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OPERATIONAL ASPECTS OF V/STOL AIRCRAFT

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VTOL aircraft have the capability of performing a wide variety of military and civil missions. In performing these missions some operational limitations, particularly in the low-speed flight regions, will exist. This paper will discuss some operational aspects of ground handling, take-off and transition, engine-out characteristics, and instrument approaches and landings.

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Several mission profiles that might be used for V/STOL aircraft are shown in figures 1 and 2. The mission profiles for military transports are shown in figure 1 as a solid line for a logistic mission and as a dashed line for an assault mission. The mission profile for a civil transport was established to utilize the airspace not used now by conventional aircraft in terminal areas. (See fig. 2.) Examination of these and other profiles indicates that the main areas of operational interest will be ground handling, take-off, transition and initial climb, and approaches and landings.

Ground handling will require careful consideration of the slipstream velocities which will vary with types of V/STOL aircraft from below 80 mph to over 1,000 mph. When this slipstream velocity is vertical, severe ground erosion as well as recirculation of debris causing foreign object damage is likely to occur unless operations are restricted to clean hard surfaces. If taxiing is done in the fully converted or cruise configuration to avoid ground erosion, operational limitations will be similar to those for current conventional aircraft having comparable slipstream velocities.

In order to discuss take-off, the turbulent air regions created by the high slipstream velocities must be considered first. As shown in figure 3, the vertical take-off will be in the highly turbulent region from lift-off until an altitude of 15 to 25 feet is attained and will probably require a stability augmentation system to correct for the erratic disturbances due to the rough air. The STOL take-off (fig. 3) can be scheduled for take-off at a conversion angle and at an airspeed where the major part of turbulent region is behind the aircraft and not affecting its flight behavior. This speed may be considerably above the optimum take-off speed, depending on the configuration, and some penetration of the turbulent region may be required even for STOL take-offs.

Figure 4 can be used to consider transition procedures typical of the power required for a four-engine tilt-wing VTOL. The dashed line shown for power available, drawn at 1.2 times the power required for hovering, was estimated to be an adequate margin to provide height control for hovering in rough air and to provide a reasonable margin of power for initial acceleration to forward flight. This margin was selected on the basis of previous experience with helicopters and one of the VTOL test beds. Dashed lines are also shown in figure 4 for three-, two-, and one-engine operation. Thus, level flight can be maintained at a speed below 20 knots with one engine out, at 35 knots with two engines out, and at about 60 knots with three engines out. The dashed line labeled overload indicates the effects of high temperatures and high altitudes or military overloads on performance capabilities. The aircraft in the overloaded condition must now have about 20 knots for take-off and about 30 knots for level three-engine flight.

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For take-offs where obstacle clearance is not a problem, vertical take-offs would only be made if a short ground run were not possible (over water, rough ground, etc.). The procedure to be followed would be vertical lift-off, conversion close to the ground to a configuration where at least a 200- to 300-ft/min rate of climb would be possible with three engines, climb to a safe altitude, and then completion of conversion to speed for best climb. The STOL take-off would differ only in that the acceleration to a three-engine safety speed would be on the ground. This procedure allows the pilot to accelerate to a safe speed even under instrument conditions and avoids configuration changes in the critical portion of flight close to the ground.

To estimate distances, an average acceleration rate to safe three-engine speed that is usable by the average pilot under both visual and instrument conditions must be established. Most present transport acceleration values are from 1/10 to 3/10 g. Modern jet fighter rates can be in excess of 1/2 g. For both of these, however, take-off speeds are high and the pilot has ample time to anticipate rotation and take-off speeds. For V/STOL aircraft with considerably lower take-off speeds and the additional requirements for properly scheduling conversion angle with airspeed and varying power to control altitude, a maximum acceleration value of about 1/4 g is usable operationally. Figure 5 shows the distances required at this acceleration for different values of three-engine safety speed. Using the four-engine VTOL of figure 4 this would show a requirement of about 100 feet for the VTOL aircraft or 200 feet for the overload or STOL aircraft.

For some military operations where vertical take-off and climb-out of very restricted areas will be required, it is necessary to evaluate the hazard involved if an engine fails abruptly. In discussing this, it is assumed that the engines are geared to the lifting and control systems in such a fashion that failure of one engine does not result in large changes in trim or reduction of control power. Figure 6 shows a comparison of the estimated ground contact regions of a four-engine-propeller VTOL and a four-engine helicopter. These regions define combination of altitude and airspeed that would require more than average piloting skill to avoid ground contact if an engine failed. The comparatively small area of the VTOL may be explained by reference to figure 7. The vertical lines on the right of each region in figure 6 are drawn at the speed at which each machine could fly level with three engines. Figure 7 shows that this would be about 20 knots for the VTOL and 30 knots for the helicopter. The upper sloping lines in figure 6 are determined by the power available for acceleration which is greater at each speed for the VTOL. It is interesting to note that in figure 7 the VTOL has a rather large range of speeds available even for two- or one-engine operation, and that the helicopter has a narrow range with two engines and cannot fly level with one.

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Since military missions operate, at present, vertically into restricted areas, it can be assumed that the hazard involved with the VTOL can be accepted and will be less than for present aircraft.

The cruise portion of the VTOL flight will be conducted at the same altitudes as present jet fighter and transport aircraft. This may create problems of traffic control since they will be operating at speeds several hundred miles an hour slower than the turbojet aircraft.

It is sometimes suggested that the last thousand feet or so of an approach be made vertically. Under visual flight conditions, this is certainly possible with due consideration of the ground contact region just discussed. However, even visually, this is not too practical due to the high fuel consumption in vertical flight and the difficulty in accurately controlling the flight path. In instrument flight, at present, vertical letdowns are not possible without completely automatic guidance and control.

The establishment of an operational VTOL instrument-approach system depends on a number of factors. Among these are aircraft-performance and handling-qualities limitations, obstruction-clearance requirements, ability of the pilot to follow the guidance system, and community acceptance.

An investigation of approach-angle limits with a helicopter has indicated some of the problem areas associated with low-speed, steep, instrument approaches which will be common to all types. First, the rate of turn for small bank angles is high and g forces in maneuvers are low. This results in requiring a more rapid scan, more concentration, and a higher degree of proficiency than for conventional approaches. Second, at lower speeds, the helicopter and VTOL aircraft will be flying at speeds on the back side of the power-required curve. This requires adjustment of the rate of descent by power changes rather than attitude and results in slower corrections for deviations. Third, wind effects, both crosswind and wind shear, are considerably more difficult to compensate for at low speeds.

A typical steep instrument approach as shown in figure 8 can be conveniently considered in two parts. The first part might be called the acquisition and stabilization portion and consists of that portion from level flight until breakout. The second part starts at breakout and includes the transition to hovering and landing. A typical flight path is shown by the dashed line in figure 8. Results of the previously mentioned steep instrument-approach investigation indicated that for the first phase, about 90 seconds would be considered a minimum operational time for stabilization on the glide path, and 25 knots a minimum speed considering wind and piloting problems. Current developments in pictorial and analog instrument displays, Doppler ground speed presentation, and omni-angle approach systems may allow lower approach speeds in the future. Research programs to investigate these systems are currently programed. If an initial altitude of 1,000 feet is specified for noise or traffic control purposes, this will result in speed-angle relationships as shown in figure 9. Speeds below 25 knots are shown for reference. Only those speed-angle combinations in the usable region are considered operational at present. This indicates that a maximum approach angle at 25 knots would be about 15° and that at 80 to 100 knots, the maximum approach angle would be about 5°.

The second phase starting at breakout is a visual phase which involves visual recognition of ground or light patterns, transition to hovering configuration, and landing. To establish a minimum time, current conventional aircraft minimums may be considered first. At present for the approach speeds and runway visual-range minimums, the pilot has about 9 seconds along the glide path to recognize his portion, align the aircraft with the runway, and arrest the rate of descent before contact. This 9 seconds includes about 3 seconds for recognition, evaluation, and decision and 6 seconds to alter the flight path and arrest descent. Speed is usually held about constant and configuration changes are usually minor or are not made at all. Since the VTOL pilot will have the additional problem of completing the conversion, a more appropriate time for VTOL might be about 12 seconds. Figure 10 shows the approach-speed—approach-angle relationship for two breakout heights based on this 12-second flare phase. The operational combinations are again shown as usable regions. This shows that the ceiling has a considerable effect on permissible approach angles, particularly at lower speeds (at 25 knots a 100-foot ceiling at 11° and a 200-foot ceiling at 21°). Also, at 90 knots and 100 feet, ceiling approach angles are about the same as current ILS glide slopes at $2\frac{2}{3}^{\circ}$.

Figure 11 shows a summary plot of approach-angle ceiling limitations based on combined limitations of the acquisition and flare phases shown in figures 9 and 10. It can be seen that at the low speed of 25 knots a ceiling as low as 50 feet can be operationally feasible at angles appreciably above current ILS approach angles. It is also apparent that an omni-angle approach system would greatly improve VTOL approach capabilities. The break in the curve at about 140 feet is a limit from the acquisition phase.

Turbulence, crosswinds, and wind shear make the steep angle, low-speed approaches more difficult than the standard 3° approach at conventional aircraft speeds. On some occasions during the steep approach program, when ground winds were 10 knots or less the winds at an altitude of 1,000 feet were in excess of 25 knots and low-speed approaches were not possible. On other approaches heading corrections required to maintain the localizer course were as high as 60° at 800 to 1,000 feet and 5° to 10° at 100 to 200 feet due to wind shift and wind shear effects. For the majority of approaches, however, in smooth air or with light turbulence the limits of figure 11 are considered to be operational limits.

In summary, operational introduction of VTOL types appears feasible with minimum disruptions of present practices and procedures. Effects of high slipstream velocities must be carefully considered in the establishment of ground taxiing, take-off, and landing areas. Partial power operation of VTOL's will probably be somewhat safer than for comparable helicopters. Steep instrument approaches will be limited to a minimum speed of 25 knots and a maximum angle of 15° until improved instrumentation permits lower speeds.

MISSION PROFILES FOR MILITARY TRANSPORTS

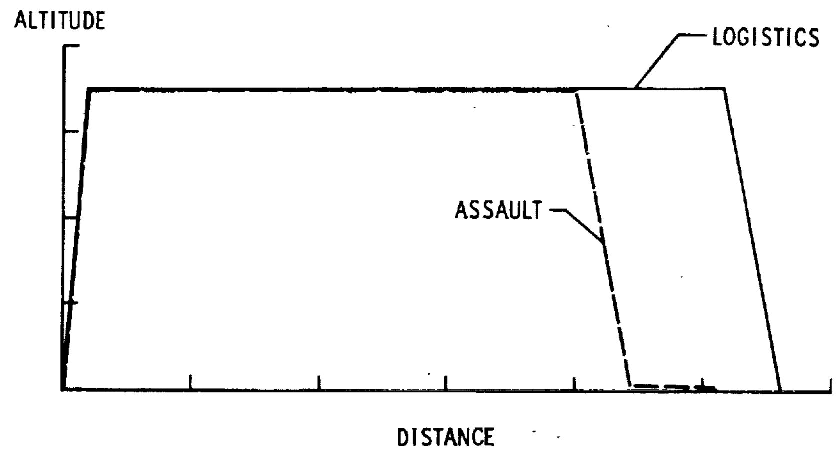

Figure 1

MISSION PROFILE FOR CIVIL TRANSPORT

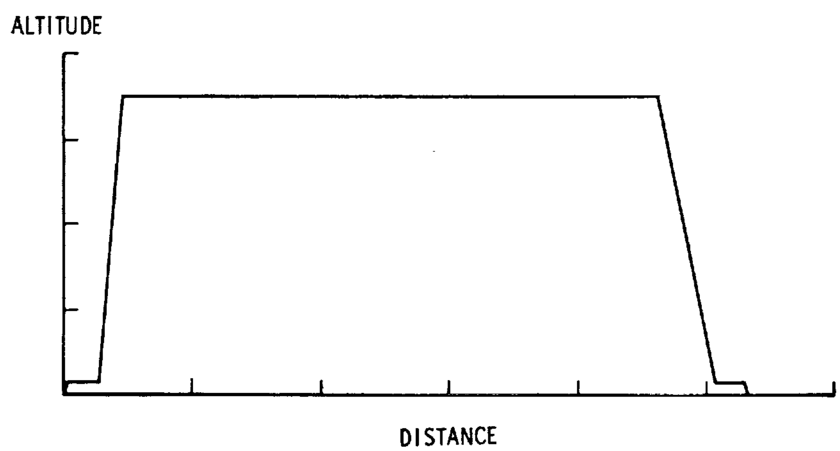

Figure 2

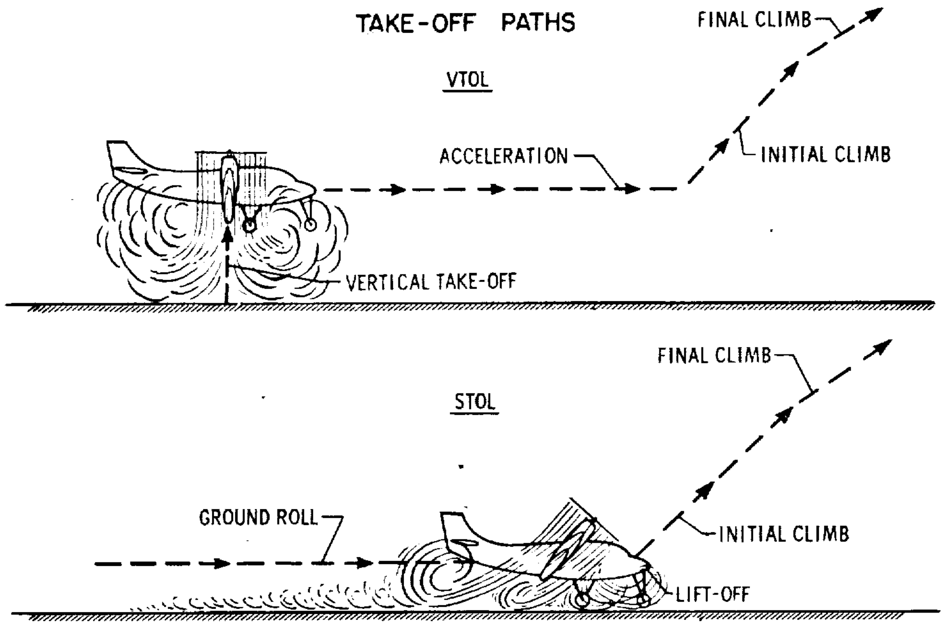

Figure 3

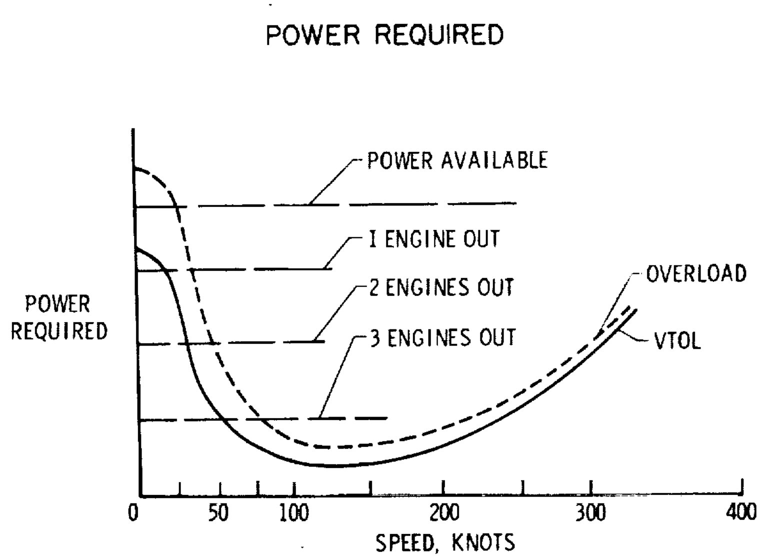

Figure 4

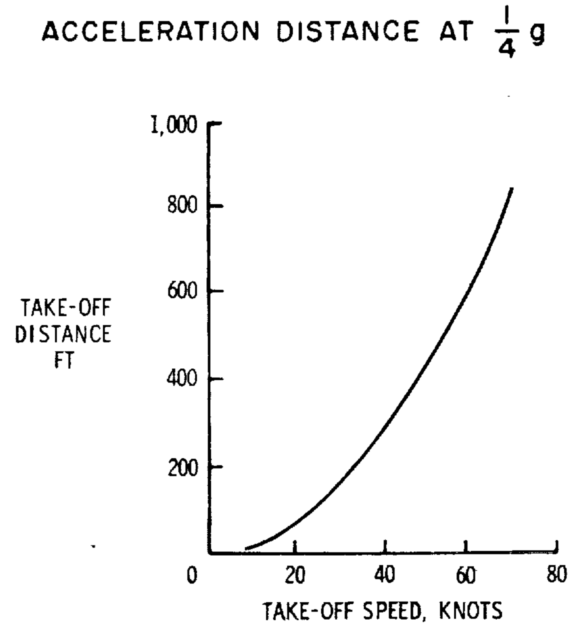

Figure 5

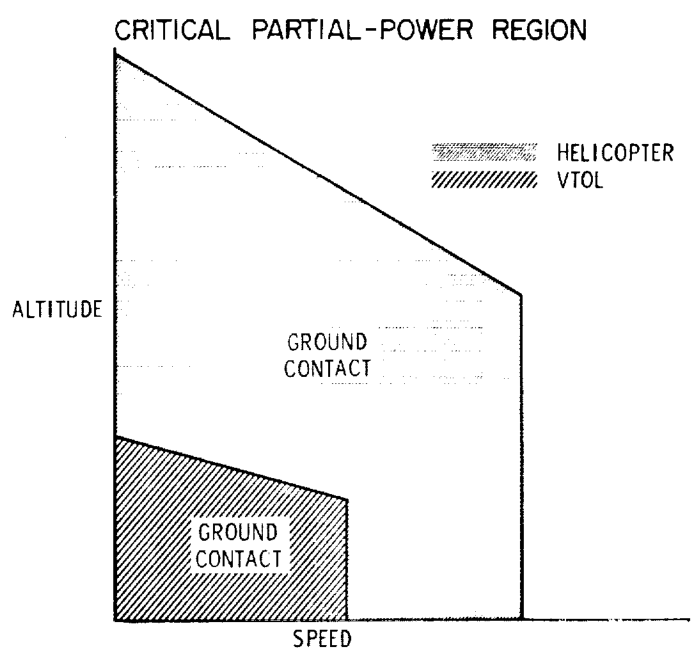

Figure 6

COMPARISON OF POWER REQUIRED FOR HELICOPTER AND VTOL

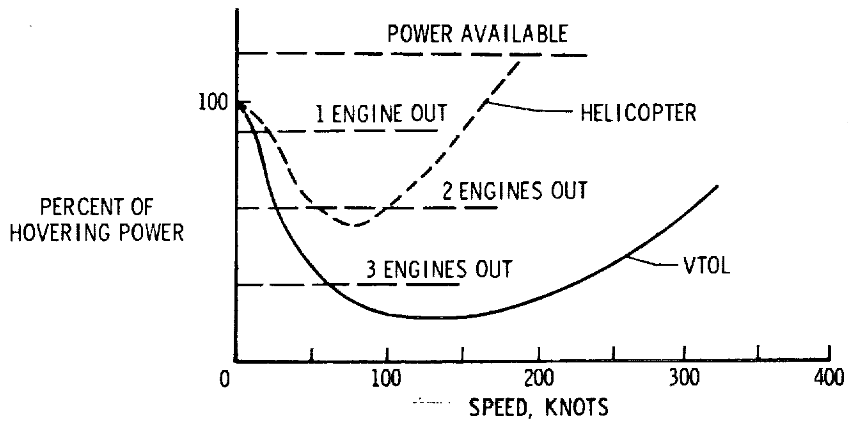

Figure 7

INSTRUMENT APPROACH

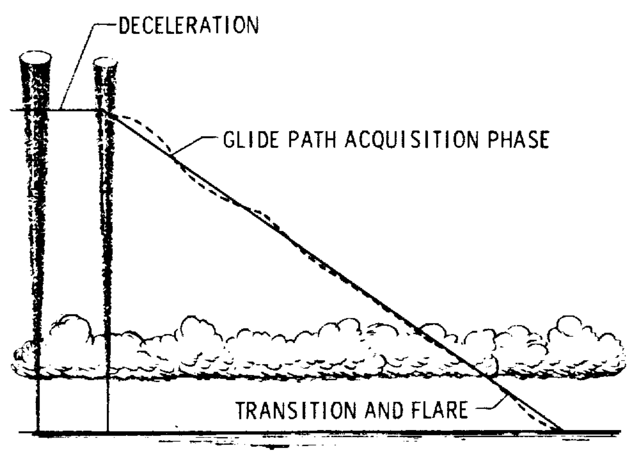

Figure 8

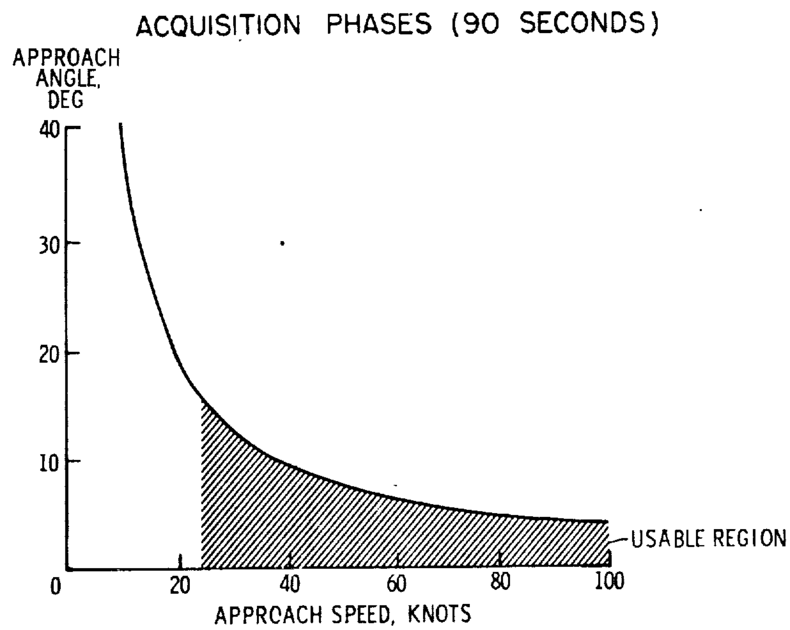

Figure 9

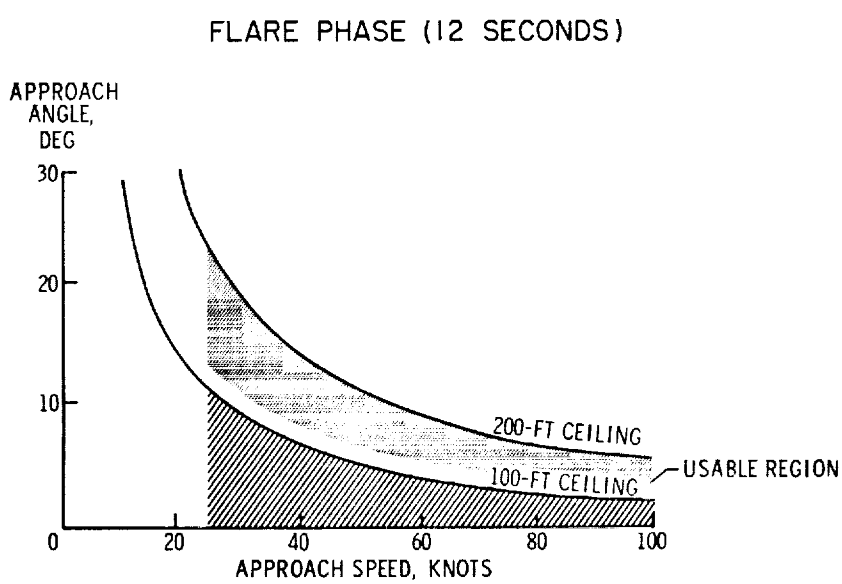

Figure 10

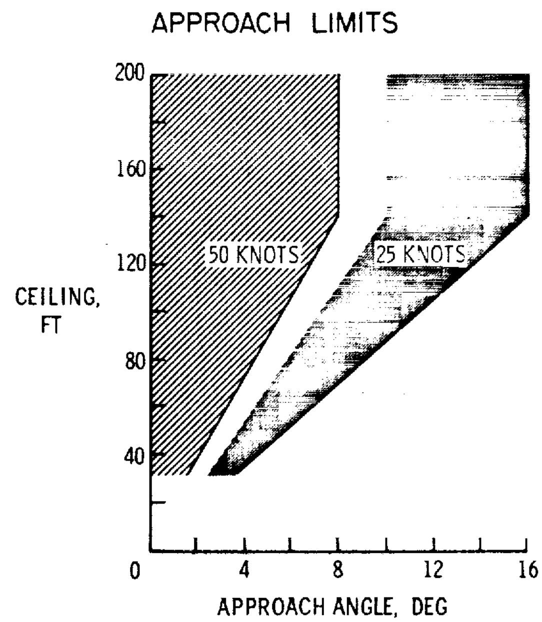
APPROACH LIMITS
200
160
120
80
40
0
4
8
12
16
50 KNOTS
25 KNOTS
CEILING, FT
APPROACH ANGLE, DEG

Figure 11