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OPERATIONAL TECHNIQUE FOR TRANSITION OF SEVERAL TYPES OF V/STOL AIRCRAFT

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INTRODUCTION

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Five representative types of V/STOL aircraft have been made available to the NASA for flight research after they had successfully demonstrated their transition capabilities. Even though the flight test life of these aircraft has been limited, pilots have been able to evaluate several different types in order to better compare and understand the various V/STOL concepts. This paper considers primarily the results of one pilot's flight experience in the transition region of each of the test-bed aircraft and points out some airplane characteristics which have a significant effect on transition performance.

DISCUSSION

The significant feature of all aircraft tested was their ability to change the direction of engine-produced thrust from horizontal in order to provide thrust for forward or wing-lift flight to vertical in order to augment wing lift at low speeds and to permit hovering. Once either a vertical or a short take-off has been made, the transition to wing-lift or translational-lift flight is started. In most cases a major change in the aircraft configuration must be made in order to allow transition. These changes are shown in figure 1. The wing-rotor system rotates on the Vertol VZ-2; the large flaps are retracted on the Ryan VZ-3; the ducts rotate on the Doak VZ-4; the rotor system is tilted 90° on the Bell XV-3; and the thrust diverter angle is changed on the Bell X-14.

The transition from V/STOL operation to conventional airplane flight is considered to be complete when sufficient lift due to airspeed is obtained so that gliding flight is possible at a sinking rate which can be arrested without adding power. In general, therefore, STOL operation is dependent on engine power to augment aerodynamic lift and to change the effective lift-drag ratio. VTOL operation implies the ability to hover out of ground effect over a given ground position in no wind. The term "conversion" is used herein to denote the mechanical configuration changes made to the aircraft to permit transition from V/STOL operation to translational-lift flight.

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In the transition speed range, therefore, if complete power failure occurs, the aircraft must be either very close to the ground or at sufficient height to allow translational lift to be obtained by diving and converting to the best glide configuration. The heights and airspeeds described in this manner roughly define "dead man's curves." The general combinations of height and airspeed or dead man's curves of a typical single-engine helicopter as compared with that of an airplane are shown in figure 2. Although the helicopter can lift off vertically, it stays close to the ground until sufficient translational lift develops. Since this occurs at a very low forward speed, the climbout and descent can be started very shortly after lift-off. The airplane, in contrast, must remain on the ground until translational lift or flying speed is attained. The transition region for V/STOL aircraft is between these two extremes - that is, translational lift must be augmented by engine-produced lift in order for the aircraft to be airborne. However, unless the dead man's curve is ignored, the aircraft should still stay very low until translational lift can support it. The alternative is to provide multiple interconnected engines for those V/STOL aircraft which do not have autorotational capability, so that the dead man's curve based on the loss of the most critical engine still allows steep take-offs and landings.

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The effects of conversion on airspeed for the XV-3 is shown in figure 3. The results indicate that the XV-3 can cover a wide range of airspeeds without conversion. The solid line indicates the usual conversion-airspeed variation during transition, with the dashed lines indicating the reasonable limits to the procedure. Forward speed is gained from hovering by lowering the nose slightly by means of forward cyclic-pitch control. At about 50 knots the transition to translational lift was complete; that is, if the engine failed, an autorotative landing could be made; therefore, the climb could be started. Tilting the rotors about 15° to 30° improved the climb performance, or if a level transition was to be made, conversion to this angle permitted more rapid acceleration to a speed in excess of the wing stall speed, which was 80 knots in this case. At this time the rotors, operated as a helicopter, could be unloaded and rotated 90° and the blade pitch could be adjusted for the best cruise efficiency. As can be seen in figure 3, however, the conversion procedure was quite flexible and was only dictated by the combinations which gave best performance. The reasons for the limiting conditions are indicated to be deterioration in stability and control to wing stall along the low-speed boundary and the usual helicopter buffeting changing to a power-available or structural limitation along the high-speed boundary.

Results for the tilt-wing, the deflected-slipstream, and the tilting-ducted-fan aircraft are combined in figure 4 since these configurations are quite similar in the aspects presented. The solid line indicates the usual conversion airspeed relation with the dashed lines indicating the reasonable limits. It is seen that these aircraft can gain very little forward speed without starting the conversion process. This limitation has certain advantages. One is that if the pilot kept the fuselage reasonably level the airspeed was dictated by the conversion angle during most of the transition and required little pilot attention. Consequently, fore-and-aft stick motions were more or less restricted to holding attitude, adjusting airspeed by the conversion control, and controlling vertical speed by power changes. Of course, as more translational lift was produced, angle-of-attack changes began to have a greater effect on flight-path angle as conventional airplane flight was approached.

There is a disadvantage in having a narrow band of airspeeds available at the start of conversion while hovering and attempting to control very low forward speeds with respect to the ground. Under these conditions small changes in conversion angle were more effective for speed control than attitude changes, but the on-off type of switching used for conversion-angle adjustments was not smooth and continuous as is required. Therefore, when speed control near hovering can be best obtained by changes in conversion angle rather than in pitch attitude, as it is in various degrees on the three types shown in figure 4, the conversion angle might be best controlled over a small range by fore-and-aft stick motion. In any case, better control of speed at very low speeds is needed for these types of VTOL aircraft.

The method of performing the transition was also similar for these three types. For example, the wing, duct, or flap angle was changed in increments at the start of the transition where airspeed was most dependent on the conversion angle. From about 40 knots the rate could be increased so that transition was completed in about 10 to 15 seconds. Large deviations from this program as indicated by the dashed lines caused some important changes in aircraft characteristics. The lowest speeds normally used at each conversion angle were limited primarily by fuselage attitude; however, a decrease in the lateral-directional damping was experienced on the Vertol VZ-2 and general controllability fell off rapidly. The deflected-slipstream Ryan VZ-3 airplane became longitudinally unstable and tended to pitch up. This characteristic brings up the point that although the aircraft handling qualities specifications define satisfactory stall characteristics and the helicopter specifications require satisfactory handling even in rearward flight, there are as yet no specifications which describe adequately the lower speed boundary which occurs at partial conversion angles. The lower speed boundary can be compared to the conventional airplane stall. However, whereas the airplane stall speed is a relatively fixed value varying with load factor, which the pilot can readily detect, and varying only little with power changes, the lower speed boundary at partial conversion angles varies directly with engine power. The boundaries shown in figure 4 are at power for level flight. At other power settings either the angle-of-attack or the rate-of-descent indicators must be used to determine the onset of a critical condition.

The high-speed boundaries indicated are reached by pushing the nose over to steep attitudes. The boundary on the deflected-slipstream airplane was determined by the flap strength, on the tilting-duct airplane by the increasing nose-up pitching moment requiring full forward stick, and on the tilt-wing airplane by a less easily defined change in the lateral-directional behavior, particularly at the higher transition speeds where the wing was carrying more of the load. Under these conditions the fuselage is diving but the wing is flying straight and level, and the motions which result from a rudder kick are hard to describe; however, the important point is that there appeared to be a tendency for a divergence to occur. The measured static directional stability of this aircraft is discussed in a subsequent paper presented by John P. Reeder, which may indicate why the directional oscillation was unusual.

The transition boundaries as they apply to the deflected-jet X-14 airplane are shown in figure 5. The take-off transition is programed almost in the same manner as the Vertol, Ryan, and Doak aircraft previously discussed in figure 4. That is, the thrust diverter must be rotated in small increments until about 40 knots are attained and then it can be converted continuously as the airplane accelerates very rapidly even at small conversion angles. In fact the stall speed is usually exceeded; that is, transition is completed before more than about 20 percent of conversion has been made, as is shown in figure 5. The reverse transition is made quite differently, however, since no large drag or moment changes were found to occur with change in thrust-diverter angle. The throttle was retarded and the diverter rotated directly to 90° (the hovering angle) while still at high speed. Power was added to keep the angle of attack below stall as the 1 g stall speed was approached, and the aircraft then decelerated rapidly to about 20 knots, below which the speed was controlled by pitch attitude, more or less like a helicopter. The angle-of-attack indicator was used to determine the power setting needed to avoid stalling during the transition at airspeeds greater than about 20 knots. Below this speed the stall moments or forces were of little consequence.

Continuous flight in the transition region (that is, flight at partial conversion) is primarily useful in order to allow steep take-offs and landing approaches at speeds lower than would be allowed by wing lift alone. Even though these aircraft had VTOL capabilities, the pilot would not normally complete transition to hovering flight at 100 feet or so above a landing spot and then descend vertically as is popularly supposed any more than he would operate a helicopter in this manner, and helicopters are the most efficient hovering devices yet conceived. One of the reasons for this restriction is the generally poor visibility straight down, but even if visibility were good, pilots find it difficult to observe the horizon when looking straight down and without this reference, attitude control becomes marginal. Also, the instruments cannot be readily observed when the pilot looks downward, and when the pilot tilts his head up and down he disturbs his sense of balance. In addition these vertical ascents and descents require nearly full engine power, so that fuel is used at a very high rate, and in most cases an engine failure under these conditions would mean loss of the aircraft.

For these reasons take-offs and landings were made at moderate angles on the test-bed aircraft with translational lift being augmented by engine power whenever possible. The translational lift, of course, is a function of the angle of attack, and in the transition region the angle of attack varies with engine power at a constant airspeed. If power is reduced in order to descend more steeply, the wing may stall, so that translational lift drops off rapidly. This loss of lift further increases the sinking rate and also the angle of attack. A large power increase is required to unstall the wing and when this happens, the added power plus the return of wing lift causes the airplane to climb. For the tilt-wing and deflected-slipstream aircraft the pilot determined his steep approach limits by reference to the rate of descent indication commensurate with his conversion angle. If he did not know the limiting conditions, the steep descent could turn out to be a series of stall recoveries. Since the wing was not in the slipstream on the tilt-duct or deflected-jet airplane, the steep descent conditions could be monitored on the angle-of-attack indicator. When wing stall was encountered at very high conversion angles and speeds less than about 25 knots, the change in lift did not create much of a problem on any of the test beds except for the deflected-slipstream airplane which still had a pitch-up problem until full conversion was reached.

The allowable vertical velocity variation with airspeed while descending in the transition region for the deflected-jet X-14 is shown in figure 6. The dashed line is the combination of rate of descent and airspeed which is limited by the wing angle of attack with the fuselage level and results in a descent angle of 10° in this case. A reduction in power to increase the rate of descent would cause the wing to stall. Figure 6 shows that below about 25 knots, however, the stall angle can be exceeded to some extent in practice since the aircraft is being supported mostly by engine thrust. The maximum flight-path angle indicated in the figure could be increased by having the wing stall at a higher angle of attack. In addition, if the jet could be deflected further than 90° relative to the fuselage, then these sinking speeds could be maintained with the fuselage in a slight nose-down attitude which would also allow steeper flight-path angles.

The rate-of-descent limitations for the tilting-rotor XV-3 are shown as a function of airspeed in figure 7. The line for a rotor-mast angle of 0° indicates the allowable sinking rates in the helicopter mode. For the most part, this is the autorotation or power-off curve except for very low speeds. At low speeds, the wing rotor interference made control difficult and limited the sinking rates to low values. At intermediate conversion angles shown on the remaining curves, the wing-stall speed is limiting again and it can be seen that there is nothing to gain in steep descents by using intermediate conversion angles. The best steep approach with the XV-3 was therefore made in the helicopter configuration.

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Sinking rates of about 500 feet per minute were used during most of the landing approaches but, of course, even sinking rates of 500 feet per minute must be reduced to near zero before touchdown. The way that this is accomplished depends on how far into the transition the approach is being made. The lift-distribution variation during an approach in the transition region of a typical V/STOL aircraft is shown in figure 8. The force-weight ratio F/W is plotted against airspeed at airspeeds less than the 1g wing-stall speed. The curved line indicates the force produced by the wing when it is at the maximum angle of attack. The maximum wing-produced force-weight ratio is of course zero at zero airspeed and 1 at the 1g stall speed. As the transition proceeds into the lower airspeed region, more reliance is placed on engine-produced lift. When the wing is still doing most of the work as at the higher speeds, a conventional flare may produce enough increase in lift to arrest the approach sinking rate. As the wing is unloaded, however, and the engines are supporting more of the load, the flare for wing lift must be used with caution, since the angle of attack can increase rapidly with very little increase in lift and a stall is likely to occur at an inappropriate time. Previous flight tests indicate that when the flare is made by using wing lift alone, at least 1.2g of flare acceleration is required, since a minimum ratio of approach speed to stall speed under ideal conditions was found to be 1.1. This ratio will provide a flare acceleration of 1.2g. The helicopter is at the other end of the spectrum and even though it may require full power to hover, a vertical acceleration of about 1.2g is available for a few seconds by increasing collective pitch and using the stored energy in the rotating blades. Neither of these methods of obtaining a transient increase in lift is available on most V/STOL designs during transition, so that this lift increment must come from an increase in power. Flight tests indicate that the excess power plus wing lift available should also permit a 1.2g flare for positive control of the touchdown for the V/STOL aircraft in any usable approach condition.

Since the final flare is a critical phase of the steep approach, the location of the flare controls is very important. Approaches were made with all of these V/STOL aircraft where power had to be increased in order to arrest the sinking rate at touchdown. Three of them had conventional throttles moving fore and aft and the other two had collective pitch-type power control. The collective pitch-type throttle actuation is considered by the author to be the most natural and convenient when power is required to assist the flare. Additional considerations regarding the location and number of controls are discussed in the next paper by John P. Reeder.

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CONCLUSIONS

1. Since pitch-attitude changes alone are not sufficient to control movement over the ground when at or near a hovering condition with some VTOL types, precise and continuous control of the conversion angle through a small range may be required.

2. A V/STOL aircraft test program should consider the effects of large deviations from the fuselage level trim speeds at partial conversion angles.

3. The wing should be capable of supporting the aircraft at as low a speed as possible in order to shorten the transition and to reduce the time spent in the critical region of high engine power.

4. The large variety of airspeed—power—conversion-angle combinations which will result in a stall requires that the pilot be given some positive indication that he is approaching a critical condition.

5. If a constant-power flare cannot be made, the power control should be actuated in a manner similar to a helicopter collective-pitch control.

6. If the V/STOL aircraft has no autorotational capability, then it should have multiple interconnected engines so that the advantages of steep ascents and descents can be realized.

7. The V/STOL aircraft must be capable of developing 1.2g for flare with the most critical engine out at its minimum acceptable approach speed.

FIVE VTOL CONCEPTS

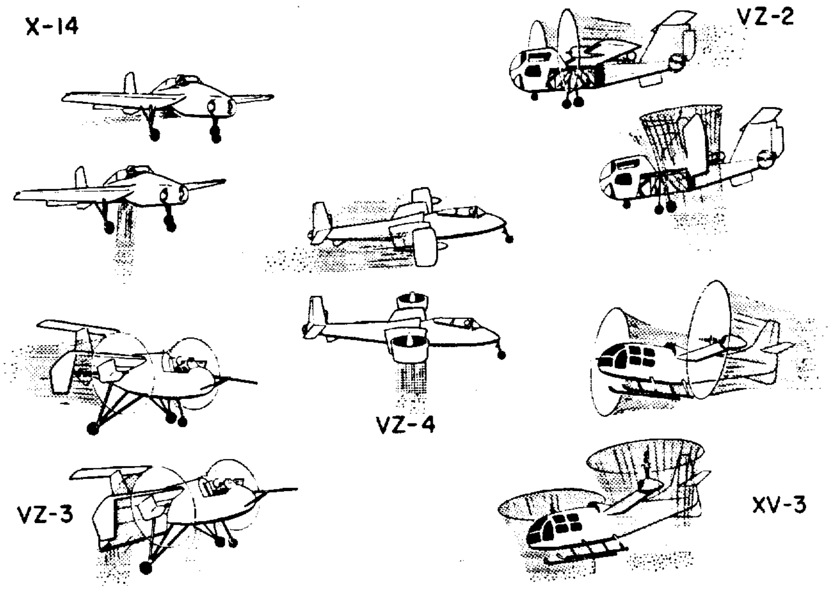

X-14
VZ-2
VZ-4
XV-3
VZ-3

Figure 1

AIRSPEED-ALTITUDE FOR SAFE POWER-OFF FLIGHT

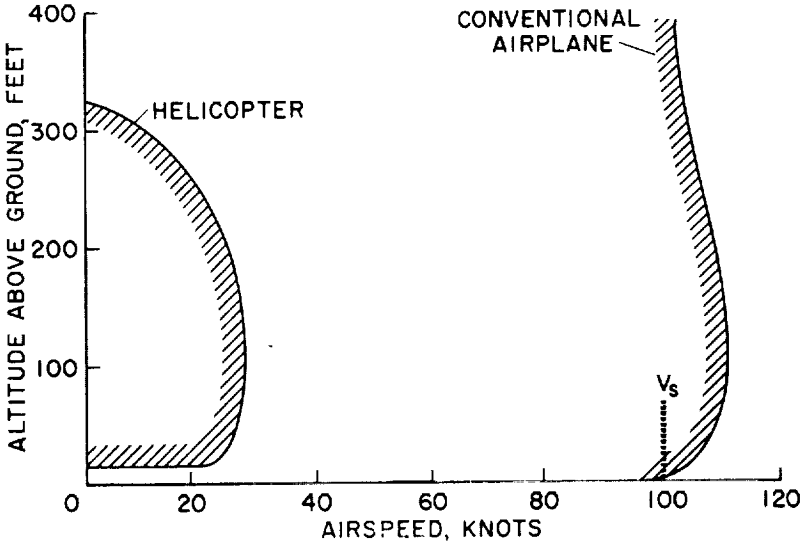
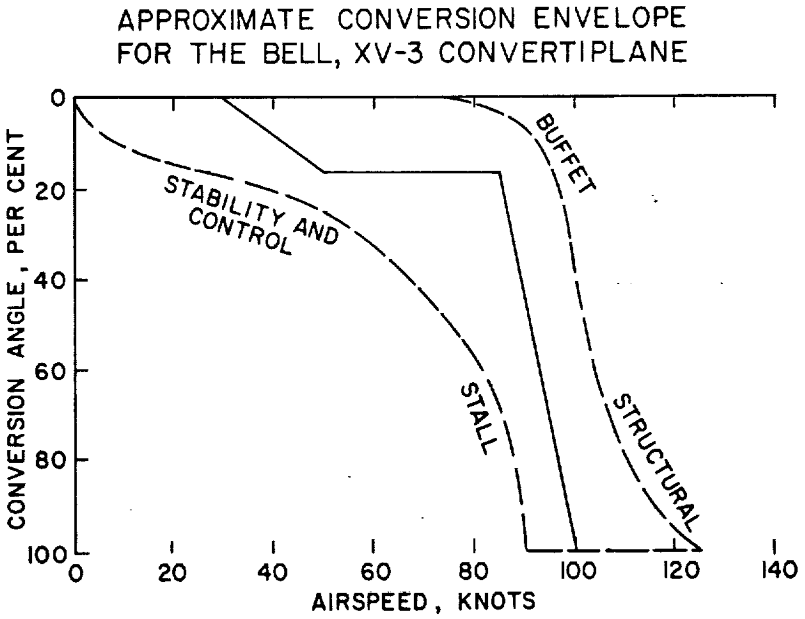


Figure 2



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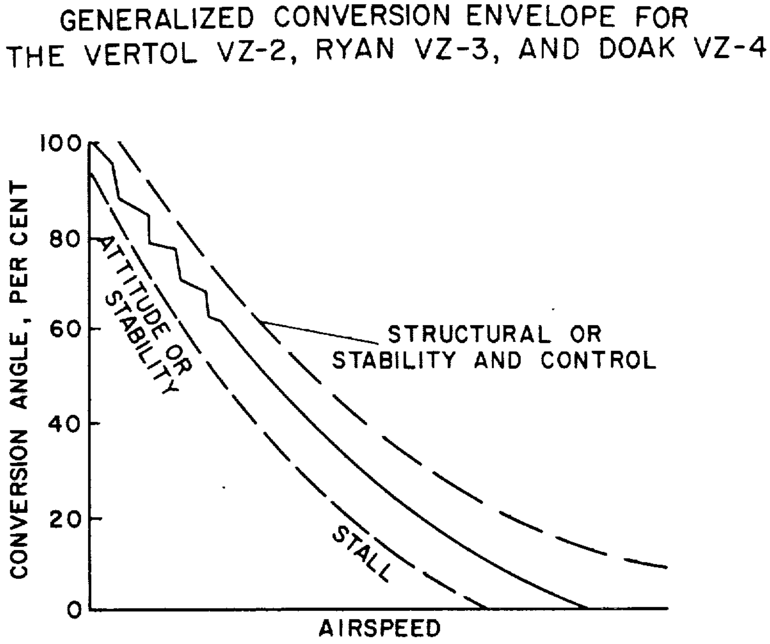

Figure 4

APPROXIMATE CONVERSION ENVELOPE FOR THE BELL X-14 AIRPLANE

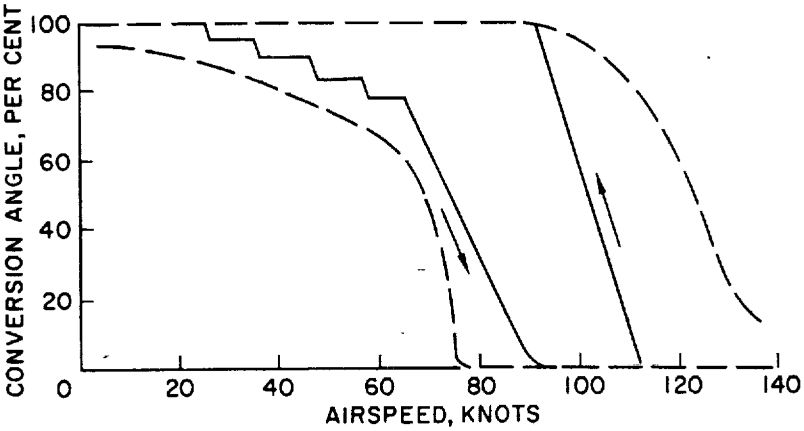

Figure 5

RATE OF DESCENT VARIATION WITH AIRSPEED FOR BELL X-14 AIRPLANE

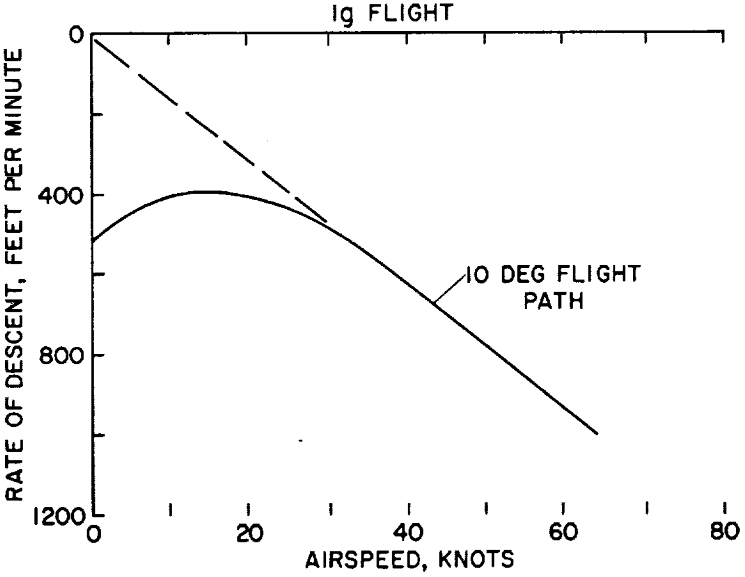

Figure 6

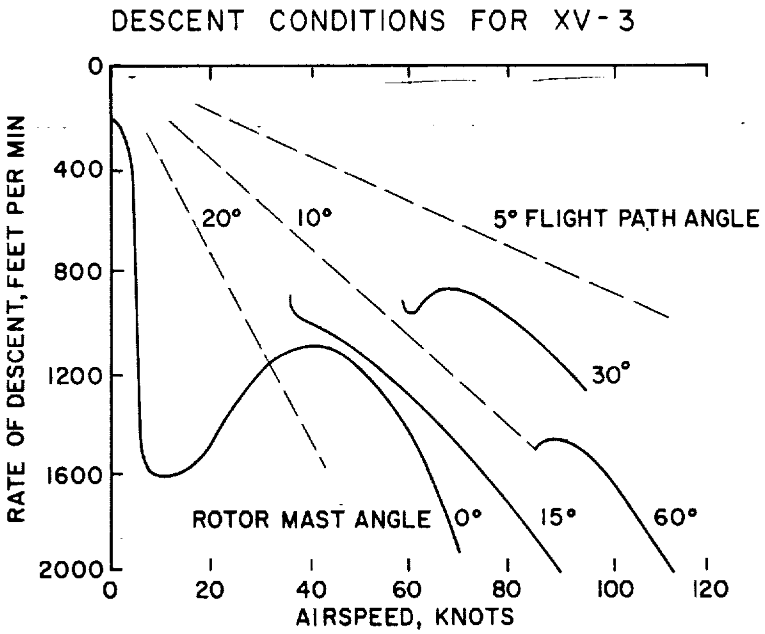

Figure 7

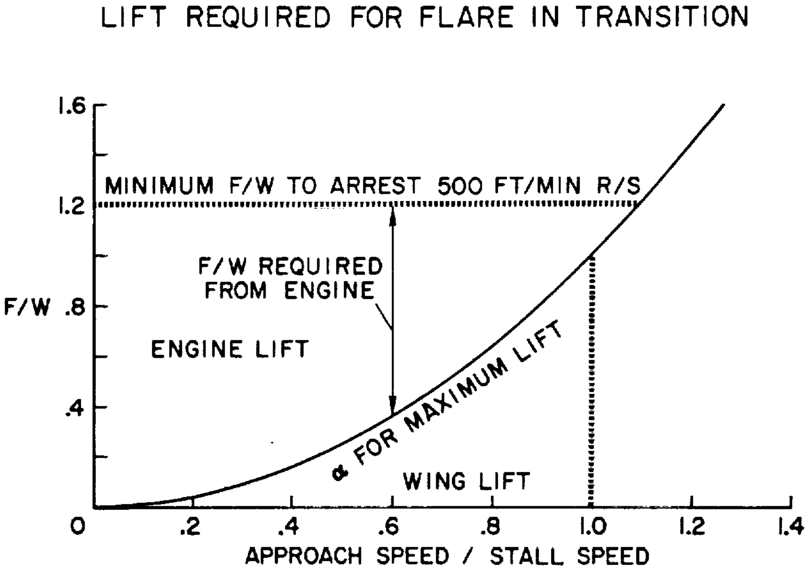

Figure 8