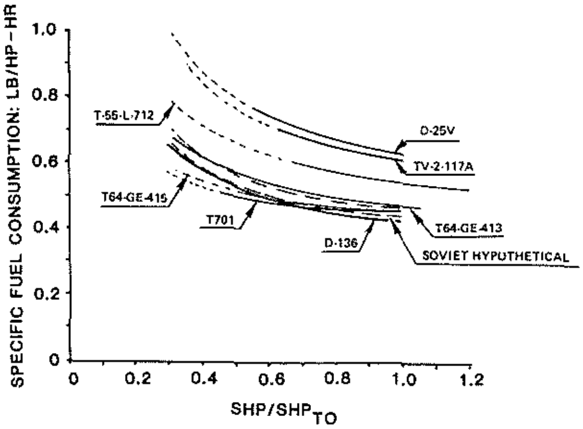

Figure 9. sfc vs relative power setting of large engines.

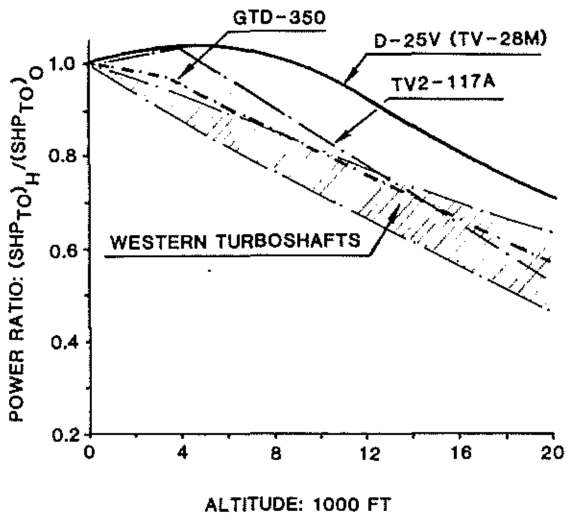

Figure 10. Relative lapse rate of takeoff power

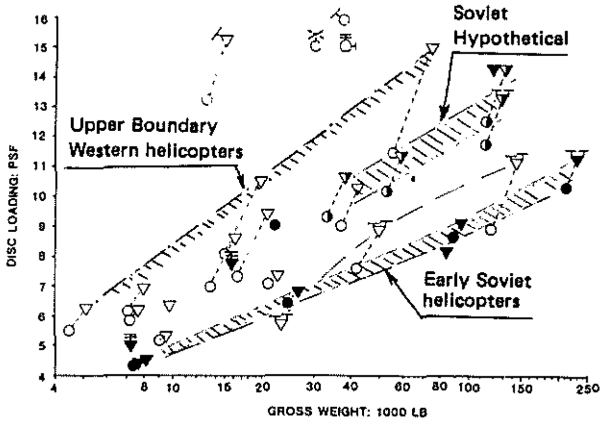

Figure 11. Disc loadings

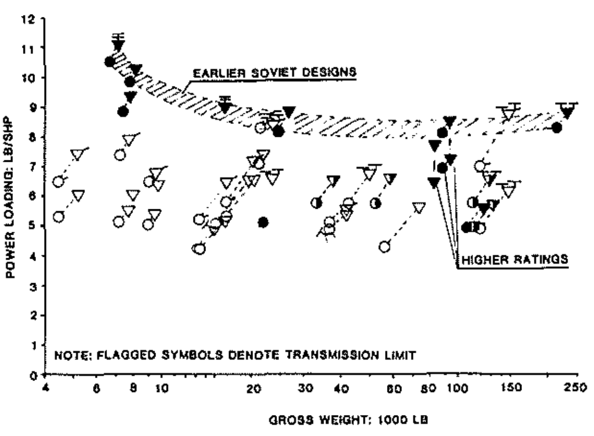

Figure 12. Installed power loadings

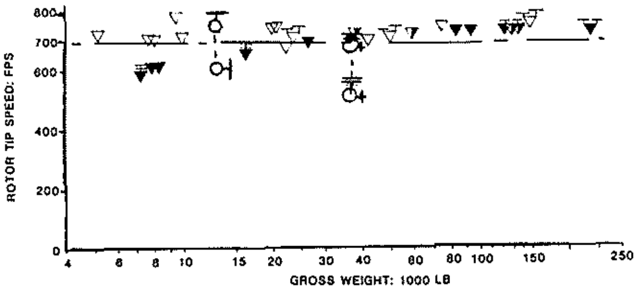

Figure 13. Tip Speeds

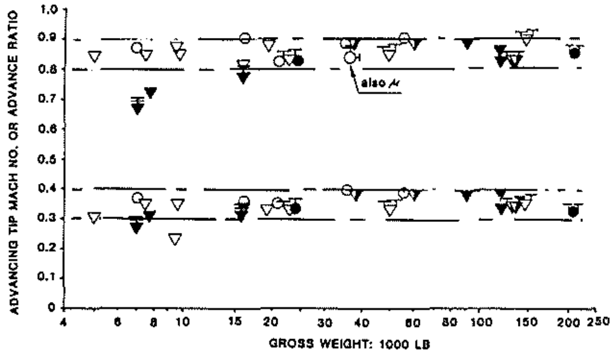

Figure 14. Advancing tip Mach numbers and advance ratios at V_{max} or $(V_{cr})_{max}$ at SL, ISA.

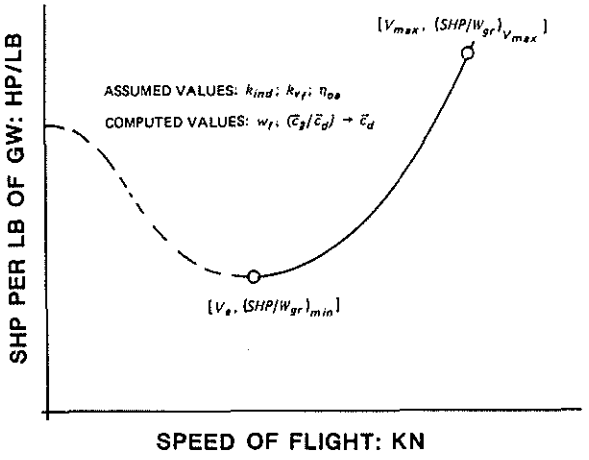

Figure 15. Scheme of the $SHP/W_{gr} = f(V)$ relationship.

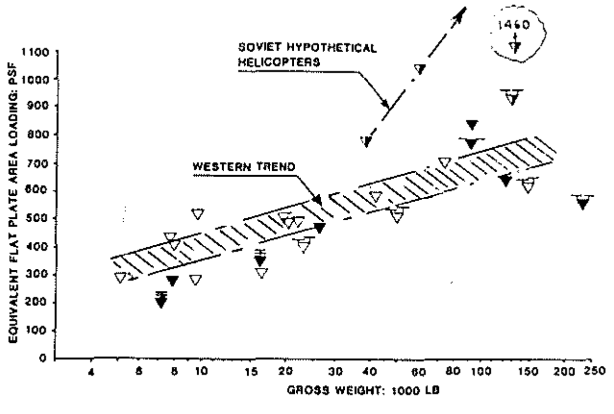

Figure 16. Trends in equivalent flat-plate area loadings.

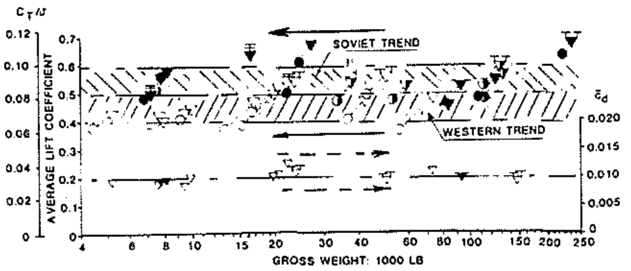

Figure 17. Trends in average blade-lift and profile-drag coefficients at SL, ISA.

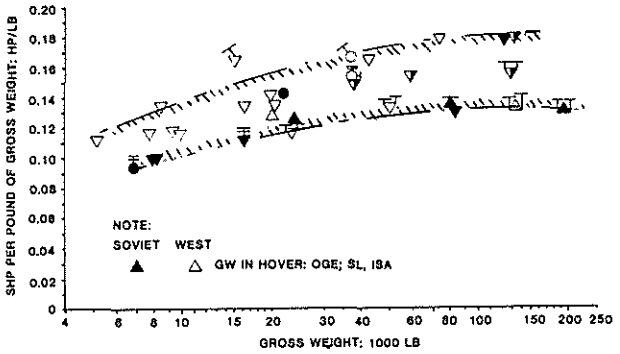

Figure 21 SHP required per pound of gross weight in hover OGE at SL, ISA

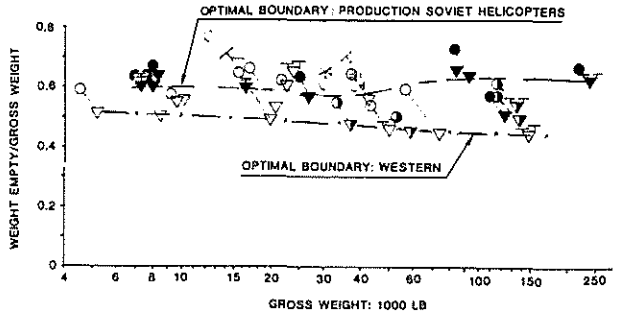

Figure 18. Weight empty to gross-weight ratios of compound rotorcraft.

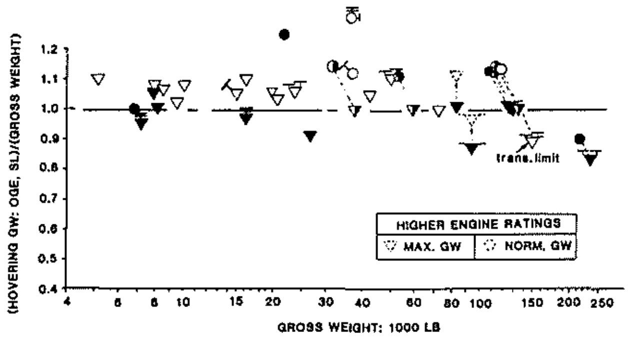

Figure 22. Ratio of SL, ISA OGE hovering gross weight to maximum and normal gross weights

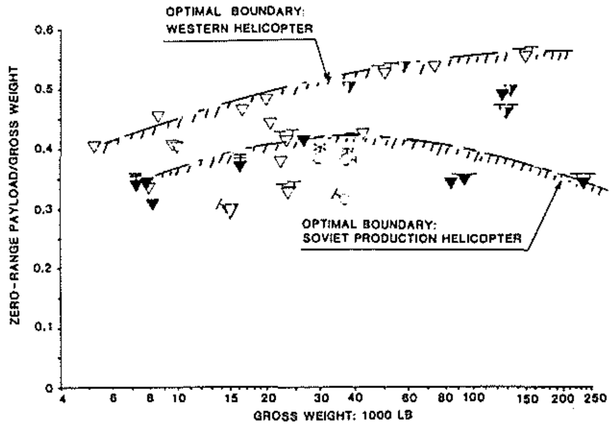

Figure 19. Zero-range payload to gross-weight ratios

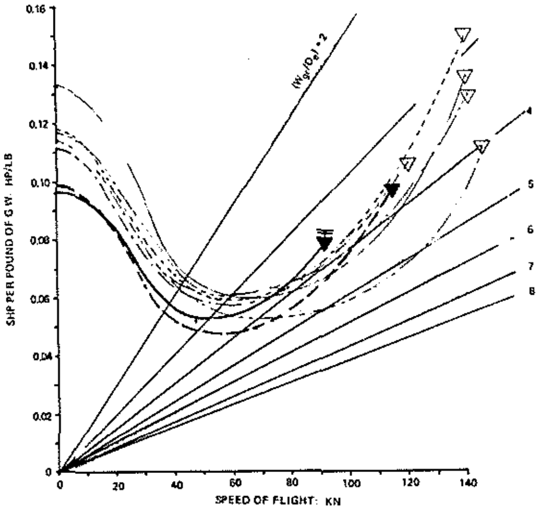

Figure 23. $(SHP/W_{gr}) = f(V)$ for aircraft weighing up to 12,000 lb gross weight.

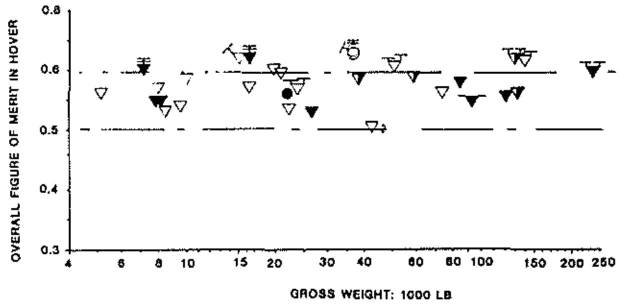

Figure 20. Overall Figure of Merit in hover OGE at SL, ISA

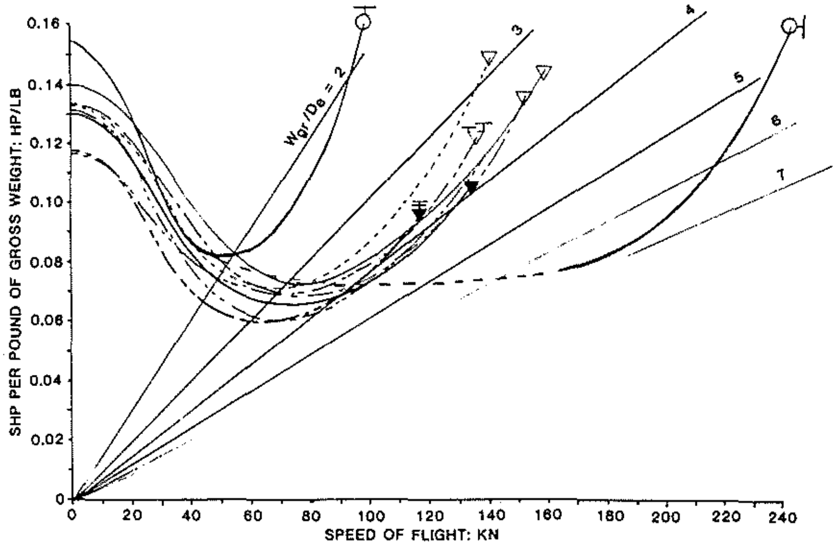

Figure 24. $(SHP/W_{gr}) = f(V)$ for the 12,000 to 30,000-lb gross weight class.

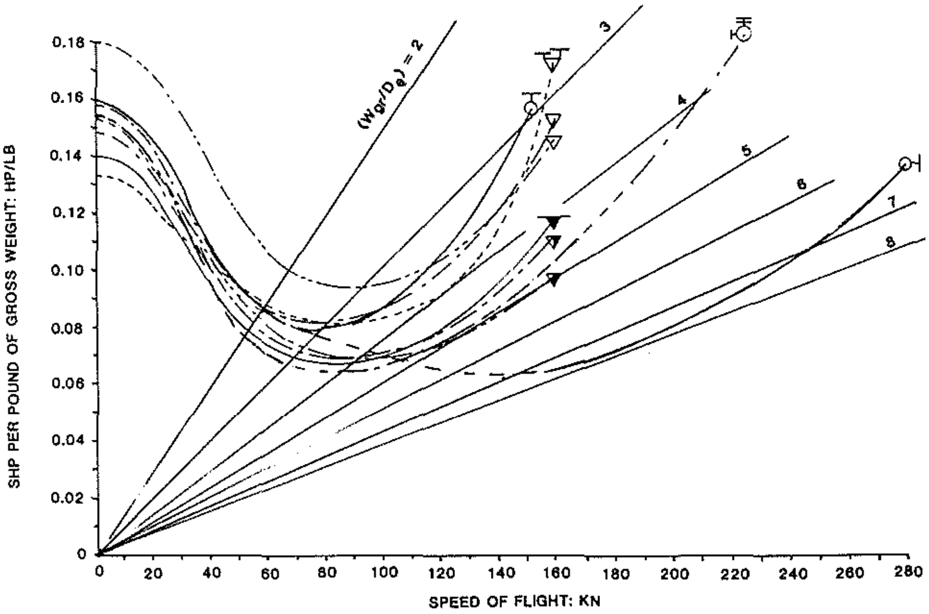

Figure 25. $(SHP/W_{gr}) = f(V)$ for the 30,000 to 100,000-lb gross-weight class.

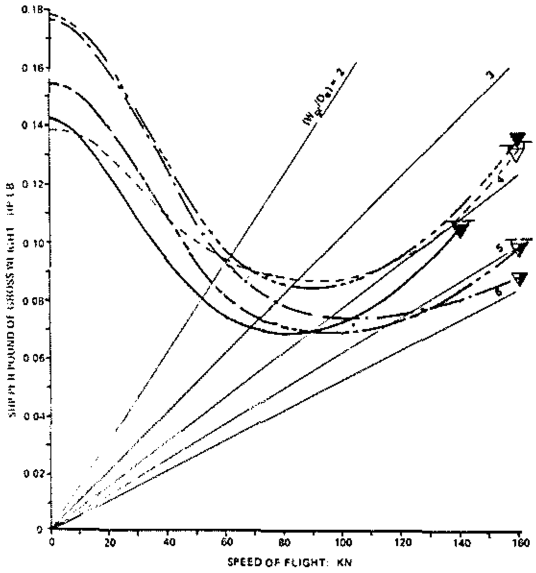

Figure 26. $(SHP/W_{gr}) = f(V)$ for aircraft weighing over 100,000 lb gross weight.

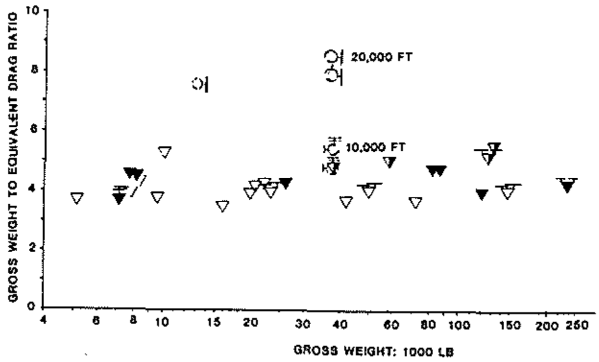

Figure 27. Optimal gross-weight to equivalent-drag ratios.

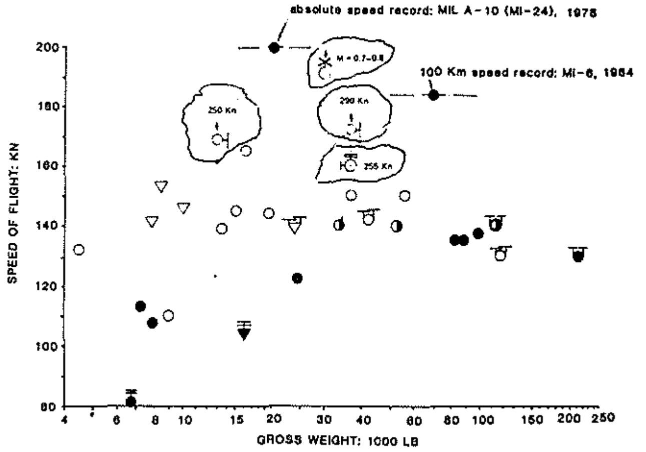

Figure 28. Fast cruise speed.

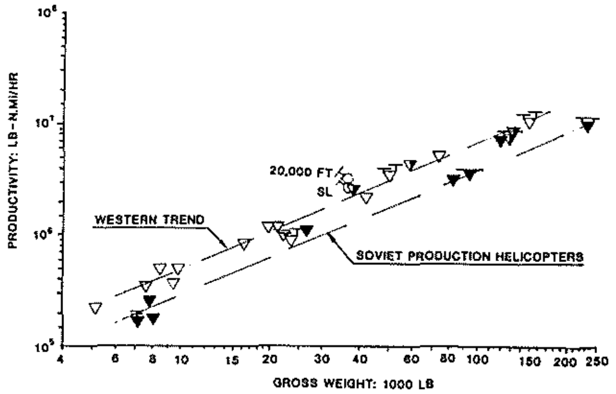

Figure 29. Ideal absolute productivity at 100 n.mi.

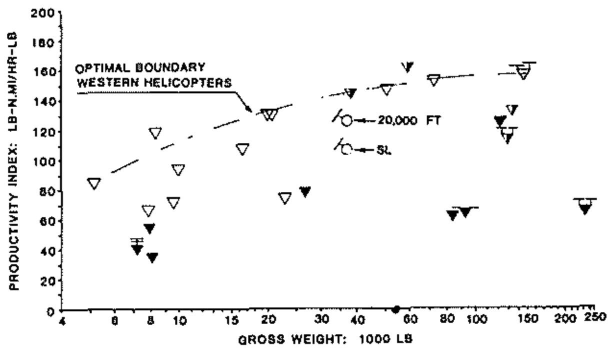

Figure 30. Ideal relative productivity at 100 n.mi.

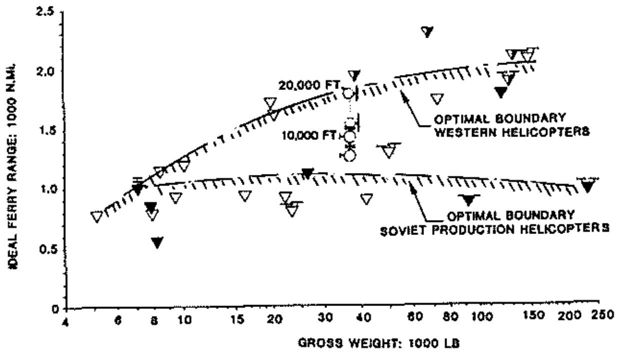

Figure 31. Ideal ferry range.

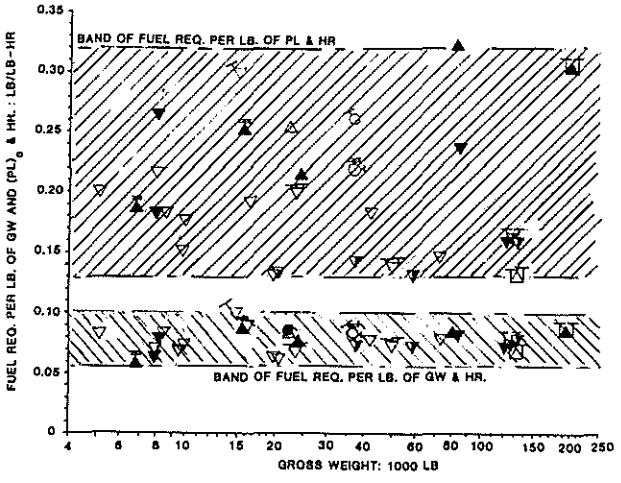

Figure 32. Fuel required per pound of gross weight and zero range payload and hour in hover OGE at SL, ISA.

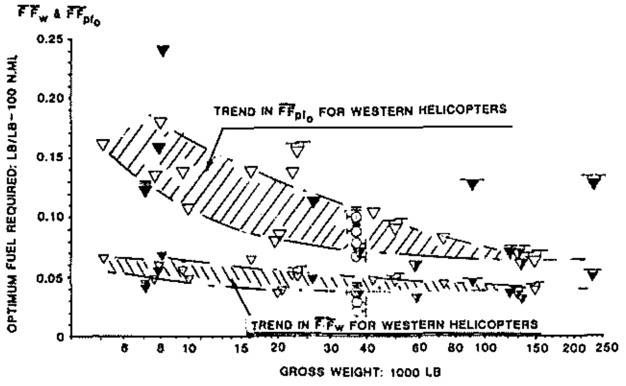

Figure 33. Optimal fuel required per 100 n.mi, referred to gross weight (F_W) and zero-range payload (F_{pl_o}).

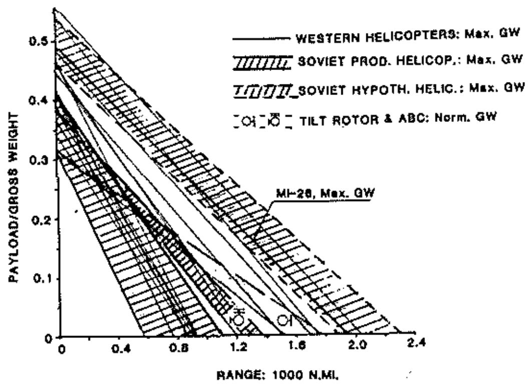

Figure 34. Payload to gross-weight ratio vs. range.