TENTATIVE CIVIL AIRWORTHINESS FLIGHT CRITERIA

FOR POWERED-LIFT TRANSPORTS

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SUMMARY

A 3-year research program sponsored jointly by the NASA and the FAA has resulted in the formulation of tentative civil airworthiness flight criteria for powered-lift transports. Representatives of the U. S., British, French, and Canadian airworthiness authorities participated. The ultimate limits of the flight envelope are defined by boundaries in the airspeed/path-angle plane. Angle of attack and airspeed margins applied to these ultimate limits provide protection against both atmospheric disturbances and disturbances resulting from pilot actions or system variability, but do not ensure maneuvering capability directly, as the 30-percent speed margin does for conventional transports. Separate criteria provide for direct demonstration of adequate capability for approach path control, flare and landing, and for go-around. Demonstration maneuvers are proposed, and appropriate abuses and failures are suggested. Taken together, these criteria should permit selection of appropriate operating points within the flight envelopes for the approach, landing, and go-around flight phases, which are the phases likely to be most critical for powered-lift aircraft. Criteria are based (1) on simulation results obtained using the Ames Flight Simulator for Advanced Aircraft, (2) on previous ARC flight experience with a variety of experimental powered-lift aircraft, and (3) on recommendations from other sources. Additional work is needed to verify and refine the present criteria in flight, to develop criteria to define field lengths, and to treat powered-lift concepts that incorporate sophisticated guidance, displays, or advanced vehicle stability augmentation.

INTRODUCTION

This paper presents the results of a 3-year research program directed toward development of tentative civil airworthiness flight criteria for powered-lift aircraft. The objectives were to develop tentative airworthiness flight criteria (concentrating on the approach and landing flight phases), to define demonstration test techniques, and to explore design implications of the criteria.

The program was sponsored jointly by NASA and FAA, with participation by the United States, British, French, and Canadian airworthiness authorities. It is hoped that standards developed from these criteria can be adopted in substantially equivalent form by each of the participating authorities.

The development of criteria was begun by using the Ames Flight Simulator for Advanced Aircraft (fig. 1) to evaluate the operating characteristics of several representative powered-lift concepts (refs. 1-6) under realistic instrument flight conditions with atmospheric turbulence and wind shear. Together with previous Ames experience with various powered-lift research aircraft (ref. 7), this evaluation enabled identification of the principal flight hazards due to powered lift.

Preliminary criteria intended to provide protection against these hazards were drafted by the Powered-Lift Standards Development Working Group, a body organized for that purpose and constituted of representatives of the participating organizations. These preliminary criteria were then examined by additional simulator testing (refs. 8, 9), and appropriately modified. Flight testing will be necessary to verify and refine the presently proposed criteria.

These criteria are presented and discussed fully in a report (ref. 10) that has recently been distributed by the FAA for comment. Criteria have been developed in the categories of flight envelope limits, safety margins, approach path control, flare and landing, go-around, and propulsion failure, together with brief guidelines on landing field length. A section on general considerations (ref. 10) is intended to treat questions of regulatory philosophy, and to clarify certain peculiarities that tend to characterize all powered-lift vehicles supported primarily by wing lift. The forms of the criteria were considered more important than the proposed numerical quantities. Although these numerical proposals were based on the flight and simulation results available at the time, it is recognized that these numerical quantities will have to be refined as flight experience is gained.

ULTIMATE FLIGHT ENVELOPE LIMITS

Turning now to the criteria themselves, it is convenient to begin by considering those basic aerodynamic characteristics of a powered-lift aircraft that determine the ultimate limits of its flight envelope. The two graphs on the left-hand side of figure 2 illustrate the lift curves and polar characteristics of a representative powered-lift transport in the landing configuration. The augmentation of lift by the propulsion system is correlated for different concepts by the blowing momentum coefficient C_J, which represents the reaction force due to the momentum discharged by the powered-lift system. The lowest curves represent the characteristics of the wing without blowing. Increased blowing at constant angle of attack augments the lift several-fold. Powered-lift aircraft may be controllable beyond the peaks of the lift curves, so that the maximum angle of attack α_{MAX} may exceed the angle for maximum lift.

The right-hand graph of figure 2 illustrates the operating envelope that results when the aerodynamic characteristics are converted from coefficient to dimensional form. The heavy contours correspond to constant thrust settings. It can be seen that the boundaries of the central clear area constitute the ultimate limits of the flight envelope. In the shaded region at the top of the chart, the thrust required for steady flight is greater than the maximum available; in the lower right-hand corner it is less than flight idle thrust. Beyond the right edge of the chart the airspeed exceeds the placard (structural) limit, and in the lower left-hand corner the aircraft is either stalled or otherwise uncontrollable. The broken minimum-speed contour V_{MIN} corresponds to $C_{L_{MAX}}$. The region of the flight envelope between the α_{MAX} and V_{MIN} contours is not useful for controlled operation, but can provide additional protection against vertical gusts. In general for powered-lift aircraft it is necessary to consider the limiting angle of attack separately from the limiting speed.

SAFETY MARGINS

Safety margins must be applied to the ultimate limits of the flight envelope to define the normal envelope. Within this normal envelope, all expected flight operations can be carried out while maintaining safe margins from the ultimate envelope limits.

Angle of Attack Margin

Considering first the angle of attack margin, it must provide protection against undesired angle of attack excursions resulting from atmospheric disturbances and unintentional pilot deviations, as well as allowing for intentional maneuvers. The proposed tentative angle of attack margin is illustrated in figure 3, and is defined by the equation

$$\Delta\alpha = \arcsin \frac{20}{V_{knot}}$$

This margin enables the aircraft to encounter an abrupt 20-knot vertical gust without exceeding α_{MAX}. The criterion was proposed by the working group after reviewing the capabilities of conventional aircraft during the landing approach, and is intended to provide vertical gust protection equivalent to that of conventional jet transports. The angle of attack excursions caused by pilot actions are smaller for powered-lift aircraft which use thrust as the primary means of flight path control than for conventional aircraft, which use pitch changes for flight path control. Since α_{MAX} is generally thrust-dependent, the margin must be established at each thrust setting throughout the flight range. This process then defines the upper light solid contour in figure 3, which constitutes one boundary of the normal operating envelope.

Speed Margin

For purposes of comparison, consider the speed margin for conventional transports. The hatched boundary on the right in figure 4 illustrates the 30-percent speed margin required for conventional transports; it is based on the power-off stall speed. It will be seen that this margin would not allow exploitation of the powered-lift envelope. The corresponding tentative speed margin proposed for powered-lift aircraft is also 30 percent (but not less than 20 knots), but it is based on the use of maximum thrust. This speed margin is intended to deal with atmospheric disturbances requiring drastic action by the pilot, such as strong wind shear. To command maximum lift, the pilot of the conventional aircraft must pitch to the stalling limit. In the powered-lift aircraft the corresponding pilot action would be to apply maximum thrust (and perhaps also to pitch moderately). It will be seen from figure 4 that the proposed criterion recognizes the effectiveness of powered lift in reducing minimum speed by allowing a corresponding reduction in approach speed. As a consequence, an aircraft with little powered lift would use an approach speed nearly the same as if it were certified under present transport-category requirements.

The right-hand chart of figure 5 illustrates a second tentative speed margin which is intended to provide protection during normal approaches <u>not</u> requiring drastic action by the pilot. For commercial operations it is necessary to fly normal approaches in light to moderate turbulence safely and routinely, with an acceptable pilot workload and without encountering nuisance warnings. After reviewing both flight and simulation experience, the working group proposed a speed margin of 15 percent (but not less than 10 knots), based on the minimum speed at the instantaneous thrust. This thrust is, of course, nominally the approach thrust. However, since the minimum speed V_{MIN} depends on thrust, it will change as thrust is set for different flight path angles. Therefore, the margin must be established at each thrust setting over the whole flight range. This process then defines the upper broken contour in the right-hand chart of figure 5. The two speed-margin criteria illustrated in figure 5 constitute two additional boundaries of the normal operating envelope.

Summary of Safety Margin Criteria

When the proposed angle of attack and speed margin criteria are applied to the ultimate flight envelope, the normal operating envelope that is thus defined is illustrated by the clear area in figure 6. The relationship of the three margin boundaries to each other determines which margin criteria govern in defining the limits of the normal envelope. This relationship will depend on design characteristics, such as the forms of lift curves and the magnitude of powered lift, and will be different for each aircraft. To reiterate, for an aircraft with little powered lift, the maximum-thrust speed margin would likely be dominant, resulting in an approach speed nearly the same as if the aircraft were certified under present requirements for conventional transport-category aircraft.

Now, where within this normal envelope should the nominal operating point be located? To answer this question, it is necessary to consider how the actual instantaneous operating point may change as the pilot makes flight path corrections during the approach. In a conventional aircraft, of course, the pilot attempts to maintain the approach airspeed nominally constant. Most of the powered-lift research aircraft have been flown to a reference angle of attack. It can be seen from figure 6 that maximum use of the powered-lift envelope would result from following the maximum-thrust speed margin boundary when flying shallow approach paths, and following the angle of attack margin boundary when flying steeper paths. There is some question whether the pilot can follow such contours successfully. This matter will be considered further in the next section.

FLIGHT REFERENCE

An enlargement of the normal operating envelope (the clear area of fig. 6) appears in figure 7. Here the concept of flight reference has been generalized to include any contour within the flight path angle vs speed plane, such as the arbitrary contour shown in figure 7. This generalized flight reference could be speed, angle of attack, or perhaps some combination of these with thrust, provided only that the reference quantity be displayed to the pilot by a single instrument and that it be adequately reliable. Simulation results indicate that use of such artificial references appears quite feasible. The dotted area in figure 7 illustrates an expected range of abuses of the flight reference resulting from atmospheric disturbances or pilot deviations.

FLIGHT PATH CAPABILITY

What increments of flight path angle above and below the scheduled path are necessary to enable the pilot to make adequate upward of downward corrections during the approach? Based on both flight and simulation experience, the working group proposed that the upward correction capability extend to an angle 4° steeper than the scheduled angle. Because powered-lift aircraft tend to operate on the back side of the thrust-required curve, slow-speed abuses tend to reduce the upward capability, and fast-speed abuses tend to reduce the downward capability. It is intended that appropriate abuses be included in the flight path control demonstrations. The size of the abuse would be related to the excursions to be expected during approaches in moderate turbulence, and the demonstration would establish the flight path capability at the abused flight reference.

Figure 7 illustrates these considerations, and shows how an appropriate operating point can be selected. The flight reference must be chosen to provide adequate flight path capability without violating any of the safety margin boundaries when the flight reference itself is maintained. In figure 7, if the chosen flight reference contour were to permit the demonstration of a steady gradient of only 10° with the fast-speed abuse, then the steepest scheduled approach angle that could meet all the criteria simultaneously would be 6°.

FLIGHT PATH CONTROL

Why is it necessary to treat the problem of flight path control separately at all? First, the characteristics of backsided operation, large thrust inclination, low lift-curve slope (heave damping), and limited pitch authority and dynamic response all tend to degrade the flight path response. Maintaining speed and angle of attack margins is not sufficient to ensure adequate maneuvering capability, as it does for conventional transports. The need for adequate flight path capability to enable the pilot to make path corrections has already been discussed.

The working group proposed several dynamic response criteria intended to ensure adequate path response without objectionable overshoot or excessive disturbance of the flight reference due to use of the primary flight path control. These proposals are presented and discussed in detail in reference 10.

Finally, the handling qualities of several powered-lift research aircraft have been objectionable during approach because of excessive complexity of controls. For example, the hot nozzles of the Augmentor Wing Research Aircraft (AWRA) are operated by a separate cockpit controller providing powerful control of thrust inclination. Flight experience with this aircraft indicates that continuous modulation of nozzles in addition to column and throttles during approach results in excessive pilot workload.

To deal with this problem, the working group proposed that there be no more than two longitudinal controls, one primarily for controlling path and the other for controlling flight reference, just as in conventional airplanes. For example, throttle might be primary for path, and column primary for flight reference. In order to limit pilot workload, any other cockpit controllers would be treated as configuration selectors not requiring continuous pilot modulation during approach.

FLARE AND LANDING

The next flight phase to be considered is the flare and landing. In this section and in those that follow, it will only be possible to indicate the general nature of the proposed criteria, concentrating on those aspects that differ significantly from conventional aircraft practice.

After considering the need for balancing various requirements on precision of control, on acceptability of dispersions in touchdown sink rate and landing distance, and on gear strength, the working group proposed that flare and landing capability be demonstrated directly in flight, with appropriate abuses. Proposed abuses of initial conditions include landing from a path 2° steeper than scheduled, as well as appropriate variations in initial flare height and in initial flight reference. These latter abuses remain to be defined from further study of operating characteristics. The steep-path abuse corresponds to use at the flare initiation point of half the proposed

4° downward correction capability, and appears to correlate well with the flight path disturbances encountered during simulation of moderate turbulence.

A second category of flare and landing abuses is concerned with abuse of the secondary control. For example, for an aircraft that relies primarily on pitch rotation for landing flare, thrust would be considered the secondary control. For powered-lift aircraft in this category, a severe thrust-reduction abuse is proposed, one amounting to irrational use of thrust. The purpose of the abuse demonstration is to ensure that the flare and landing technique normally used in the conventional regime would not be catastrophic if applied to the same aircraft in the powered-lift regime. If the aircraft were flared primarily with thrust, this thrust abuse would not be needed (although the effect of an inadequate pitch rotation should then be demonstrated). Flaring with thrust alone appears acceptable if the heave response is sufficiently rapid.

GO-AROUND

The principal differences between go-around criteria for conventional aircraft and those for powered-lift aircraft are concerned with the acceptability of re-configuration. Some powered-lift aircraft may not be capable of positive climb angles without re-configuration, such as closing upper-surface spoilers, even with all engines operating. Under the proposed criteria, an acceptable re-configuration would be accomplished quickly by a single-action selection that would not require the pilot to remove his hands from the primary or secondary controls, and would not require further attention.

PROPULSION FAILURE

After considering the questions concerning propulsion failure in a powered-lift aircraft, the working group proposed the following criteria. First, failure of all critical system elements should be considered, including such elements as cross-shafting or cross-ducting as well as the engines themselves. Second, all available alternatives, such as reversion to conventional operation, should be considered. The need to take account of propulsion failure affects the specific criteria in all categories. In view of the low probability of propulsion failure following commencement of an approach, the group believed it reasonable to accept slight reductions in safety margins and flight path capability following the failure. Capability for safe landing (within structural limits) would be demonstrated following failure below a certain commit height, and capability for safe go-around would be demonstrated following failure above this commit height.

LANDING FIELD LENGTH

A great deal of work is still needed to develop methods for determining landing field length. Summarizing the general considerations the working group believed most important: the field length determination should be based on the operational (rather than maximum-effort) technique; abuses related to flare and landing should be demonstrated; and propulsion failure should be considered. It may be significant that powered-lift aircraft could be limited by landing distance rather than takeoff distance; such a limitation could complicate the determination of landing field length and lead to a complexity similar to that for determining takeoff field length for conventional transports.

CONCLUDING REMARKS

The need for flight examination of these proposed criteria is fully recognized. Ames is in the midst of a 50-hr flight program using the Augmentor Wing Research Aircraft (AWRA). This work is directed toward verification and refinement of the tentative criteria, and is planned for completion next year. It is hoped that this process of refinement can be continued by selected experiments using other powered-lift aircraft, and that the design implications of the criteria can be more thoroughly explored.

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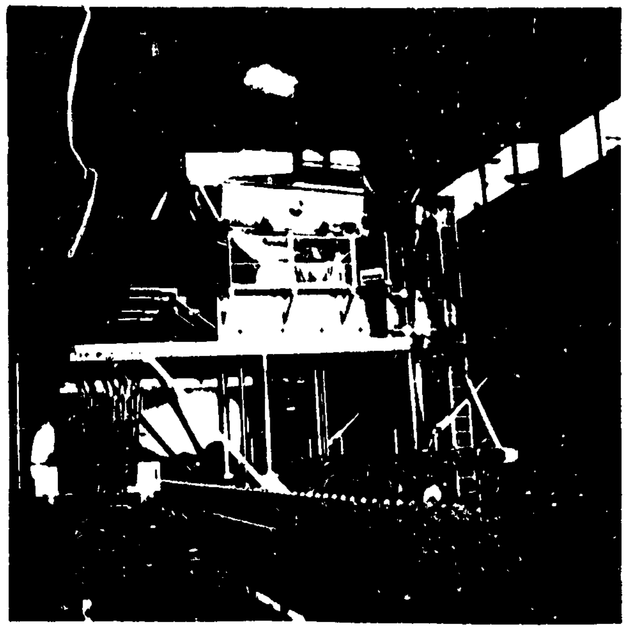

Figure 1.- Flight Simulator for Advanced Aircraft.

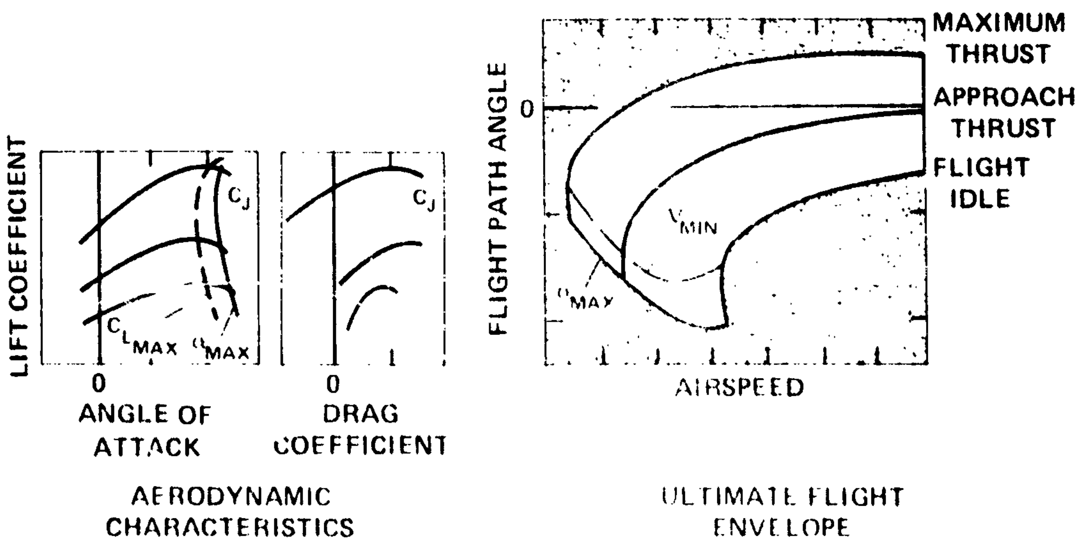

Figure 2.- Aerodynamic characteristics and flight envelope of powered-lift transport: [illegible] configuration.

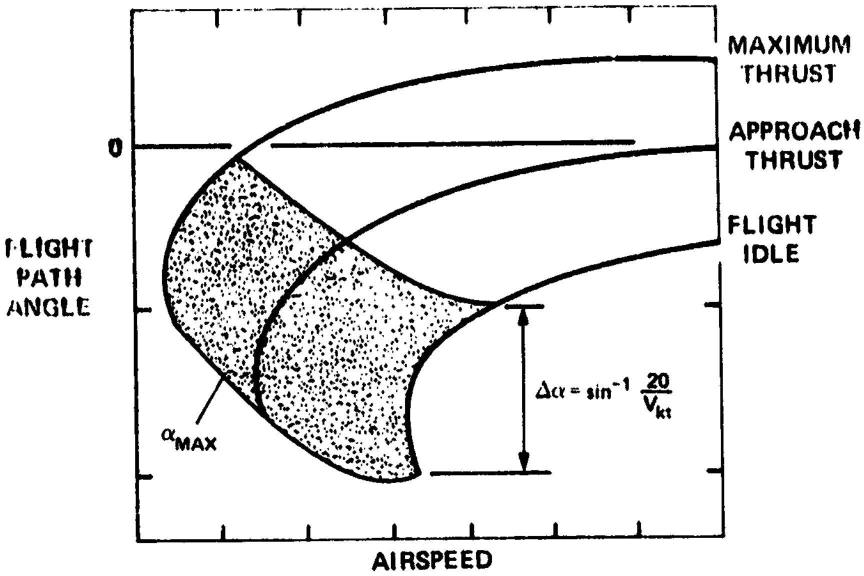

Figure 3.- Proposed angle of attack margin criterion: all engines operating.

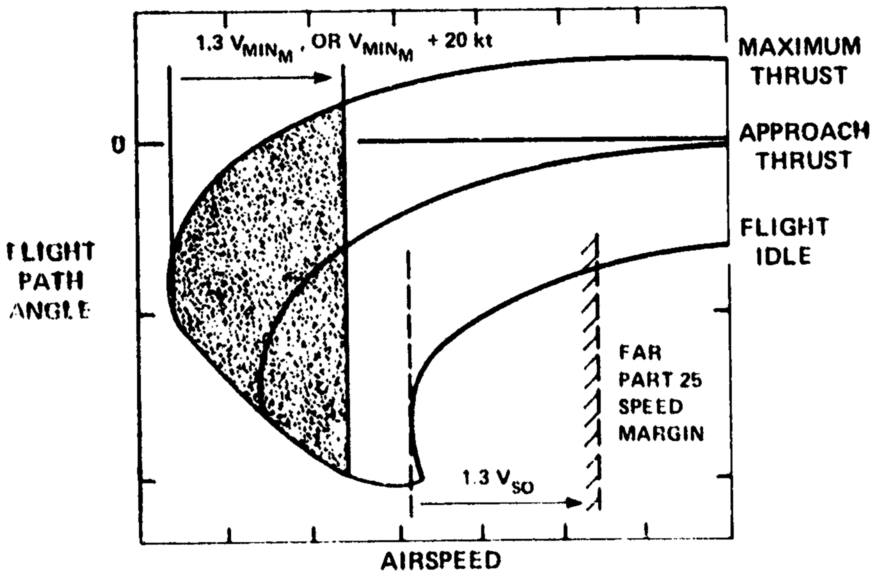

Figure 4.- Proposed speed margin criterion, maximum thrust: all engines operating.

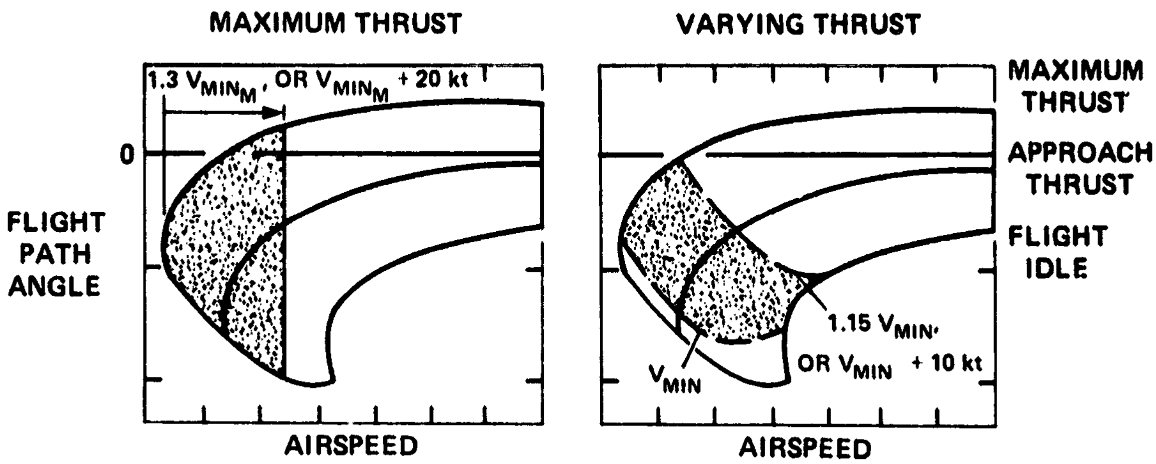

Figure 5.- Proposed speed margin criteria: all engines operating.

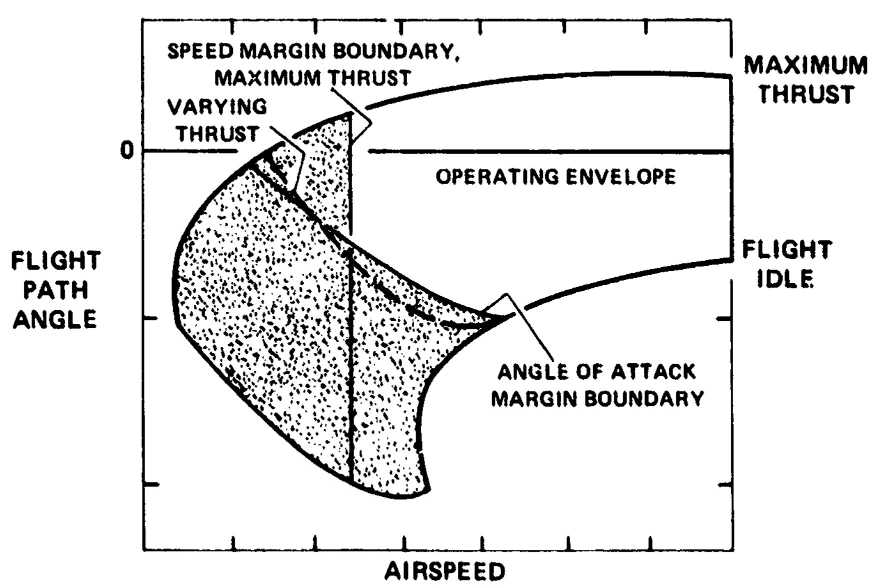

Figure 6.- Operating envelope limited by proposed margin criteria: all engines operating.

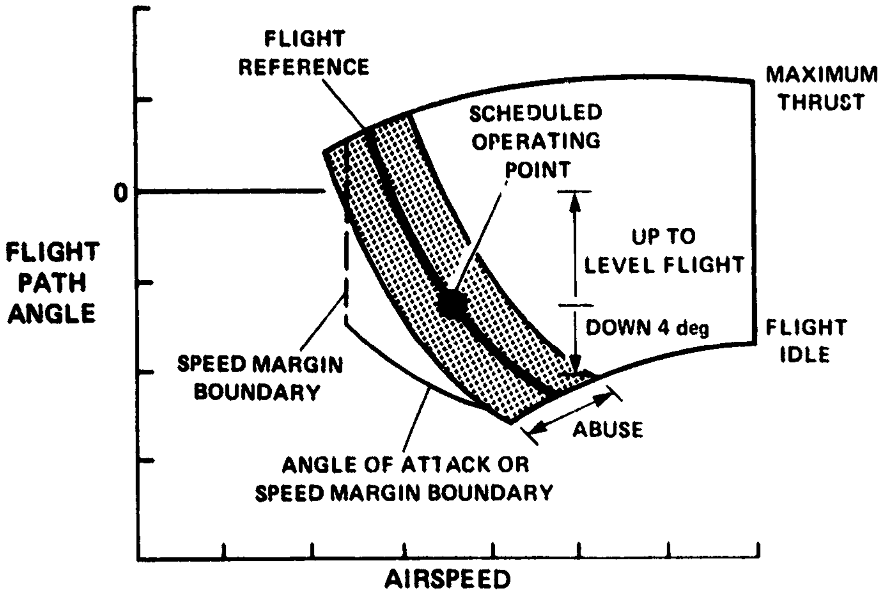

Figure 7.- Proposed criteria for flight path capability: all engines operating.