Design Philosophy and Operational Requirements of Subsonic VTOL Aircraft

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The growth-factor concept is used to investigate the influence of operational requirements (hovering altitude, temperature, and time) on gross and empty weight of three VTOL configurations (mechanically driven compound helicopter, tilt wing, and jet lift). Conventional STOL is also considered. With additional criteria of the relative productivity and fuel index, all these concepts are evaluated vs a combat mission (payload 1500 lb, 3 hr on station at 225 knots, 6 min of hovering at 6000 ft, 95°F; ground run for STOL is 300 ft). For this mission, tilt wing appears to be the best over-all configuration. Relaxation of the on-station speed requirements (150 knots) and more emphasis on hovering and low-speed operation greatly increases attractiveness of the compound helicopter. By contrast, shifting of speed requirements to higher values makes the jet lift quite competitive. To make the STOL competitive with the VTOL's, 300-ft ground-run requirements would need relaxing. A similar analysis of four configurations for the Intra-Theater Transport mission (10-ton payload, over 500-naut mile radius) shows that for the defined mission requirements, the shaft-driven propeller or rotor systems have the necessary capability, high productivity, and excellent fuel indexes required to provide a low-cost intra-theater transportation service.

Nomenclature

AR = aspect ratio
B = bypass ratio
c = chord, ft
C_{LTO} = lift coefficient at takeoff
G = growth factor (ratio of gross to invariant weight)
G_E = weight empty growth factor (ratio of empty to invariant weight)
K_n = ratio of cost per lb of group n to lowest cost/lb
n = number
R = radius, ft
s = takeoff ground run, ft
T = thrust, lb
V = speed of flight, fps or knots
V_t = tip speed, fps
V_{TO} = takeoff speed, fps
W = gross weight, lb
W_{CR} = weight of crew, lb
W_E = weight empty, lb
W_F = weight of fuel, lb
W_i = weight of group i, lb
W_{INV} = invariant weight in mission definition, lb
w = disk loading, psf
w_f = equivalent flat-plate area loading, psf
w_w = wing loading, psf
μ = friction coefficient
ρ = air density, slugs/ft^3
τ = throttling ratio for turboshaft and turbofans

Introduction

VTOL compound aircraft can be defined as air vehicles that, in high-speed regimes of flight, depend either entirely, or at least partially, on lifting devices different from those which support them in vertical (including hovering) and slow-speed flights. At present, compounds consist of a combination of various vertical-lift generators (from lightly loaded helicopter rotors to heavily loaded turbojets) with a fixed wing. Dependence on the fixed wing for a complete, or at least partial, lift generation at high flying speeds exists because until now this has been the most efficient device for maintaining medium, subsonic, and higher speeds (see Fig. 9 of Ref. 1).

The great variety of possible vertical-lift generators leads to many different design philosophies of compounding. It may be expected, hence, that for a given mission and defined operational requirements, some design concepts should be more effective than others. In this paper, an attempt is made to establish a method and examine selected VTOL compounds from the point of view of their effectiveness in performing certain missions under varying operational requirements. In order to perform this task, some criteria of effectiveness are established and missions selected. Furthermore, the necessary relationships are given as simply as possible to clarify the influence of operational requirements on the effectiveness of various VTOL compound systems.

There are many compound systems capable of vertical takeoff and landing, hovering, and medium and high subsonic or even supersonic speeds. However, since the present study is directed toward subsonic V/STOL's, only the following three representative types are considered: compound helicopter, tilt wing, and jet-lift airplane—a wide spectrum of VTOL compounds, ranging from those incorporating lightly loaded helicopter rotors to those based on turbofans. In some cases, conventional STOL aircraft and pure helicopters are also examined for comparison.

Two missions are studied which represent the lower and the upper limits of the gross-weight spectrum of V/STOL's. The lower end of the gross-weight spectrum is represented by the so-called Combat Mission, synthetizing requirements for the helicopter escort, armed reconnaissance, and Counter-Insurgency (COIN), and the higher limit is represented by a mission based on the Intra-Theater Transport (10-ton payload). The first of the two missions receives more attention than the second, since it demonstrates the basic methods used here.

Criteria for Aircraft Evaluation

Three simple criteria are established to evaluate performance of the selected types of V/STOL during the two missions. These criteria are relative productivity, fuel index, and growth factor.

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Relative Productivity (RP)

Relative productivity for transport missions is expressed as

$$RP_{tr} = (\text{cruise speed} \times \text{payload})/\text{weight empty} \quad (1)$$

For missions involving time on station (loitering) it may be written as follows:

$$RP_{t} = (\text{time on station} \times \text{payload})/\text{weight empty} \quad (2)$$

Both expressions (1) and (2) attempt to relate the most important performance aspects with cost of aircraft by assuming that the cost is proportional to the weight empty. This is essentially correct for machines based on the same design concept. However, V/STOL aircraft of such different types as compound helicopters and jet-lift airplanes both incorporate systems and assemblies which may considerably vary in their cost/lb. Therefore, it is suggested that, in Eqs. (1) and (2), instead of the weight empty directly, the factored value (W_{EF}) be used:

$$W_{EF} = W_1 + K_2 W_2 + \ldots + K_n W_n \quad (3)$$

where W_1 is the weight of an assembly or system with the lowest cost/lb pound, and K_n = cost/lb of assembly n/cost/lb of assembly 1. In the present study, distinction in cost/lb is made only between airframe and un-installed powerplants, and for the latter, $K = 2$ is assumed.

Fuel Index (FI)

Because of its logistic implications, fuel requirements in military missions assume special importance. For transport missions, ton-miles or lb-miles of payload per pound of fuel consumed can be used as a fuel index:

$$FI_{TR} = (\text{payload} \times \text{range})/\text{fuel} \quad (4)$$

Analogous to Eq. (4), fuel index for missions involving time on station (loitering) can be defined as follows:

$$FI_{t} = (\text{payload} \times \text{time on station})/\text{fuel} \quad (5)$$

In order to give better insight into fuel requirements of the considered aircraft (hourly fuel flow)/(gross weight) is plotted vs flying speed from V equals 0 to V_{max}. From such plots, optimum speeds for range and time on station can easily be spotted, total fuel requirements for a mission established, and fuel indexes computed. Furthermore, it can be seen quickly how, for example, in the escort mission, various V/STOL concepts would compare when loiter speed is fixed at an arbitrary value of, say, 40 or 200 knots, etc.

Growth Factor (G)

With respect to the gross weight, growth factor is defined in the present study as the ratio of mission gross weight W to the mission invariant weight W_{INV}:

$$G = \text{mission gross weight}/\text{mission invariant weight} \quad (6)$$

Growth factor with respect to the weight empty G_E can be expressed analogously to Eq. (6), as

$$G_E = \text{weight empty}/\text{mission invariant weight} \quad (7)$$

This concept of the growth factor is based on the definition of the initial mission gross weight, some part of which may be considered as invariant. For instance, in the helicopter support mission, the invariant weight is assumed to be comprised of payload (active armament and ammunition), crew, armor, fixed equipment, cockpit flight and engine controls, and stability augmentation system (SAS).

The remaining gross weight can be broken down into several items n, such as weights of components of the airframe, powerplants, fuel, etc. If these items can be expressed as linear functions of the gross weight and some functions of the design parameters (wing aspect ratio, wing loading, rotor or propeller loading, tip speed, bypass ratio, etc.) and operational parameters (hovering altitude and ambient temperature, time, speed and altitude when on station, distance and speed of flight in the transport operation, etc.), then the initial mission gross weight can be expressed as follows:

$$W = W_{INV} + W \sum_{1}^{i=n} \left(\frac{W_i}{W}\right) \quad (8)$$

where (W_i/W) is the relative weight (fraction of the gross weight) of group i, expressed as a function of design and operational parameters: $(W_i/W) = f(AR, w, w_{pr}, w_f; H, T, t, V_{max}, \text{etc.})$. Eq. (8) can be solved for W:

$$W = W_{INV} \frac{1}{1 - \sum_{1}^{i=n} \left(\frac{W_i}{W}\right)} \quad (8a)$$

and the fractional term in Eq. (8a) easily can be recognized as the growth factor G:

$$G = \frac{1}{1 - \sum_{1}^{i=n} \left(\frac{W_i}{W}\right)} \quad (9)$$

Accuracy will obviously increase with the number n of weight items selected for the analysis. However, because the comparative character of the present study favors simplicity and clarity of presentation over exactness of analysis, only a few weight items are considered.

There are structural weights which, for a given type of aircraft that will perform a given mission and that belongs to a defined gross-weight class, may be considered as a linear function of the gross weight only. Landing gear, body, and wing structures (for a constant wing loading) form this category. Relative weights of these components, once established, can be considered, henceforth, as independent of operational parameters.

However, there are components, such as rotors, propellers, transmissions, and powerplants, whose weights are functions of gross weight, design, and operational parameters. Furthermore, for some (e.g., rotors, propellers, and transmissions) linearization of their weights with respect to gross weight cannot readily be obtained for the whole range of gross-weight values. Even in such cases, however, the desired linearity, with a very small margin of error, can be achieved for a defined gross-weight class.

Having established the formulas, it is possible to find (either through closed-form analytical solutions or repetitive numerical calculations) one or more combinations of design parameters rendering, for given operational requirements, the minimum growth factor—that is, to find one or more combinations of design parameters assuring the lowest gross weight of aircraft capable of performing a given mission.

For a rapid evaluation of the influence of important operational parameters, such as ambient temperature T in hovering at an altitude H of 6000 ft and sea level, as well as of the intermediate standard altitudes, the following graphical method is used (Fig. 1). Relative weights of items that may be considered to be independent of temperature and altitude are separated from those which are influenced by one or both of these factors. The sum of these relative weights, of course, remains constant for all the considered ranges of hovering altitudes and ambient temperatures. Auxiliary scales of temperatures at H = 6000 ft and at sea level are provided which permits our plotting the variation of the relative weight of components with temperature. Between the two sets of temperature scales at H = 6000 ft and H = 0, a scale of standard altitude from 6000 ft to 0 is provided. In this way, variation of the relative weights vs standard altitude can also be examined.

Utilizing those auxiliary scales, variation of the relative weight of a particular component or system can be watched

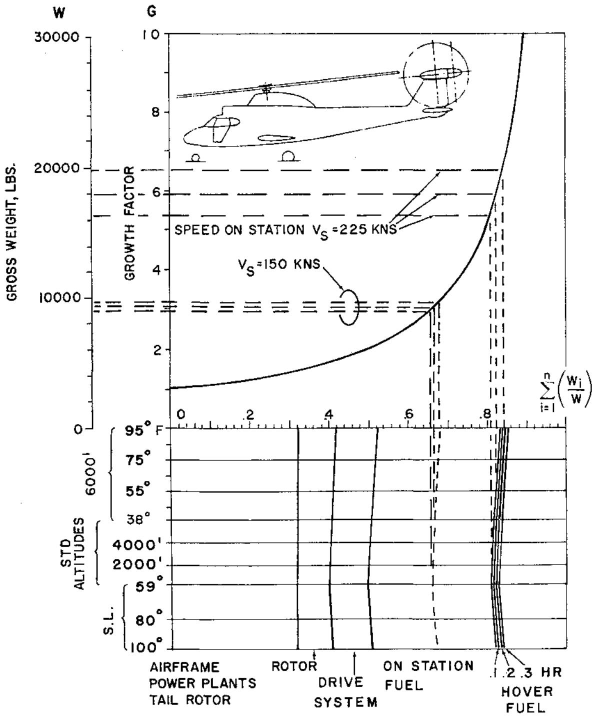

Fig. 1 Compound helicopter growth factor and mission gross weight for various hovering requirements.

throughout the entire range of possible hovering conditions. The influence of those conditions on the sum of relative weights of the components can be examined.

Relative weight of fuel required in forward flight $(W_F/W)_f$ is added to the sum of the relative weights of structures. Finally, relative weight of fuel required for different times in hovering $(W_F/W)_h$ is also added. Thus, it can be seen rapidly to what extent operational requirements of altitude and ambient temperature in hovering, as well as time on station and time in hover, should affect the growth factor and, therefore, the mission gross weight. For a defined invariant weight, an auxiliary scale can be provided, allowing us to find immediately the growth weight (see Fig. 1).

Knowledge of the growth factor permits also a rapid calculation of weight empty as it can be expressed in terms of the growth factor, the invariant weight, relative weight of total fuel required for the mission $(W_F/W) = (W_F/W)_f + (W_F/W)_h$, and the ratio of the weight of payload and crew to the total invariant weight $(W_{PL} + W_{CR})/W_{INV}$:

$$W_E = GW_{INV}\left[1 - \left(\frac{W_F}{W}\right)\right] - (W_{PL} + W_{CR}) \quad (10)$$

The ratio of weight empty to invariant weight (which may be called the weight-empty growth factor G_E) becomes

$$G_E = G\left[1 - \left(\frac{W_F}{W}\right)\right] - \frac{W_{PL} + W_{CR}}{W_{INV}} \quad (10a)$$

Table 1 Combat mission requirements

Criteria	Requirements
Payload	1500 lb
Endurance	3 hr
Speed on station	225 knots
Maximum speed[a]	...
Hover time[a]	...
Hovering altitude and temperature[a]	...
Cabin dimensions	Two-place
Limit load factor	8

[a] Note: These criteria appear to be the major operational parameters.

If optimization of the weight empty becomes a criterion of design effectiveness for a given mission, then through analytical or numerical methods, design parameters should be selected to bring Eqs. (10) and (10a) to a minimum for a given set of operational requirements. A similar approach can also be applied in an optimization of any other index of aircraft effectiveness by maximizing Eqs. (1), (2), (4), and (5). We shall now discuss the influence of operational requirements on design philosophy of compound aircraft suitable for combat and transport missions.

Compounds for Combat Mission

Mission Definition

Recent developments in limited war tactics have shown a need for specialized combat aircraft capable of performing a variety of missions in close cooperation with the ground forces. These missions have been defined generally as Fire Support Aerial System, COIN, Armed Reconnaissance, and Armed Escort for transport helicopters. Many partial definitions of these missions appear in aeronautical magazines, based on unreleased military requirements and/or opinions of experienced observers of the conflict in Viet Nam. All these inputs were synthetized in a combat mission, as shown in Table 1.

Payload of 1500 lb and endurance on station of 3 hr were obtained as an average of the published inputs; on-station speed of 225 knots was based partially on the same source and partially on the logical assumption that, with transport helicopters approaching cruising speeds of 150 knots, their escorts should be able to remain on station at speeds at least 50% higher. Other requirements, such as hover time, maximum speed, hovering altitude, and ambient temperature, are the subject of this study.

The invariant weight of the mission is assumed to be W_{INV} = 3030 lb and to have the breakdown shown in Table 2.

The combat mission is assumed to be performed at sea level, standard, whereas hovering requirements of the compounds considered vary from H = 6000 ft, T = 95°F to sea level, standard. Influence of varying hovering requirements on the effectiveness of the considered compounds in performing the combat mission is examined.

For comparison, a conventional (horizontal thrust) STOL airplane is also considered for this mission. It is assumed that its ground-run distance of s = 300 ft remains constant from H = 6000 ft, T = 95°F to sea level, standard.

Types of Aircraft Considered

The following configurations, based on the airscrew type of vertical-lift generators, are considered: one compound helicopter and two tilt-wing aircraft. The tilt-wing aircraft are of the same two-propeller configuration but differ in the wing loading (w_w = 40 and 80 lb/ft²).

In the jet configurations, one of the aircraft considered is based on the concept of using the same high bypass ratio (B = 8) thrust system both in hovering and in forward flight, whereas the other concept is assumed to have separate lift engines to provide an auxiliary vertical thrust in hovering. Finally, the conventional STOL is assumed to be of the propeller type, with no provision for thrust vectoring.

The compound helicopter, tilt wing, and the STOL are assumed to be powered by shaft turbines having specific dry weight of (W_{EN}/SHP_{max}) = 0.24 lb/hp and installed $(W_{EN}/SHP_{max})_{inst}$ = 0.36 lb/hp. Variation of specific fuel consumption (sfc) with partial power setting ($\tau = SHP/SHP_{max}$) and lapse of power with altitude and temperature are taken as for modern turboshaft engines (Fig. 20 of Ref. 1).

Assumed characteristics of high-bypass ratio turbojets were deduced from Refs. 2–4. On that basis, specific dry weight of a turbofan of bypass ratio B = 8 has been assumed

$(W_T/T_{max}) = 0.11$ lb/lb, and installed weight $(W_T/T_{max})_{inst} = 0.16$ lb/lb. Variation of thrust specific fuel consumption with throttling ratio ($\tau = T/T_{max}$) and speed at sea level for turbofans of bypass ratio $B = 8$ and $B = 6$ was assumed, as in Fig. 2, and static thrust reduction with altitude and ambient temperature was taken as an average for turbofans with bypass ratios from $B = 2$ to $B = 8$ (see Fig. 5, Ref. 5). Expressions for relative weights of structural components and fuel are given in Table II of Ref. 5, and the development of some of these formulas can be found in the Appendix of Ref. 5.

Definition of Aircraft

Compound helicopter

This is a single rotor configuration (Fig. 1) with a tail propeller used in hovering for torque compensation. This propeller swivels in the horizontal plane through 90° to provide propulsive thrust at high forward speeds. In this regime of flight, a tapered wing of $AR = 6$ is assumed to support 50% of the aircraft weight. Rotor disk loading in hovering is $w = 10$ psf, and tip speed is $V_t = 700$ fps which, at high forward speeds, is reduced to $V_t = 600$ fps. The equivalent flat-plate area loading $w_f \equiv W/f = 1500$ psf.

In light of the present state of the art of compound helicopters, maximum flying speed at sea level of 250 knots was selected as a practical limit. As a result of this assumption, high-speed requirements dictate the power installed per pound of gross weight $(SHP/W)_{inst}$, which thus remains constant and independent of the hovering conditions we have considered (from 6000 ft, 95°F to sea level, standard). On the basis of relative power installed, relative power required, specific fuel consumed $= f(\tau)$, relative fuel flow per pound of gross weight is computed for two cases: with all engines running and with 50% of the engines operating as shown later. In Fig. 1 is shown a graph of variation of the growth factor and mission gross weight with hovering altitude and temperature.

It can be noticed from Fig. 1 that, because the installed power remains independent of hovering altitude and temperature, the sum of relative weights varies little between $H = 6000$ ft, $T = 95$°F, and sea level, standard. However, the growth factor varies from $G = 6.55$–5.4 and gross weight from $W = 19{,}900$–$16{,}400$ lb. This disproportionally large variation of the growth factor and gross weight exists because the sum of relative weights approaches values corresponding to the steep part of the $G = f[\Sigma(W_i/W)]$ curve. This in itself is sufficient warning that the considered concept is not suitable for the mission. Further analysis would show that this unsuitability of the considered compound helicopter for the combat mission (as defined in Table 1) stems from the demand of 3 hr on station at a speed of 225 knots, which, in turn, leads to a very high $[(W_F/W) = 0.31]$ demand on fuel. Relaxation of this condition to 3 hr at 150 knots (with unchanged $V_{max} = 250$-knot capability) would lead to the reduction of relative fuel weight to $(W_F/W) = 0.16$ and, consequently, to a growth factor of about 3 and a gross weight of less than 10,000 lb. Furthermore, with this lower speed on station, the growth factor would be little affected by the requirements of altitude and temperature in hovering. It should also be noticed that, owing to the light

Table 2 Invariant weight of flight mission

Item	Weight, lb
Payload	1500
Crew	400
Fixed equipment	820
Armor	200
Cockpit flight and engine controls	80
SAS	30
Total	3030

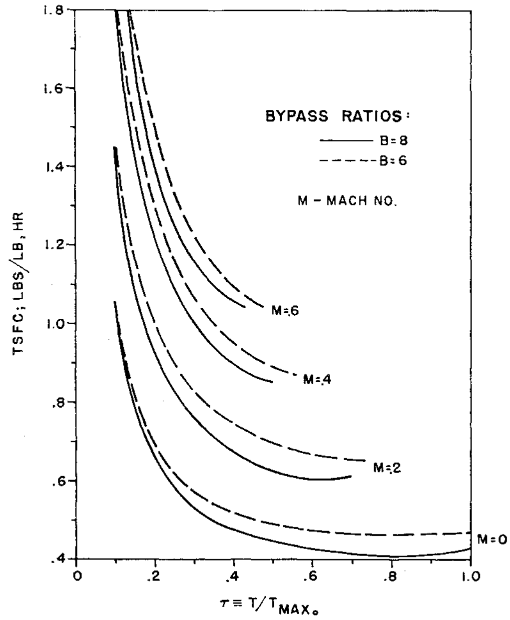

Fig. 2 Thrust specific fuel consumption vs throttling for turbofans.

loading of the vertical-thrust generator, an increase in hovering time from 0.1 to 0.3 hr would little affect the relative fuel required.

Tilt-wing aircraft

These aircraft are represented by two machines of the same aspect ratio, $AR = 5$, same propeller-radius to wing-chord ratio of $R/c = 1.0$, and identical equivalent flat-plate area loading of $w_f = 4000$ psf. They differ, however, in their wing loading being $w_w = 40$ and $w_w = 80$ psf and, consequently, in the propeller disk loading in hovering which are, respectively, $w = 32$ and $w = 64$ psf.

As can be expected in this type of more highly loaded vertical thrust generators, power installed per pound of gross weight resulting from hovering exceeds that dictated by forward flight up to high flying speeds, and therefore relatively high maximum speeds at sea level become possible. For instance, with power installed resulting from the hovering requirements at $H = 6000$ ft and $T = 95$°F, $V_{max} = 340$ knots at sea level for the tilt wing with $w_w = 40$ psf, and $V_{max} = 400$ knots for $w_w = 80$ psf become possible. For aircraft designed for sea level, standard hovering, the maximum speeds would drop, respectively, to $V_{max} = 290$ and 350 knots.

Comparison of relative fuel flow, discussed later, shows that considerable fuel savings can be accomplished by operating 50% of the engines, whenever possible. With relative weights of structural components and fuel computed by the formulas from Table II of Ref. 5, Fig. 3, showing variation of the growth factor and mission gross weight with hovering requirements of altitude, temperature, and time, is constructed.

As can be seen from Fig. 3, both growth factor and gross weight of the two considered tilt wings are considerably affected by hovering requirements: For $H = 6000$ ft, $T = 95$°F, and 0.1 hr of hovering time, gross and empty weights would be $W = 12{,}000$ lb, $W_E = 7700$ lb for 40 psf; and $W = 11{,}000$ lb, $W_E = 6900$ lb for the 80 psf aircraft. Those figures would drop to $W = 10{,}300$ lb, $W_E = 6550$ lb for the first, and to $W = 9100$ lb, $W_E = 5560$ lb for the second aircraft, if hovering requirements were relaxed to $H = 6000$ ft, standard, or $H = 0$, $T = 100$°F. Still further reduction of hovering requirements to sea level, standard, would result in $W = 9100$ lb, $W_E = 5560$ lb for $w_w = 40$ and $W = 8200$ lb, $W_E = 4900$ lb for $w_w = 80$ psf aircraft. It

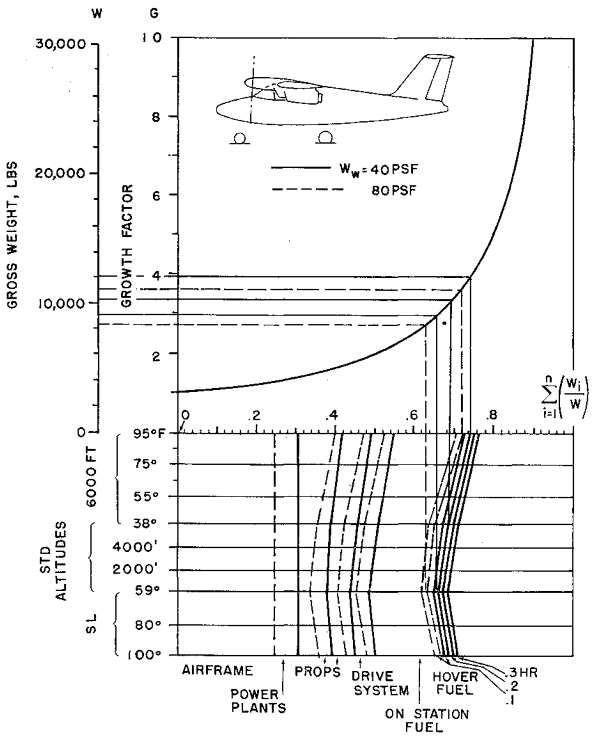

Fig. 3 Tilt wing growth factor and mission gross weight for various hovering requirements.

can also be seen from Fig. 3 that an increase in hovering time from 0.1–0.3 hr would have a noticeable effect on the increase of the growth factor and, consequently, on the mission gross weight.

Conventional STOL

Here (no thrust vectoring) the aircraft is assumed to have the same basic configuration as the previously considered

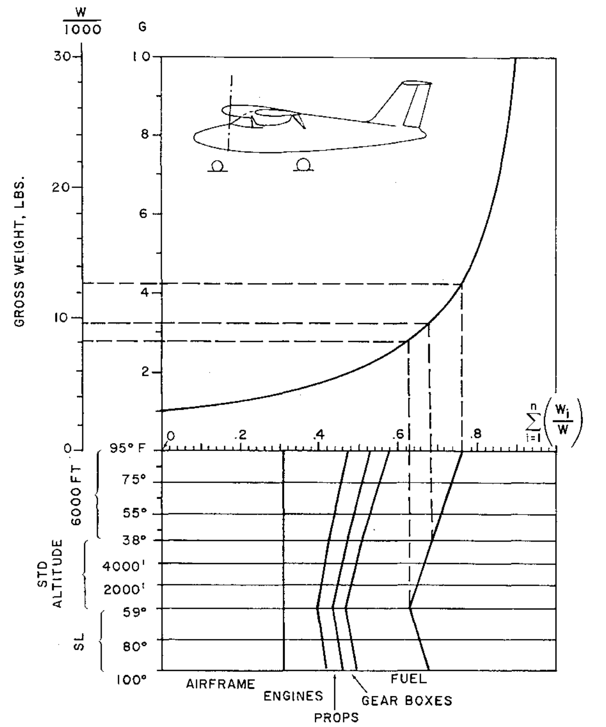

Fig. 4 Conventional STOL growth factor and gross weight for fixed ground run of 300 ft at various altitudes and ambient temperatures.

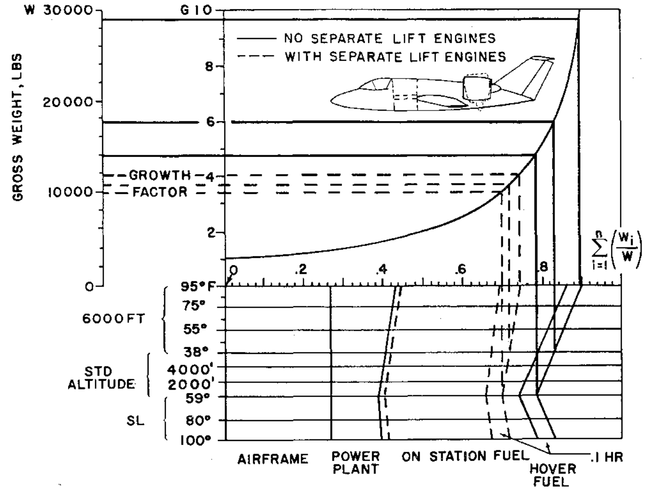

Fig. 5 Jet lift growth factor and gross weight for various hovering requirements.

tilt wings with the wing down. Also, its aspect ratio (AR = 5) and level of aerodynamic cleanliness (w_f = 4000 psf) is the same as for the tilt wings. The wing loading is assumed to be equal to that of the more lightly loaded tilt wing (w_w = 40 psf). However, because of the lack of mechanical interconnection between propellers, as well as the absence of zero speed controls, the empennage area of the STOL should represent a larger proportion of the wing area than in the tilt wing case.

In order to approximate the required and installed relative thrust (T/W), the well-known formula for the takeoff ground run s,

$$s \cong V_{TO}^2/2g[(T/W) - \mu]$$

is rewritten as follows:

$$(T/W) = (w_w/C_{LTO})(1/g\rho s) + \mu \tag{11}$$

where C_{LTO} is aircraft-takeoff-lift coefficient, g the acceleration of gravity, s the takeoff ground run in feet, and μ the ground-friction coefficient.

Assuming (w_w/C_{LTO}) = 15 psf and accepting that the ground run of a true STOL should not exceed s = 300 ft, it is clear from Eq. (11) that for H = 6000 ft, T = 95°F, and μ = 0.25, the required thrust-to-weight ratio becomes (T/W) = 1.1, i.e., higher than for the VTOL configurations. For a ground-friction coefficient of μ = 0.15, it would drop to (T/W) = 1.0, i.e., to approximately the same value as for the VTOL. For the sea level standard conditions, the required thrust-to-weight ratio values still would be (T/W) = 0.9 for μ = 0.25 and (T/W) = 0.8 for μ = 0.15. It is apparent that, for the assumed w_w/C_{LTO}, only through relaxation of the takeoff distance requirements may the thrust-to-weight ratio required be lowered considerably below those of the VTOL aircraft.

Assuming, however, that the ground-run requirement of s = 300 ft is valid and further assuming that w = 60 psf,‡ it can be easily found that the installed power per pound of gross weight will be higher for the STOL than for w_w = 40 psf tilt wing. This high power installed will result in V_{max} = 370 knots, which would decrease to V_{max} = 340 knots for the takeoff requirements at H = 6000 ft, standard, and V_{max} = 310 knots for the specified ground-run distance of 300 ft at sea level, standard.

Using the weight formulas given in Table II of Ref. 5, growth factors under various altitude and temperature requirements are presented in Fig. 4. The gross-weight scale in Fig. 4 is drawn for a slightly lower (no SAS) invariant

‡ This loading is selected in order to provide a sufficient propeller ground clearance.

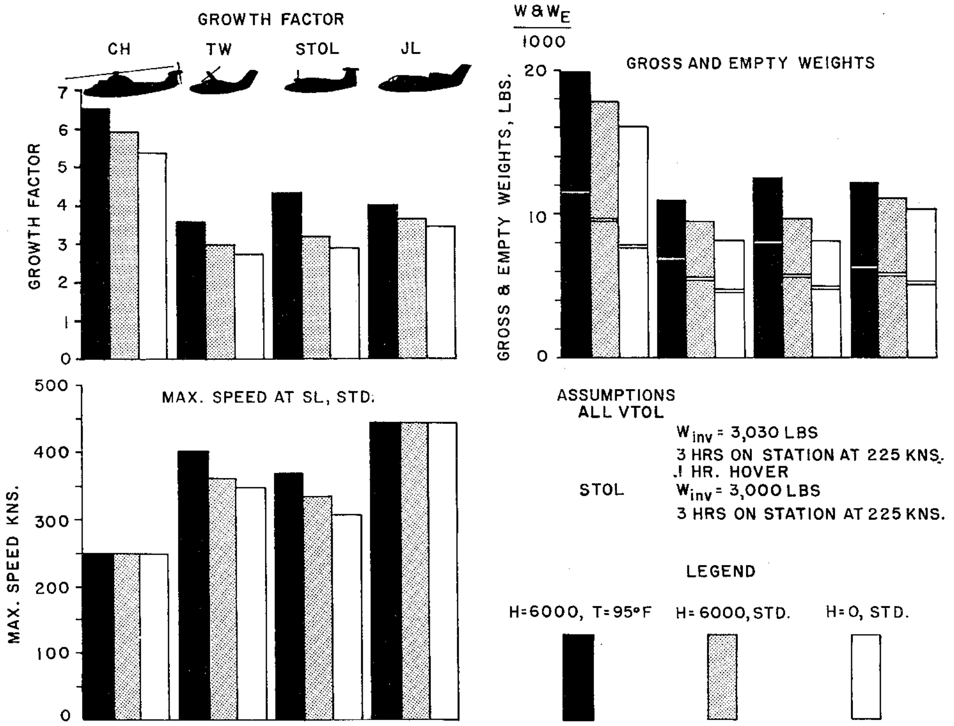

Fig. 6 Comparison of various configurations for "combat" mission.

weight of $W_{INV} = 3000$ lb. It can be seen from this figure that for $H = 6000$ ft and $T = 95°F$, $G = 4.2$, $W = 12{,}600$ lb, and, consequently, $W_E = 8300$ lb can be expected for the STOL aircraft, whereas for sea level, standard, the corresponding figures would be $G = 2.6$, $W = 8400$ lb, and $W_E = 5100$ lb.

Jet-lift aircraft

In the present paper we considered two versions. The first is a single system in which the same gas generators are used to drive all three lifting fans in hovering and then to provide forward propulsion by driving the two external fans that can be tilted to the horizontal positions (Fig. 5). With all gas generators operating, bypass ratio in hovering is assumed to be $B = 8$, whereas in forward flight $B = 5.3$. In this arrangement, installed thrust, as dictated by hovering requirements, suffice to provide almost transonic speeds at sea level. However, in the present study, a V_{max} of 440 knots was assumed as a limit in order to eliminate additional structural weight penalties resulting from higher speeds.

In the second version of the jet-lift aircraft, two combined lifting systems were assumed. One system of tiltable turbofans of $B = 8$ is selected to provide the thrust necessary for a speed of 440 knots at sea level, standard. In hovering, it obviously cannot provide enough vertical thrust and thus is supplemented by an auxiliary system of lift engines, $B = 2.5$. With the assumed $w_w = 80$ psf, $AR = 4.5$, and $w_f = 5000$ psf, the required relative thrust vs speed can be easily computed.

A comparison of relative fuel flow for the single and the combined systems will indicate that, with the exception of hovering and near hovering, the combined propulsion system is superior to the single system. Considerable reductions in the relative fuel flow (especially for the single system) with 50% of gas generators operating can be noticed.

Figure 5, showing growth factors and gross weights for the two systems, evidences that the single system configuration, owing to its very high fuel requirements that result in an excessive growth factor and gross weight, is not suitable for the combat mission as defined in this study. By contrast, the aircraft with the combined system, incorporating propulsive turbofans designed to fulfill the needs of forward flight, appears quite attractive.

The question remains, however, to what extent such factors as higher downwash velocity of the lift engines and the increased number of powerplants (representing, in addition, two types of engines) would reduce the attractiveness of this configuration.

Discussion

A comparison of growth factors, gross and empty weights, and maximum flying speeds at sea level, standard for the considered configurations is given in Fig. 6. Relative productivities based on the factored weight empty are shown in Fig. 7. Finally, relative fuel flows and fuel indexes are given in Figs. 8 and 9.

It should be emphasized at this point that all calculations leading to summary Figs. 8 and 9 are based on 3 hr on station (no reserve) at 225 knots, with 50% of powerplants operating, and on a hovering duration of 0.1 hr. Modification of any or all of these conditions would obviously change the growth-factor values and, consequently, the corresponding gross and empty weights, as well as other characteristics. When the growth factor exceeds $G = 4$ and approaches the steep region of the $G = f[\Sigma(W_i/W)]$ curve, even small changes in the sum of relative weights may bring significant changes in the growth factor, gross weight, etc.

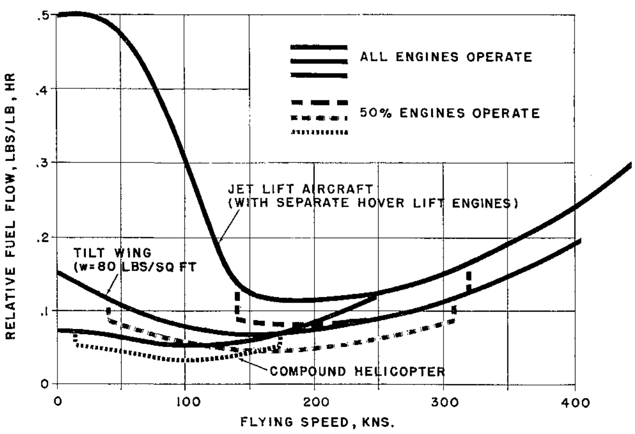

Fig. 7 Comparison of relative fuel flow.

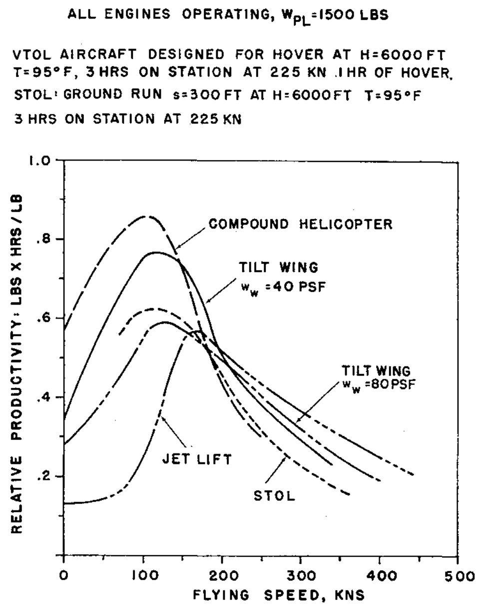

Fig. 8 Relative productivity based on factored weight empty.

It should also be remembered that for a fixed growth-factor value, the gross and empty weights of an aircraft depend on the invariant weight. For example, for $G = 4$, reduction of the invariant weight by 500 lb (say, by elimination of armor and reduction of payload by 300 lb) would decrease the gross weight by 2000 lb.

Figure 6 reveals how important the requirements of altitude and ambient temperature are. Growth factors, the gross and empty weights, all radically decrease with a relaxation of these requirements, and cost of aircraft should also follow the downward trend. For this reason, establishment of hovering requirements should undergo extensive operational analysis. However, there are strong indications at present that a requirement of 6000 ft and 95°F may be justified. Operational analysis should also define requirements of time in hovering, as well as which spectrum of the time on station and flying-speed combination is most desirable. It should be indicated, for instance, whether an ability to loiter for 0.5 hr at a speed of, say, 40 knots is more important than the same time spent at, say, 300 knots. What should be the maximum speed capabilities? These and other requirements must be known in order to select a design philosophy and optimum configuration for a given mission.

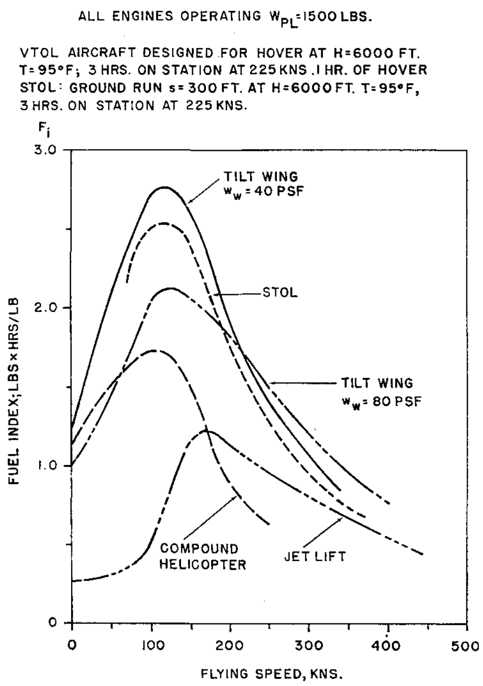

Fig. 9 Fuel index vs flying speed.

Table 3 Transport mission requirements

Criteria	Requirements
Payload (outbound only)	20,000 lb
Radius	500 naut miles
Cruise speed[a]	...
Hovering altitude and temperature (midpoint)[a]	...
T/W at hover	1.05
Reserve fuel	10%
Cabin dimensions	9 ft $H \times$ 10 ft W $\times$ 34–50 ft L
Limit load factor	3

[a] These criteria appear to be the major variables.

Conclusions

For the combat mission as defined at the beginning of this paper, and incorporating a requirement of hovering for 0.1 hr at 6000 ft, 95°F (for STOL ground run of 300 ft under the same conditions) some conclusions, valid only for this particular mission, may be reached. Upon examination of Figs. 6–9, the following may be stated.

1) Tilt wing with the higher wing loading (w_w = 80 psf) appears to be the most promising configuration. At the specified speed on station (225 knots) it shows the best fuel index and relative productivities to be only slightly lower than the highest one. It possesses well-balanced capabilities at the off-design speeds on station, especially at speeds higher than 225 knots. Its maximum speed exceeds 400 knots and is combined with the high wing loading that is so important for the low-level operations. These high-speed aspects, plus relatively good hovering and low-speed characteristics, make this aircraft especially attractive for escort duties of the much faster transport helicopters expected in the future. Finally, it is dimensionally small, since its span is only 26 ft.

2) Jet-lift aircraft, with auxiliary lift engines for hovering and low-speed flight, emerges as an interesting concept. It shows the best relative productivities at the specified speed on station and at higher speeds. The "Achilles heel" of this configuration is its thirst for fuel which is reflected in the fuel index throughout the whole speed range, and it affects relative productivities at lower speeds. Also, one questions the acceptability of high downwash velocities and exhaust temperatures associated with the lower (B = 2.5) bypass ratio of the lift engines. Dimensionally, the jet lift belongs in the same class with the tilt wing, since its span is also 26 ft.

3) Compound helicopter is not very suitable for the present mission, chiefly because of relatively high (for this configuration) speed on station. However, at the low flying speeds, its light loading of the lift generator makes it superior, in many respects, to other concepts. Its high-speed performance presently is, and probably will, in future, remain inferior to such aerodynamically cleaner compounds aircraft concepts as tilt wings and jet-lift aircraft.

4) As to conventional STOL, it is difficult to find any characteristics that would make this configuration competitive (for the assumed mission, and especially ground-run distance) with the leading VTOL concepts.

V/STOL Aircraft for Transport Mission

Mission Definition

A proposed requirement for a tactical transport is delivery of a 20,000-lb payload from a prepared field at the Army

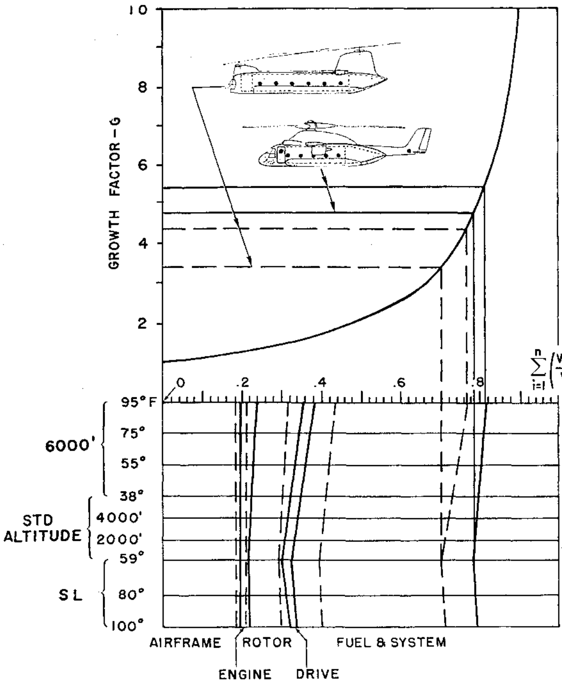

Fig. 10 Growth factor for hot-cycle compound and tandem-helicopter transport.

rear to a position in the combat zone, 500 naut miles distant. Air protection is assumed throughout the operation, but the final 200 naut miles into the midpoint station and the initial 200 naut miles on return trip must be flown at sea level to increase survivability from ground fire and/or for penetration under enemy radar. During this sea-level segment, the need for high dash-speed specifies cruise at normal rated power or at 300 knots (whichever is smaller). At the midpoint, a vertical landing and takeoff is made. For this discussion, hovering altitude and temperature at the midpoint are the major variables, and the effects of cruise speed are reflected in the relative productivity. Table 3 lists the basic criteria under which this design study was accomplished.

Types of Aircraft Considered

The following types of V/STOL aircraft are considered: Compound helicopter, tilt wing, and a jet-lift airplane. In addition, a tandem helicopter configuration, although it does not have the speed potential of the compounds, is shown to be competitive in this transport mission.

Compound helicopter

The compound helicopter is a single-rotor configuration utilizing the hot-cycle concept for hovering power. Two gas generators supply the hot gases for tip jet drive during hovering. In forward flight, the jet exhaust is diverted to two high-bypass ratio cruise fans on the wings. In order to combine the rotary-wing features with the fixed-wing transport, a serious compromise in flat-plate area results. Therefore, this compound transport does not realize the usual benefits expected from compounding. Although the empty weight-to-gross weight ratio is smaller than for the other types, the fuel consumption in both cruising and hovering flight is such that the growth-factor trend is not favorable (Fig. 10).

Tilt wing

The tilt-wing airplane is a four-propeller configuration using monocyclic pitch change in the propellers for longitudinal control. Since the power required for hovering exceeds that required for forward flight up to relatively high speeds, it is possible to operate at high cruise speeds with some engines shut down and the others at optimum power settings. The resulting fuel economy is reflected in the favorable growth-factor trend (Fig. 11).

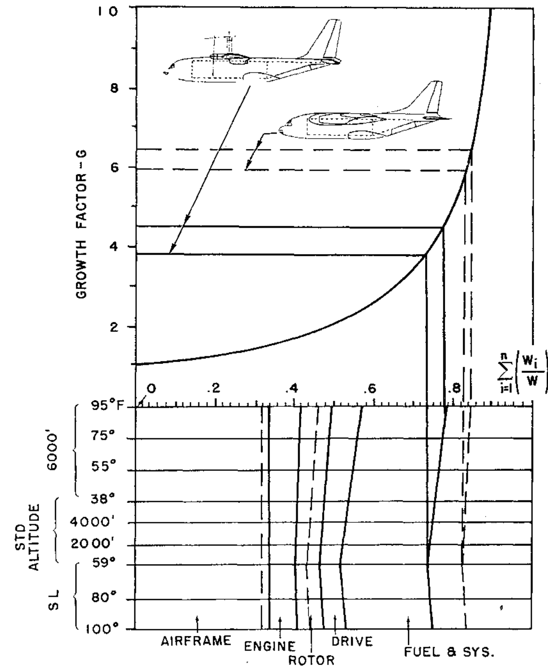

Fig. 11 Growth factor for the jet-lift and tilt-wing transport.

Jet lift

The jet-lift configuration considered in this study combined the direct-lift engine concept with deflected low-bypass ratio cruise engines for the hovering mode. In this manner, a better balance of cruising-to-hovering thrust is obtained with resultant fuel economy. However, the mission requirement for the 200-mile-radius segment to be flown at sea level is extremely demanding for any jet aircraft. The high fuel requirements for takeoff and landing of a jet-lift VTOL airplane, along with the high cruise fuel requirements in this mission, combine to show a poor growth-factor trend (Fig. 11).

Tandem helicopter

The helicopter is considered here as a result of recent and projected advancements in its cruising speed potential. It is apparent that the next generation of helicopters will be able to realize a 200-knot speed (higher in certain configurations). The tandem helicopter shown is powered by shaft

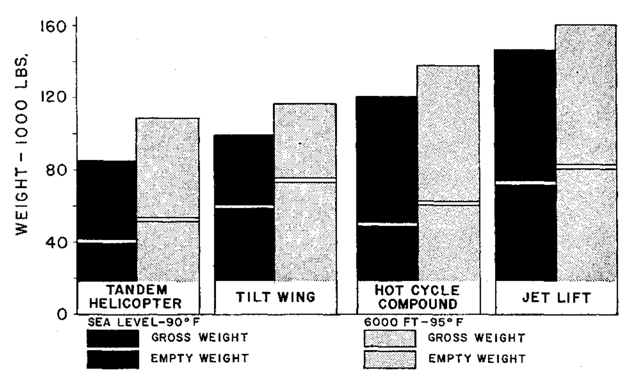

Fig. 12 Gross and empty weights of transport aircraft.

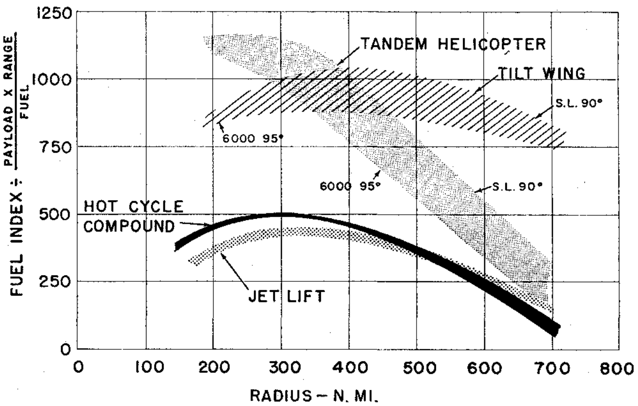

Fig. 13 Fuel index summary for transport missions.

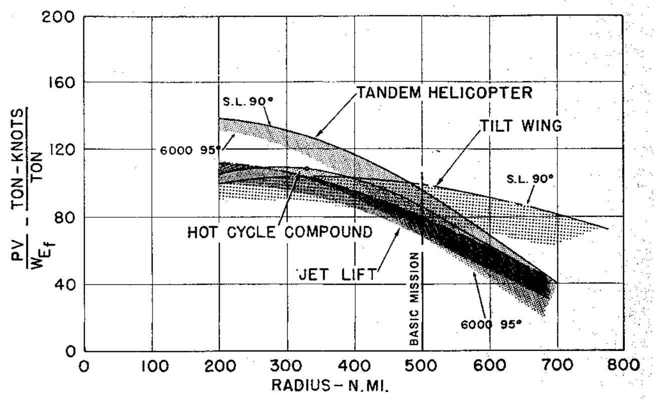

Fig. 14 Relative productivity vs mission radius based on factored weight empty.

turbine engines driving through a transmission system to the rotors. The overlapped tandem configuration allows a moderate disk loading to be used with a resulting favorable fuel consumption. Figure 10 presents the growth-factor trend for this configuration and illustrates the low empty-weight to gross-weight ratio attainable in this weight class.

Discussion

From analysis of the four configurations and the mission requirements, an invariant weight for the transport mission was calculated to be 25,250 lb. Using the growth factors previously established, Fig. 12 presents the takeoff gross weights and empty weights for this mission at both sea level, 90°, and at 6000 ft, 95°, midpoint hover criteria. It is quickly apparent that the cost of altitude and hot-day performance is quite large and, therefore, the optimum aircraft must be selected to perform the mission. Conversely, mission requirements must also be carefully projected, so that the need for altitude and temperature-hovering capability is not overstated.

Since the logistics of fuel supply are extremely important, an analysis of mission fuel requirements is given in Fig. 13. It is obvious from this figure that shaft-driven concepts, propeller or rotor, are much easier to supply in the field. In addition, fuel costs are a major item in total operating costs, and close scrutiny of the jet configurations is recommended.

The familiar term *productivity*, Eq. (1), has been modified by a factored value for empty weight [Eq. (3)] wherein a distinction in cost per pound was made between airframe and powerplants. In order to show productivity as a function of mission radius, the 200-naut-mile sea-level segment is held constant, whereas length of the optimum cruise altitude segment is varied. Figure 14 presents these results for the configurations having sea level, 90°, hover capability and the data for 6000 ft, 95°F, hover capability. For the basic mission (500-naut-mile radius), the relative productivity of the shaft-driven configurations exceeds that of the jet concepts. The helicopter competes surprisingly well out to a radius of nearly 500 naut miles, until the tilt-wing configurations take over for longer radii.

On the basis of these studies, it is concluded that for the transport mission, the shaft-driven rotor or propeller systems described here have the necessary capability, high productivity, and excellent fuel indexes required to provide a low-cost, intra-theater transportation service. Since radii for such missions are more likely to be from 100–500 naut miles, the tandem-helicopter configuration, showing the better over-all efficiency in this range, would provide a versatile, multipurpose vehicle for these missions.

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