REVIEW OF BASIC PRINCIPLES OF V/STOL AERODYNAMICS

By Richard E. Kuhn

Langley Research Center

SUMMARY

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This paper reviews the principal factors that determine the performance of V/STOL aircraft. These can be summarized as follows. In hovering, the power required, the fuel consumption, and the downwash dynamic pressure are all determined by and increase with increasing slipstream area loading. In transition the wing span, the distribution of load on that span, and the power required in hovering determine the shape of the power-required curve and through this the engine-out safety and STOL performance. In cruise some compromises are required but, generally, the same rules for designing good cruise performance into conventional airplanes still apply to V/STOL configurations, namely, attention to aerodynamic cleanliness to reduce the parasite power and a wing of appreciable span to reduce the induced power.

INTRODUCTION

During the past few years a great variety of V/STOL type aircraft have been proposed and investigated. The choice among these of a particular V/STOL configuration to fill a given mission will depend largely upon the specifications of the mission and a matching of the mission requirements with the airplane performance. This paper reviews the principal factors that govern the performance of V/STOL aircraft in the hovering, cruise, and transition speed ranges.

One of the primary performance considerations in any airplane is the power required. Most points concerning the performance of V/STOL aircraft can be made on the basis of the typical power-required curve for V/STOL aircraft such as shown in figure 1. The expressions that determine the power requirements in the three areas to be discussed are also shown.

SYMBOLS

A	disk area of propeller or rotor, sq ft
A_e	exit area of duct, sq ft

A_s	cross-sectional area of slipstream, sq ft
b	wing span, ft
$C_{D,o}$	parasite drag coefficient
$c_{l,i}$	design section lift coefficient
D	slipstream diameter, ft; also exit diameter of duct, ft
e	span efficiency factor
$(L/D)_{MAX}$	maximum lift-drag ratio
P	shaft power, hp
q	average downwash dynamic pressure, lb/sq ft
r	inlet radius, ft
S	wing area, sq ft
SFC	specific fuel consumption, lb/hp/hr
T	thrust, lb
t	time, hr
V	velocity, ft/sec unless otherwise noted
W	airplane weight, lb
W_f	fuel weight, lb
η	propulsive efficiency
η_{st}	static thrust efficiency (ratio of slipstream kinetic energy to shaft power), $\frac{T^{3/2}}{1100P\sqrt{\rho A_s}}$
ρ	mass density of air, slugs/cu ft

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HOVERING PERFORMANCE

Power Required

As is well known, all hovering aircraft support themselves by accelerating air downward. A helicopter imparts a low downward velocity to a large diameter stream of air, whereas a jet V/STOL gives a very small diameter stream of air a very high downward velocity to produce the same vertical thrust. In both cases the thrust is given by $T = mV$ where m is the downward mass flow of air per unit time $(m = \rho A_s V)$.

The power required to produce this thrust, however, is a function of the thrust multiplied by downward velocity imparted $\left(P = \frac{TV}{1100\eta_{st}}\right)$. Thus the power increases rapidly as the diameter of the actuator used decreases as shown in figure 2.

The major difference between the shrouded and unshrouded configurations is shown by the sketch at the top of the figure. The presence of the shroud prevents the contraction of the slipstream which occurs with the unshrouded configuration. Thus the diameter of a shrouded configuration can be about 70 percent of that of an unshrouded configuration. Note that it is the exit area of a shrouded configuration that governs the power required of this configuration.

Experimental data have shown that, for the unshrouded configurations, static thrust efficiencies between 0.7 and 0.8 (depending on the degree of compromise required with the high-speed characteristics) can be achieved.

For the shrouded configurations the reduction in tip losses due to the presence of the shroud should give some improvement in efficiency. However, careful attention must be paid to the internal drag of the shroud, struts, and counter vanes to prevent these losses from nullifying the gains due to tip-loss reductions. Very little full-scale data are available for the shrouded configurations but in general it is expected that static thrust efficiencies of 0.75 to 0.85 should be obtainable with careful design.

Fuel Consumption

Two other quantities are of concern in hovering: the fuel consumption, which is directly proportional to the power required, and the downwash dynamic pressure, which is one-half the slipstream area loading. These are plotted in figure 3.

The leaders from the configuration sketches in figure 3 do not indicate a specific point but rather the general area in which current practice usually places these configurations. All V/STOL configurations except jet pump schemes, which are not considered here, fall in one general band.

Turbojet and turbofan configurations, which were omitted from figure 2 because these engines are not usually thought of in terms of horsepower, are included in figure 3. If these configurations were presented in terms of power they would fall at or above the top edge of figure 2. These configurations have very high fuel consumption; one hour of hovering would burn a weight of fuel almost equal to the weight of the aircraft. Therefore, with these configurations, hovering time must be restricted to the $1\frac{1}{2}$ to 2 minutes required for take-off and landing. Obviously if long hovering time is required, a rotor configuration is dictated. A more complete discussion of power required and fuel consumption in hovering is presented in reference 1.

Downwash

A point of concern with V/STOL aircraft is the effect of the downwash from these aircraft on the ground under the aircraft. The average downwash from unshrouded configurations is equal to the disk loading and that from shrouded configurations is equal to one-half the exit-area loading. Experience has shown that loose sand and dirt will be blown up by helicopters with disk loadings, and therefore downwash dynamic pressures, as low as 2 to 3 pounds per square foot. On the other hand, good sod can withstand downwash dynamic pressures as high as 1,000 to 2,000 pounds per square foot. The downwash problem is discussed more fully in reference 2.

CRUISE PERFORMANCE

General Considerations

In figure 4 the power required for 40,000-pound cargo-type aircraft operating at sea level is plotted as a function of speed. V/STOL aircraft can be classified in three categories: those that use rotors for both lift and propulsion in cruise (the pure helicopters), those that operate as conventional aircraft using wing lift and separate propulsion in cruise, and combination configurations (the compound or unloaded helicopter). Requiring the helicopter rotor to provide both lift and propulsion in cruising flight results in problems of retreating blade stall and advancing blade compressibility effects which increase the rotor profile power requirements of the helicopter and limit its cruising speed.

In the compound configuration the propulsion job is taken over by separate propellers or ducted fans and part of the lift is transferred to a wing; thus the rotor is unloaded and the speed capability is increased. The parasite drag of the rotor and pylon remains, however, with the result that the power required remains above that of more conventional aircraft.

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The other V/STOL aircraft cruise on wing lift, and for these the same rules for obtaining good cruise performance that have always applied to conventional aircraft still apply, namely, aerodynamic cleanliness to reduce parasite drag and power and a wing designed for the desired cruising altitude and speed to minimize the induced power.

Good aerodynamic design is important not only at the highest speeds but throughout the speed range because most aircraft cruise in the speed range near the maximum lift-drag ratio where the span is important. A large wing span is needed to minimize induced drag and therefore power, as can be deduced from the expression of figure 1. A clean aerodynamic design is needed to minimize power throughout the speed range. A good case in point is the helicopter where the high parasite drag of current configurations is largely responsible for the difference in power between the helicopter and the airplane as shown in figure 4 near the speed for helicopter minimum power. This point is discussed more completely in reference 3.

The power required for the V/STOL aircraft in cruise is a little greater than that for the conventional airplane because of the reduction in propulsive efficiency which results from the fact that the propulsion units must also be designed to provide the lift in hovering for most V/STOL configurations; thus, a compromise in the design must be made.

Propulsive Efficiency Compromise

Each V/STOL type has a different propulsion-hovering design compromise. An example of one such design compromise for the propeller-driven V/STOL aircraft is shown in figure 5. For best static thrust a relatively large amount of camber, as indicated by the design section lift coefficient, is required. With a lot of camber, however, the cruise efficiency is relatively poor. Best cruise efficiency occurs with relatively little camber.

The design compromise for maximum range is shown by the solid symbol. If less camber is used, the weight of fuel that can be lifted in vertical take-off is reduced and this causes a reduction in range. Increases in camber above this point give a small increase in fuel weight lifted but the cruise efficiency decreases so rapidly that again the range is decreased.

Another compromise for the propeller aircraft occurs in connection with the operating rotational speed. If the relatively wide-blade large-diameter propellers required for good static thrust are operated at hovering rotational speed while in cruise, the tip sections of the blade are operating well below their most efficient angle of attack. A reduction in rotational speed (to 80 percent in the case of fig. 5) is required to achieve good cruise efficiencies. This problem is even more severe for tilt-rotor configurations.

A different type of compromise is involved for the ducted-fan configuration as shown in figure 6. With a generous inlet radius a good level of static thrust is obtained. However, experimental investigations have shown that if a small inlet radius such as is desired for the cruise condition is used, the lip will stall internally and the thrust drops appreciably. Thus, either a thick shroud or a variable-geometry inlet must be used.

Also a compromise must be made at the duct exit. As mentioned in the section "Hovering Performance" the power required depends on the exit diameter. Thus a diffuser, as indicated, is desired to increase the exit diameter and thus reduce the power required. In cruising flight, however, the exit diameter is too large and the flow may separate from the diffuser. For the optimum duct performance it may in some cases be necessary to vary both the inlet and the exit geometry.

Cruising Speed

The cruising speed attained will depend on both the aerodynamic cleanliness and the power installed as shown in figure 7 where the compound helicopter, the flapped tilt wing, and the tilt-duct configuration are compared. The power installed must be somewhat greater than the bare power required to hover in order to allow for temperature and altitude effects and to provide a margin for climb.

At maximum cruise power the example compound helicopter used in figure 7 for illustration would have a speed of about 200 knots. The tilt-wing and tilt-duct configurations would have higher speeds, both because they can be cleaner aerodynamically and because of the higher installed power required for hovering. The tilt-duct configuration is shown above the tilt-wing configuration because design studies of these usually utilize a higher slipstream area loading in hovering.

Range

At maximum cruising speed at sea level the engine specific fuel consumption is low (SFC = 0.50, see fig. 8); this indicates that the engine is operating near peak efficiency. The range would be severely limited, however, because the airplane is operating far beyond the point of maximum aerodynamic efficiency or $(L/D)_{MAX}$. However, when current turbine engines are throttled to 20-percent power (as in this case), the fuel consumption is more than doubled so that again the range is far from optimum. Actually maximum range would occur between 175 and 200 knots for the example shown.

Conventional turbine-powered airplanes also face this same problem, and therefore current turbine transports operate at high altitude. As shown in figure 8 an altitude can be found, in this case 40,000 feet, at which both the engine and the airframe can be operated at or near maximum efficiency. In the present example, the range obtained by operating at 40,000 feet would be about three times that obtained by operating at the same speed at sea level.

It is recognized that in military operations it is sometimes desirable or necessary to fly "on the deck." The example airplane used could fly at about 180 knots on only one of four engines at a specific fuel consumption of about 0.50 and could thus almost match best aerodynamic efficiency and best engine efficiency at sea level. The resulting range would be only slightly less than that at altitude. Although it is recognized that shutting down and restarting engines in flight is not generally considered good practice, with current engines it will be necessary for operating personnel to make a choice between shutting down engines, flying at altitude, or accept the penalty in fuel consumption and range for high-speed on-the-deck flight.

As shown in figure 1, the parasite drag is the primary contribution to the power requirements at high speeds. For those missions in which very high-speed flight at sea level is of paramount importance, some decrease in power required and therefore increase in range at very high speeds can be achieved by reducing the wing size as shown in figure 9.

The altitude capability and maximum firing range would be seriously reduced, however, because of the increase in power at the speed for $(L/D)_{MAX}$, as shown in figure 9. This increase in power is, of course, due to the increase in induced power which, as shown in figure 1, is proportional to $(W/b)^2$.

The relative speed ranges of application for turbojet and turboprop propulsion systems are indicated in figure 10. At the higher speeds the approach of the transonic drag rise and the reduction in propeller efficiency caused by the blade tips reaching transonic speeds causes a rapid increase in power required and therefore fuel consumption for the turboprop configuration as shown in figure 8.

Because of the high exhaust velocity of the turbojet the propulsive efficiency is low at low speeds but increases with speed and above 450 to 500 knots is better than that of the turboprop; thus, less fuel is consumed. This is the obvious speed range of operation for turbojet propulsion systems. However, the penalty for operating turbojet configurations at lower speeds is readily apparent.

TRANSONIC PERFORMANCE

General Considerations

Obviously, the most important requirement in transition is that the power required should not exceed the power required in hovering. However, two other considerations are also important. The first is the problem of the minimum speed at which flight can be continued in the event of partial power failure. The second is the problem of STOL performance with overload or in operation at altitudes and temperatures above those at which the airplane can hover. Both of these problems depend upon the rate of decrease in power with speed as the aircraft departs from hovering; a rapid decrease is desired from both considerations. The steepness of the back side of the power curve is definitely desirable from the viewpoint of performance; however, whether this steepness is a basic problem in handling qualities is yet to be decided.

The shape of the power-required curve in transition depends upon the following items: the disk loading, which determines the power required in hovering (the low-speed end point of the transition), and the wing span and the distribution of load on the span, which determine the power required at the high-speed part of the transition.

Effect of Span

Figure 11 shows the effect of span on the power required as a function of speed for a 40,000-pound airplane. Because of the low speeds involved the parasite power is small or negligible throughout most of the transition. The power required is all induced power which is determined, as shown in figure 1, by the span loading - that is, the weight divided by the wing span. The calculated power required shown in figure 11 is based on conventional low-speed aerodynamics (calculations performed with expressions from fig. 1) and indicates that throughout most of the transition the airplane is operating on wing lift. Below about 30 knots there is a transition from wing lift to propeller lift in hovering.

A 25-percent reduction in wing span results in about a 50-percent increase in induced power because as shown in figure 1 the induced power is proportional to $(W/b)^2$. Thus, a decrease in span results in an increase in engine-out speed, and for the overloaded take-off condition, an increase in take-off distance because the short-span airplane would have to accelerate to a higher speed for take-off.

These curves are for the case without wing stall. If the wing stalls in transition, the power curve is even flatter. Design compromises necessary to avoid wing stall on flapped tilt-wing configurations are discussed in reference 4.

Effect of Load Distribution

The considerations shown in figure 11 are for the condition of a fairly uniform distribution of load. The effects of a poor load distribution are shown in figure 12. In cruising flight and at the high-speed end of the transition the load distribution would be fairly uniform, but as the airplane slows down in the transition the part of the wing that is not in the slipstream cannot continue to carry its share of the load. A load distribution of the type shown develops with the result that the power required corresponds to a wing of appreciably less span. These effects are shown for tilt-wing and tilt-duct configurations but apply also to buried-fan and even to a greater extent to jet V/STOL configurations.

COMPARISON OF CONFIGURATIONS

In figure 13 the hovering and cruise considerations have been used to present a plot of hovering time against the cruising speed range of application for several V/STOL aircraft. This comparison assumes burning a weight of fuel equal to three percent of the gross weight of the aircraft. The choice of configuration will depend on the mission to be filled. If long hovering time is of paramount importance a rotor configuration would be dictated. Obviously jet types will be restricted to missions where the only hovering time required is the $1\frac{1}{2}$ or 2 minutes required in take-off and landing.

Between these two extremes are several types that could find application as transport types but here no clear choice is indicated. For these configurations, as is frequently the case, off-design considerations may dictate the choice. One such off-design consideration is the STOL performance as shown in figure 14.

The comparison is for overloaded conditions of 120 percent of the VTOL weight. The rotor types have relatively high take-off distances because the low power requirement in hovering results in a relatively flat variation of power with speed in the transition. The flapped tilt wing makes efficient use of wing lift in the transition and the other types suffer to varying degrees from a short span or a relatively poor load distribution in transition.

CONCLUDING REMARKS

In hovering the power required, the fuel consumption, and the downwash dynamic pressure are all determined by and increase with increasing slipstream area loading. In transition the wing span, the distribution of load on that span, and the power required in hovering determine the shape of the power-required curve and through this the engine-out safety and STOL performance. In cruise some compromises are required but, generally, the same rules for designing good cruise performance into conventional airplanes still apply to V/STOL configurations, namely attention to aerodynamic cleanliness to reduce the parasite power and a wing of appreciable span to reduce the induced power.

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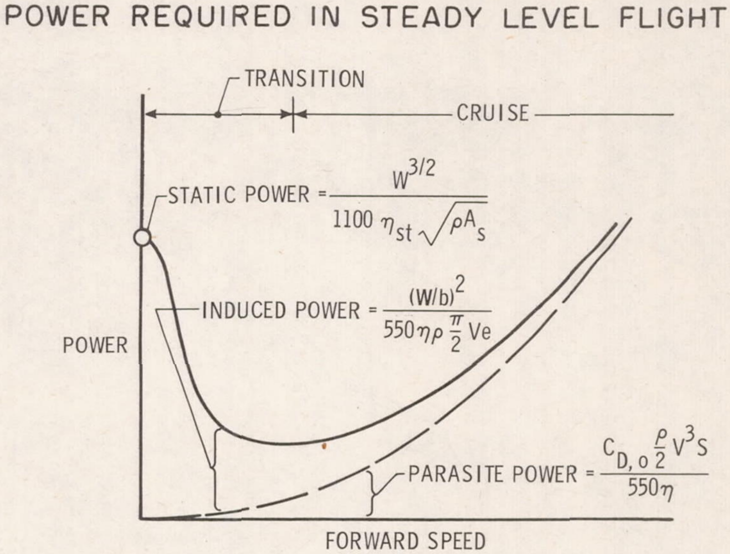


Figure 1

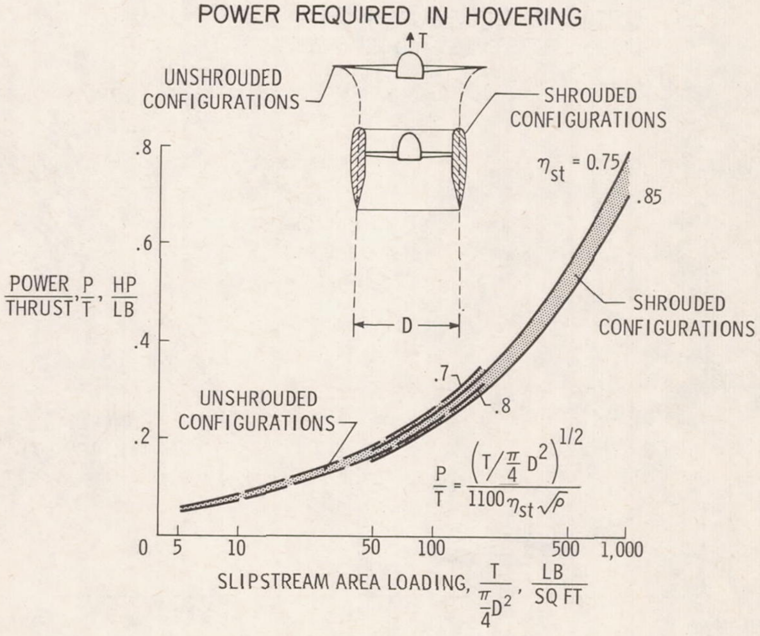


Figure 2

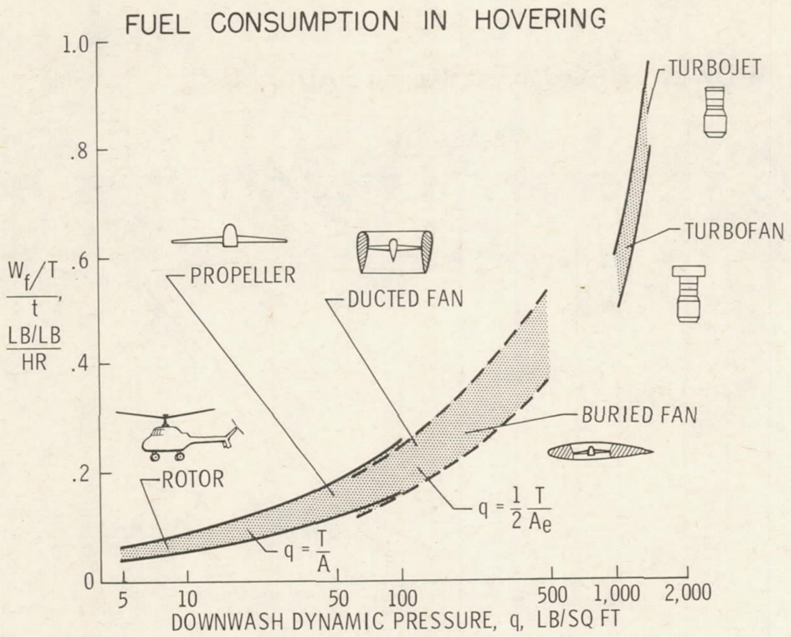


Figure 3

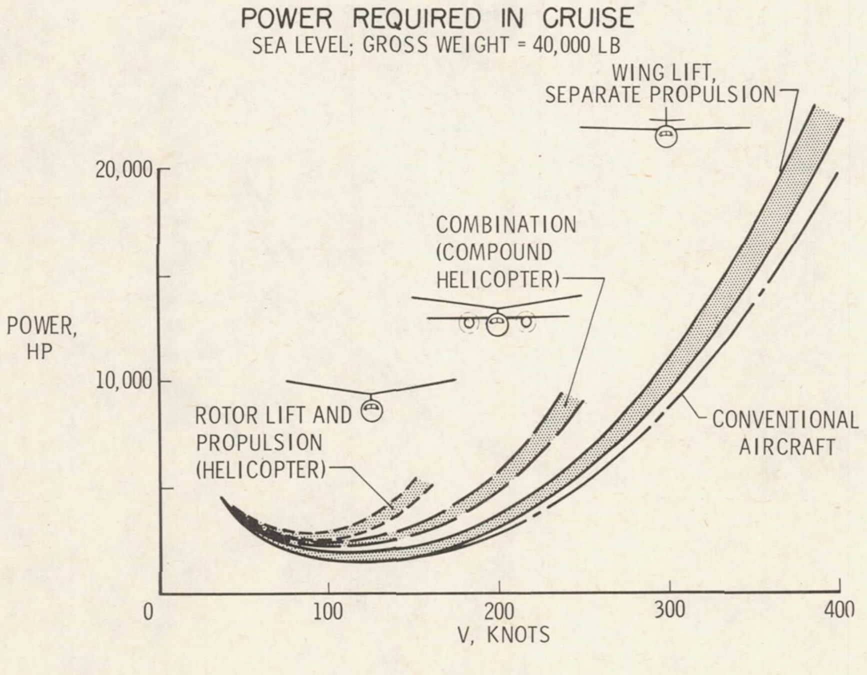


Figure 4

PROPELLER DESIGN COMPROMISE

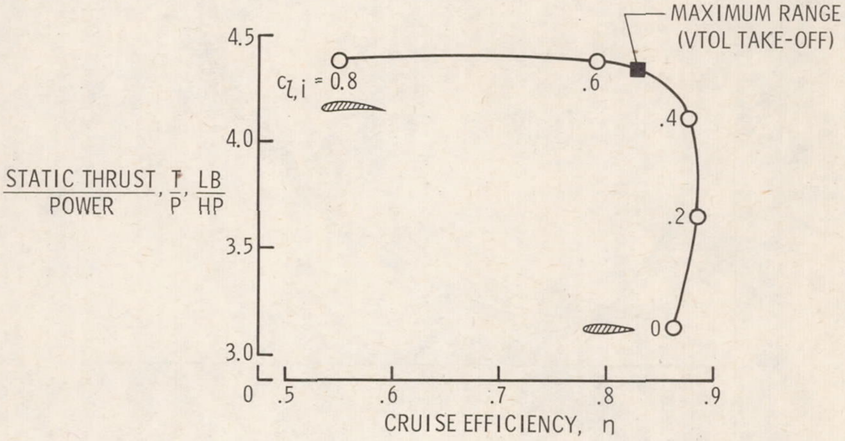


Figure 5

DUCTED-FAN DESIGN COMPROMISE

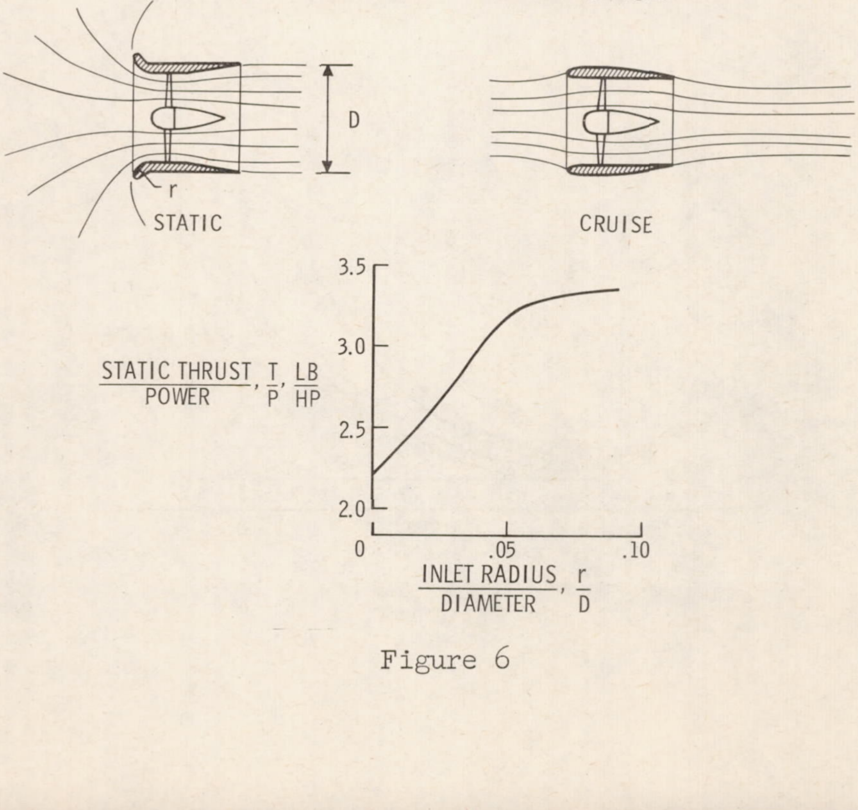


Figure 6

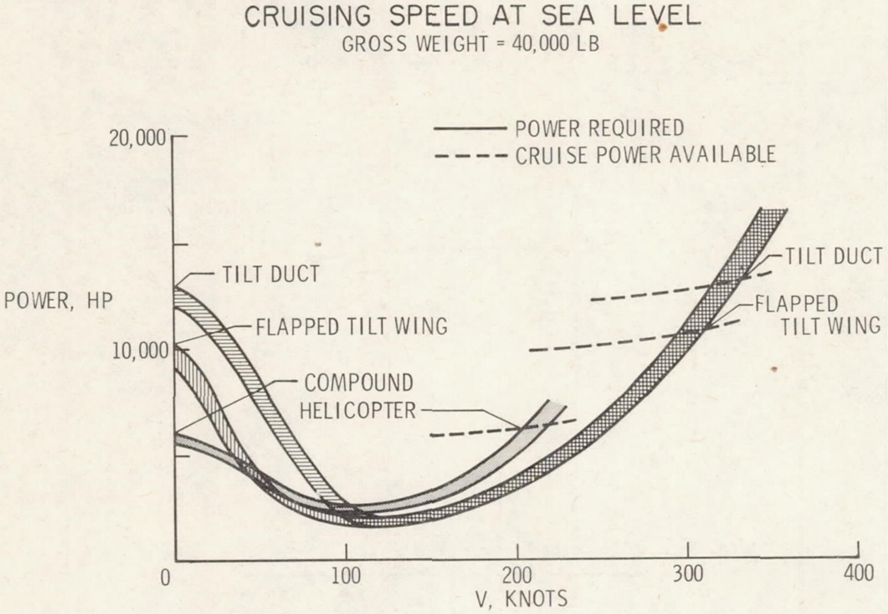


Figure 7

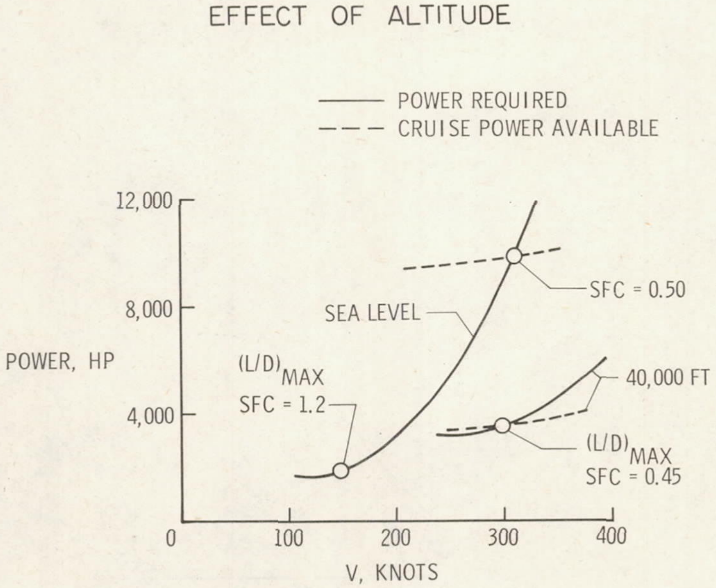
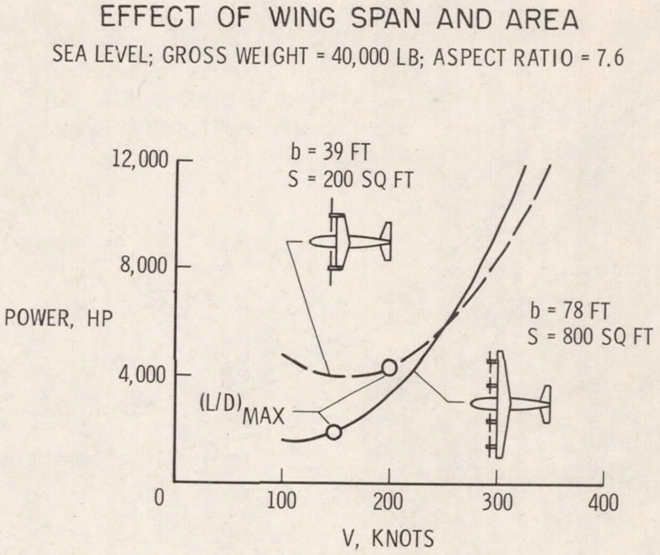


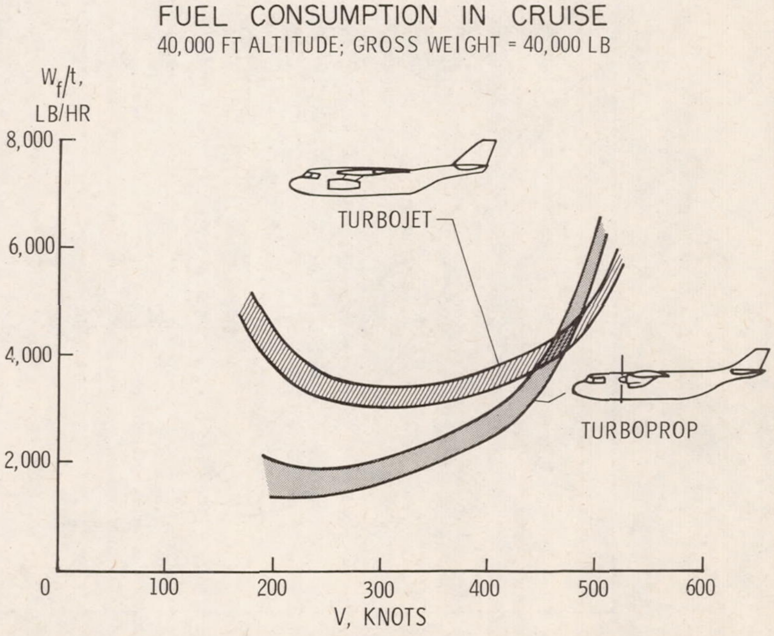
Figure 8



EFFECT OF WING SPAN AND AREA

SEA LEVEL; GROSS WEIGHT = 40,000 LB; ASPECT RATIO = 7.6

Figure 9



FUEL CONSUMPTION IN CRUISE

40,000 FT ALTITUDE; GROSS WEIGHT = 40,000 LB

Figure 10

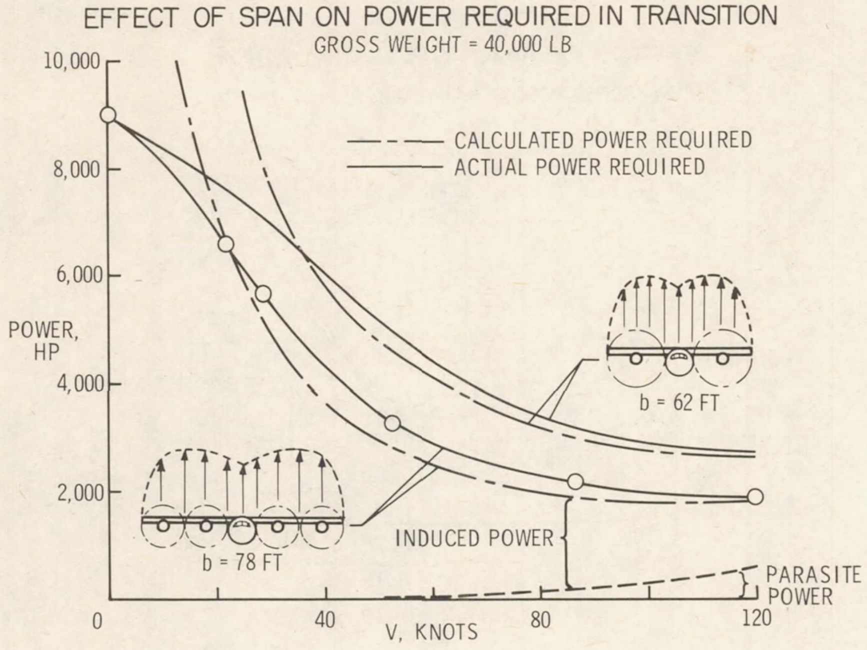


Figure 11

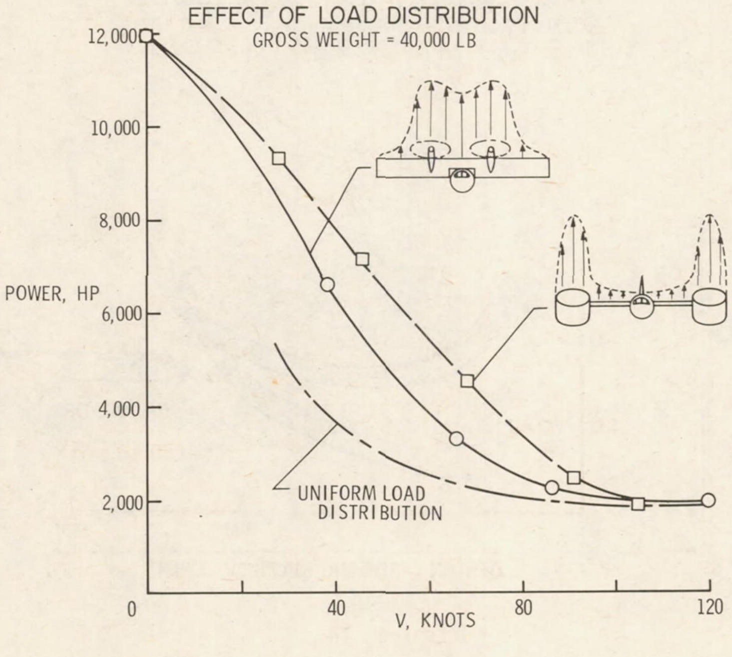


Figure 12

HOVERING AND CRUISE PERFORMANCE

W_f = 0.03 GROSS WEIGHT

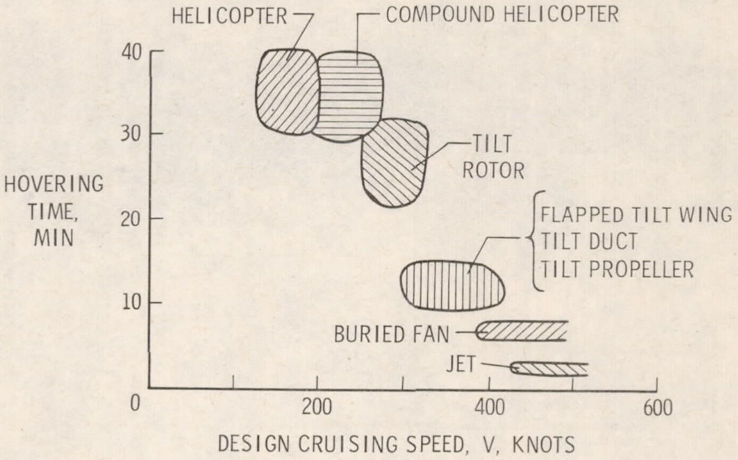


Figure 13

STOL PERFORMANCE

TAKE-OFF DISTANCE OVER 50-FOOT OBSTACLE;

$$\frac{W}{W_{VTOL}} = 1.2$$

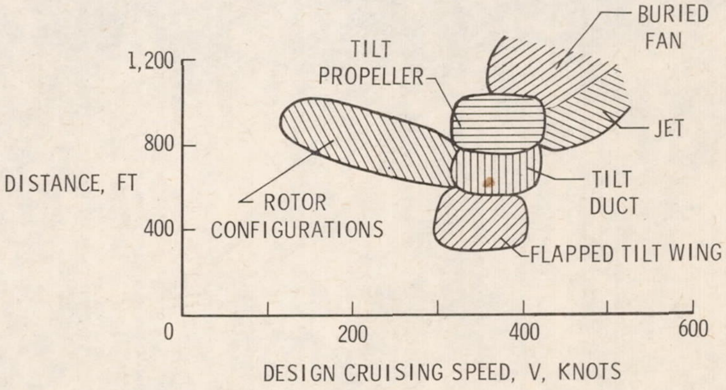


Figure 14