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TAKEOFF CERTIFICATION CONSIDERATIONS FOR LARGE SUBSONIC AND SUPERSONIC TRANSPORT AIRPLANES USING THE AMES FLIGHT SIMULATOR FOR ADVANCED AIRCRAFT

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16. Abstract

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SYMBOLS AND ABBREVIATIONS

a_z	body axis vertical acceleration, m/sec^2 (ft/sec^2) or g units as noted
$\bar{c}$	wing-mean-aerodynamic chord, m (ft)
C_D	drag coefficient, $\frac{\text{drag force}}{qS}$
C_L	lift coefficient, $\frac{\text{lift force}}{qS}$
C_m	pitching-moment coefficient, $\frac{\text{pitching moment}}{qS\bar{c}}$
D	aerodynamic drag, N (lb)
g	acceleration due to gravity, 9.8 m/sec^2 (32.17 ft/sec^2)
h	airplane height above takeoff surface, m (ft)
h_{tc}	airplane tail clearance height, m (ft)
I_{yy}	pitching moment-of-inertia, kg-m^2 (slug-ft^2)
$K^1 D/W$	induced drag to weight ratio (dimensionless)
L	aerodynamic lift, n (lb)
$\frac{L}{D}$	lift to drag ratio, $\frac{C_L}{C_D}$
m	mass, kg (slugs)
q	dynamic pressure, $\frac{\rho V^2}{2}$, kg/m^2 (lb/ft^2)
S	reference wing area, m^2 (ft^2)
s	distance from brake release, m (ft)
sm	static margin
s_{35}	measured takeoff distance to clear a 10.7-m (35-ft) obstacle from brake release, m (ft)
T	thrust, N (lb)

t_r	rotation time (to lift-off), sec
$\frac{T}{W}$	thrust to weight ratio
V	equivalent airspeed, m/sec (ft/sec) or knots as noted
V_{EF}	speed at engine failure, knots
V_{LOF}	speed at main gear lift-off, knots
$V_{max\alpha}$	minimum demonstrated straight-flight speed without exceeding the absolute angle-of-attack limitation, knots
V_{MC}	minimum control speed, knots
V_{MC_A}	minimum control speed in free air, knots
V_{min}	minimum demonstrated flight speed, knots
V_{MU}	minimum unstick speed, knots
V_R	speed at time of rotation control input, knots
V_S	stall speed, knots
V_{ZRC}	zero rate of climb speed, knots
V_1	takeoff decision speed, knots
V_2	takeoff safety speed (one-engine-inoperative initial climb speed), knots
V_3	all-engines-operating initial climb speed, knots
V_{35}	speed attained at 10.7-m (35-ft) height, knots
W	weight, kg (lb)
$\frac{W}{S}$	airplane wing loading, kg/m^2 (lb/ft^2)
α	angle of attack, radians or degrees as noted
β	sideslip angle (relative wind from right, positive), deg
γ	climb gradient, percent (e.g., 1 percent gradient defines 1 m of vertical travel per 100 m of horizontal travel)

δ_e	elevator deflection angle (trailing-edge down, positive), deg
δ_f	flap deflection angle, deg
θ	airplane pitch attitude relative to horizontal (ANU, positive), deg
θ_{LOF}	airplane pitch attitude at lift-off, deg
ρ	standard air density, kg/m^3 (slug/ft^3)
ϕ	bank angle (right wing down, positive), deg
Δ	incremental change
$(\dot{\ })$	derivative with respect to time, $\frac{d}{dt}$
ACH	achieved
AEO	all engines operating
ANU, AND	airplane nose up, airplane nose down
C.G.	center of gravity
FAR	Federal Aviation Regulations
FSAA	Flight Simulator for Advanced Aircraft
GU	landing gear up
GD	landing gear down
JJT	jumbo jet transport
MAX	maximum
MPR	maximum practical rate
OEI	one engine inoperative
RJT	reference jet transport
RTO	refused takeoff
SST	supersonic transport
TASST	Tentative Airworthiness Standards for Supersonic Transports

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SUMMARY

The objective of this joint NASA/FAA study was to provide data for use in development of takeoff airworthiness standards for new aircraft designs such as the supersonic transport (SST) and the large wide-body subsonic jet transport. For this purpose, an advanced motion simulator was used to compare the performance and handling characteristics of three representative large jet transports during specific flight certification tasks. Existing regulatory constraints and methods for determining rotation speed were reviewed, and the effects on takeoff performance of variations in rotation speed, pitch attitude, and pitch attitude rate during the rotation maneuver were analyzed. A limited quantity of refused takeoff information was obtained. The aerodynamics, wing loading, and thrust-to-weight ratio of the subject SST resulted in takeoff speeds limited by climb (rather than lift-off) considerations. Takeoff speeds based on U.S. subsonic transport requirements were found unacceptable because of the criticality of rotation-abuse effects on one-engine-inoperative climb performance. Adequate safety margin was provided by takeoff speeds based on proposed Anglo-French supersonic transport (TSS) criteria, with the limiting criterion being that takeoff safety speed (V_2) be at least 1.15 times the one-engine-inoperative zero-rate-of-climb speed. Various observations related to SST certification are presented.

INTRODUCTION

With the advent of new aircraft designs, whose performance and handling characteristics differ in important respects from those of earlier designs, the validity of existing airworthiness criteria for advanced aircraft has come into question. A series of cooperative NASA/FAA studies was initiated at Ames Research Center in which advanced piloted simulators were used to provide data as a basis for the development of takeoff certification criteria for new aircraft designs, such as the SST and the large wide-body subsonic jet transports. This study, the first research program conducted on the Flight Simulator for Advanced Aircraft, was made in late 1969.

Results of earlier Ames simulator studies with certification-related objectives are contained in references 1 and 2. Reference 1 reports on the validation of a fixed-cockpit simulator for takeoff certification investigations and points out the requirement for lateral motion of the cockpit for tests involving asymmetric thrust where recognition of engine failure is important.

The program reported in reference 2 used the same fixed-cockpit simulator to study the takeoff performance and handling qualities of a delta-wing SST designed to take off and land at speeds comparable to those of existing subsonic jet transports. In the present study, an SST configuration closer in size and wing loading to Anglo-French and Russian SST configurations was used, and the tests were conducted on an advanced piloted simulator with a large lateral motion capability.

EQUIPMENT

The study was conducted using the Ames Flight Simulator for Advanced Aircraft (FSAA) (fig. 1). The simulator had five-degrees-of-freedom motion with a nominal lateral capability of $\pm g/2$ (± 16 ft/sec^2) acceleration and ± 17 m (± 50 ft) of displacement (refs. 3 and 4). This capability provided realistic motion cues for such tasks as control following engine failure and lateral maneuvering. Simulator performance characteristics are given in table 1. The simulator was designed for six-degrees-of-freedom motion, but the pitch rotational motion was not yet operable at the time of this study. As discussed in appendix A, which describes the motion drive computations and system effectiveness, this was not considered a limiting factor.

The FSAA cab was equipped with a conventional flight test instrument display (fig. 2), as well as instruments for indicating normal and longitudinal acceleration, angle of attack, angle of sideslip, tail clearance, and control surface deflections. Figure 3 shows photographs of the FD-109 attitude display and the airspeed indicator. No flight director commands were provided to the pilot. The control-column, control-wheel, and rudder-pedal force characteristics were provided by hydraulic control loaders.

Closed-circuit color television provided the external visual scene, which was viewed through a collimating lens substituted for the windshield. This visual system provided a 3,300-m (10,700-ft) runway for the takeoff task (refs. 3 and 4).

The data generated during the simulator tests were recorded in time-history form, and included control deflections, thrust, airspeed, airplane attitudes, airplane position, translational accelerations, angular rates, angles of attack and sideslip, and simulator cab accelerations and positions. A digital printout (fig. 4) of significant discrete performance parameters followed each simulated takeoff, and pilot comments were recorded.

SIMULATED TEST AIRPLANES

The three airplane types simulated were: (1) reference jet transport (RJT), approximating the 707, DC-8, and 990 classes of jet transports with a maximum takeoff weight of 136,000 kg (300,000 lb); (2) jumbo jet transport (JJT), modeled as an RJT scaled up in size to provide the same wing loading for a maximum takeoff weight of 317,000 kg (700,000 lb); and (3) supersonic transport (SST), a tailless double-delta-wing airplane with no high-lift devices, with a maximum gross weight of 168,000 kg (370,000 lb) and with aerodynamic characteristics determined from wind tunnel tests (ref. 5).

The significant physical parameters for each of the three airplanes are given in table 2. Figure 5 shows two-view diagrams of the airplanes. Airplane geometry was such that tail contact with the runway (with oleos fully extended) would occur at a pitch attitude of 13.8° with the RJT and JJT and at 13.1° with the SST. Basic lift, drag, and pitching-moment characteristics for free-air and in-ground-effect conditions are presented in figure 6. SST elevator effectiveness was increased progressively to a maximum increment of 20 percent when in full ground effect.

An error was made in programming the ground-effect height factor for the JJT, which caused the differences shown in figure 6 between RJT and JJT aerodynamics near the ground. This error was discovered after testing was completed, but the effects were well understood, so repeat testing was not warranted. As shown in figure 7, the error resulted in excessive ground effect at wheel heights between 0 and 7.6 m (25 ft), the maximum error occurring at zero wheel height. Above 7.6 m the error is considered negligible for takeoff operations. In terms of total aerodynamic lift, drag, and pitching moment, the consequences of the error for the JJT were that: (1) drag was 6.1 percent low during the ground roll; (2) lift was 7.6 percent high at lift-off (equivalent to 1.2° $\Delta\alpha$); (3) about 25 percent (2°) more elevator was required during rotation; and (4) L/D at lift-off was about 23 percent high (lift-off climb performance was 13.3 percent high with all engines operating and 23 percent high with one engine inoperative at standard-day thrust). The significance of these effects will be indicated at appropriate points in the discussion. The effect on normal takeoffs was primarily to cause lift-off at a slightly lower attitude than intended, and the effect on general handling characteristics during takeoff was minimal.

Irreversible control systems were assumed for all three airplanes; control characteristics are given in table 3. Control force displacement characteristics remained unchanged with variations in dynamic pressure and normal acceleration. Simple pitch and roll damping augmentation was normally "on" for the SST takeoffs.

Figure 8 shows the available thrust variation with speed assumed for these tests. The thrust-to-weight ratio as a function of speed was essentially the same for the RJT and JJT. The limit value of $(T - D)/W$ resulted from adjusting thrust so that climb performance in the second segment configuration equaled 3 percent gradient, as required by reference 6. Engine spindown dynamic response approximated a 1-sec first-order lag for most of the engine-failure tests conducted.

TEST PROCEDURE

Over 500 takeoffs were made and included all-engines-operating normal takeoffs, all-engines-operating abused takeoffs, one-engine-inoperative takeoffs, one-engine-inoperative abused takeoffs, and refused takeoffs. Two NASA and three FAA research test pilots participated in the study. Each pilot was given a flight card for each test series, which defined the task, the configuration, and the corresponding reference speeds (takeoff decision speed V_1, rotation speed V_R, and takeoff safety speed V_2).

The pilots were briefed to abort the takeoff in the event of engine failure prior to V_1; for engine failure following V_1, the pilot was to acquire V_2 by the 10.7-m (35-ft) height and use it as the climb speed. With all engines operating, the target climb speed was V_2 + 10 knots. During most of the takeoffs, an observer in the copilot seat called out "100 knots," "V_1," and "rotate" as these speeds were reached.

Takeoff reference speeds used for normal operation of the RJT and JJT were based on information from the appropriate subsonic jet transport operational flight manual. The same speeds were used for both the RJT and JJT for corresponding conditions of wing loading, flap position, and thrust-to-weight ratio. Selection of SST reference speeds was based on requirements in references 6, 7, and 8, as discussed in appendix B. SST speeds were selected for the maximum takeoff gross weight and were usually based on the Anglo-French requirement that V_2 be greater than 1.15 times the zero rate of climb speed in the one-engine-inoperative landing-gear-retracted configuration (TSS standard 2, 6.2.2.2 (b) (i), ref. 7). The reference speeds used are shown in table 4 and figure 9.

Each piloted session was approximately 1-1/2 hr long and averaged 20 takeoff runs. For each test condition, the pilot was allowed to make as many runs as he considered necessary to meet the test objective. The runs were discontinued after the pilot had stabilized on climb speed and attitude (approximately 20 sec after lift-off). Sea-level standard calm conditions and zero runway gradient were assumed for all runs except those in which a 25-knot steady crosswind was added.

PILOT ASSESSMENT OF NORMAL TAKEOFF CHARACTERISTICS

Each pilot made a series of normal takeoffs with each airplane at maximum gross weight. Flaps were set at 25° for the two subsonic airplanes. The cg position was 0.25 $\bar{c}$ for all three airplanes, corresponding to a midrange value for the RJT and JJT and the forward limit for the SST.

All participating pilots considered the simulator quite realistic for the reference jet at maximum takeoff gross weight. Directional control through the pedal-connected nose-wheel steering was good. A smooth rotation at V_R resulted in lift-off at speeds slightly below V_2. The RJT accelerated through V_2 as a positive rate of climb was established and airspeed continued to increase. Normal takeoffs with the JJT and RJT were remarkably similar, differing mainly in the noticeably slower response of the JJT in roll and pitch.

Normal takeoffs with the simulated SST were different from those of the subsonic configurations tested. Four-engine performance was outstanding. Takeoff technique was more critical from a safety and performance standpoint. Variations from the best rotation rate, angle, and speeds caused larger deviations in takeoff distance, and could cause tail strikes. There seemed to be little problem with tail strikes when the rotation and lift-off were performed in a smooth and continuous manner, and at a rate which allowed the airplane to accelerate through V_2 before reaching the final climb attitude. On the other hand, there was sufficient control power to cause an unwanted tail strike, the result if the rotation rates were comparable to those currently used on the small trijets, for example. Pilots used the real-world cues for reference more than the attitude indicator in performing rotation. The pitch attitude during rotation could be judged by an occasional glance at the airspeed indicator just as is done with a conventional heavy jet transport, but with the SST it was more important to ensure that the airspeed continued to increase as the aircraft was rotated. There was definitely no advantage in a fast rotation to a preset attitude with this airplane. After lift-off with all engines operating, climb attitudes and airspeed were easily established even without stability augmentation.

PILOT ASSESSMENT OF ONE-ENGINE-INOPERATIVE TAKEOFF CHARACTERISTICS IN A CROSSWIND

At the end of each series of normal takeoffs a 25-knot crosswind was introduced, and a series of takeoffs was made with an engine failure usually occurring at or after V_1. At unannounced times throughout the program, engine failure occurred prior to V_1, resulting in a refused takeoff (RTO) (see appendix C). Five comparative time histories of the one-engine-inoperative crosswind takeoffs are given in figure 10.

All participating pilots considered the simulator quite effective for coping with an engine failure during takeoff, largely because of the high fidelity of reproduction of the cockpit lateral accelerations. The crosswind condition combined with an engine failure produced a most demanding task with the RJT. The transition from ground directional control (which requires rudder and spoiler to balance the sideslip) to airborne directional control was very critical. The rudder required for ground directional control had little to do with the pedal force required to maintain zero sideslip flight as lift-off occurred. During the ground run, the rudder deflection required is defined by the thrust asymmetry, rudder effectiveness, nose-wheel steering effectiveness, direction and magnitude of the crosswind component, and the airplane static directional stability. Once the craft is airborne, only the first two factors define the rudder deflection required. Figure 10([illegible]) shows that, with an engine failure on the downwind side, a reversal of rudder deflection was required during lift-off.

For the JJT, yaw following the failure was less abrupt than for the RJT and consequently easily controlled (fig. 10(a)). The roll control power was low for the transition from ground directional control to balanced flight, but the roll-yaw mode was not as easily excited and a smoother second segment climb was established.

The engine-out takeoff with the simulated SST contrasted sharply with the all-engines-operating case. The engine-out performance degradation was severe and produced a very critical piloting task to get the airplane airborne in a condition where it would continue to gain energy. Piloting technique and the avoidance of early rotation was of utmost importance. Airspeed had to be closely monitored because it was easy to become airborne in ground effect, without the ability to accelerate or climb, unless rigid attention was paid to V_R and the airplane was flown off the ground so that speed continued to increase as altitude was gained. If speeds were not abused, the engine failure was not as hard to manage for the SST as it was for the RJT. Directional control at lift-off was improved over the RJT, and during the transition, the yaw motion to reduce sideslip did not require damping by the pilot. Thus, as the ground control rudder forces were eased during rotation, balanced flight was attained quickly. Sideslip due to a failed engine was easy to sort out and lateral controllability was very good. Again, it was important to adjust the rudder forces quickly to allow neutral lateral control in the engine-failed case, especially since performance was marginal and cross control was not beneficial.

EFFECTS OF PILOT TECHNIQUE ON NORMAL TAKEOFF DATA

To make a quantitative comparison of the normal takeoff characteristics of the three airplanes it is necessary to separate out variations that occur because of differences in pilot technique. This was done by examining "average" takeoff time histories of airspeed, pitch attitude, and altitude for individual pilots for each airplane. The next step was to examine histograms that show variability in the takeoff time histories for several pilots.

Average Normal Takeoffs

Near the end of the study, each of the two NASA pilots was asked to make approximately 10 calm-air maximum-gross-weight takeoffs with each airplane as he normally would with that particular airplane in commercial operation. The records from these runs were then used to generate the "average" time histories (fig. 11) by reading values at 1-sec intervals over a 25-sec time span starting 5 sec before V_R, computing the average at each time, and plotting the averages. The extreme high and low values at each time define the shaded regions in figure 11. Because of significant differences in pilot technique, separate time histories are shown for each pilot.

The takeoffs made by pilot A were representative of operational takeoffs, while those of pilot B were more typical of those conducted in certification testing where minimizing takeoff distance to the 10.7-m height is a primary consideration. Pilot A tended to use lower rotation rates than pilot B, rotating smoothly to the climb attitude over a 10 to 15-sec time span. This allowed simultaneous acquisition of the desired climb speed (V_2 + 10) and attitude with the two subsonic airplanes. With the SST, pilot A used a climb attitude about 3° less than that required for a constant speed climb, and obtained a 1 knot/sec accelerating climb. This technique allowed the L/D to increase as speed increased and resulted in a more efficient climb, while still providing a substantial initial climb gradient.

Pilot B used a more rapid rotation, attaining the climb attitude in less than 5 sec with the RJT and JJT. Although this technique satisfied the V_2 requirement at the 10.7-m height, it resulted in acquisition of climb attitude at a speed less than V_2 + 10, and a need to accelerate during the initial climb. As a result, the climb attitude was lower than that used by pilot A. Pilot B used 6 to 10 sec to rotate to the climb attitude with the SST, because of the large attitude change required and concern over the possibility of tail strike. He viewed the V_2 + 10 target climb speed as a more rigid requirement than did pilot A, and therefore used a constant-speed climb with the SST.

Histograms

To obtain the largest histogram sample sizes possible, data from normal takeoffs made throughout the study were included with those from the runs conducted to form the average normal takeoff time histories described above. Mean values are indicated in the histograms by vertical dashed lines.

The variability in rotation speed that occurred during attempts to rotate at target values is shown in figure 12. With all engines operating and at maximum gross weight, all rotations were within a band ranging from 8 knots below to 6 knots above the target speed. The variability of rotation speed for the one-engine-inoperative case was slightly less than that for the all-engines-operating case. The scatter in SST rotation speed was greater than for the subsonic transports, primarily because of the higher acceleration.

A small sample of RJT and JJT takeoff runs at light weight (high T/W) indicate a tendency to exceed the target rotation speed in that condition.

The rotation time was defined as the interval from the time the control column was moved beyond 2.5 cm (1 in.) aft to the time the main landing gear lifted off the runway. The rotation time is shown in figure 13. The RJT and JJT mean rotation times were 3.5 and 3.7 sec, respectively, while that for the SST was 4.5 sec. The effect of rotation time on minimum tail clearance is shown in figure 14. Rotation times for the JJT would have been 0.5 to 1 sec longer and tail clearance about 0.61 m (2 ft) less if the in-ground-effect aerodynamics had been identical with those of the RJT.

The rotation data were reviewed to determine whether some common maximum value of pitch rate, pitch acceleration, or pilot-station normal acceleration governed rotation for all three airplanes but none was found. It is not yet possible to state whether the results would have been different had pitch motion cues been present, although as discussed in appendix A, pilots subjectively considered the combined vertical acceleration motion cues and visual cues adequate for the rotation task. Evidence indicates that the vertical acceleration motion cues were helpful during rotation; for example, following a series of RJT takeoffs in which fairly consistent peak rotation rates were used, the motion system was made inoperative and a fixed-base takeoff was made. The peak pitch rate used in the fixed-base run was 2.5 times greater than in the motion runs, yet the pilot considered the run a "carbon copy" of the preceding run with motion.

Pitch attitude at lift-off and maximum pitch attitude to the 10.7-m height are shown in figure 15 for each airplane. The mean lift-off attitude of the JJT was about 1° less than that of the RJT, showing the effect of the difference in programmed ground-effect lift. Figure 16 shows the variability of V_{LOF} and V_{35} for the three airplanes; and figure 17 shows the speed gained between rotation initiation and lift-off and between lift-off and the 10.7-m height. The effect of the SST's high T/W is evident in the large speed gain realized during the rotation prior to lift-off, 16 to 34 knots for the SST with all engines operating compared with 6 to 13 knots for the RJT. During the airborne segment to the 10.7-m height, however, the SST speed gain was no greater than that for the RJT, a result of the greater "flare-up" vertical acceleration used with the SST (shorter air time) and the associated higher induced drag. With one engine inoperative, the speed gain in the airborne segment was less for the SST than for the RJT and was negative in four of seven runs, indicating a decelerating condition after lift-off.

Figure 18 presents measured distances to lift-off s_{LOF} and to the 10.7-m altitude s_{35}. (Throughout this report, measured takeoff distance s_{35} is defined as distance from brake release to the achieving of 10.7-m wheel height.) Two small compensating factors – the greater ground effect and the use of lower rotation rates – resulted in JJT distances about equal to those of the RJT. In figure 19, measured takeoff distance s_{35} is plotted versus the time to rotate for the all-engines-operating and one-engine-inoperative cases. The definite correlation indicates that the greater variation of takeoff distance shown for the SST in figure 18 may be due primarily to the variation in rotation time at the higher takeoff speeds of the SST. The speeds at the 10.7-m height corresponding to the extreme rotation times for each condition are also shown in figure 19. Although this figure shows that SST takeoff distance increases rapidly with increased rotation time, it should not be interpreted as suggesting the use of high rate rotations with this aircraft – other factors must be considered. As discussed in the next section, high rotation rates seriously increased measured takeoff distance when one engine was inoperative and acceleration to V_2 was accomplished in the airborne segment prior to reaching the 10.7-m height.

The maximum incremental vertical acceleration ($\Delta a_{z_{max}}$) during the flare-up maneuver and the height at which $\Delta a_{z_{max}}$ occurred are shown in the histograms of figure 20. The mean of $\Delta a_{z_{max}}$ (for both NASA pilots) was 0.15 g for the RJT, 0.11 g for the JJT, and 0.31 g for the SST. The differences in pilot technique are evident in these SST data. For pilot A only, the mean $\Delta a_{z_{max}}$ during SST takeoffs was 0.225 g. The high accelerations occurring during the SST takeoffs performed by pilot B appear to be the result of his rigid adherence to the use of $V_2 + 10$ as a climb speed. The data of pilot B at Δa_z above 0.3 are questionable because the vertical motion cues of the simulator were truncated for low-frequency accelerations exceeding 0.25 g, as indicated in appendix A.

An interesting observation was made regarding the height at which $\Delta a_{z_{max}}$ occurred. During most of the SST runs, $\Delta a_{z_{max}}$ was seen to occur as the pitch rate was arrested to establish the climb attitude, which was at a mean height of 18.5 m (61 ft) (fig. 20), whereas $\Delta a_{z_{max}}$ for the subsonic airplanes often occurred during the initial portion of the flareup. Figure 21 is a time history of vertical acceleration at the center of gravity and pilot's station for one of the SST takeoffs performed by pilot B. The peak accelerations sensed by the pilot (in the calm air environment of these tests) were less than those experienced at the center of gravity because of elevon lift effect and the pilot location about 27 m (90 ft) forward of the center of gravity.

TAKEOFF ABUSE TESTS

During the certification testing of a new airplane and after the normal takeoff speeds and procedures are established, tests are conducted to prove that handling qualities and distances are satisfactory when the normal speeds and procedures are abused. Airworthiness requirements applicable to subsonic jet transports require that expected service variations, such as overrotation or out-of-trim conditions, will not result in unsafe flight characteristics or in marked (defined as 1 percent) increases in scheduled takeoff distances. One such demonstration specifically required is that the one-engine-inoperative takeoff distance with a rotation speed 5 knots less than the established V_R does not exceed the corresponding one-engine-inoperative takeoff distance with the normal V_R.

Concern about possible SST takeoff characteristics led to the generation of numerous proposals for additional takeoff abuse demonstrations for SST aircraft. In this study, existing and proposed abuse tests were assessed at maximum takeoff gross weight conditions in an effort to identify appropriate tests and eliminate unnecessary ones. The effects of the abuses were compared with the normal takeoff, and as a further basis for comparison, similar abuse tests were conducted with the RJT at climb-limited thrust (limit $(T\text{-}D)/W$, see fig. 8). For the one-engine-inoperative tests, an outboard engine was made to fail at approximately V_1 (175 knots for the SST and 138 knots for the RJT).

The two parameters of primary importance during takeoff are distance from brake release to the 10.7-m height and the corresponding speed at that point. The intent is, of course, to become airborne at the lowest practical speed to minimize the tire speed requirements, reach 10.7-m height in the least distance to minimize runway length requirements, and yet have acquired sufficient speed at the 10.7-m height to provide satisfactory climb performance with an engine failed. The latter consideration is of increased importance for SST aircraft; as indicated in figure 9, the climb capability of these airplanes is considerably more sensitive to speed variations than that of current sweptwing transports.

Some insight is gained into the effects of different types of takeoff abuses by recognizing the relationship of speed versus distance during takeoff. During the takeoff ground run, this relationship approximates a parabola of the form $s = V^2/2a$ with acceleration nearly constant and with a slope $dV/ds = a/V$ (fig. 22). Acceleration varies slightly with speed as a result of aerodynamic drag, rolling resistance, and thrust variations. Factors that can affect acceleration significantly during takeoff, and thus the slope dV/ds, include engine failure, drag increases due to rotation, decrease in L/D as ground effect decreases, and the flight path angle during the airborne portion to the 10.7-m height. The variations in pilot technique (abuse effects) cause variations from the nominal, or normal takeoff, curves defined – a measure of the efficiency of the takeoff.

The data points on figure 22 show speed and distance at the 10.7-m height for a number of takeoffs using normal technique. These values can be used as the basis for evaluating the abuse effects.

Figure 23 shows the data of figure 22, as well as the results from various takeoff abuses. Data points that fall below those representing normal takeoffs indicate less efficient takeoffs in which (1) less speed was acquired for a given distance, and thus the resulting climb away capability was degraded; or (2) excessive distance was used. Variations in pilot technique caused greater variations in performance for the SST than for the RJT, as evidenced by the greater scatter in the SST data, especially for the one-engine-inoperative case. As described in appendix B, the criticality of the effects of takeoff abuses when one engine was inoperative made it clear that reference speeds (V_R and V_2) based on requirements applicable to current subsonic transports, FAR 25 (ref. 6), would not provide sufficient margin for the SST. The SST abuse tests described in this section used reference speeds based on the proposed TSS requirements (ref. 7), while FAR 25 requirements yielded reference speeds about 15 knots less.

Supersonic Transport – All Engines Operating

Normal rotation technique.– Measured takeoff distance with all engines operating and using normal technique (○ in fig. 23) was nominally 2640 m (8670 ft), as shown in figures 18 and 23. The all-engines-operating s_{35} was 2270 m (7450 ft) when speed at the 10.7-m (35-ft) height equaled V_2 (225 knots, table 4). In fact, a maximum-practical rotation rate was required to achieve V_2 and the 10.7-m height simultaneously. (For the SST, a maximum practical rotation rate was defined by ground clearance considerations, as indicated in fig. 14.)

Three-seconds late rotation.– The most critical abuse test with all engines operating was the 3-sec late rotation (□ in fig. 23), which yielded measured distances ranging from 2540 m (8320 ft) with $V_{35} = V_2 + 15$ to 2960 m (9700 ft) with $V_{35} = V_2 + 32$. The rotation speed produced by a 3-sec delay was about 20 knots greater than the normal V_R (table 4), resulting in a target rotation speed of 229 knots. The shortest distances represent rotations at the maximum practical rate, while the longer distance represents a normal rotation rate. The opinion of one pilot was that these higher rotation speeds were desirable (in the absence of tire limit considerations) to permit prompt flareup to climb attitude with little chance of striking the tail.

Two-degrees underrotation.– The 2° underrotation tests (◻ in fig. 23) resulted in measured takeoff distances ranging from 2610 to 2870 m (8570–9430 ft). The major problem in underrotation testing appeared to be one of clearly defining the proper target attitude. Should rotation be arrested at 2° below lift-off attitude, or below climbout attitude? It appears that this test is significant only if the normal rotation technique with the airplane being evaluated uses a two-step rotation, whereby the lift-off may be delayed by the underrotation. In these tests, the pilots rotated to a 10° to 11° pitch attitude, maintained it for about 2 sec, then continued the rotation. The underrotated attitude was sufficient to provide lift-off and simply resulted in a shallow initial flight path until rotation continued. The penalty associated with underrotation depends primarily on the time considered sufficient for recognition and the resumption of rotation. Current proposed values of 1 to 2 sec (or the equivalent speed increment) did not appear critical.

Severe overrotation.– A severe overrotation test (not included in fig. 23) was conducted in which the airplane was rotated more rapidly than practical, with a tail strike occurring at lift-off, and pitch attitude reaching 22° at 10.7-m (35-ft) height. At the 10.7-m (35-ft) height, the speed was 221 knots and decreasing, and distance was 2380 m (7500 ft). The minimum speed reached was 209 knots, but recovery was not difficult with the all-engines-operating T/W. The effect of overrotation on takeoff distance was, of course, to decrease it. Exceptions could result from such effects as thrust degradations due to the abnormal angle of attack (an effect not included in the simulation) or from a pitch attitude rebound following a tail strike due to either pilot reaction or structural effects. With the speed margins provided by the reference speeds, the all-engines-operating overrotation demonstration appeared to be unnecessary.

Early rotation.– The various early rotation abuse tests, including those accomplished during the development of the takeoff reference speeds, resulted in reduced takeoff distance, but at the expense of reduced (but noncritical) climb performance.

In general, abuse considerations did not appear very significant for the subject SST with all engines operating. Takeoff speeds selected to ensure adequate safety in the event of engine failure made the airplane quite forgiving of early, rapid, and overrotation abuses with all engines operating. In the high T/W condition, the primary concern appeared to be that of exceeding critical tire limit speeds due to slowed-, late-, or underrotation abuses.

Supersonic Transport – One Engine Inoperative

Normal rotation technique.– The nominal one-engine-inoperative measured takeoff distance using normal rotation technique (● symbols in fig. 23) was 2900 m (9580 ft) with V_1, V_R, and V_2 equal to 175 knots, 209 knots, and 225 knots, respectively. As indicated previously, with one engine inoperative, the airplane's performance was sensitive to rotation and climb speed abuses. To illustrate this sensitivity, a number of time histories have been included throughout this section. Figure 24 is a time history of a one-engine-inoperative takeoff. No rotation abuse task was specified for this run. Measured takeoff distance was less than the nominal OEI value and V_{35} was 2 knots less than V_2 and decreasing due to a slight overrotation. Acceleration was severely reduced in the rotated attitude with one engine inoperative, and therefore to obtain V_2 speed it also was necessary to avoid rapid and early rotations. Very little speed gain occurred during the flareup; thus, the V_2 speed had to be nearly acquired by lift-off.

Nearly all the abuse tests, except early rotation tests where the target V_R was less than 200 knots and the airplane was decelerating at the 10.7-m height resulted in measured takeoff distances about equal to the normal one-engine-inoperative distance. On these runs, climb capability beyond the 10.7-m height was a more critical factor than distance. In many instances, pilots found it difficult to climb or accelerate after leaving ground effect until gear retraction occurred (12 sec after activation).

Five-knot early rotation.– The 5-knot early rotation (▼ in fig. 23), target V_R of 204 knots, resulted in a measured takeoff distance about equivalent to that corresponding to the normal rotation speed, but with V_{35} ranging from 215 to 223 knots. Figure 25 is a time history of this takeoff abuse test. The pilot commented on the need to reduce either pitch rate or target pitch attitude at lift-off to avoid overrotation. With slight overrotation of the aircraft, the 10.7-m wheel height could be readily achieved at 10 knots below V_2, in which case the climb performance was marginal.

Ten-knot (5 percent) early rotation.– Five takeoff runs were performed by three pilots for the 10-knot (5 percent) early rotation case (◆ in fig. 23). The difference in results of these runs again illustrates the sensitivity of SST takeoff performance to variations in technique. Measured takeoff distance varied from 2660 m (8740 ft) to 3670 m (12,030 ft). Rotation speed varied approximately 2 knots above and 6 knots below the target speed of 199 knots. Rotation time varied from 4.6 to 7.9 sec, and lift-off speed varied from 213 to 222 knots. Despite the rotation variations, deceleration occurred after lift-off for four of the five runs, with V_{35} 1 to 3 knots less than at lift-off and decreasing. For the run best satisfying the test objective of recovery of one-half the rotation speed error, V_{35} was 221 knots and the measured takeoff distance was slightly greater than that corresponding to the normal rotation speed. The pilots commented that it was necessary to consciously use a reduced pitch rate and pitch attitude when attempting to recover the speed error.

The ground effect was especially apparent in the marginal performance condition provided by the one-engine-inoperative 10-knot early takeoff task. Figure 26(a) is a time history of the run yielding the shortest takeoff distance of those discussed in the preceding paragraph. The airplane decelerated from 213 to 207 knots during the climb to 30 m (100 ft) where the pilot arrested the climb rate and was unable to climb or accelerate until the landing gear retracted. Figure 26(b) is the time history of the second attempt by the same pilot using a reduced attitude.

The airplane lifted off and attained a 75 m/min (250 ft/min) climb rate, which reduced to zero as the ground effect diminished. The angle-of-attack trace illustrates that if 1 g flight is to be maintained, the angle of attack must be increased from approximately 11° at lift-off to about 13° during the climb out of ground effect, indicating the criticality of attitude control in this phase. Nearly 3670 m (12,000 ft) of runway were consumed from brake release to the 10.7-m height.

Two takeoff runs were accomplished by one pilot early in the program with V_R equal to 200 knots and V_2 not specified. Time histories for these two runs are given in figure 27. Times to rotate were 6.3 and 3.6 sec and lift-off speed was 224 and 211 knots, respectively, for the first and second runs. There was little or no acceleration in the airborne phase to the 10.7-m height in either run, but the total measured distance to 10.7 m was actually less for the higher lift-off speed. The run with the early lift-off appears to be an exception to the general finding that distance to the 10.7-m height and speed at 10.7 m are closely related; it appears to be the result of a takeoff (fig. 27(b)) where attitude was not increased beyond that barely required for lift-off during the subsequent 5 sec, during which little acceleration was possible because of the marginal performance at the low lift-off speed. These runs demonstrate the sensitivity of the combined one-engine-inoperative speed abuse situation to rotation technique, and indicate the difficulty of identifying a single representative takeoff distance to the 10.7-m height.

Maximum practical rate rotation.– Maximum practical rate rotation (◆ in fig. 23) resulted in speed at the 10.7-m height about 5 knots below V_2. Two takeoff runs shown as time histories in figure 28 emphasize the poor acceleration capability during the airborne segment following a premature lift-off. Figure 28(a) represents a near optimum recovery following a maximum practical rate rotation to lift-off, and figure 28(b) shows the second run by the same pilot in which he used a reduced pitch attitude in an attempt to attain a speed near V_2 at the 10.7-m height. The initial climb was very shallow, and acceleration was low. With runway being used at 110 m/sec (370 ft/sec) it was necessary to continue the flareup. Two knots of the speed gained were lost in this maneuver and 400 m (1327 ft) more runway were used.

Five-knot early rotation at maximum practical rate.– The combined abused takeoff with rotation 5 knots early and at the maximum practical rate (■ in fig. 23) resulted in measured takeoff distance about equal to the nominal one-engine-inoperative distance and V_{35} about 6 knots below V_2, or in a significantly increased S_{35} for higher V_{35}. An example of the former is shown in the time history of figure 29(a) and represents a good recovery from the rotation abuse. Figure 29(b) represents a run, with the same task, by another pilot, who rotated 2 knots below the target of 204, experienced a tail strike during lift-off at 212 knots, accelerated to 221 knots (4 knots below V_2) before passing through the 10.7-m height, and used 4760 m (15,630 ft) of runway.

Analysis of early rotation effects.– The data from the various early rotation abuse takeoffs were analyzed to determine how the measured distance to the 10.7-m height varies with the rotation speed abuse for the SST and RJT (fig. 30). The effect of speed at the 10.7-m height, was considered by grouping the data for conditions in which (1) the entire rotation speed error was eliminated before reaching the 10.7-m height; (2) one-half the rotation speed error was eliminated before reaching the 10.7-m height; and (3) the entire rotation speed error was carried through the 10.7-m height. The distances shown represent near-minimum values for each condition (i.e., considerable scatter in the data existed with much longer distances measured for certain runs than indicated in the figure). This was most often true in the one-engine-inoperative case where rotation was at the maximum practical rate. Rapid rotation resulted in an early lift-off and required more acceleration in the airborne segment where the beneficial ground effect was less than at the ground level and where the airplane was in an increased drag condition.

During the testing and preparation of the data for figure 30 it was obvious that requiring acceleration to V_2 before reaching the 10.7-m height following an early rotation with one engine inoperative was an unrealistic and severe task. In fact, it was extremely easy to arrive at the 10.7-m height with a larger speed error than the rotation speed abuse. On the other hand, with all engines operating and the requirement that V_{35} equal V_2 the task was not severe, although the effect of early rotation with both airplanes (SST and RJT) was to increase the takeoff distance as shown.

If half the speed error was eliminated before the 10.7-m height was reached, early rotation at a nominal rate resulted in a small reduction in distance, as shown by the dashed lines in figure 30. Almost no reduction resulted for the SST with one engine inoperative, even though the reference speeds used for the SST provided it with a greater first-segment climb capability than that of the RJT. This is probably due to the greater rate of degradation of climb capability with early speed abuses, higher induced drag during the flareup, and perhaps partially to a greater rate of reduction of ground effect with increasing height. It is also worth pointing out that although the SST possesses a much greater ground effect lift than the RJT, the increase in trimmed L/D (which is the important factor in the ability to accelerate) due to ground effect is not significantly different.

General remarks.– Attitude control has been shown to be very critical during SST initial climb with one engine inoperative. Following lift-off at 10° to 11°, attitude had to be increased to about 14°; less than 13° would result in zero rate of climb in partial ground effect and greater than 15° in a decelerating climbout.

Perhaps for this type of aircraft it would be worthwhile to consider a takeoff procedure tailored about the one-engine-inoperative takeoff condition so that in the event of engine failure the consequences would be minimized. For example, all takeoffs would use a common reference attitude, such as 14°, for the initial climb. With all engines operating, the resulting accelerating climb would be more efficient because of the improving L/D although the initial climb rate in the airport vicinity would be reduced.

Additional study appears necessary to define the probability of occurrence of various takeoff abuses, and of the factors influencing them. Consideration of combined abuses may be needed because of the severity of the consequences. For example, failure of an engine near V_1 and the accompanying control problem may generate anxiety leading to an early, high-rate rotation to an excess attitude. Conversely, knowledge of the penalties associated with early lift-off could influence a tendency toward underrotation in the one-engine-inoperative condition.

CONCLUDING OBSERVATIONS

Subsonic Jet Characteristics

This study concentrated on the portion of takeoff up to attainment of the 10.7-m altitude. The results obtained for the RJT demonstrated that the FSAA realistically simulated the takeoff tasks. These tests included a most demanding piloting task – takeoff of the RJT with one engine inoperative in 25-knot crosswind. For the RJT takeoffs, differences in piloting techniques produced speed abuses as large as those specified in proposed speed abuse tests. The effects of these speed abuses on measured takeoff distance and the speed at 10.7 m provide a good basis of comparison for the SST abuse test results.

The characteristics of the JJT were generally similar to those of the RJT; observed differences resulted primarily from the larger moments of inertia and reference length. (No control system differences, such as greater friction or hysteresis effects, were programmed.) The increased reference length and inertias made the yawing motion following engine failure less abrupt and more easily controlled; they also made early and rapid rotation abuses appear less likely.

Supersonic Transport Characteristics

The primary factors in SST takeoff characteristics differing significantly from those of the subsonic jet transports were the T/W and the effects of the low-aspect-ratio wing, which include the low lift-curve slope, the high induced drag, and the large ground-effect lift.

The low lift-curve slope and absence of high-lift devices resulted in higher lift-off attitudes and takeoff speeds than for subsonic transports of comparable wing loading. These factors in turn resulted in greater sensitivity of takeoff distance to variations in rotation rate and time leads or lags.

The high induced drag resulted in a large decrease in acceleration in the takeoff rotation, a greater degradation of climb gradient with decreasing speed, and a greater performance penalty (acceleration or climb gradient) during such maneuvers as the takeoff flareup.

The large ground-effect lift made it possible to lift off at speeds significantly below that required to continue climbout with one engine inoperative. The high T/W provided a high acceleration and climbout capability with all engines operating, which resulted in large speed increments between rotation initiation, lift-off, and climbout. The large thrust loss, due to a failed engine combined with the high induced drag of the airplane when rotated, caused a pronounced loss in performance and resulted in a large difference between the speed increments for one-engine-inoperative and all-engines-operating takeoffs. Pilots said that the one-engine-operative performance degradation was severe, producing a very critical piloting task to get the airplane airborne in a condition where it could continue to gain energy. Because of the severe loss in acceleration accompanying rotation and the climb gradient sensitivity to climb speed abuse, proper piloting technique, including the avoidance of rapid and early rotations, was imperative. These results indicate the advantages to be gained from some type of guidance to assist the pilot in avoiding speed abuses and in managing the rotation and initial climb phases of the takeoff more efficiently.

SST Certification

A tailless delta-wing SST of relatively high wing loading (463 kg/m^2, 95 lb/ft^2) at maximum gross weight has been considered in this study. This configuration has proved useful for pointing out the effects of the basic aerodynamic and geometric differences between delta supersonic and swept-wing subsonic transports; however, its characteristics will not necessarily be evident in all delta SST aircraft. The on-ground lift capabilities and T/W of the subject airplane resulted in takeoff speeds limited by climb considerations. Had the same airframe possessed higher T/W or lesser on-ground lift, the takeoff speeds could have been limited by lift-off considerations, and many of the concerns regarding climbout diminished. However, operating economics (the need to fly the largest possible payload) indicate that the subject configuration is not unrealistic. Certainly, such characteristics are a possibility that must be accounted for in the formulation and development of airworthiness standards for supersonic transports. Some of the certification-related observations follow.

1. Takeoff speeds based on FAR 25, criteria for subsonic transports, were unacceptable because of the criticality of rotation-abuse effects on one-engine-inoperative performance. The greater degradation of SST climb gradient with decreasing speed creates the need for a requirement providing protection against climb speed abuse.

2. Satisfactory takeoff speeds for the subject SST were based on proposed Anglo-French TSS criteria, the dominating criterion being that V_2 be at least 1.15 times the one-engine-inoperative zero-rate-of-climb speed. A V_R was then selected that would allow the attainment of V_2 at the 10.7-m height following a normal rotation with one engine inoperative. Even though these reference speeds provided a greater first-segment climb capability than for the RJT, the speed increment between lift-off and the 10.7-m height with one engine inoperative was typically less than for the RJT (and was frequently negative), apparently as a result of induced drag during the flareup and a greater rate of decreasing ground effect with increasing height. This made it necessary to have V_2 nearly attained prior to lift-off with an engine inoperative.

3. It appears advisable to require that the first-segment climb gradient be realized at a lift-off speed that results from a maximum-practical-rate rotation initiated at V_R with one engine inoperative. Lift-off speed following a maximum practical rate rotation with one engine inoperative was about 5 knots less than following a normal rotation and resulted in a degradation in climb gradient greater than the present required first-segment gradient (0.5 percent).

4. For abused takeoff tests, especially with one engine inoperative, distance to the 10.7-m height should not be the sole criterion. Because the ability to climb or accelerate is so sensitive to speed, abuse test results should be based on a combination of distance to the 10.7-m height and climb capability at that point. For example, this could be accomplished by requiring that the airplane be able to exceed some minimum acceptable climb angle during the initial climbout.

5. Takeoff speeds selected to ensure adequate safety in the event of engine failure made the airplane quite forgiving of early, rapid, and overrotation abuses with all engines operating.

6. Late, slowed, or underrotations coupled with the high acceleration cause larger overshoots of the normal lift-off speed and may require larger margins between lift-off speed and critical tire limit speeds than with the subsonic transports. Lift-off distance is also greatly increased

by these abuses, but it does not appear to be a very important factor unless visibility conditions or cockpit procedures hinder the pilot's ability to foresee an impending overrun. Climb capability will be significantly greater at the higher lift–off speeds.

7. If takeoff abuse tests are to be evaluated on the basis of distance to the 10.7–m height, it is considered necessary to specify V_{35} for early rotation tests because takeoff distance varies greatly depending on V_{35}. However V_{35} should not be specified for a specified attitude control task (overrotation or underrotation) because the attitude requirement, in itself, determines the V_{35}. For one–engine–inoperative speed–abuse takeoffs, it should be permissible to carry the entire speed abuse to the 10.7–m height. For all–engines–operating abuses, it appeared reasonable to require recovery of one–half the speed error by the 10.7–m height.

8. On several occasions during one–engine–inoperative tests, the large ground effect on lift appeared to contribute to an inadvertent and significant increase in distance to the 10.7–m height. On these occasions, the pilot would typically rotate to and maintain a pitch attitude of 11° to 12°, rather than the normal 14°. In the condition of full ground effect, lift–off occurred along with a satisfactory initial rate of climb. As height increased, ground effect lift decreased, causing a decrease in flight path angle. Angle of attack correspondingly increased since pitch attitude was being held constant, and a checked ascent resulted. The pilot was not immediately alerted to the reduced climb rate because of his intense concentration on attitude and airspeed during this critical flight phase. To avoid this situation, the pilot must gradually increase attitude during the initial departure from the ground, a technique that should be introduced in pilot training, but with some warnings against overrotation.

9. Further research, such as observations of actual aircraft operations, is needed to define the probability of occurrence of various takeoff abuses, and the factors influencing them. Consideration of combined abuses (e.g., early rapid rotation with one engine inoperative) may be needed because of the severity of the consequences.

10. Takeoff and climbout procedures tailored to minimize the effects of an engine failure should be evaluated for specific SST (and other high T/W) configurations.

11. During surprise refused takeoffs, the sequence of application of deceleration devices (throttles, brakes, spoilers) differs from that commonly assumed in the certification process of determining the accelerate–stop distance and has the effect of increasing the stopping distance. The effects of this difference could be greater for SST airplanes. (See appendix C.)

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APPENDIX A

USE OF THE MOTION SYSTEM

The FSAA described in this report and in references 3 and 4 was designed for operation with six-degrees-of-freedom, although the pitch degree of freedom was not operable when the tests discussed here were conducted. This appendix describes the motion drive computations used for the simulator motion system and gives an assessment of resulting system effectiveness.

Motion Drive Computations

The motion drive computations (ref. 9) were developed during an initial simulator "shake-down" period and consisted primarily of second-order washouts with 0.7 damping ratio for all degrees of freedom. Break frequencies were 0.5 rad/sec for lateral, roll, and yaw accelerations, and 1.4 rad/sec for vertical and longitudinal accelerations. In addition, roll acceleration was attenuated 0.5, and a "residual tilt" was used to sustain prolonged steady-state lateral accelerations. Residual tilt consisted of a washed-in bank angle phased with the washout of acceleration along the lateral track. These computations resulted in a maneuvering envelope that allowed 35° banked turns and incremental vertical accelerations up to 0.25 g without encountering the lateral and vertical travel limits.

A second motion configuration was sometimes used for tests where very little lateral maneuvering was anticipated. This configuration was identical to the first except that roll was not attenuated and the "residual tilt" was not used; lateral maneuvering was restricted to ±18° of airplane bank angle, and for maneuvers within this bank angle range, the differences between the two motion configurations were not readily apparent.

Flap, spoiler, and stall buffeting were included in the computations for the vertical drive for enhancement of the "flight" environment.

Computations were performed by a hybrid digital-analog system, with digital operations on the basic equations of motion and the analog operations dealing with motion washout and computer-cockpit interface. The program was expedited by the rapid changeover time achievable with this computer arrangement; changes from one airplane to another could be made in less than 5 minutes.

System Effectiveness

All participating pilots were enthusiastic in their acceptance of the motion system, because it allowed them to use a natural piloting technique and provided them with a relatively realistic environment. They considered the forces imposed on them to be "very realistic" and to blend well with the visual cues. They found the cues extremely effective in easing the control task following an engine failure and for lateral maneuvering tasks (e.g., an offset correction during landing approach).

Pilots felt that "with motion, the takeoff rotation seemed a lot more natural" even though there was no pitch motion. One pilot said "I don't notice the lack of the pitch motion. I think that the combination of a_Z that we get with the vertical drive and the visual pitch cues that we get essentially fulfill the sensation requirements. I have a very definite sensation that we are pitching, and if nobody had told me we didn't have pitch motion I don't think I would recognize it."

Even though the pitch rotational motion was not operative in these tests, the pilot received significant pitch cues through the vertical motion drives, because of the large pilot-to-center-of-gravity lever arms for the three subject airplanes, and through the visual display. The lack of pitch motion was not considered a limitation in this study; however, it should not be interpreted that pitch motion is unnecessary in general. The necessity of pitch motion depends on such factors as the task, other cue-producing capabilities of the simulator being used, and the geometry and control characteristics of the vehicles being simulated.

Figure 31 illustrates motion system fidelity by comparing computed accelerations with measurements taken from simulator-mounted accelerometers. Figure 31(a) shows the lateral and roll accelerations accompanying a Dutch roll oscillation, which indicate good motion-system response. The high-frequency content, due primarily to structural noise, is characteristic of that present in actual aircraft and therefore adds to the realism.

Figure 31(b) shows lateral and vertical accelerations during a takeoff in which an outboard engine fails. On comparison of the computed and resulting vertical acceleration traces, the good response is apparent, as is the washout of the lower frequency content. The lateral acceleration traces demonstrate the nearly one-to-one relationship between the computed and measured values. The important lateral acceleration cue accompanying the engine failure is clearly shown.

Figure 32 illustrates the significance of the motion cues by comparing motion-on and motion-off time histories of SST takeoffs with an outboard engine failure near lift-off. Without motion, there is a 2.3-sec lag in the time required for the pilot to recognize the failure and react with corrective rudder. He must wait to observe visually the effect of his control inputs and has a tendency, apparent in the control traces shown, toward excessive control motions and severe overcontrolling. The bank angle and sideslip excursions were twice as great without motion as with motion, and the resulting penalties on performance were critical.

APPENDIX B

SELECTION OF SST TAKEOFF REFERENCE SPEEDS

As a prerequisite to the takeoff tests, it was necessary to determine a set of takeoff reference speeds for the SST about which speed abuses could be imposed. Three sets of reference speeds were considered from the different available airworthiness standards: (1) Federal Aviation Regulations (FAR 25) (ref. 6), the U.S. airworthiness standards for transport category airplanes; (2) TSS standards (TSS) (ref. 7), Anglo-French airworthiness requirements for supersonic transports; and (3) Tentative Airworthiness Standards for Supersonic Transports (TASST) (ref. 8), current thinking of U.S. authorities on SST standards at the time of this study.

The various requirements on V_R and V_2 from these three sets of standards are listed in tables 5 and 6. The relation of all takeoff speeds and takeoff distances as established by the various requirements is depicted in figure 33. The primary factors considered were the minimum control speed (V_{MC}), the first- and second-segment climb capability (γ_1 and γ_2), maneuverability at V_2, margin between one-engine-inoperative climb speed (V_2) and the corresponding zero-rate-of-climb speed (V_{ZRC}), and margin between lift-off speed (V_{LOF}) and minimum unstick speed (V_{MU}).

FAR 25 and Early TASST Requirements

Of the various criteria for defining V_R and V_2 given in FAR 25 and TASST (as they existed at the initiation of this study), the most critical was the FAR 25 requirement of a 3 percent second-segment-climb gradient at V_2. Figure 9 shows climb gradient versus speed for the SST and, for comparison, that for the RJT. Note that to provide 3 percent second-segment climb, V_2 for the SST must be at least 211 knots. Piloted simulator runs then determined that a rotation speed V_R of 193 knots allowed attainment of V_2 by the 10.7-m height with one engine inoperative. This value for V_R also satisfied the requirements related to V_{MU} and V_{MC}, in contrast to experience with subsonic swept-wing jet transports, where the V_{MU} requirement usually defined the value of V_R.

It was immediately obvious that because of the rapid decrease in climb gradient available with decrease in speed for the SST (fig. 9), these reference speeds did not provide sufficient margin for rotation abuses with one engine inoperative. Simulator experience with these reference speeds led to the observation that characteristics of delta-wing aircraft can create a false sense of security. The high T/W and low drag in the taxi attitude resulted in impressive takeoff acceleration and all-engines-operating climb performance. With an engine inoperative, ground acceleration remained impressive until rotation when performance was seriously degraded as a result of the high induced drag. If the takeoff reference speeds selected were too low, the large ground effect lift made it possible to lift off before sufficient speed was acquired to enable safe climbout, acceleration, or maneuvering with an engine inoperative. In addition, if speed became too low, there were no configuration changes (after gear retraction) or thrust augmentation on which the pilot could rely for recovery by improving the effective L/D. Figure 9 shows that at speeds less than 195 knots and with an engine inoperative, the airplane was unable to climb and could not accelerate to a better L/D condition without sacrificing altitude. On several occasions, pilots found themselves "trapped" in ground effect as a result of an early rotation accompanied by engine failure.

TASST revisions, which would specify higher values for V_R and V_2 and thereby provide more protection in the event of climb-speed abuse with one engine inoperative, appear necessary to provide a level of safety for SST takeoff equivalent to that provided for the existing subsonic jet transports. Possible revisions are discussed below.

Anglo-French TSS and Revised TASST Requirements

The Anglo-French TSS provides protection against climb-speed abuse by requiring that V_2 be at least 1.15 times the one-engine-inoperative zero-rate-of-climb speed V_{ZRC}; in addition, climb gradient requirements are specified in terms of the induced-drag-to-weight ratio ($K^1 D/W$). The first of these requirements was the critical one for the subject SST, although both define higher takeoff speeds than do the FAR 25 and TASST requirements. In figure 9, it can be seen that V_{ZRC} is 195.5 knots; therefore, V_2 must be at least 225 knots. Based on one-engine-inoperative simulator runs, a rotation speed of 209 knots was found to be compatible with the 225-knot V_2.

Proposed revisions to the TASST were submitted by the FAA while this study was in progress. These included the added requirement that V_R be "a speed at which a measurably positive rate of climb exists out of ground effect in the gear-down takeoff configuration with the critical engine inoperative." For the subject SST in this configuration, the zero-rate-of-climb speed was about 205 knots; thus, this criterion was satisfied by the use of the 209-knot V_R.

Pilots felt that the 209-knot V_R provided an adequate safety margin in the event of engine failure, and that 205 knots represented a minimum satisfactory speed. One pilot felt that 209 knots was insufficient from the ground clearance consideration. The high takeoff speeds and low static longitudinal stability resulted in an elevator deflection for rotation about one-half that for the RJT. Thus, until pilots became accustomed to the excess control power, it was easy to rotate the SST abruptly and inadvertently strike the tail, especially with the reduced acceleration associated with a failed engine.

For the majority of the subsequent SST takeoff tests, the basic target value of V_R was 209 knots and V_2 was 225 knots.

REFUSED TAKEOFF TESTS

The certification of an airplane under FAR 25 (ref. 6) includes measurements of the accelerate-stop distance to determine the pilot's decision speed V_1 and to provide one of the factors used to establish the takeoff field length requirements. Reference 10 is a review of the criteria used to obtain this distance and indicates several areas where additional test data would help to resolve differences between the interpretation of the regulations as applied to flight test measurements and operational procedures. The large number of takeoffs to be performed during the general test program of this report presented a unique opportunity to investigate pilot responses to surprise engine failures occurring before the V_1 speed that result in refused takeoffs (RTO). The realism of the simulator cockpit, visual scene, and 1:1 lateral motion available during the takeoff allowed real world cues to alert the pilot to the loss of an engine; consequently, his responses are very like an operational situation.

Applicable Criteria

The takeoff field length requirements for large civil jet transport aircraft is the greater of: (1) *the field length determined by balancing the accelerate-stop distance with the takeoff distance* to a height of 10.7 m at V_2 speed, assuming the critical engine to fail at V_1 speed in both cases; and (2) 115 percent of the horizontal distance required to take off and climb to 10.7 m at V_2 speed with all engines operating. In most cases, (2) is the determining factor; however, the decision speed V_1 is based on accelerate-stop criteria that are heavily influenced by individual aircraft and control configurations. Engine failures prior to V_1 were therefore introduced at unannounced times during the test program to induce takeoff refusals so that criteria for the simulated SST could be developed and compared with that used for the reference jet during its certification. FAR 25.109 (ref. 6) defines the accelerate-stop distance as the sum of the distances necessary to: (1) accelerate the airplane from a standing start to V_1; and (2) come to a full stop from the point at which V_1 is reached, assuming that the critical engine fails at V_1.

The greatest flexibility in the interpretation of this regulation is in the determination of the distance traveled from the point of engine failure to the attainment of the full deceleration configuration. The certification procedure provides for a pilot reaction time after engine failure to the point of brake application, followed by the allotted times for retardation of throttles and application of spoilers and other approved deceleration controls. One second is added to the measured times for each additional control action after brake application. Figure 34 illustrates the conventional method of determining the transition time. The distance traveled during the transition time depends to a large degree on the sequence of control actions and the speed gained after engine failure recognition. During certification tests to measure the transition time intervals, the pilot applies brakes immediately; however, as discussed in reference 10, several factors suggest that brake application will not be the pilot's first action in an actual refused takeoff.

Simulation Test Procedure

The timing and sequencing of the pilot's actions following engine failure were recorded from 20 surprise RTO's involving four pilots and the three airplanes (SST, RJT, and JJT). The pilots were briefed to expect engine failures before V_1; however, the ratio of about one RTO for each 25 takeoffs maintained a significant surprise factor. The only technique briefed was that the pilot keep his hand on the throttles until V_1 speed, which was called out by the copilot. In all cases, rudder-pedal nose-wheel steering was provided on a simulated dry runway, and the task included maintaining directional control during the deceleration.

The cockpit side force and heading deviations noted on the visual display were representative of an abrupt failure of an outboard engine on airplanes of the types tested.

Observations

The test data for the 20 events are presented in table 7. Most of the engine failures occurred at about 15 knots below V_1 speed, which may have reduced the sense of urgency. However, the pilots were briefed to provide as quick a stop as feasible.

The timing of the pilots' control actions is shown in figure 35. The control sequence used was basically the same for all three aircraft and four pilots. In all cases, the throttles were retarded first. In four cases, the spoilers were deployed before wheel brakes. Average times from engine failure were 1.6, 3.9, and 5.5 sec for throttle chop, brake application, and spoiler actuation, respectively. The airspeed overshoot after engine failure is shown in figure 36. The RJT and JJT had essentially identical characteristics, so their data are combined. Because of the higher thrust-weight ratio and lower drag in the taxi attitude, SST acceleration was greater than for the RJT and JJT, and larger speed overshoots resulted.

The consistency of the pilots' control sequence in the simulated operational refused takeoff indicated a well-developed behavior pattern formed through training and experience in normal stops that reinforce this sequence. In addition, the pilots were primarily concerned with maintaining directional control during the ground run. The decision to stop was followed by retardation of throttles and application of rudder to correct the track down the runway. Simultaneous rudder input for yaw control and brake application did not occur. Once the throttles were retarded, the pilot's hand was free to apply spoilers. The fact that the pilots delayed braking until yaw control was applied introduced a significant delay in attaining the full deceleration configuration.

The control sequence generally applied during certification accelerate–stop distance demonstrations compares with the sequence observed in the simulated operational refused takeoffs as follows:

Certification demonstration	Simulated operational RTO
1. wheel brakes	1. throttle cut and rudder applied
2. throttle cut	2. wheel brakes
3. spoilers	3. spoilers

The differences in brake application time of the two sequences would result in significant increases in stopping distance. This effect could be greater for SST aircraft.

REFERENCES

1. Jackson, Charles T., Jr.; and Snyder, C. Thomas: Validation of a Research Simulator for Investigating Jet Transport Handling Qualities and Airworthiness Criteria During Takeoff. NASA TN D-3565, 1966.

2. Snyder, C. Thomas; and Jackson, Charles T., Jr.: A Piloted Simulator Study of Takeoff Performance and Handling Qualities of a Double-Delta Supersonic Transport. NASA TN D-4396, 1968.

3. White, Maurice D.; and Dusterberry, John C.: Simulator to Match the Transports to Come. Astronaut. Aeron., vol. 7, no. 9, Sept. 1969, pp. 54-60.

4. Zuccaro, Joseph J.: The Flight Simulator for Advanced Aircraft—–A New Aeronautical Research Tool. AIAA Paper 70-359, 1970.

5. Corsiglia, Victor R.; Koenig, David G.; and Morelli, Joseph P.: Large-Scale Tests of an Airplane Model With a Double-Delta Wing, Including Longitudinal and Lateral Characteristics and Ground Effects. NASA TN D-5102, 1969.

6. Anon.: Federal Aviation Regulations, Part 25-Airworthiness Standards: Transport Category Airplanes. Federal Aviation Agency, Feb. 1, 1965.

7. Anon.: TSS Standards No. 2 Issue 2, Supersonic Transport Aircraft Performance Specification. Air Registration Board (England), Feb. 28, 1964.

8. Anon.: Tentative Airworthiness Standards for Supersonic Transports. Federal Aviation Administration, Nov. 1, 1965 (Rev. Jan. 1, 1969).

9. Bray, Richard S.: Initial Operating Experience with an Aircraft Simulator Having Extensive Lateral Motion. NASA TM X-62,155, 1972.

10. Foxworth, T. G.; and Marthinsen, H. F.: Another Look at Accelerate-Stop Criteria. AIAA Paper 69-772, 1969.

TABLE 1.– PERFORMANCE CHARACTERISTICS OF THE SIMULATOR MOTION SYSTEM AS USED IN THIS STUDY

Mode	Travel	Acceleration	Frequency at phase lag = 30°, Hz
Lateral	±12.2 m (±40 ft)	3.66 m/sec^2 (12 ft/sec^2)	1.0
Vertical	±1.22 m (±4.0 ft)	3.66 m/sec^2 (12 ft/sec^2)	2.2
Longitudinal	±1.07 m (±3.5 ft)	2.74 m/sec^2 (9 ft/sec^2)	1.8
Yaw	±24°	1.6 rad/sec^2	1.7
Pitch	Not yet operative		
Roll	±36°	3.2 rad/sec^2	3.0

TABLE 2.– COMPARISON OF SIGNIFICANT PARAMETERS AT V_2 FOR THE THREE SIMULATED AIRPLANES

	Supersonic Transport (SST)	Reference Jet Transport (RJT)	Jumbo Jet Transport (JJT)
Gross weight, kg (lb)	167,900 (370,000)	136,000 (300,000)	317,600 (700,000)
Maximum T/W	0.411	0.223	0.226
Wing loading, kg/m^2 (lb/ft^2)	463 (95)	532 (109)	532 (109)
Roll inertia, kg-m^2 (slug-ft^2)	2.04X10^6 (1.5X10^6)	7.72X10^6 (5.7X10^6)	42X10^6 (31.0X10^6)
Pitch inertia, kg-m^2 (slug-ft^2)	14.2X10^6 (10.5X10^6)	5.42X10^6 (4.0X10^6)	29.6X10^6 (21.8X10^6)
Yaw inertia, kg-m^2 (slug-ft^2)	15.1X10^6 (11.1X10^6)	12.6X10^6 (9.3X10^6)	68.7X10^6 (50.6X10^6)
Pilot-to-CG distance, m(ft)	27.9 (91.5)	18.3 (60.0)	27.9 (91.6)
Maximum ground attitude, deg	13.1	13.8	13.8
$M_\alpha = \dfrac{q S \bar{c}}{I_{yy}} \dfrac{\partial C_m}{\partial \alpha}$, 1/sec^2	-0.379 to -0.698	-0.916 to -1.805	-0.599 to -1.180
$L_\alpha = \dfrac{qS}{mV} \dfrac{\partial C_L}{\partial \alpha}$, 1/sec	0.494	0.479	0.479
$M_{\delta e} = \dfrac{q S \bar{c}}{I_{yy}} \dfrac{\partial C_m}{\partial \delta_e}$, 1/sec^2	-1.15 to -1.23	-1.17	-0.766
$L_{\delta e} = \dfrac{qS}{mV} \dfrac{\partial C_L}{\partial \delta_e}$, 1/sec	0.1105	0.0268	0.0268
C.G.	0.25 $\bar{c}$ to 0.275 $\bar{c}$	0.19 $\bar{c}$ to 0.32 $\bar{c}$	0.19 $\bar{c}$ to 0.32 $\bar{c}$

TABLE 3.– CONTROL CHARACTERISTICS FOR THE THREE AIRPLANES

	RJT	JJT	SST
Control column			
Force gradient, N/cm (lb/in.)	17.5 (10)	17.5 (10)	17.5 (10)
Breakout force, N (lb)	±17.8 (±4)	±17.8 (±4)	±17.8 (±4)
Travel, aft/fwd., cm (in.)	22.2/12.7 (8.75/5)	22.2/12.7 (8.75/5)	22.2/12.7 (8.75/5)
Control wheel			
Force gradient, N/deg (lb/deg)	1.47 (0.33)	1.47 (0.33	1.47 (0.33)
Breakout force, N (lb)	±17.8 (±4)	±17.8 (±4)	±17.8 (±4)
Travel, deg	±80	±80	±80
Rudder pedal			
Force gradient, N/cm (lb/in.)	40.3 (23)	40.3 (23)	40.3 (23)
Breakout force, N (lb)	±44.5 (±10)	±44.5 (±10)	±44.5 (±10)
Travel, cm (in.)	±8.9 (±3.5)	±8.9 (±3.5)	±8.9 (±3.5)
Maximum control surface deflection			
Elevator, T.E. up/down, deg	25/15	25/15	25/15
Aileron, deg	±17.5	±17.5	±20
Lateral spoiler, deg	±60	±60	- - -
Rudder, deg	±18	±18	±30
Elevator trim, T.E. up/T.E. down, deg	- - -	- - -	15/10
Horizontal stabilizer, ANU/AND, deg	8/5	8/5	- - -
Nose-gear steering, deg	±10	±10	±10
Stability augmentation system			
Pitch damper authority, deg	- - -	- - -	±2.0
Pitch damper gain, δ_e/q, sec	- - -	- - -	1.3
Roll damper authority, deg	- - -	- - -	±2.0
Roll damper gain, δ_a/p, sec	- - -	- - -	-1.0
Control system gearing			
Elevator, deg/cm (deg/in.)	1.14 (2.91)	1.14 (2.91)	1.14 (2.91)
Aileron, deg/deg	0.22	0.22	0.25
Rudder, deg/cm (deg/in.)	2.02 (5.14)	2.02 (5.14)	3.41 (8.66)
Lateral spoiler, deg/deg[1]	1.55	1.55	- - -
Rate limits			
Elevator, deg/sec	±60	±60	±60
Aileron, deg/sec	±60	±60	±60
Lateral spoiler, deg/sec	±60	±60	
Rudder, deg/sec	±60	±60	±60
Elevator trim, deg/sec	- - -	- - -	±0.33
Horizontal stabilizer, deg/sec	±0.33	±0.33	- - -
Nose-gear steering, deg/sec	±10	±10	±10

[1] Lateral spoilers are deflected in proportion to the wheel deflection exceeding ±41° when the landing gear is extended.

TABLE 4.– TAKEOFF REFERENCE SPEEDS

Airplane configuration	Gross weight	Flap position, deg	V_1, knots	V_R, knots	V_2, knots
RJT	136,000 kg (300,000 lb)	15 25	138 134	153 147	164 158
	90,700 kg (200,000 lb)	15 25	114 114	131 129	149 146
JJT	317,600 kg (700,000 lb)	15 25	138 134	153 147	164 158
	209,000 kg (460,000 lb)	15 25	114 114	131 129	149 146
SST (FAR)	167,900 kg (370,000 lb)	--	175	193	211
(TSS)	167,900 kg (370,000 lb)	--	175	209	225

TABLE 5.– AIRWORTHINESS CRITERIA FOR V_R AT TIME OF STUDY

TABLE 5

FAR Part 25	TASST	Anglo-French TSS
25.107 (e) V_R, in terms of calibrated airspeed, must be selected in accordance with the conditions of subparagraphs (1) through (4) of this paragraph: (1) V_R may not be less than – (i) V_1; (ii) 105 percent of V_{MC}; (iii) The speed that allows reaching V_2 before reaching a height of 10.7 m (35 ft) above the takeoff surface; or (iv) A speed that, if the airplane is rotated at its maximum practicable rate, will result in a V_{LOF} of not less than 110 percent of V_{MU} *in the all-engines-operating* condition or less than 105 percent of V_{MU} in the one-engine-inoperative condition.	25.107 (d) V_R in terms of calibrated airspeed shall be selected by the applicant and may not be less than: (1) Speed V_1 (2) 1.05 V_{MCA} (3) A speed that when rotation is in a normal manner will attain the scheduled V_2 speed prior to reaching a 10.7-m (35 ft) height. (4) A speed that when rotation is initiated at the maximum practical rate will not result in a marked increase in overall distance to the 10.7-m (35 ft) height nor result in undesirable buffet or handling characteristics. (5) A speed that when rotation is initiated at the selected V_R - 5 knots with the critical engine inoperative, the overall distance to a height of 10.7 m (35 ft) shall not exceed the corresponding one engine inoperative takeoff distance as determined with the selected V_R speed, nor result in unsafe flight characteristics. (6) A speed selected for the initiation of rotation with all engine operating at a speed of V_R - 10 knots achieving a minimum of 2° beyond the normal attitude in the airborne segment between lift-off and 10.7-m (35 ft) height. The overall distance shall not result in a marked increase in the scheduled takeoff distance nor result in unsafe flight characteristics.	6.2.5.1 The rotation speed V_R shall not be less than: (a) The speed V_1; (b) A speed equal to 1.05 V_{MCA}; (c) A speed which permits the attainment of the speed V_2 prior to reaching a height of 10.7 m (35 ft) above the runway; (d) A speed which, if the aeroplane is rotated at its maximum practicable rate, will result in a lift-off speed V_{LOF} not less than 1.12 V_{MU} in all-engines-operating condition. If in the demonstration of V_{MU} the ability of the aeroplane to leave the ground is limited solely by the aircraft geometry, the factor 1.12 may be reduced to 1.07; (e) A speed at which the controllability specification of 6.2.1 is met at all times during rotation at the normal rate.
(2) For any given set of conditions (such as weight, configuration, and temperature), a single value of V_R, obtained in accordance with this paragraph, must be used to show compliance with both the one-engine-inoperative and the all-engines-operating takeoff provisions.		6.2.5.2 For any given set of conditions (weight, configuration, temperature, etc.) a single value of V_R shall be used in showing compliance with both the one-engine-inoperative and all-engines-operating takeoff specifications.
(3) It must be shown that the one-engine-inoperative takeoff distance, using a rotation speed of 5 knots less than V_R established in accordance with subparagraphs (1) and (2) of this paragraph, does not exceed the corresponding one-engine-inoperative takeoff distance using the established V_R.		6.2.5.3 It shall be shown that the one-engine-inoperative takeoff distance determined, the aeroplane being rotated at its maximum practicable rate with a rotation speed 5 knots less than V_R, does not exceed the corresponding one-engine-inoperative takeoff distance determined with the established V_R speed. The speed at the 10.7 m (35 ft) height point may be as low as V_2, with one engine inoperative, minus 5 knots.
(4) Reasonably expected variations in service from the established takeoff procedures for the operation of the airplane (such as overrotation of the airplane and out-of-trim conditions) may not result in unsafe flight characteristics or in marked increases in the scheduled takeoff distances.	25.107 (e) Reasonably expected variations in service from the established takeoff procedures for the airplane (such as over-rotation of the airplane and out-of-trim conditions) may not result in unsafe flight characteristics or in marked increases in the scheduled takeoff distances.	
	25.103 (b) The selected speeds shall not require body attitudes that may result in unwanted contact of airplane structure with the ground. (In determining maximum allowable ground attitude, there shall be considered airplane pitch dynamics, landing flare characteristics, and attitude information presentation. Adequate clearance shall be provided when considering the most adverse extension of the landing gear shock absorbing mechanism.)	
25.121 (a) Takeoff climb; landing gear extended. In the critical takeoff configuration existing along the flight path (between the points at which the airplane reaches V_{LOF} and at which the landing gear is fully retracted) but without ground effect, the steady gradient of climb must be not less than 0.5 percent at V_{LOF} and with the critical engine inoperative.	25.121 (a) Takeoff climb landing gear extended. – same requirement as in FAR 25.	7.3.1 Takeoff Climb; landing gear extended In the critical takeoff configuration existing at the point in the flight path where the aeroplane lifts off but without ground effect, the steady gradient of climb shall not be less than 7 $K^1 D/W$ with the critical engine inoperative and the speed equal to the speed at which the aeroplane first becomes airborne.

TABLE 6

TABLE 6.– AIRWORTHINESS CRITERIA FOR V_2 AT TIME OF STUDY

FAR Part 25	TASST	Anglo-French TSS
25.107 (b) & (c) V_2 may not be less than – (1) 1.2 V_S (2) 1.10 V_{MC} (3) V_R plus the speed increment attained before reaching a height of 10.7 m (35 ft) above the takeoff surface with critical engine inoperative. 25.121 (b) Takeoff climb, landing gear retracted. In the takeoff configuration existing at the point of the flight path at which the landing gear is fully retracted, but without ground effect, the steady gradient of climb may not be less than 3.0 percent at V_2 with the critical engine inoperative.	25.107 (b) V_2 in terms of calibrated airspeed shall be selected by the applicant and may not be less than: (1) A speed that will meet the requirements of 25.103 and 25.201. [25.103 requires that the applicant select speeds which provide for adequate detailed margins above the minimum demonstrated speeds of sections 25.201 and 25.205. 25.201 defines a minimum speed demonstration using symmetric power and 25.205 defines a minimum speed demonstration with a critical engine inoperative.] (2) Provide at least the gradient of climb [one engine inoperative, gear retracted] required in FAR 25.121(b). (3) V_R plus the speed increment attained before reaching a height of 10.7 m (35 ft) above the takeoff surface. 25.143 (f) There shall be demonstrated sufficient maneuvering capability when at the critical centers of gravity and weights to account for turbulent air, required turning maneuvers, and avoidance maneuvers, the following conditions are met: (1) Configuration and velocities for takeoff and enroute at the minimum performance as scheduled during climb with no less than 0.5 delta "g" capability.	6.2.2.2 The initial climb-out speed one engine inoperative (V_2) shall be such that: – (a) With one engine inoperative and with the remaining engines operating at takeoff power and, if different, at the thrust recommended for the portion of the takeoff path under consideration. (i) It is possible to apply an acceleration normal to the flight path of 1.45 g without encountering hazardous characteristics. (ii) It is possible to meet the controllability criteria appropriate to V_2 of TSS Standard No. 5. (iii) V_2 is not less than 1.1 V_{MCA}. (b) With one engine inoperative and with the remaining engines operating at takeoff power:– (i) The zero rate of climb speed in the configuration existing immediately after lift-off except that the landing gear is retracted is not greater than $V_2/1.15$. (ii) The zero rate of climb speed in the most adverse configuration existing between lift-off and a gross height of 120 m (400 ft) is not greater than $V_2/1.1$. (iii) V_2 is not less than the lift-off speed V_{LOF} plus the increment in speed attained between lift-off and climbing to a height of 10.7 m (35 ft) when using the appropriate technique. 7.3.2 Takeoff Climb; landing gear retracted In the takeoff configuration existing at the point of the flight path where the landing gear is fully retracted, but without ground effect, the steady gradient of climb shall not be less than $1.8 + 13\ K^1 D/W$ with the critical engine inoperative and the speed equal to V_2. 11.4 Maneuverability It shall be possible to obtain the following load factors in a reasonable time:– 1.45 g at V_2, with the critical engine inoperative

TABLE 7.– REFUSED TAKEOFF DATA

Run	Airplane	Speeds, knots				Time from failure, sec		
		V_1	V_{EF}	V_{max}	ΔV	TH	BR	SP
1	R	134	120	127	7	3.6	10.0	18.0
2	R	134	120	126	6	2.7	5.1	8.0
3	R	134	120	126	6	1.9	3.4	ND
4	J	134	120	125	5	1.4	3.7	ND
5	R	134	120	125	5	1.5	2.5	ND
6	J	134	126	129	3	1.5	9.2	6.0
7	J	134	120	124	4	1.1	2.6	3.6
8	J	134	122	126	4	1.3	4.1	6.1
9	R	134	136	140	4	1.5	2.5	7.8
10	R	134	121	126	5	1.5	7.9	3.5
11	J	138	120	124	4	1.1	3.0	2.0
12	R	134	121	126	5	1.5	3.0	4.0
13	J	134	121	125	4	1.0	3.0	3.0
14	R	134	120	123	3	1.0	1.5	9.0
15	J	134	120	122	2	1.0	2.3	2.3
16	S	175	150	160	10	1.7	3.9	6.0
17	S	175	140	148	8	2.8	5.0	4.0
18	S	175	160	164	4	.7	1.0	1.7
19	S	175	159	165	6	1.4	2.0	5.0
20	S	175	153	160	7	1.0	2.1	2.9

TH Throttles
BR Brakes
SP Spoilers
R Reference Jet Transport
J Jumbo Jet Transport
S Supersonic Transport
ND Not Deployed

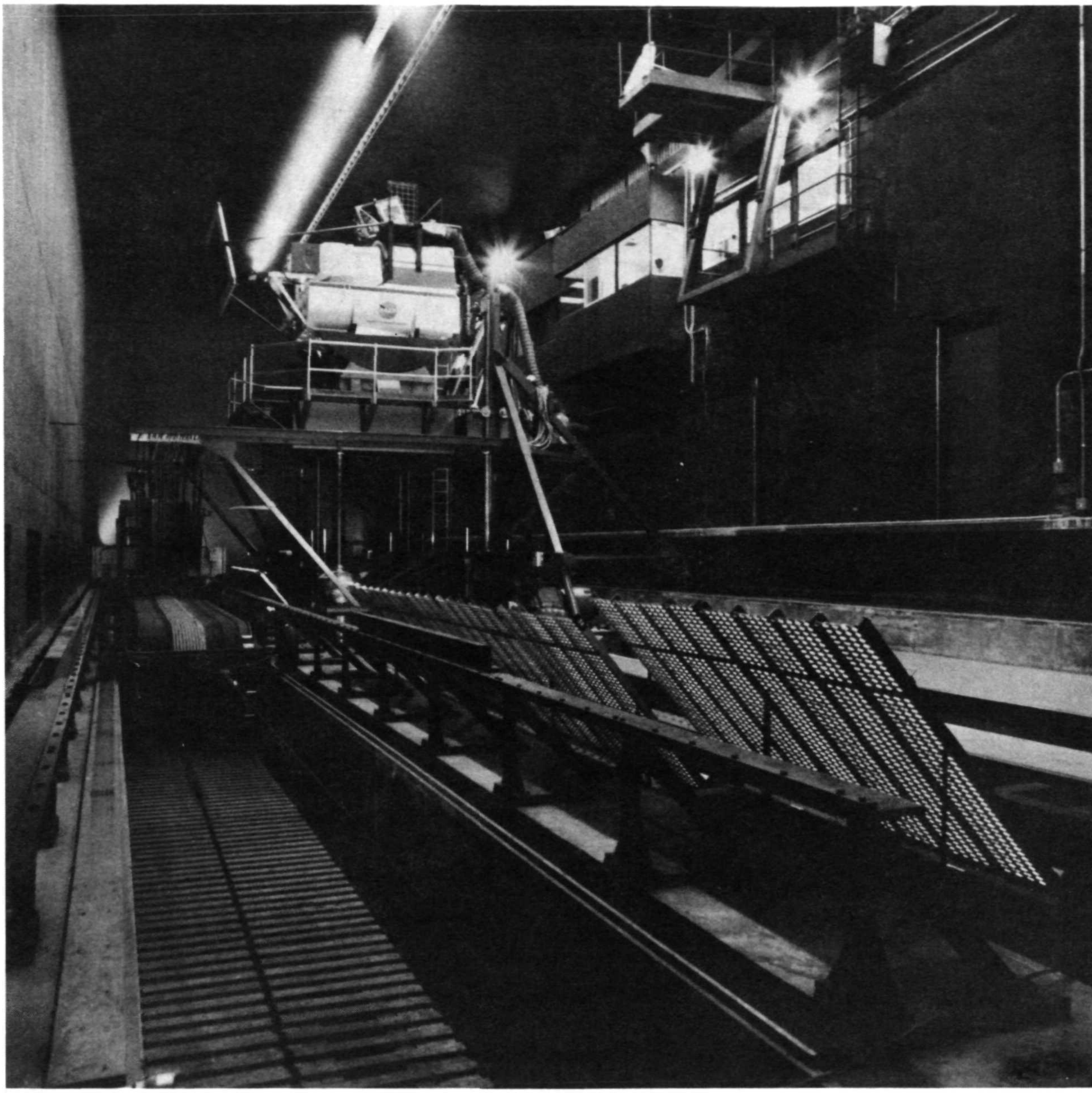
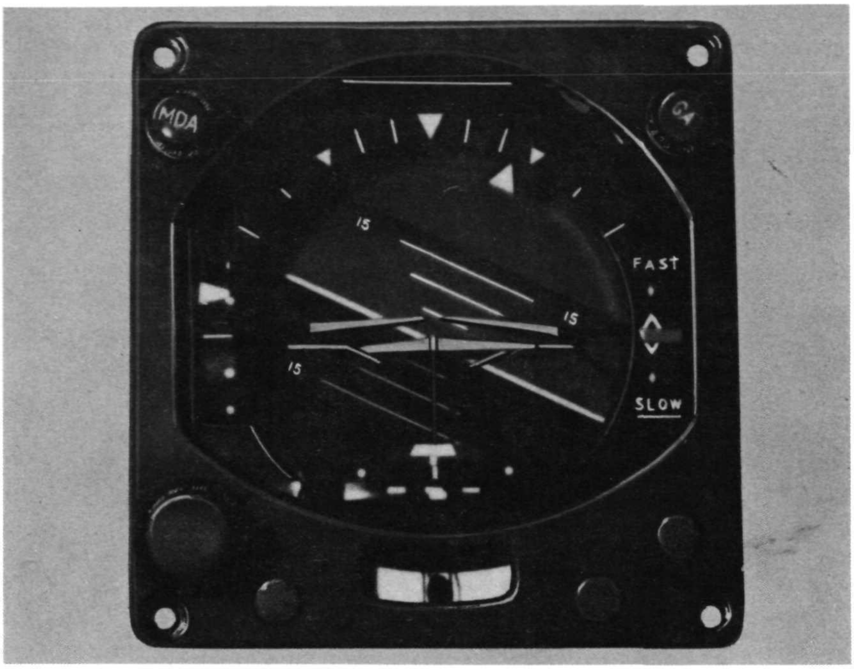
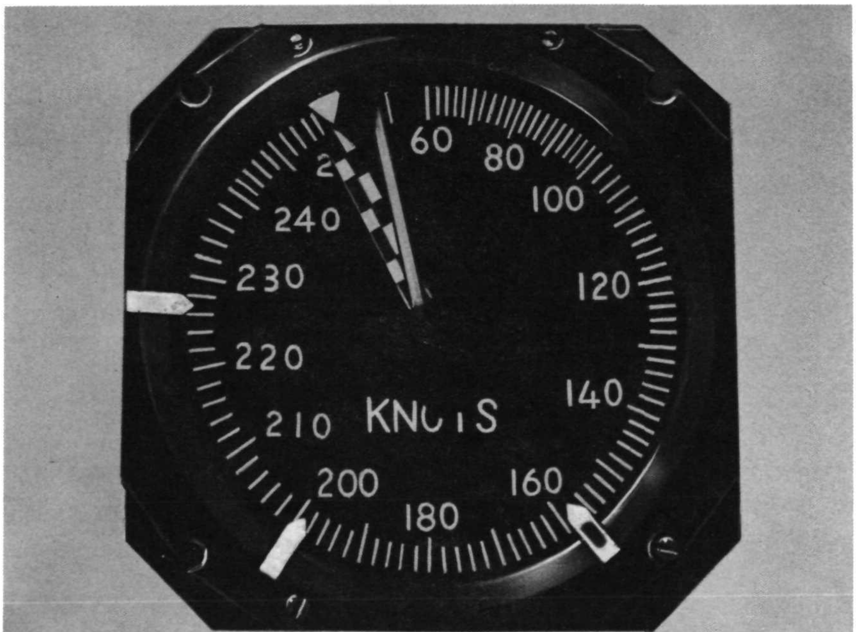


Figure 1.– Flight Simulator for Advanced Aircraft (FSAA) motion system.

Figure 2.– Pilot's station in the FSAA.



(a) FD–109 attitude indicator.

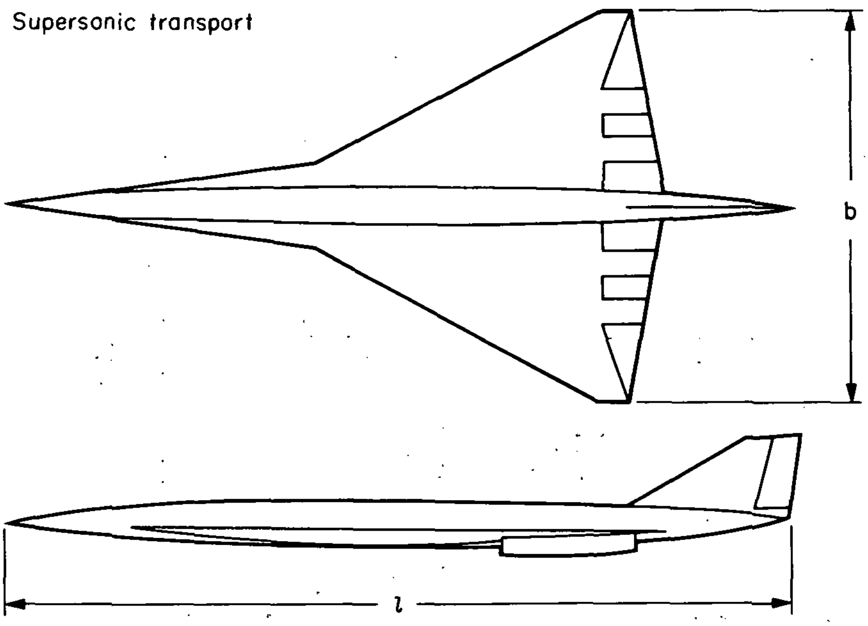


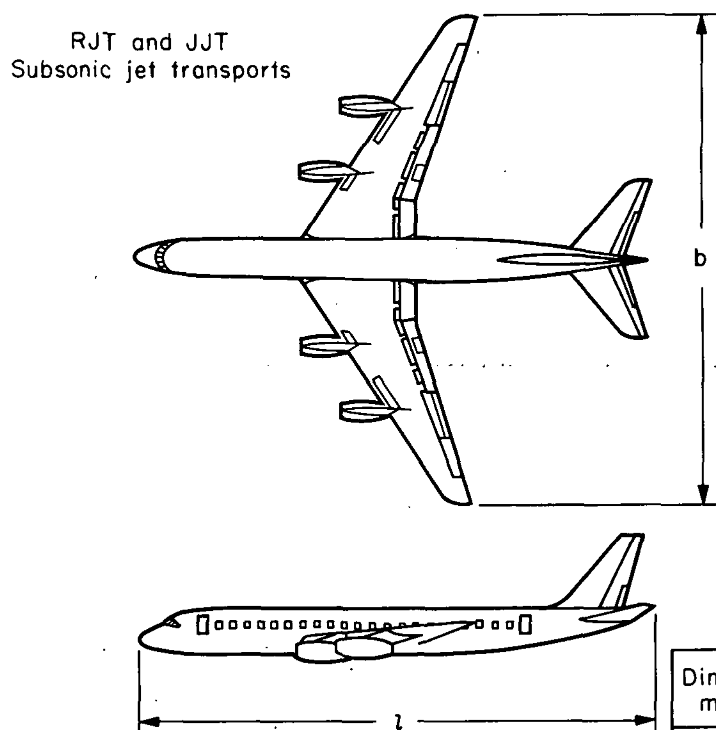
(b) Airspeed indicator.

Figure 3.– Attitude and airspeed instruments used in the study.

	19	RUN NUMBER
0.300000E	06	INITIAL WEIGHT (LBS)
0.657211E	05	TOTAL THRUST I.C. (LBS)
0.249062E	02	FLAP ANGLE (DEG)
0.145845E	03	SPEED AT WHICH COL EXCEEDS 1 INCH AFT (KNOTS)
0.151027E	03	SPEED WHERE GEAR REACTIONS REACH ZERO (KNOTS)
0.971103E	01	PITCH ATTITUDE AT LIFT OFF (DEG)
0.934840E	01	ANGLE OF ATTACK AT LIFT OFF (DEG)
0.188625E	01	LONG. ACCEL. AT LIFT OFF (KNOTS/SEC)
0.564765E	04	DISTANCE TO LIFT OFF (FT)
0.650395E	04	DISTANCE TO 35 FT ALT (FT)
0.781342E	01	ENERGY PARAMETER AT 35 FT ALT (FT/SEC)
0.131732E	02	MAX PITCH ATTITUDE TO 35 FT ALT(DEG)
0.195999E	01	TIME FROM COL BACK TO LIFT (SEC)
0.150186E	03	SPEED AT 35 FT ALT (KNOTS)
0.232197E	00	MAX G FOR 10 SEC FOLLOWING LIFT (G'S)
0.364882E	01	HEIGHT AT MAX G ABOVE (FT)
0.318906E	01	MINIMUM TAIL CLEARANCE (FT)
0.150884E	03	SPEED AT ENGINE FAILURE (KNOTS)
0.124801E	02	MAX LAT DEV DURING GROUNDROLL (FT)
0.731238E	00	MAX BANK ANGLE DURING GROUNDROLL (DEG)
0.730322E	01	MAX BANK ANGLE FOR 10 SEC FOLLOWING LIFT(DEG)
0.254068E	01	MAX SIDESLIP FOR 10 SEC FOLLOWING LIFT(DEG)

Figure 4.– Sample of the digital printout of discrete takeoff performance parameters.





Dimension m (ft)	RJT	JJT	SST
b	42.6 (139.7)	65 (213)	25.6 (84)
l	46 (150.5)	70 (229.5)	58.9 (193)

Figure 5.– Two-view sketches of the airplanes simulated for this study.

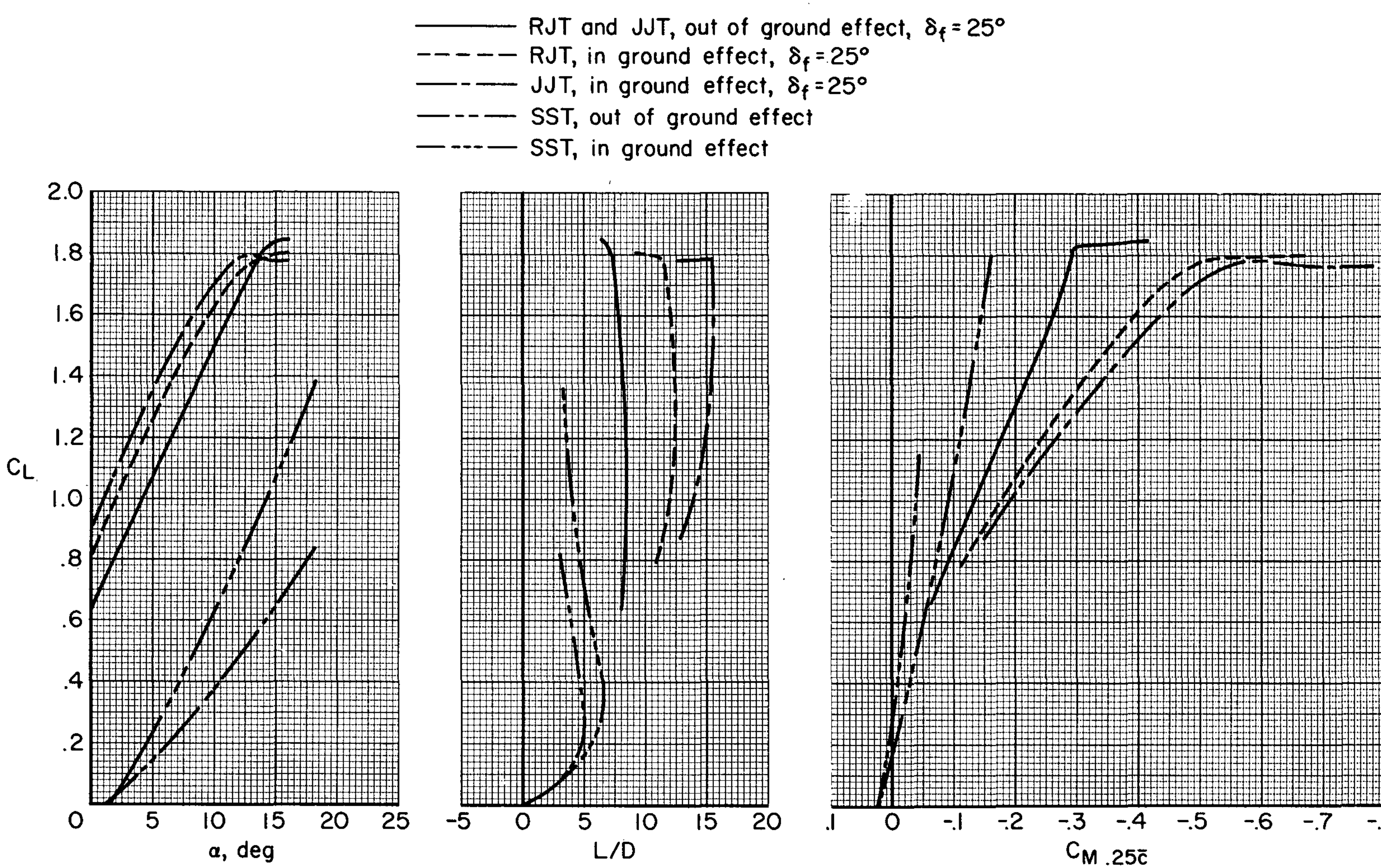


Figure 6.– Lift, drag, and pitching-moment characteristics of the three airplanes, landing gear extended.

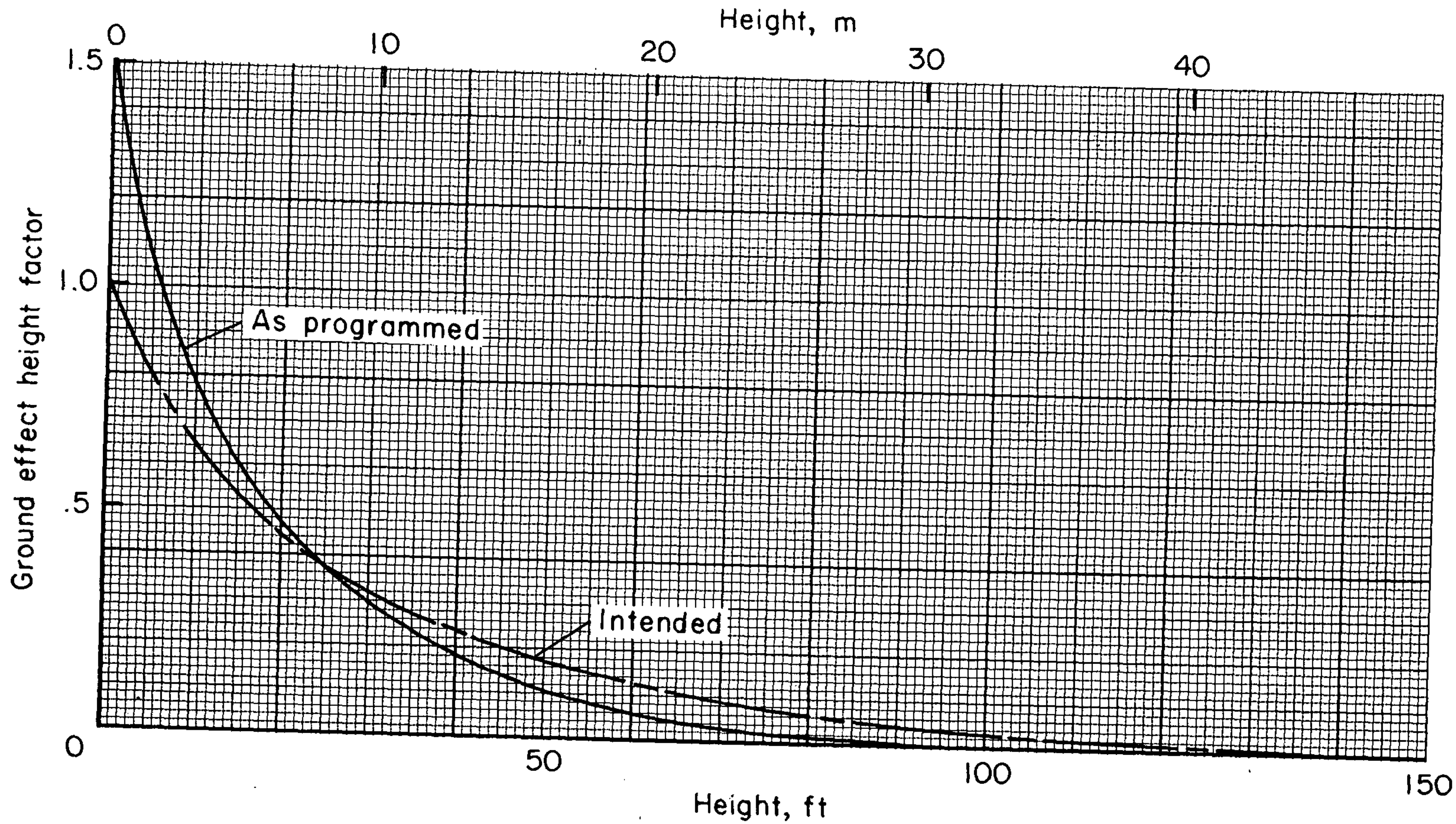


Figure 7.– Ground effect height factor for the Jumbo Jet Transport.

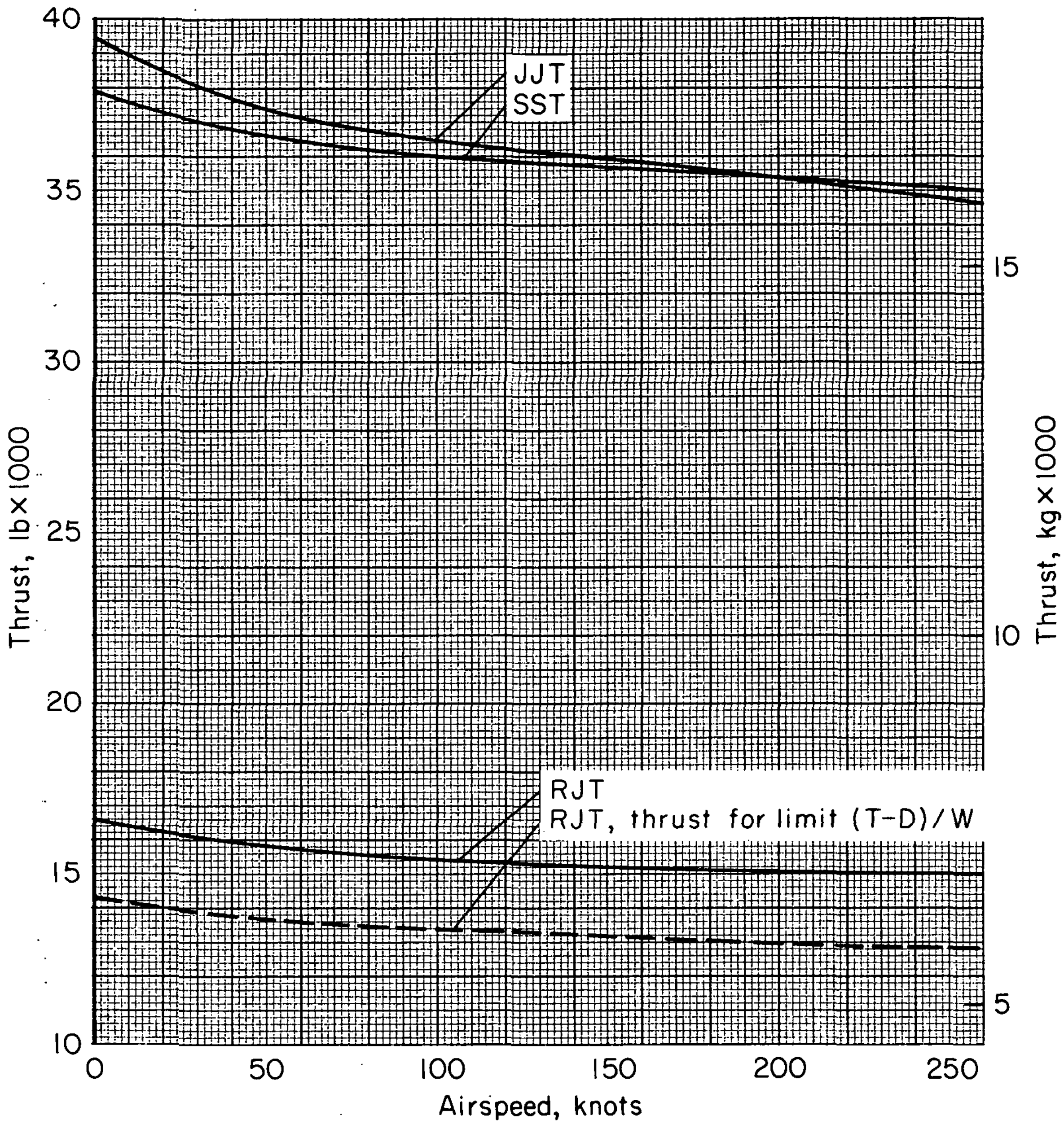


Figure 8.— Assumed available sea-level thrust (per engine) vs speed for the three simulated airplanes.

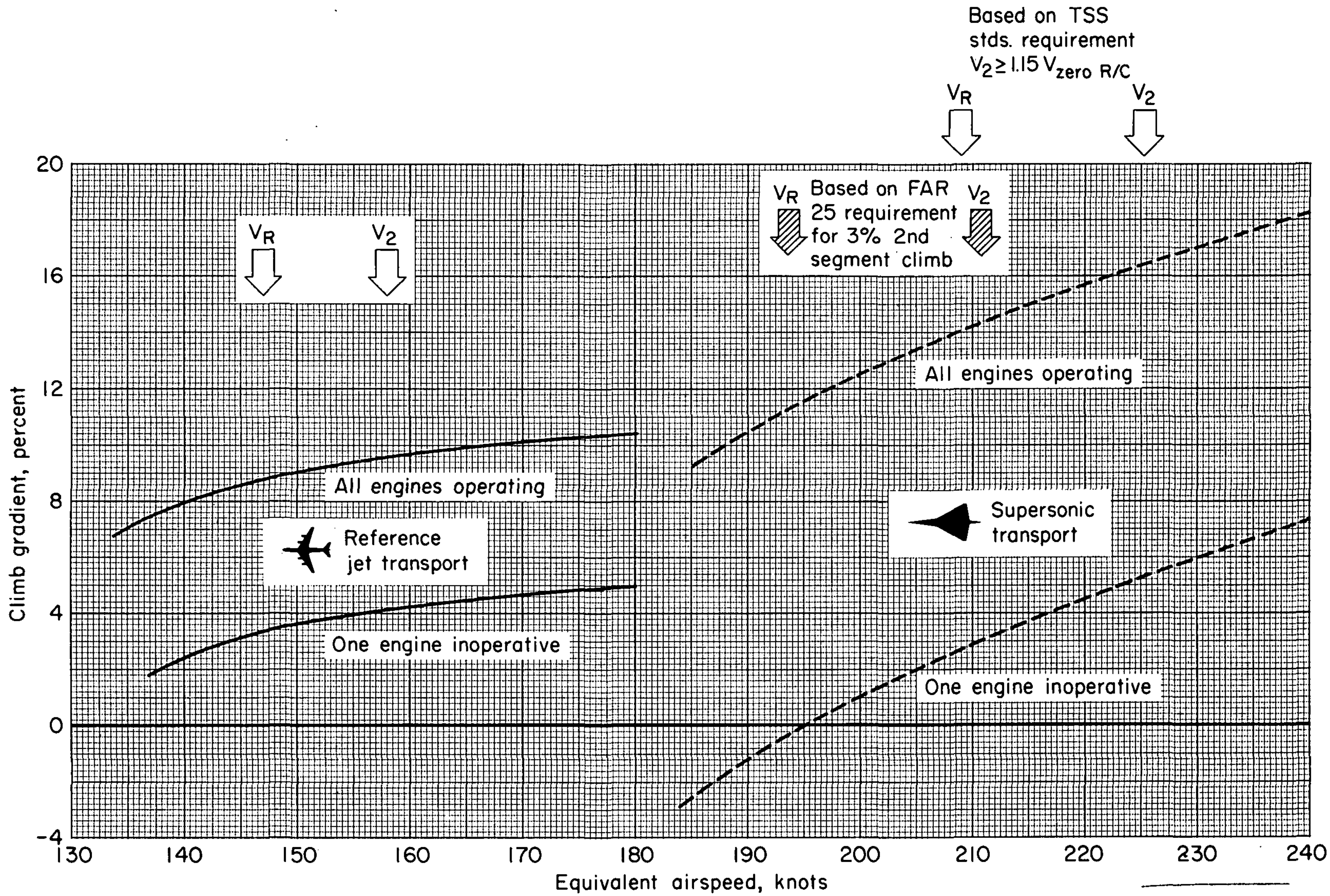
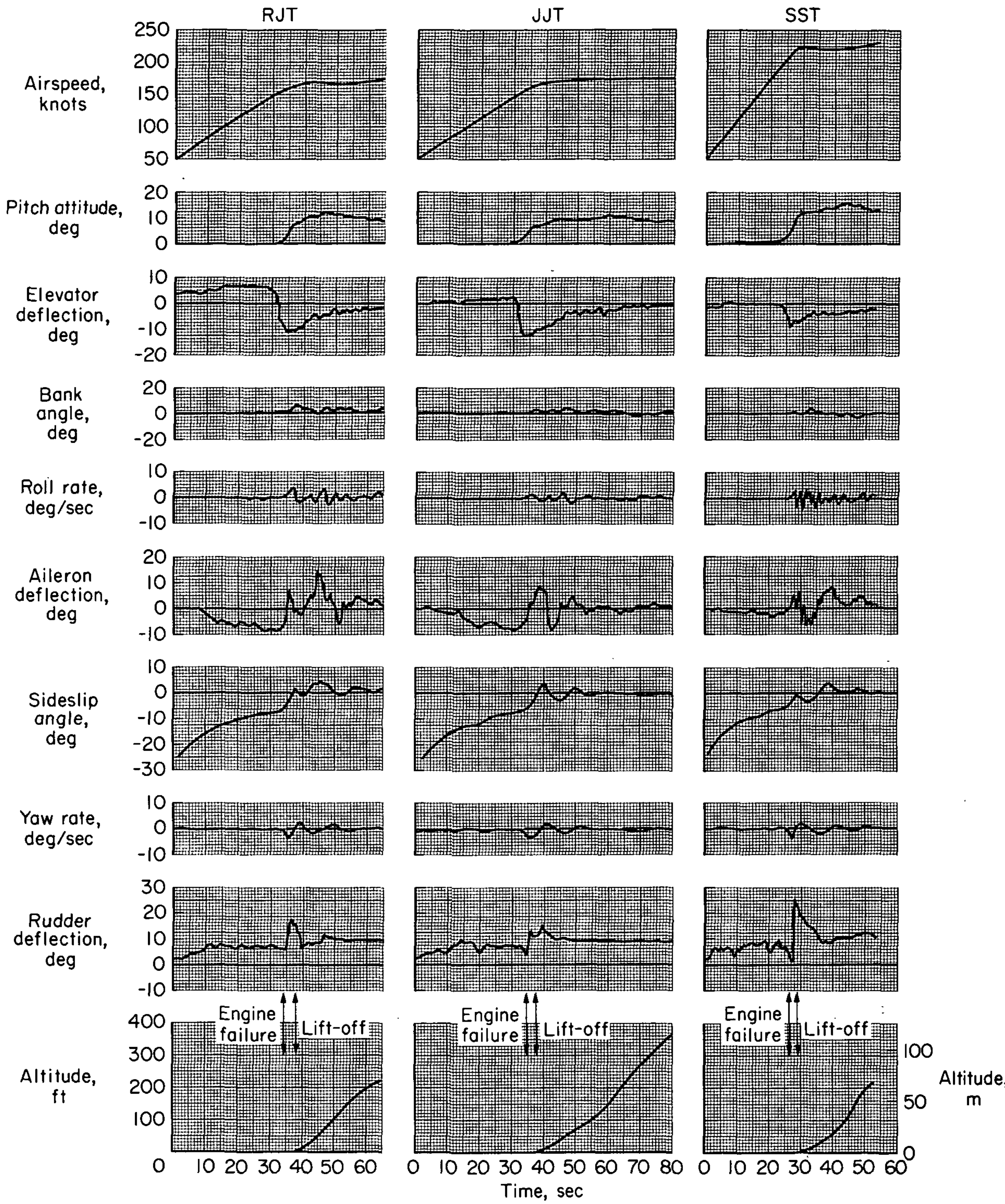
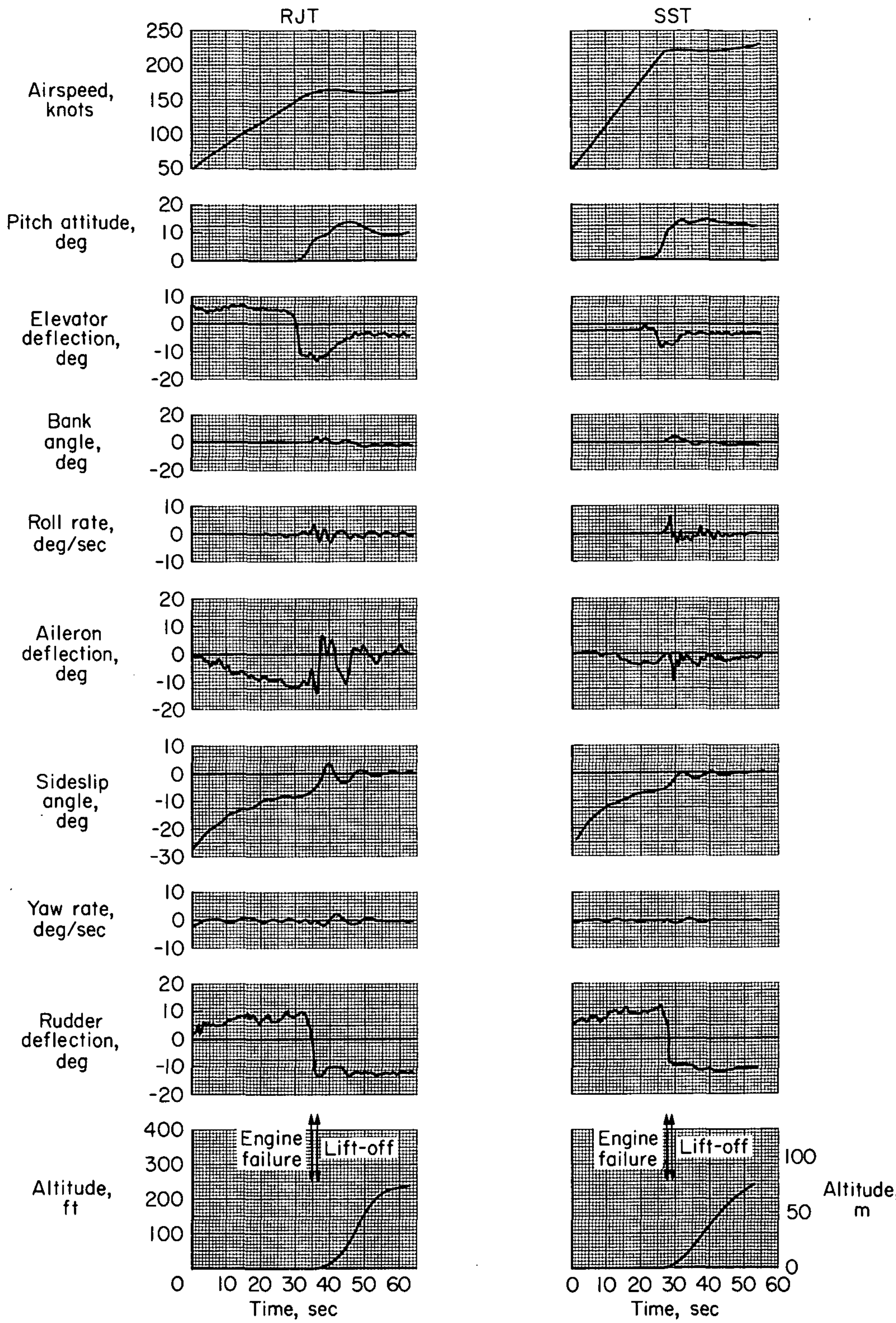


Figure 9.– RJT and SST climb performance at maximum takeoff gross weight, standard sea-level thrust, and with landing gear retracted; directional trim drag not included.



(a) Left outboard engine failure during rotation.

Figure 10.– Time histories of one-engine-inoperative crosswind takeoffs; 25-knot crosswind from the left, rudder-pedal nose-wheel steering operative, pilot A.



(b) Right outboard engine failure during rotation.

Figure 10.– Concluded.

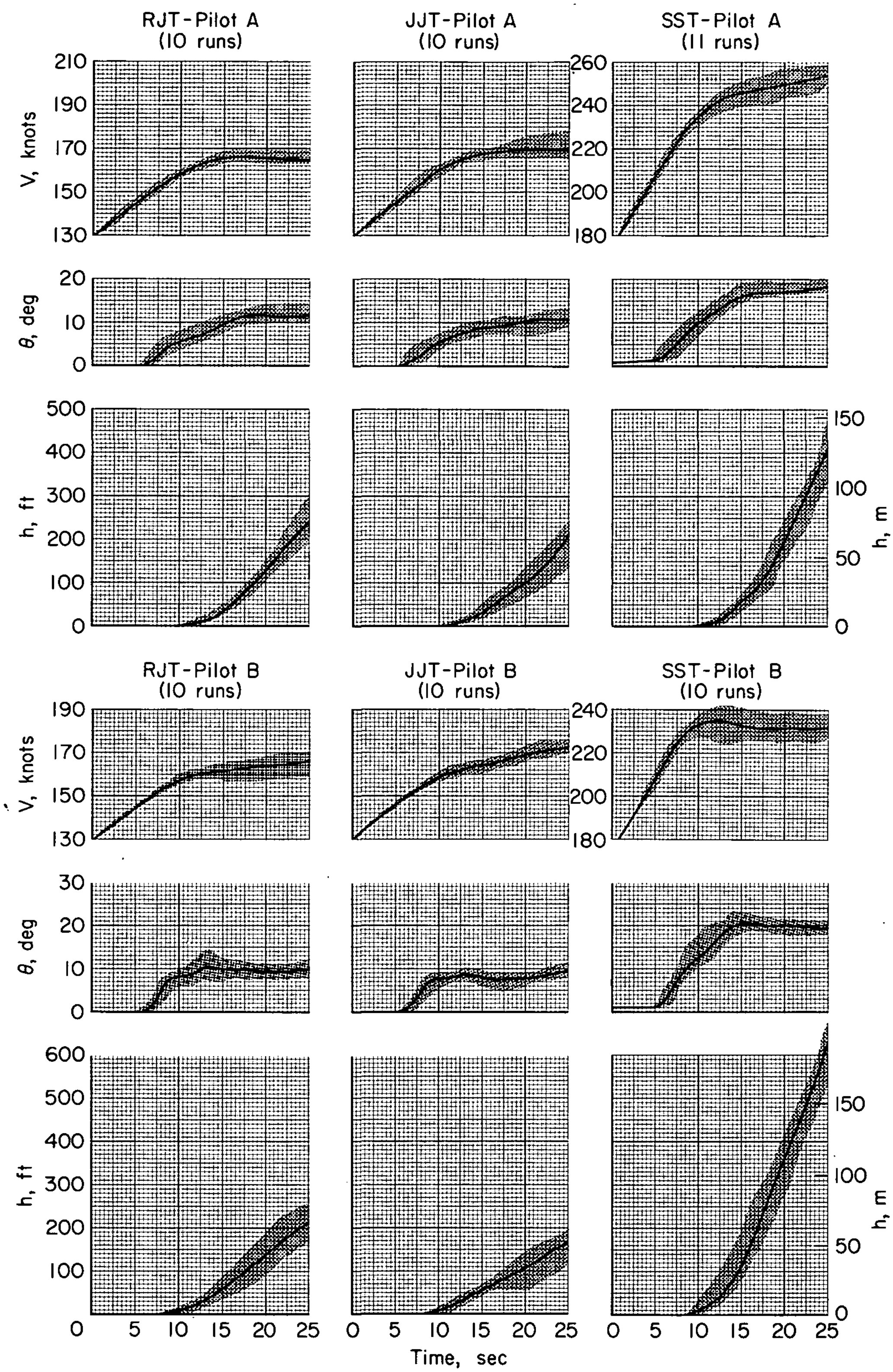


Figure 11 – Average normal takeoff time histories and envelopes of extremes.

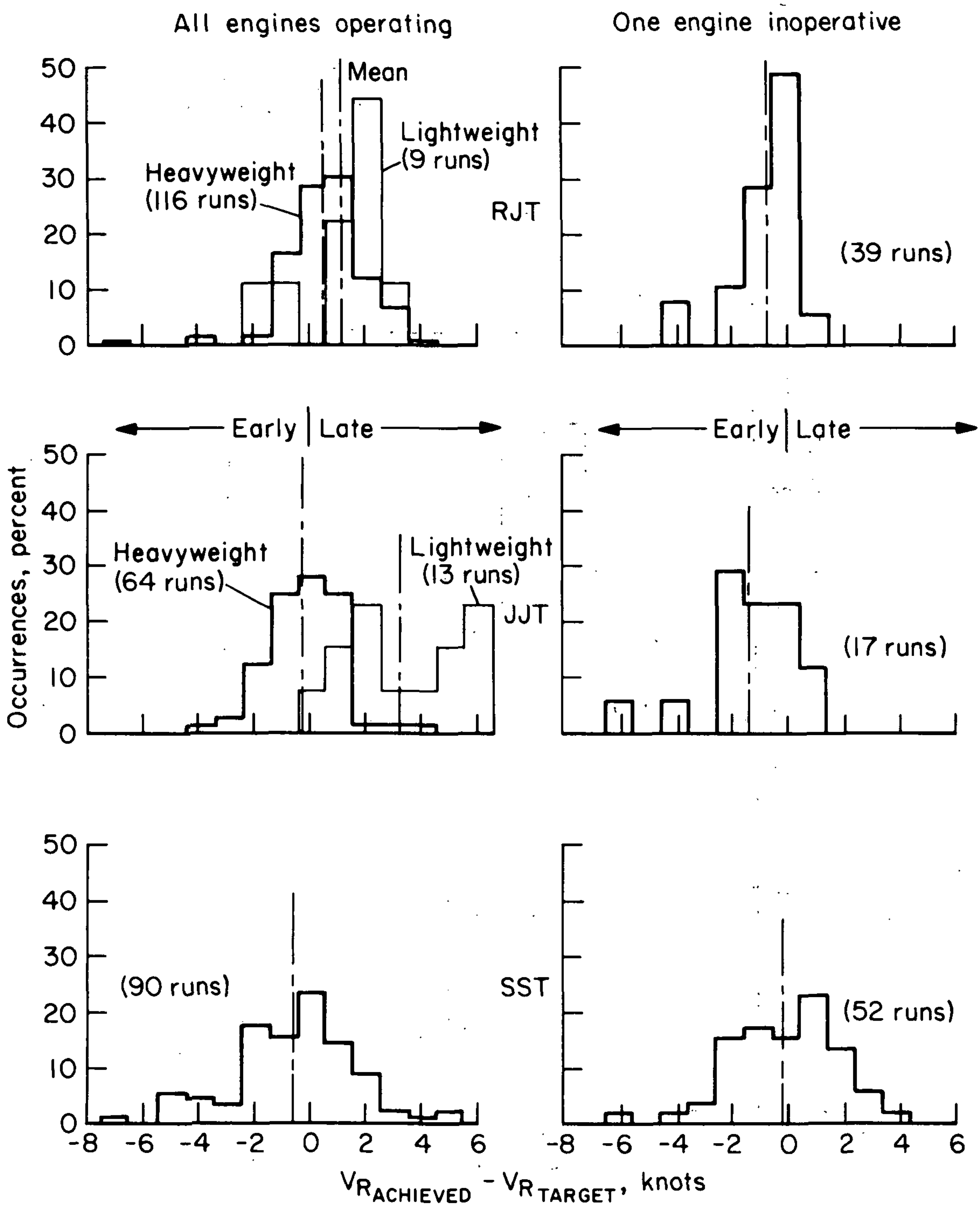


Figure 12.– Histogram comparison of rotation speed errors; maximum takeoff gross weight except as noted.

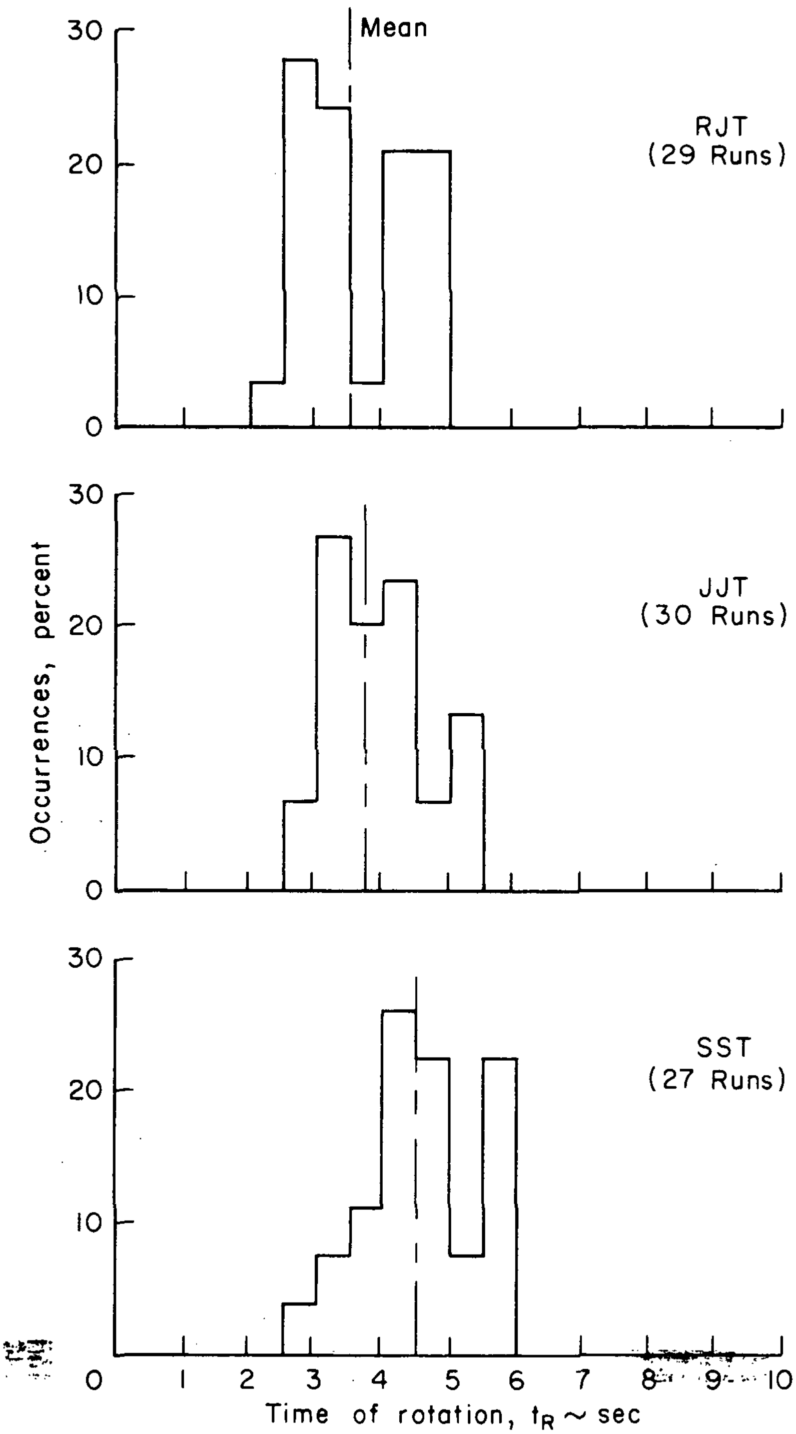


Figure 13.– Histogram comparison of time elapsed between rotation initiation and lift–off. All engines operating, maximum takeoff gross weight.

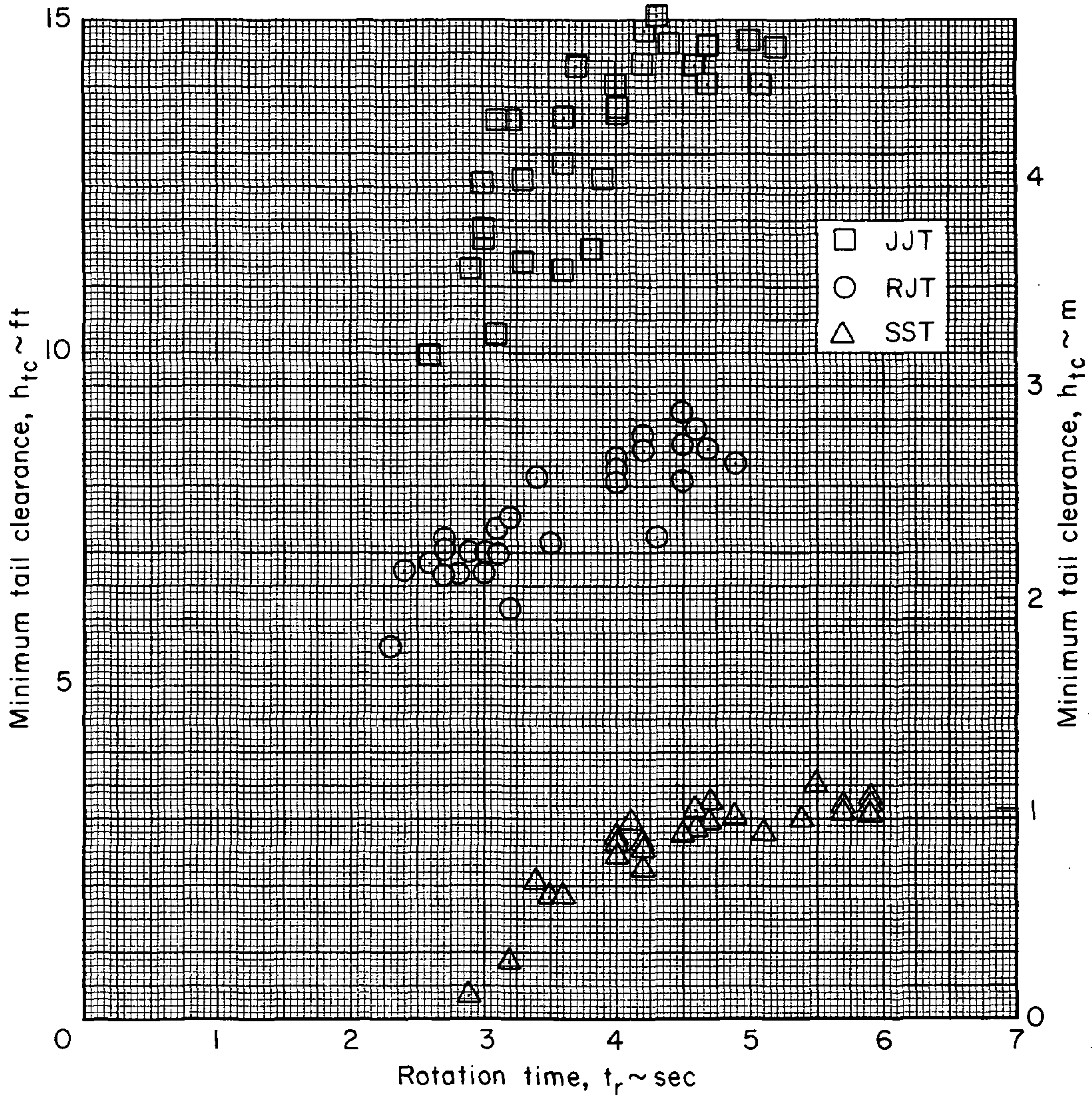


Figure 14.– Minimum tail clearance vs rotation time. All engines operating, maximum takeoff gross weight.

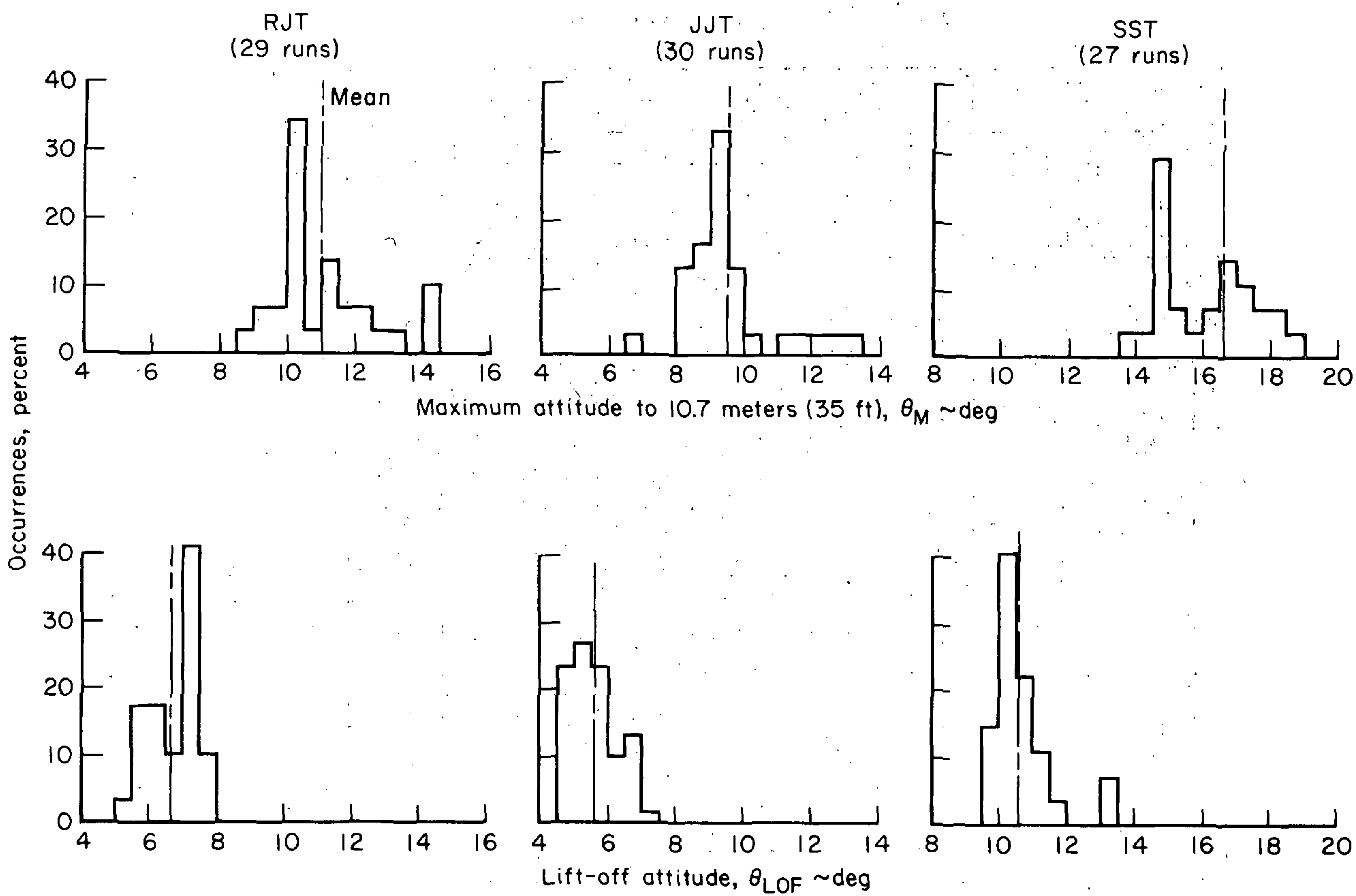


Figure 15.– Histogram comparison of pitch attitude at lift-off and maximum pitch attitude acquired during transition to 10.7-m (35 ft) height. All engines operating, maximum takeoff gross weight.

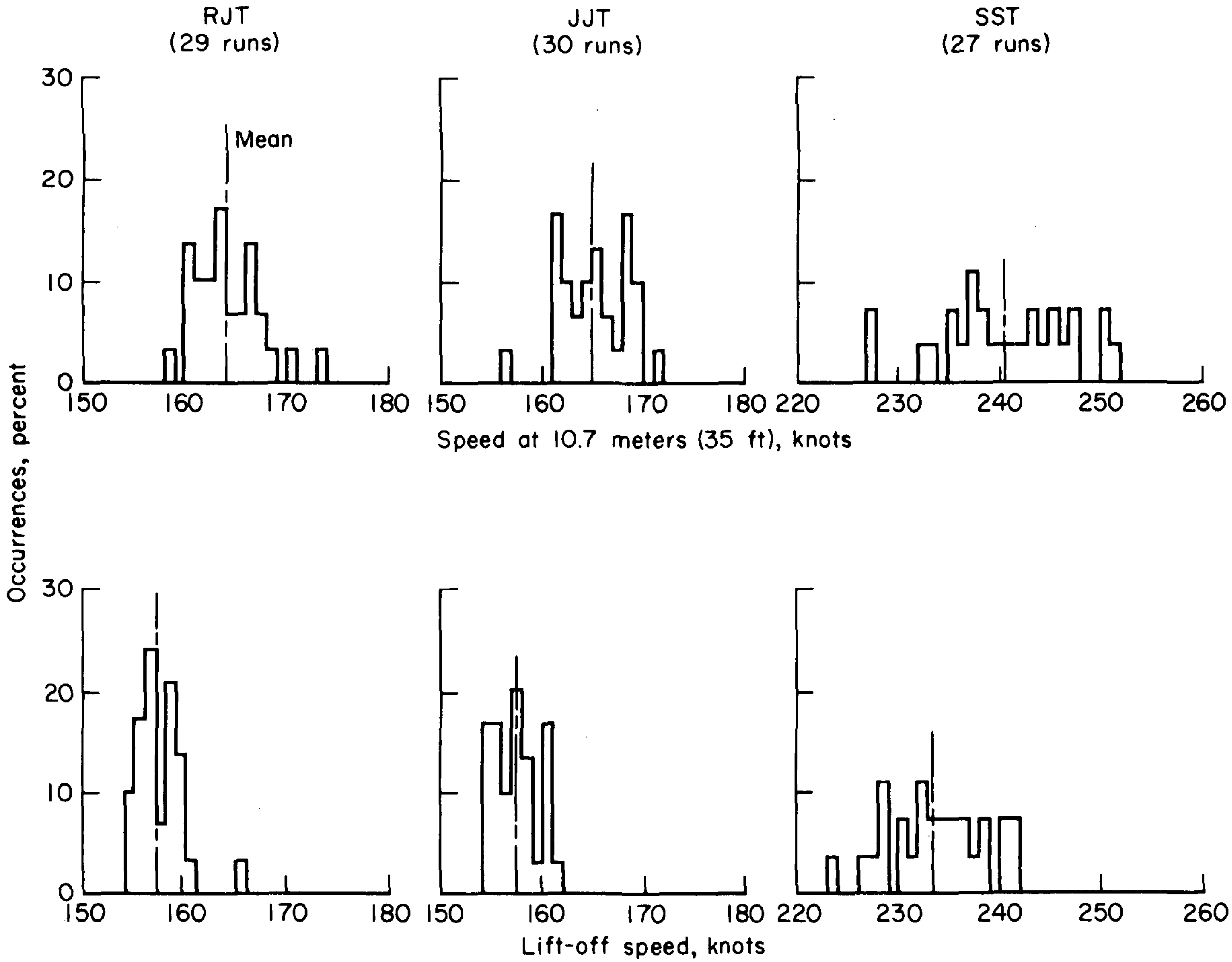


Figure 16.– Histogram comparison of lift-off speed and speed at the 10.7-m (35 ft) height. All engines operating, maximum takeoff gross weight. RJT and JJT: V_R = 147 knots, V_2 = 158 knots. SST: V_R = 209 knots, V_2 = 225 knots.

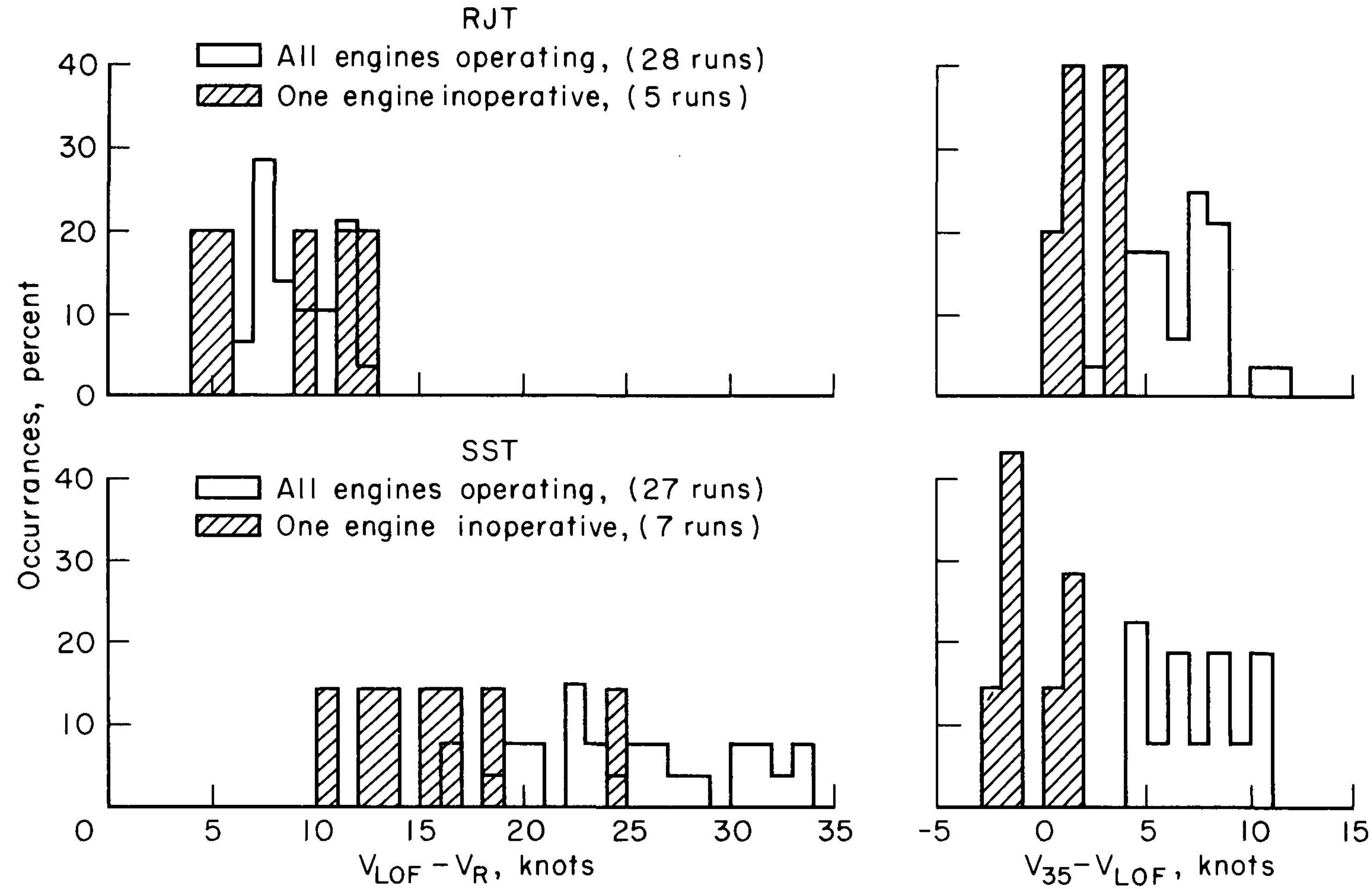


Figure 17.– Histogram comparison of speed spreads during rotation and transition to the 10.7-m (35 ft) height; maximum takeoff gross weight.

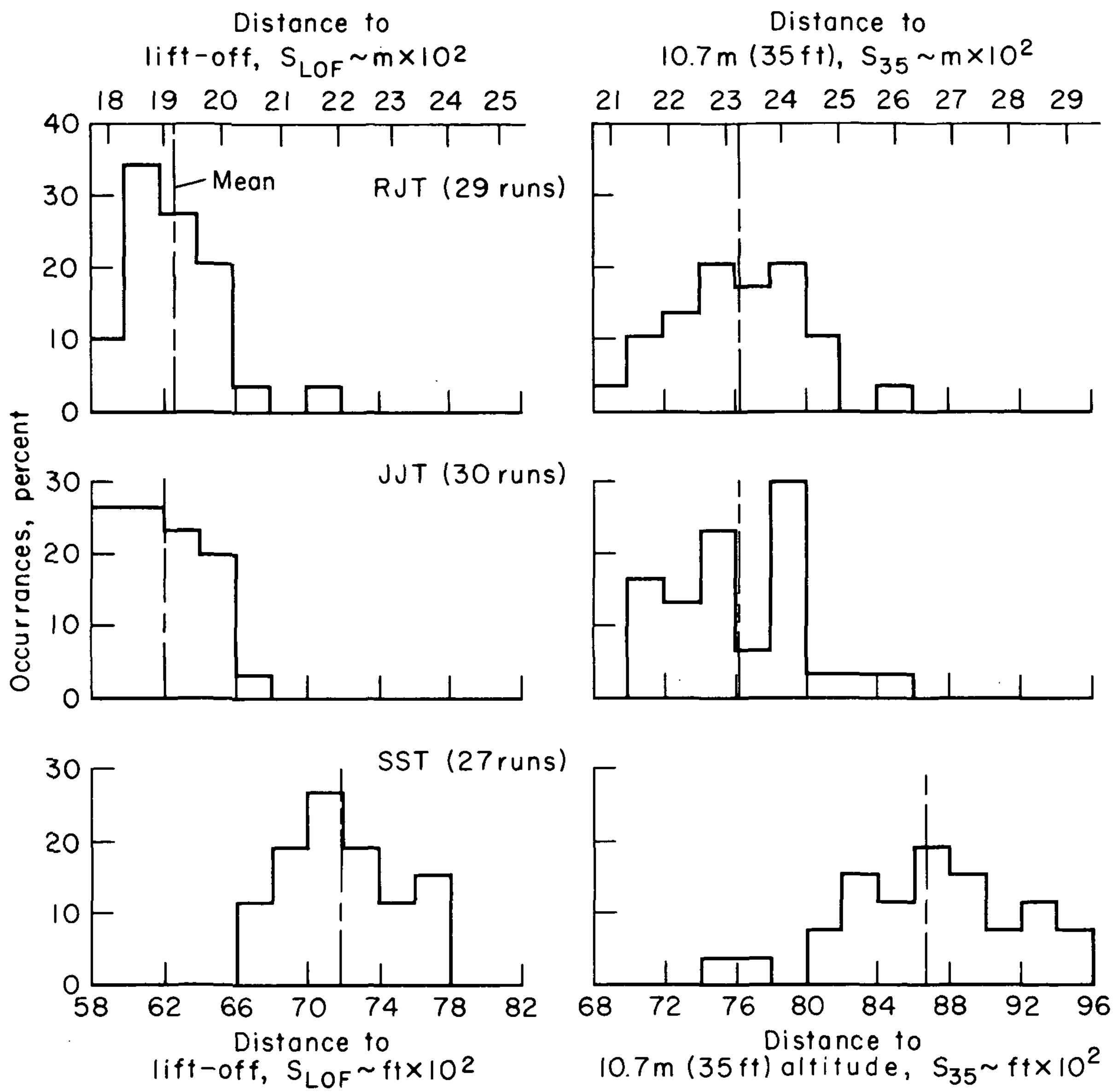


Figure 18.– Histogram comparison of measured distance to lift-off and distance to the 10.7-m (35 ft) height. All engines operating, maximum takeoff gross weight.

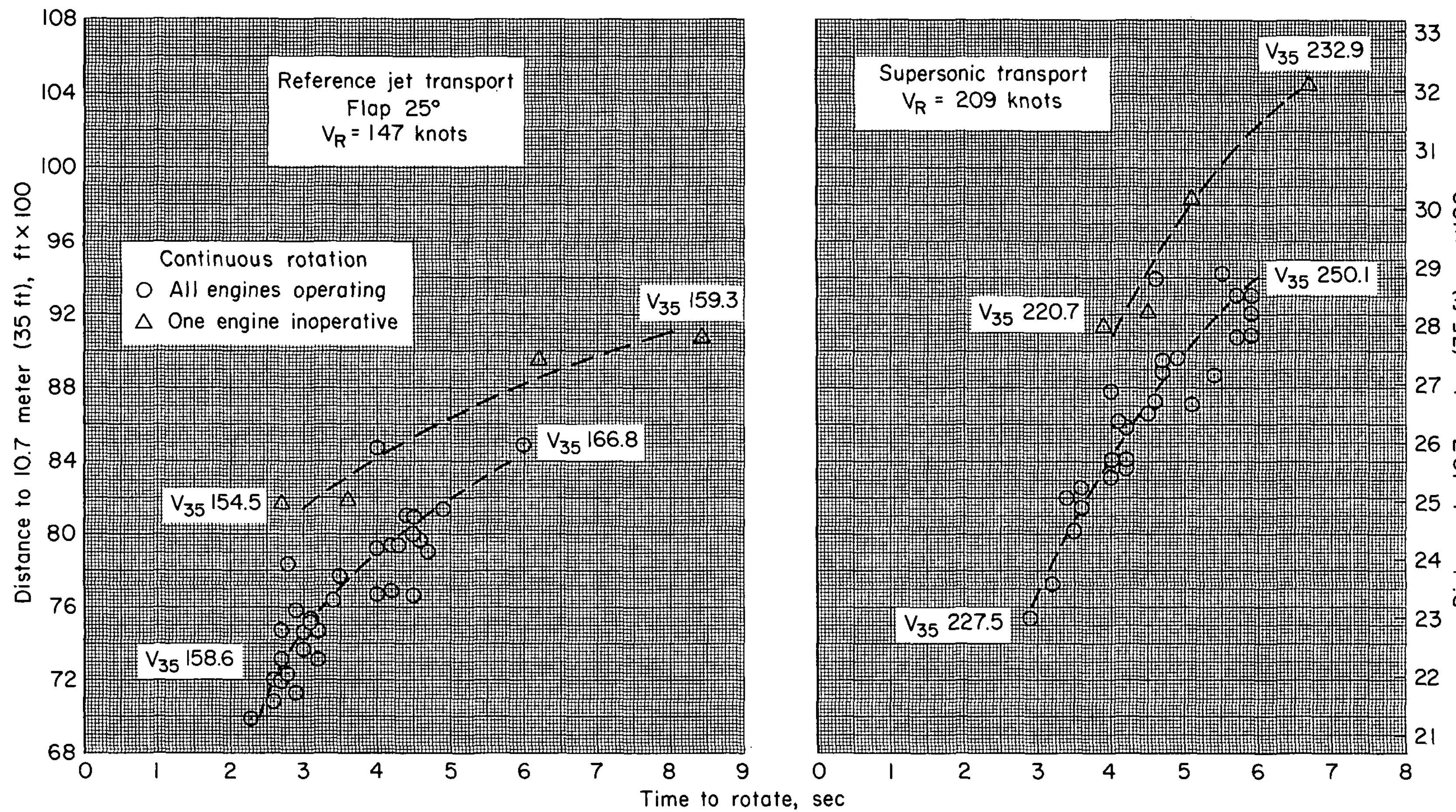


Figure 19.– Effect of rate of rotation (time to rotate) on measured takeoff distance to the 10.7–m (35 ft) height; maximum takeoff gross weight.

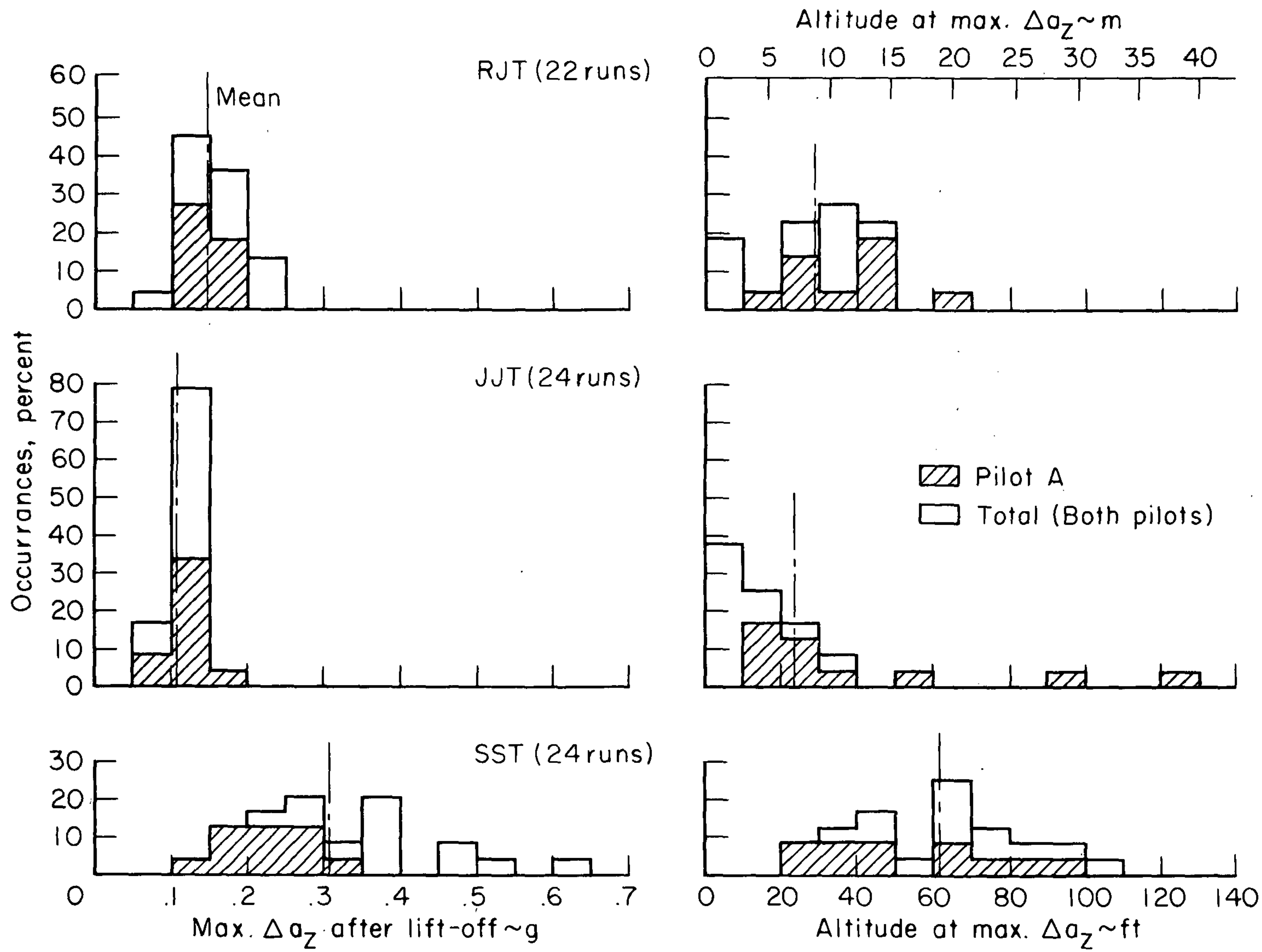


Figure 20.– Histogram comparison of maximum incremental vertical (relative to airplane body axes) acceleration at the C.G. and corresponding altitude. All engines operating, maximum takeoff gross weight.

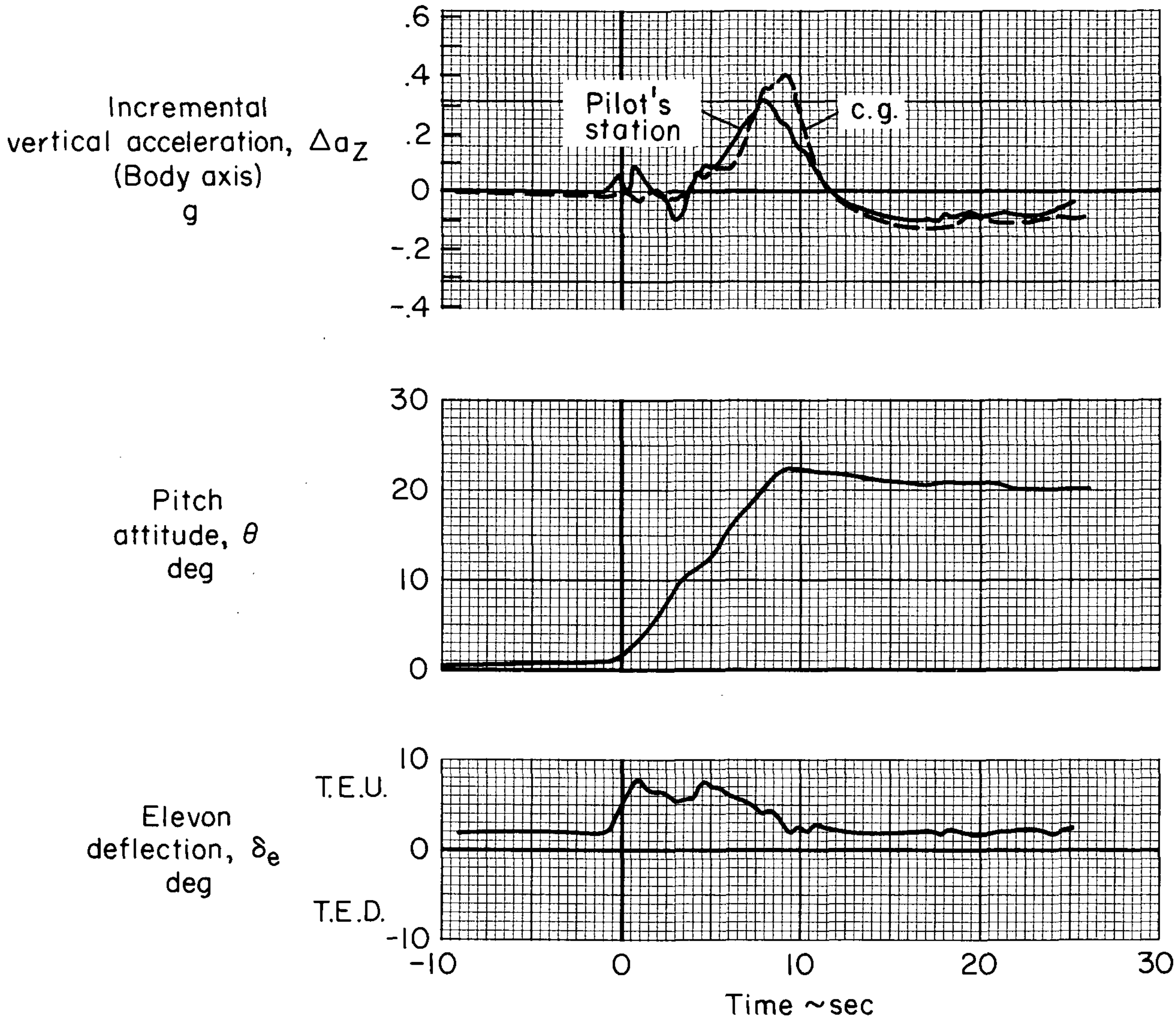


Figure 21.– Comparison of the incremental vertical acceleration at the C.G. and at the pilot's station during an SST takeoff, pilot B.

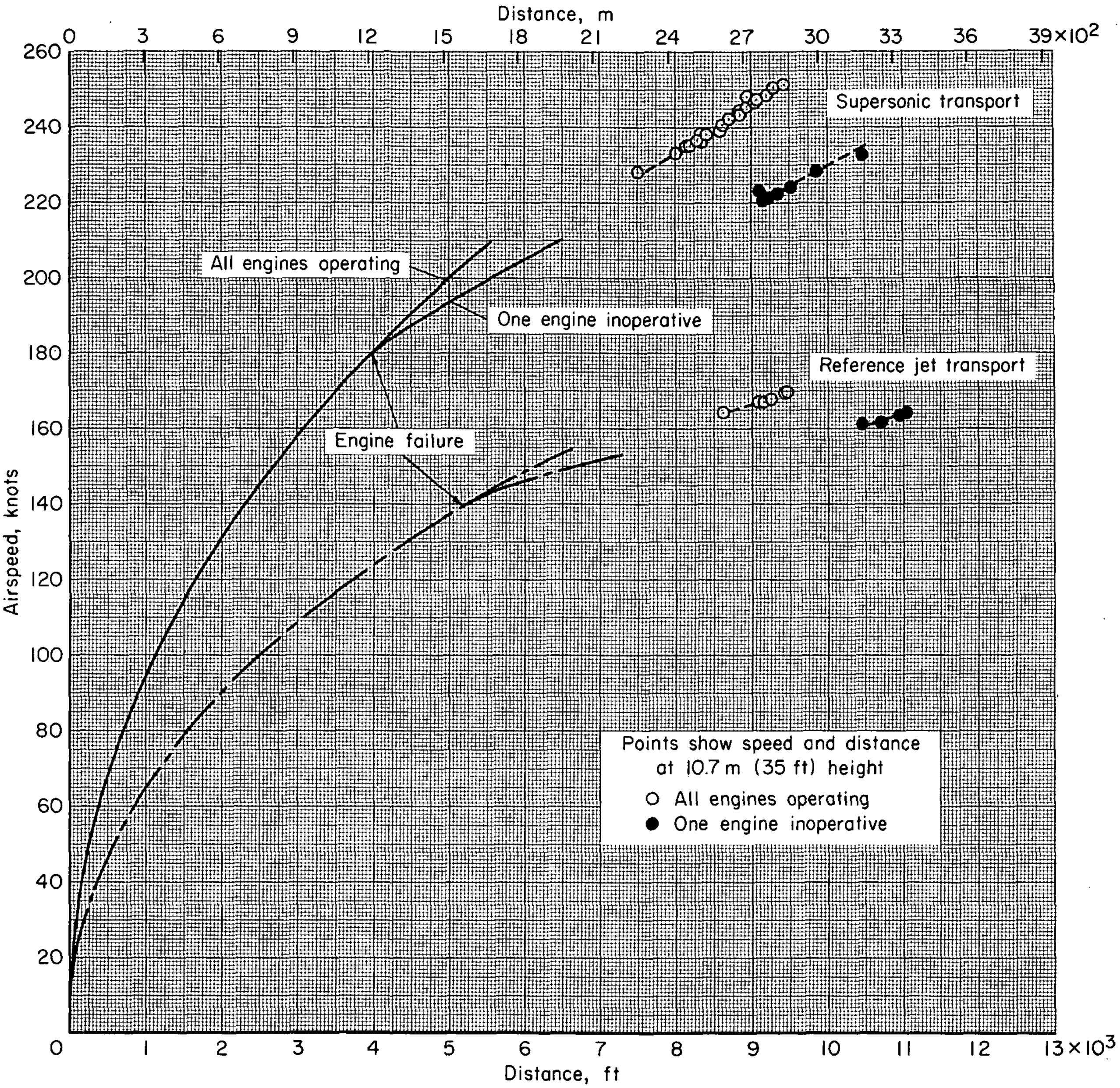


Figure 22.– Speed vs distance during maximum-weight takeoffs. RJT at 15° flaps and limit $(T\text{-}D)/W$.

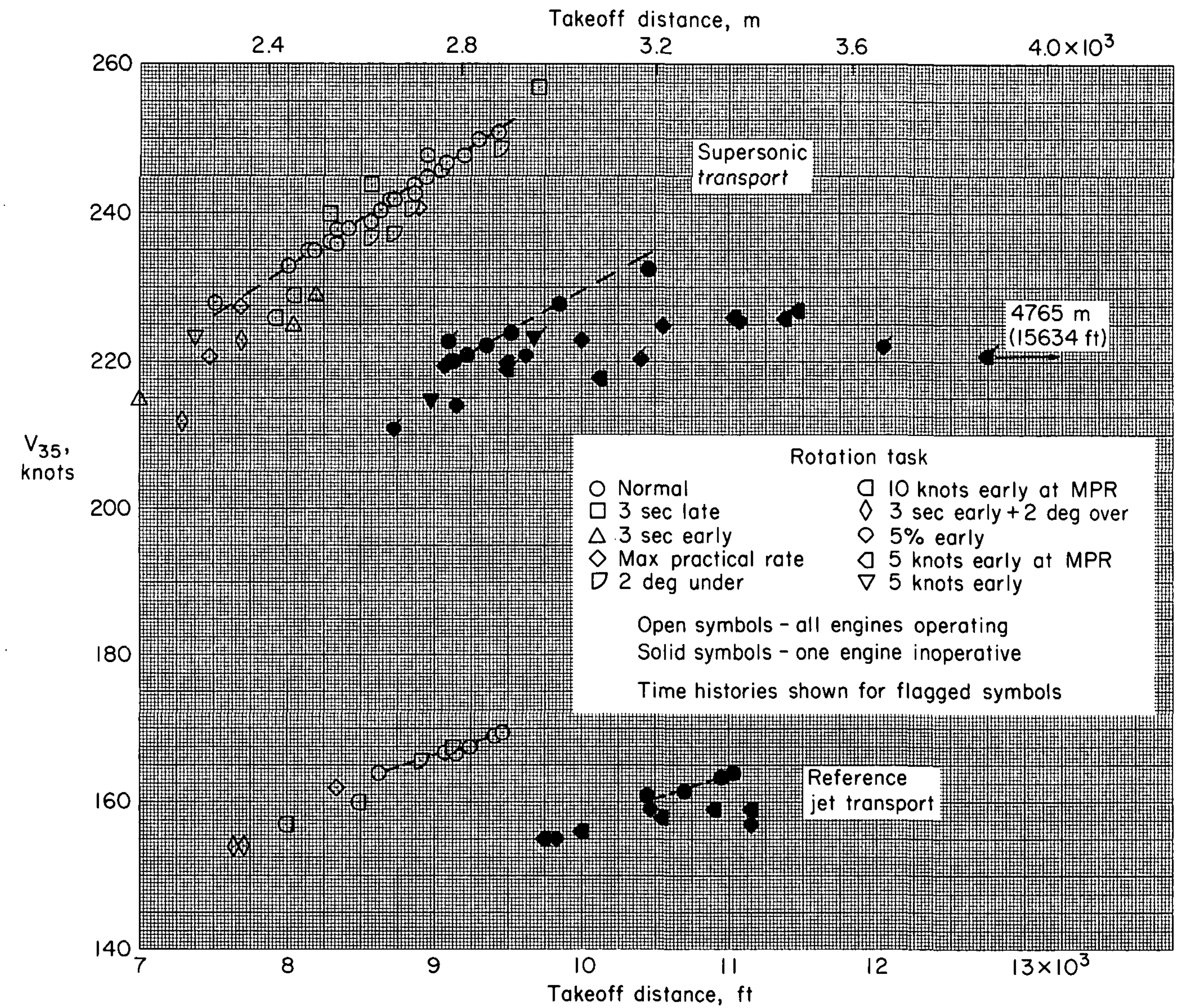


Figure 23.– Speed vs measured distance at 10.7-m (35 ft) height for normal and abused takeoff tests. Maximum takeoff gross weight. RJT at 15° flaps and limit $(T\text{–}D)/W$.

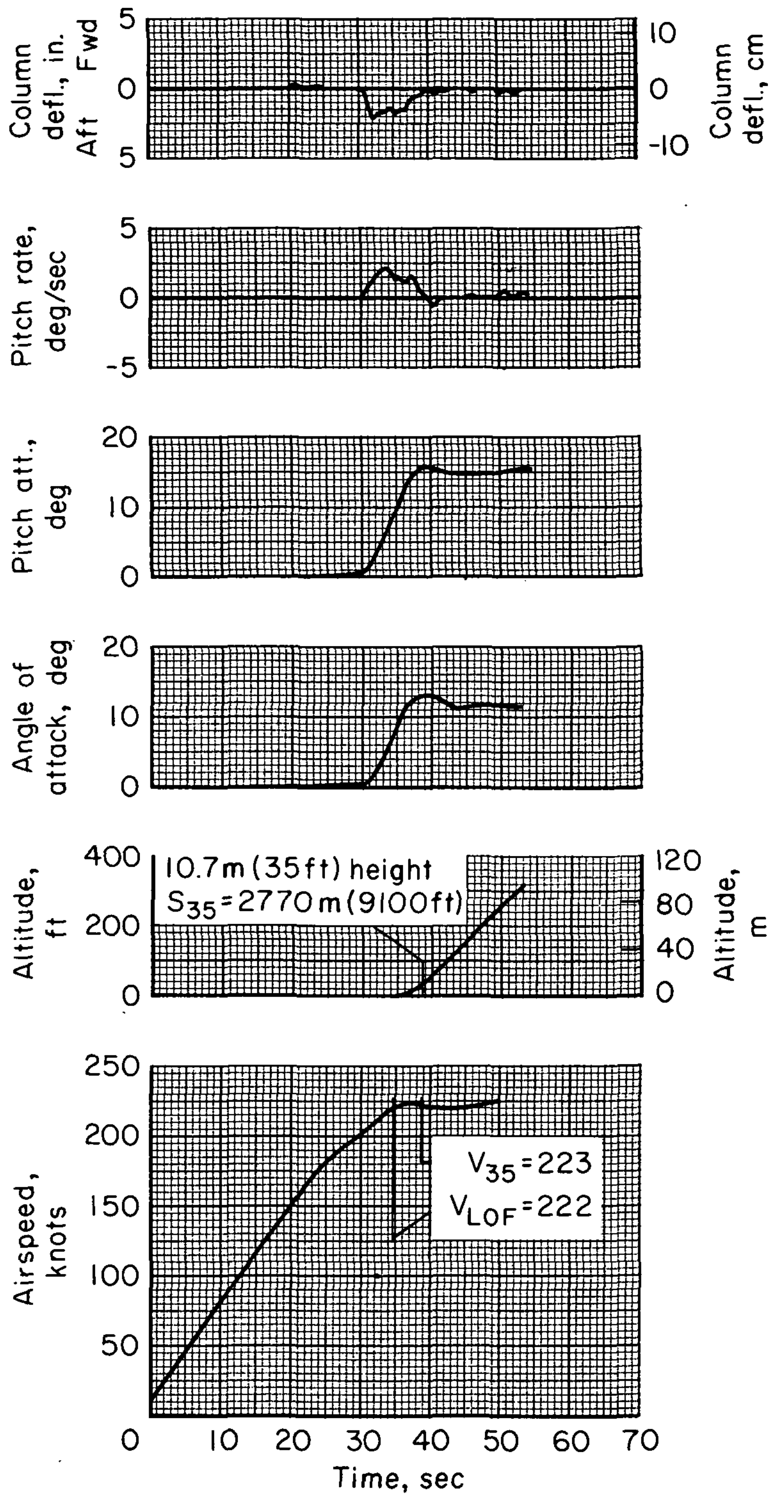


Figure 24.– Time history of a one-engine-inoperative SST takeoff, with rotation at the correct speed and near-proper rate; $V_{R_{ACH}}$ = 209.0 knots, $V_{EF} \cong 175$ knots.

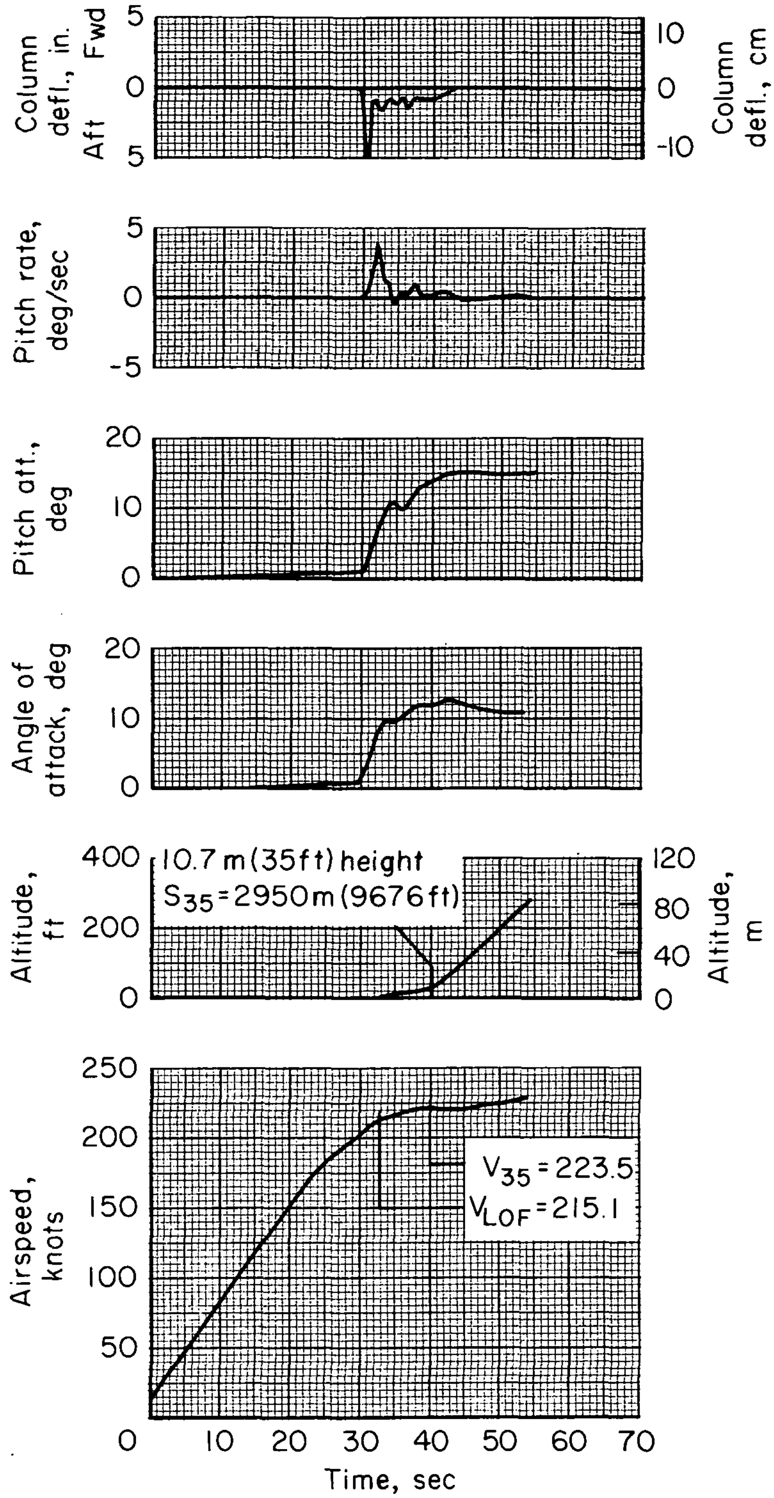
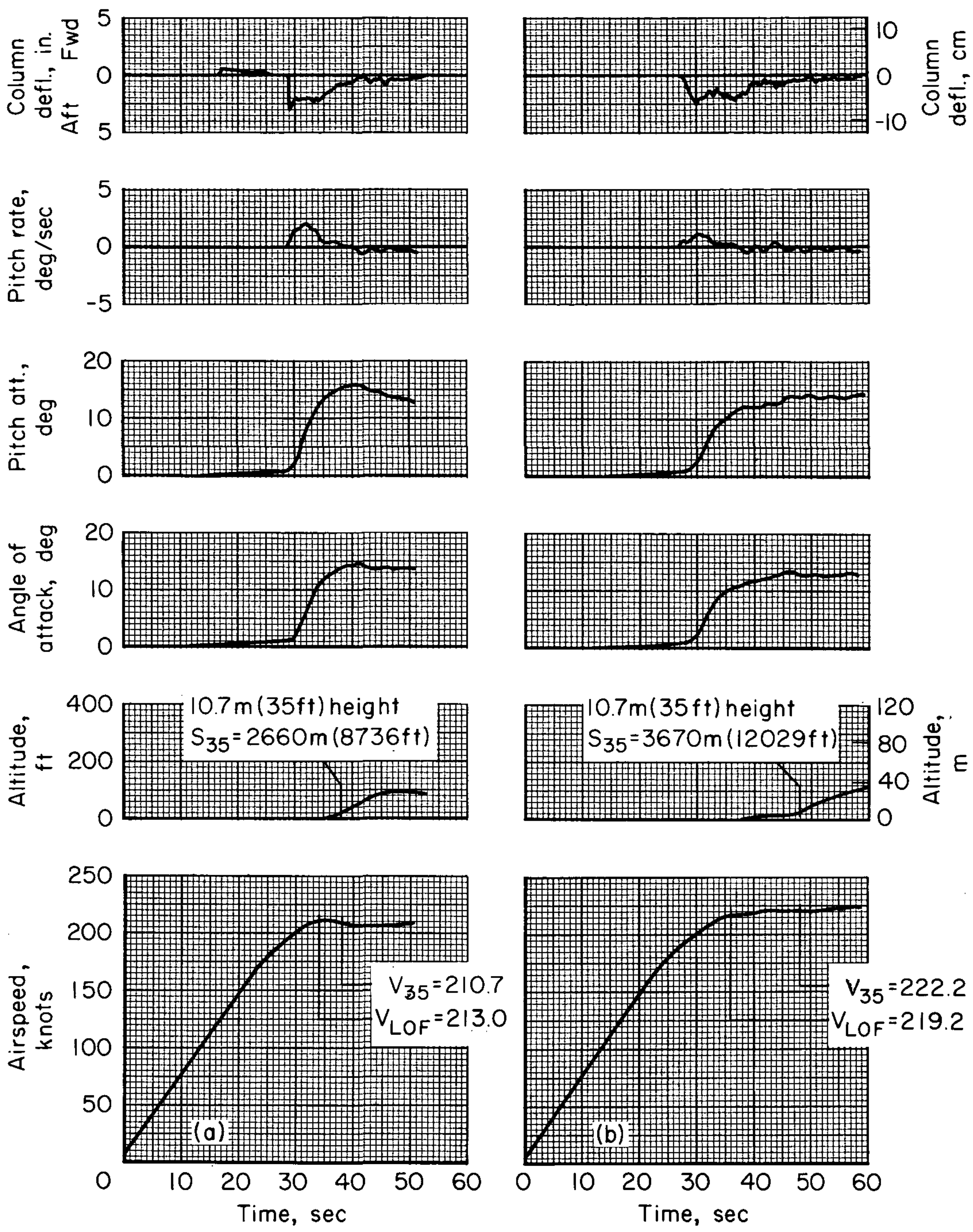


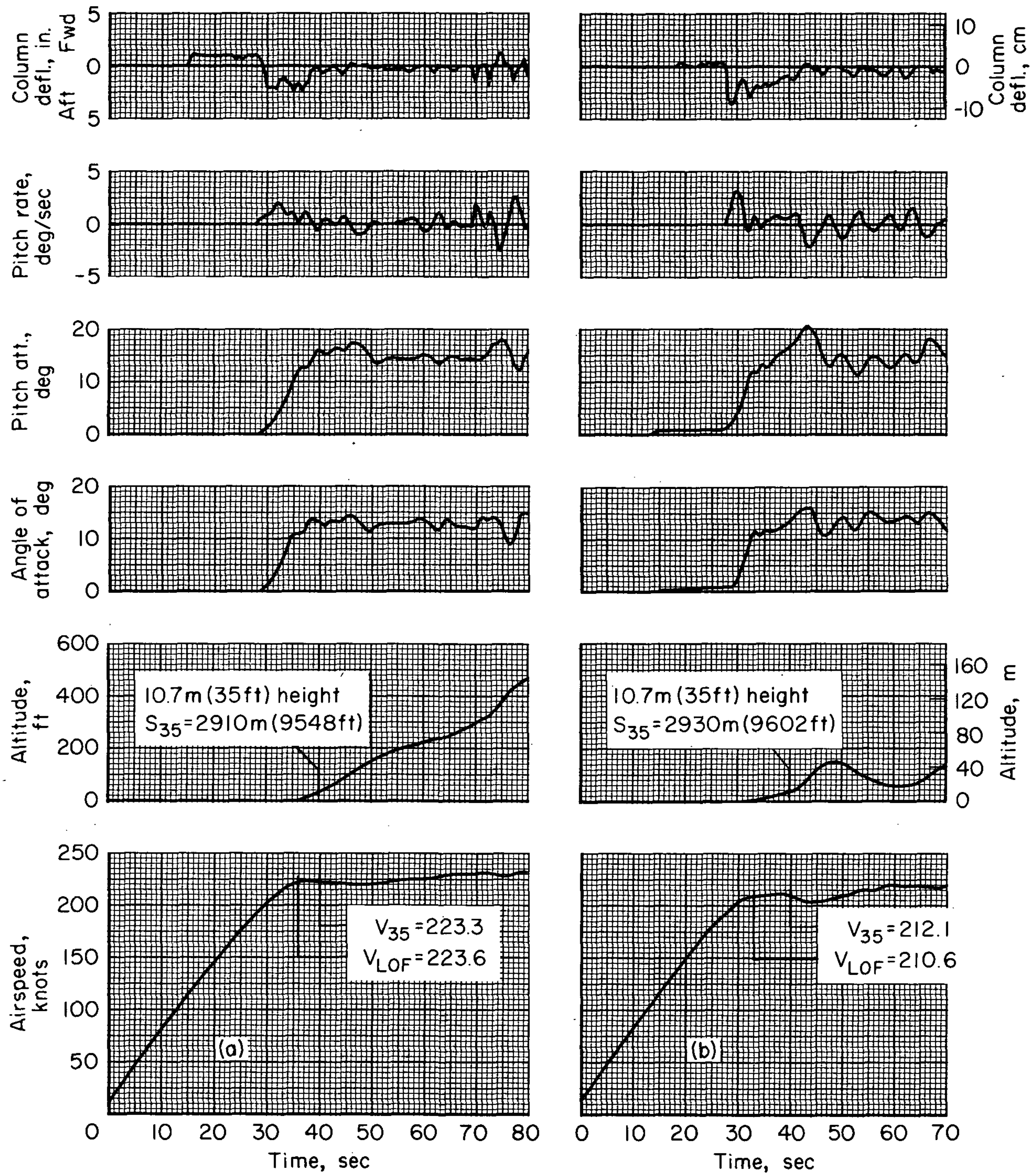
Figure 25.– Time history of one-engine-inoperative SST takeoff with rotation 5 knots early; $V_{R_{ACH}}$ = 204.8 knots, $V_{EF} \cong$ 175 knots.



(a) Excessive climb attitude; $V_{R_{ACH}}$ = 197.3 knots.

(b) Reduced attitude; $V_{R_{ACH}}$ = 193.3 knots.

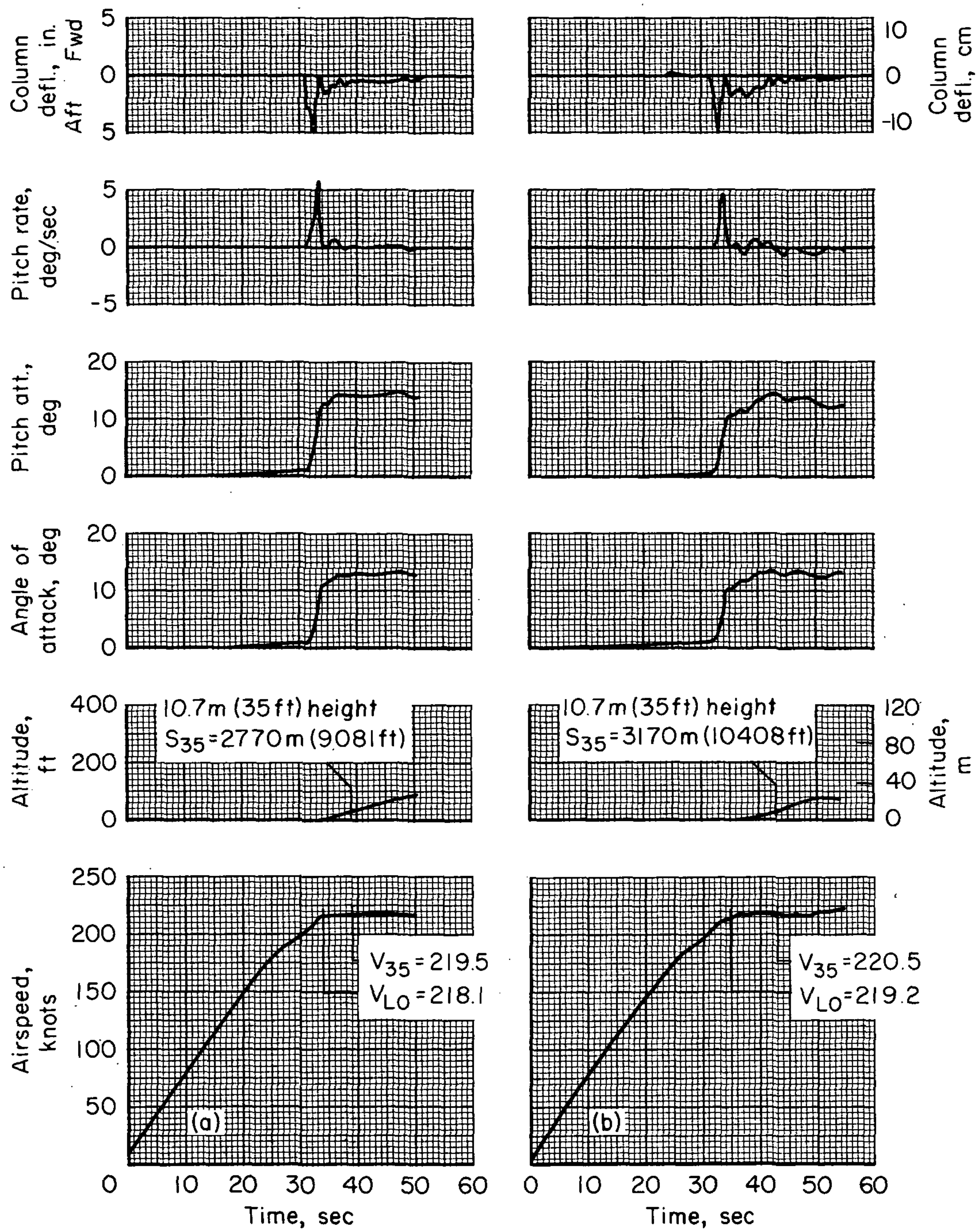
Figure 26.– Time histories of one–engine–inoperative 10–knots–early takeoff task with the SST; V_{EF} = 175 knots.



(a) Normal rotation rate; $V_{R_{ACH}}$ = 201.7 knots.

(b) Rapid rotation; $V_{R_{ACH}}$ = 198.5 knots.

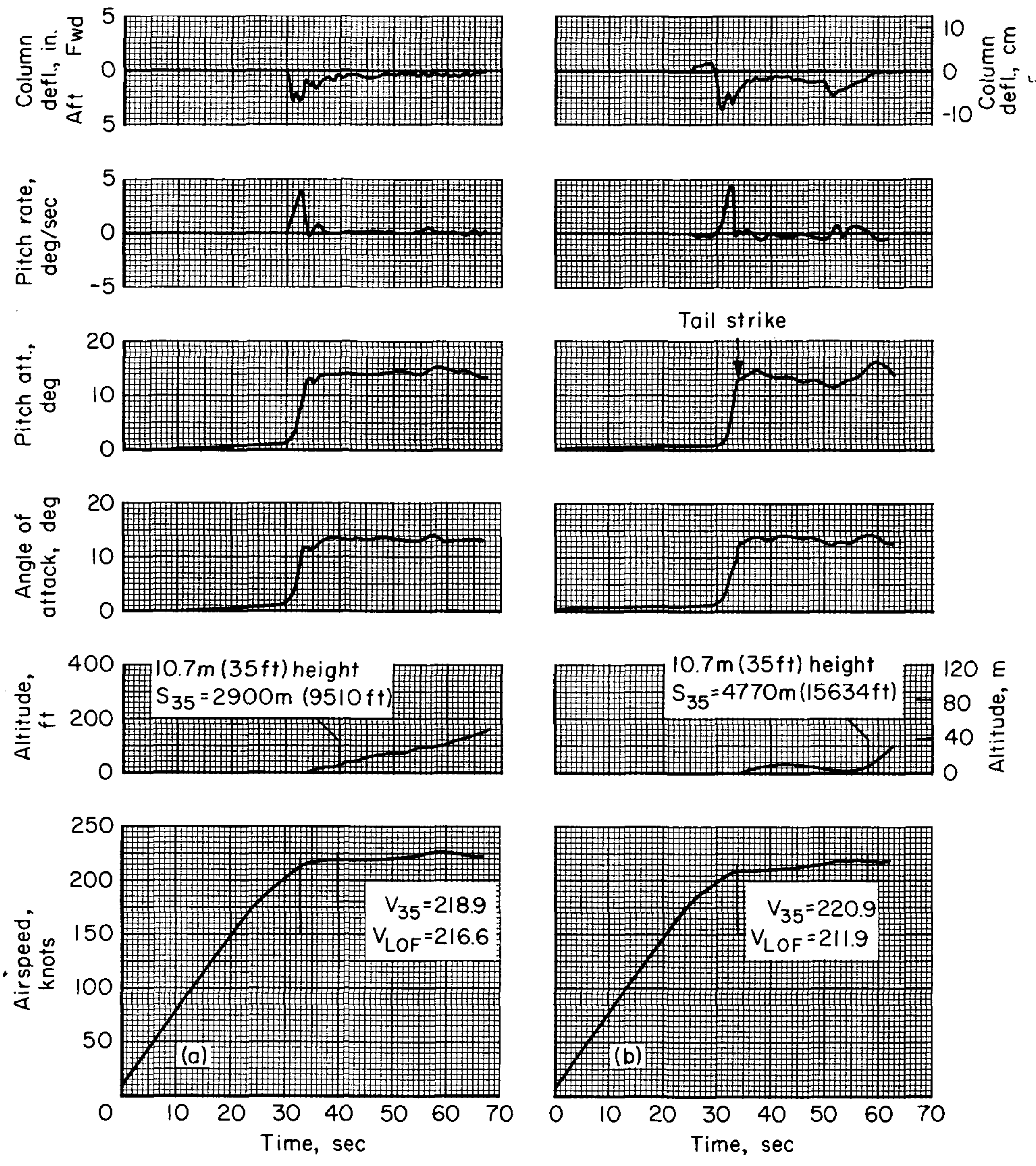
Figure 27.– Time histories of one-engine-inoperative SST takeoffs with V_R = 200 knots; $V_{EF} \cong$ 175 knots. Note: Dampers off, column gradient reduced to 6 lb/in.



(a) Proper climb attitude; $V_{R_{ACH}} = 209.3$ knots.

(b) Reduced climb attitude; $V_{R_{ACH}} = 209.9$ knots.

Figure 28.– Time histories of one-engine-inoperative SST takeoffs with rotation at the maximum practical rate; $V_{EF} \cong 175$ knots.



(a) Proper climb attitude; $V_{R_{ACH}} = 205.4$ knots.

(b) Attempt to accelerate to V_2 before reaching the 10.7-m (35 ft) height; $V_{R_{ACH}} = 202.0$ knots.

Figure 29.– Time histories of one-engine-inoperative SST abuse takeoffs with rotation 5 knots early at the maximum practical rate; $V_{EF} \cong 175$ knots.

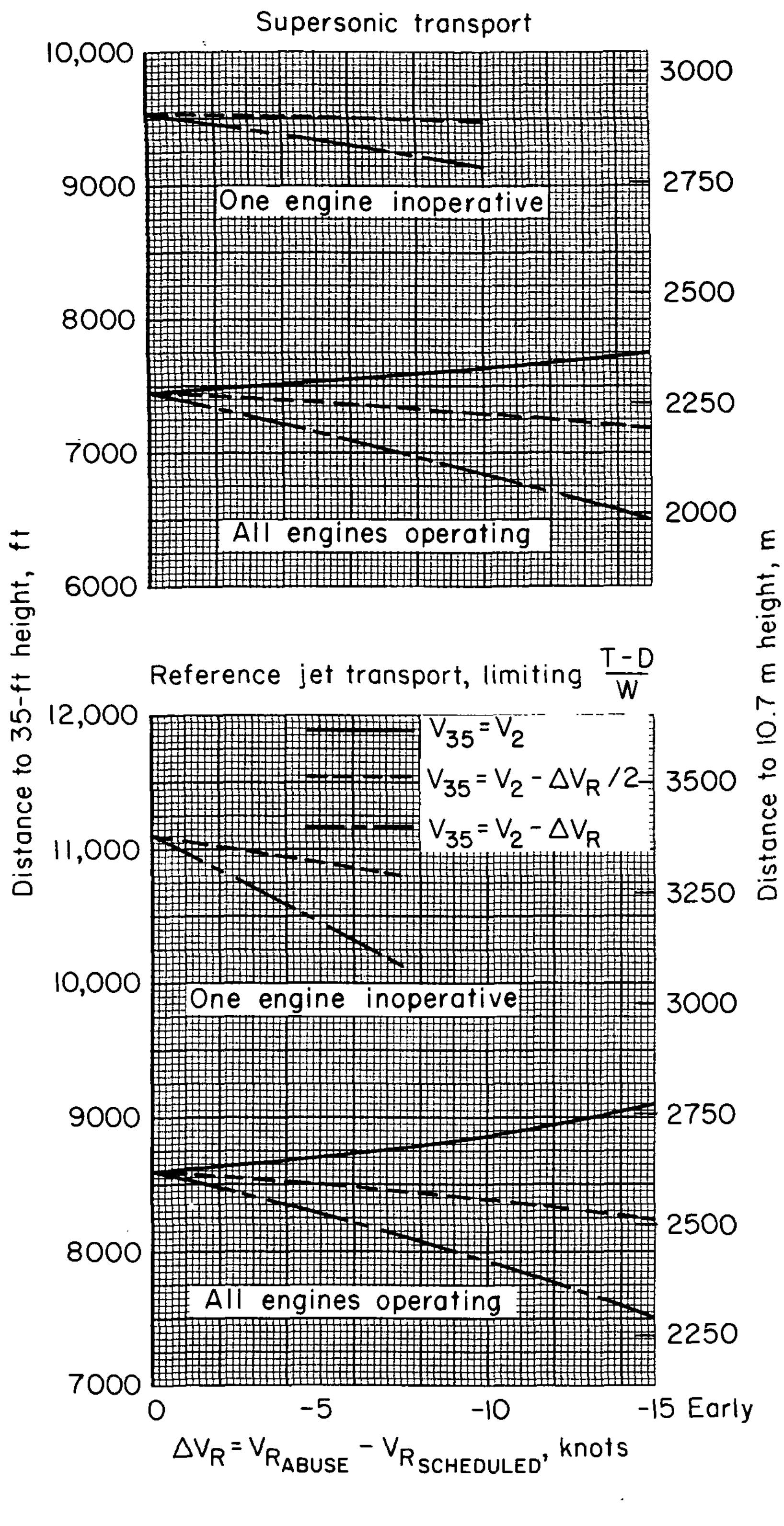
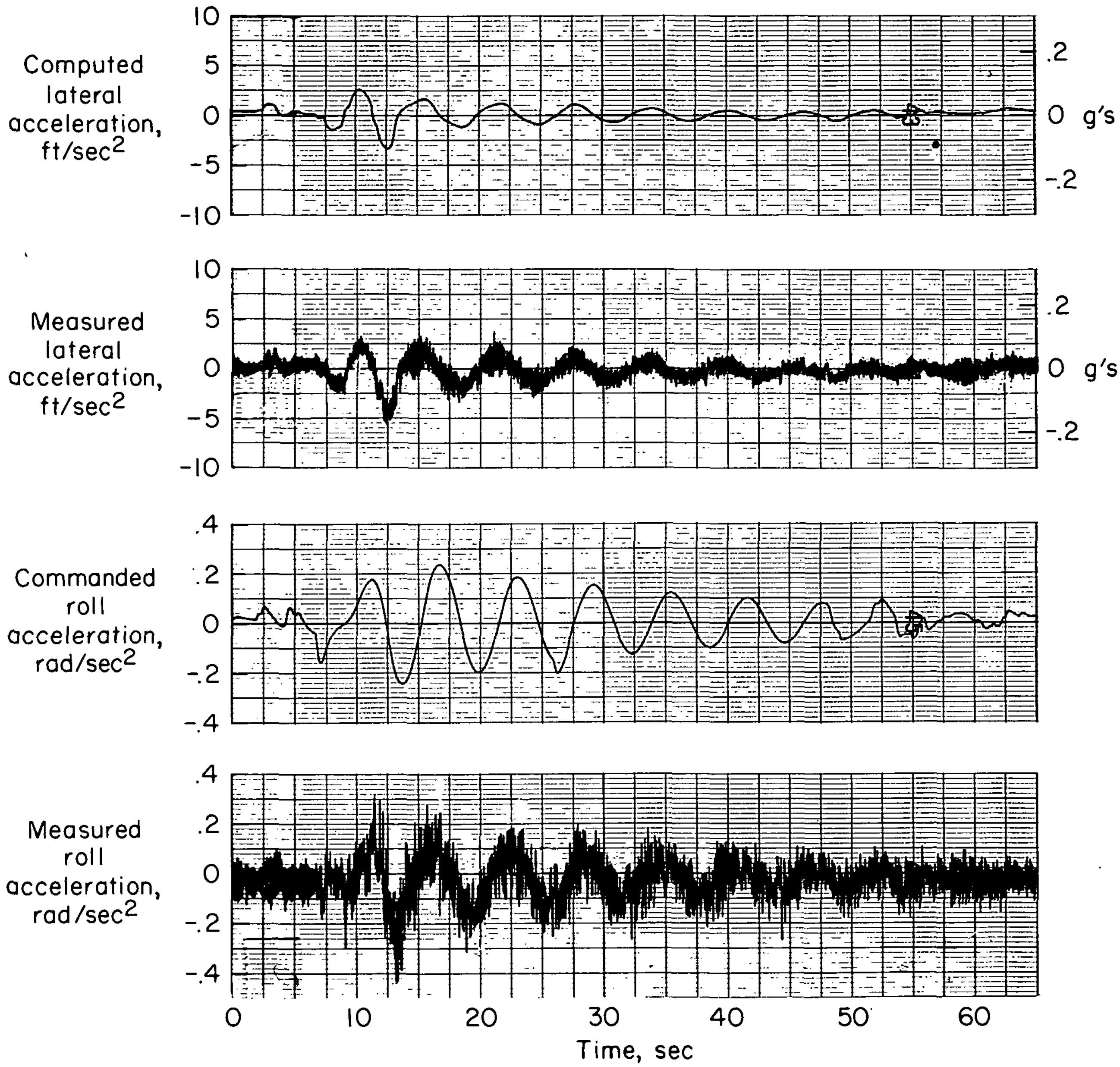
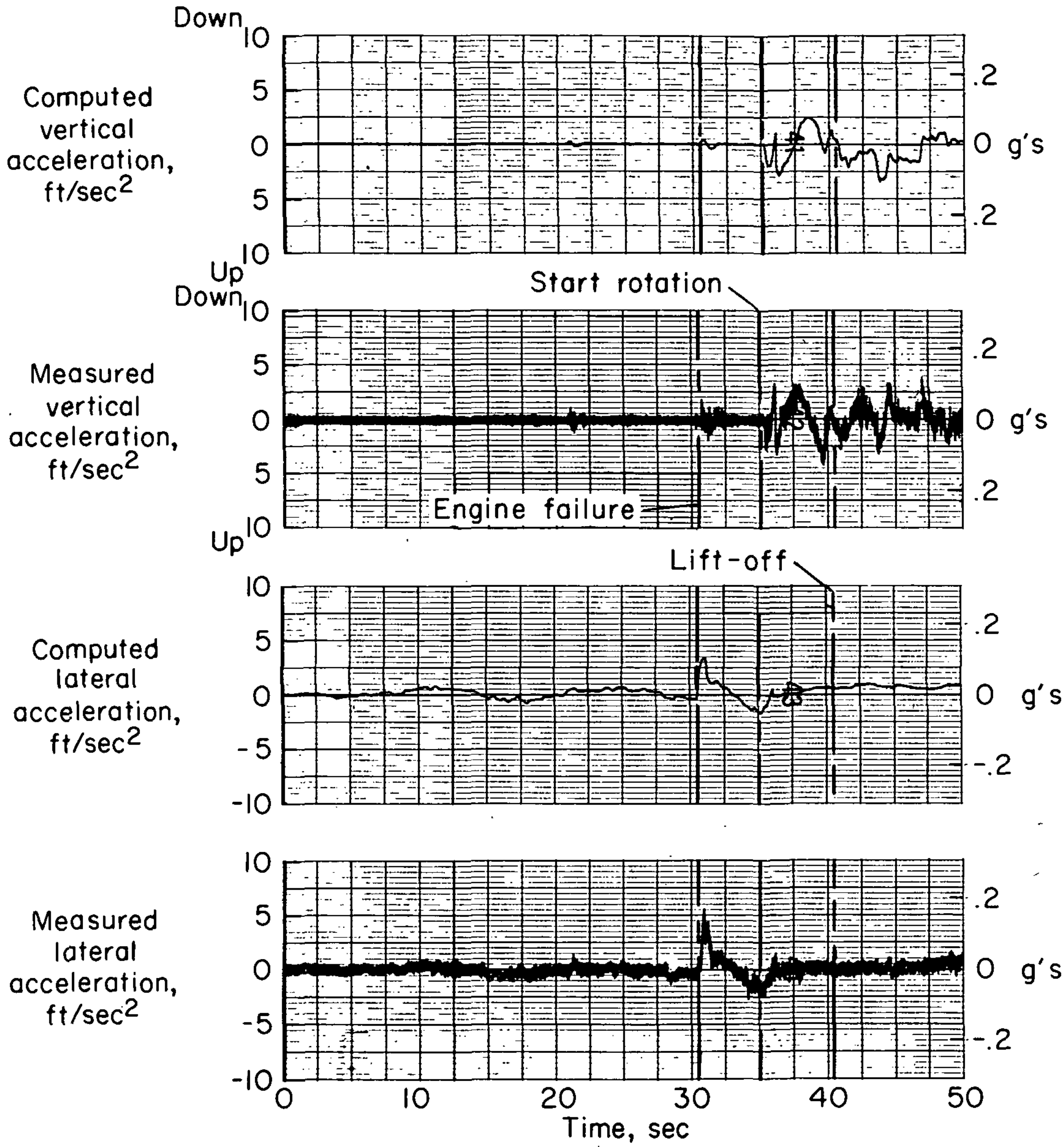


Figure 30.– Effect of rotation speed abuse, ΔV_R, on measured takeoff distance to the 10.7-m (35 ft) height, maximum takeoff gross weight.



(a) Comparison of computed and measured accelerations during a Dutch roll oscillation.

Figure 31.– Fidelity of the simulator motion system.



(b) Accelerations at the pilot's station during a one–engine–inoperative takeoff with the RJT.

Figure 31.– Concluded.

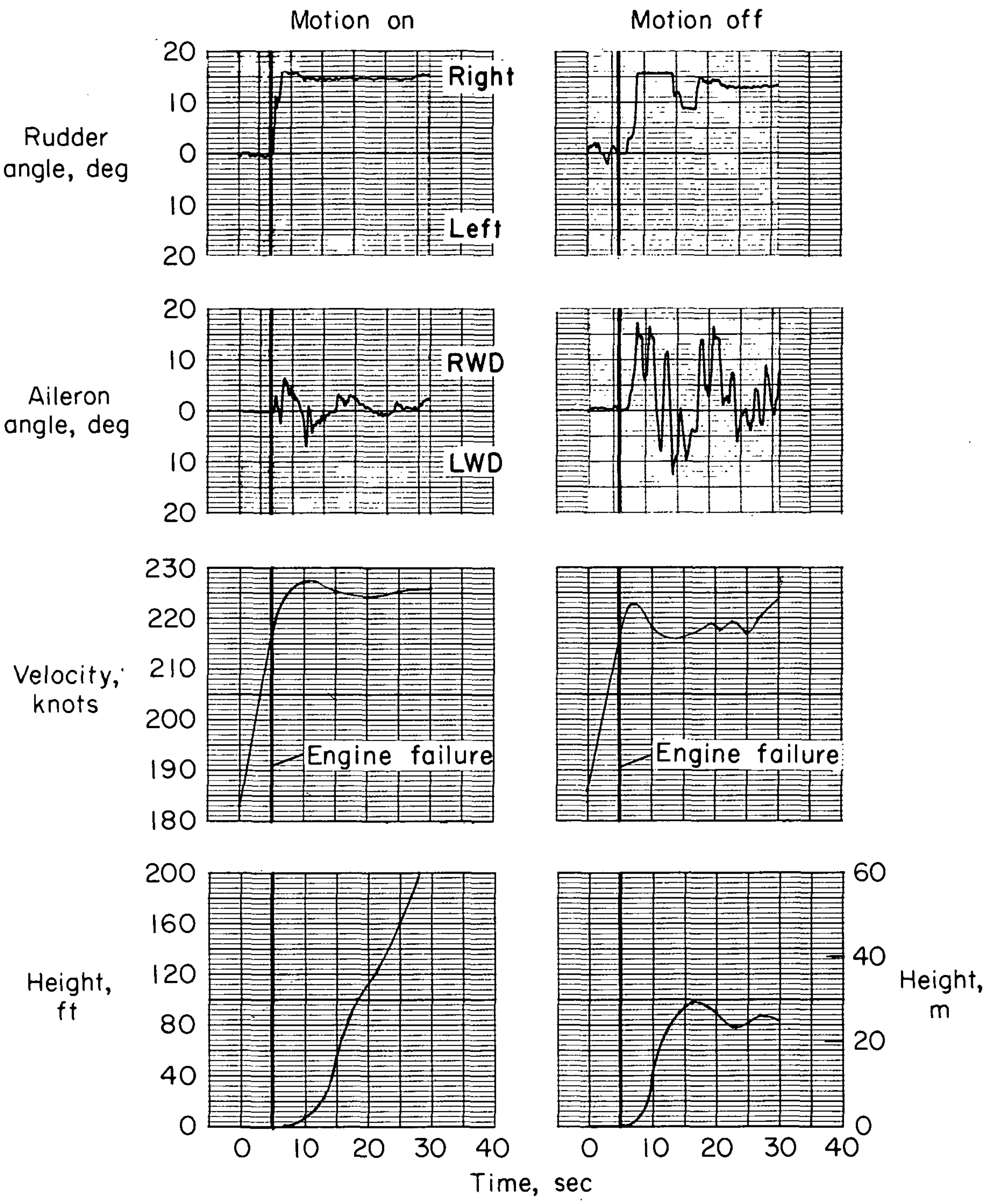


Figure 32.– Effect of motion on controllability of an SST takeoff with an outboard engine failure near lift-off.

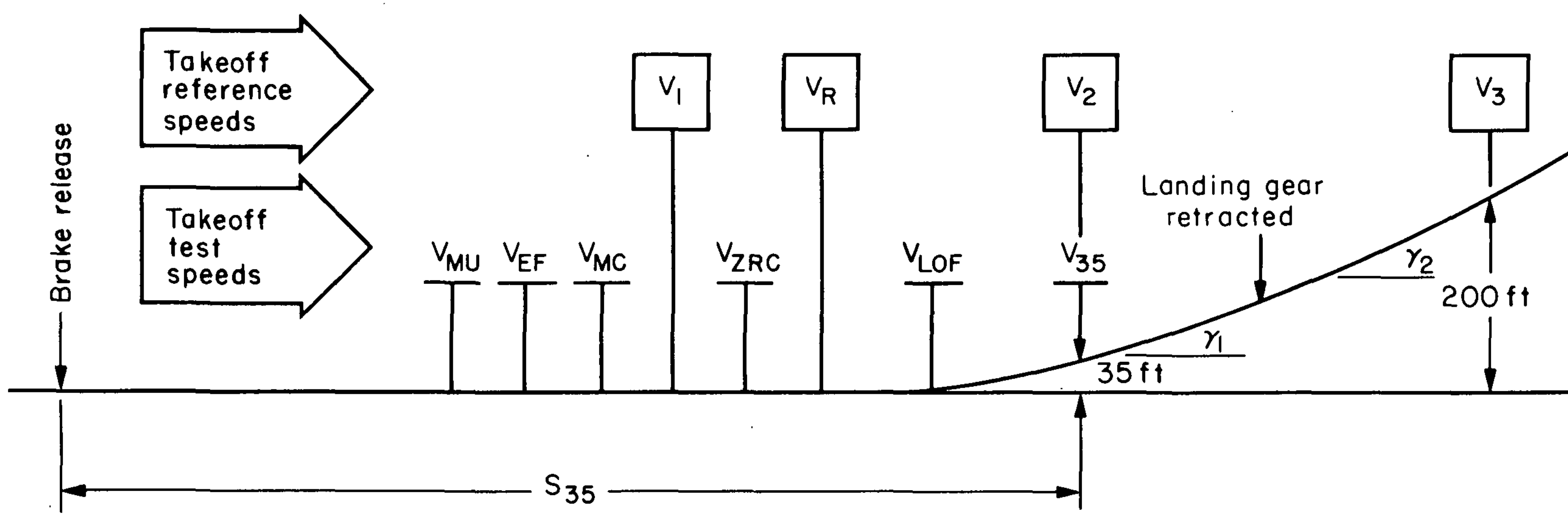


Figure 33.– Summary of takeoff speed and takeoff distance relations.

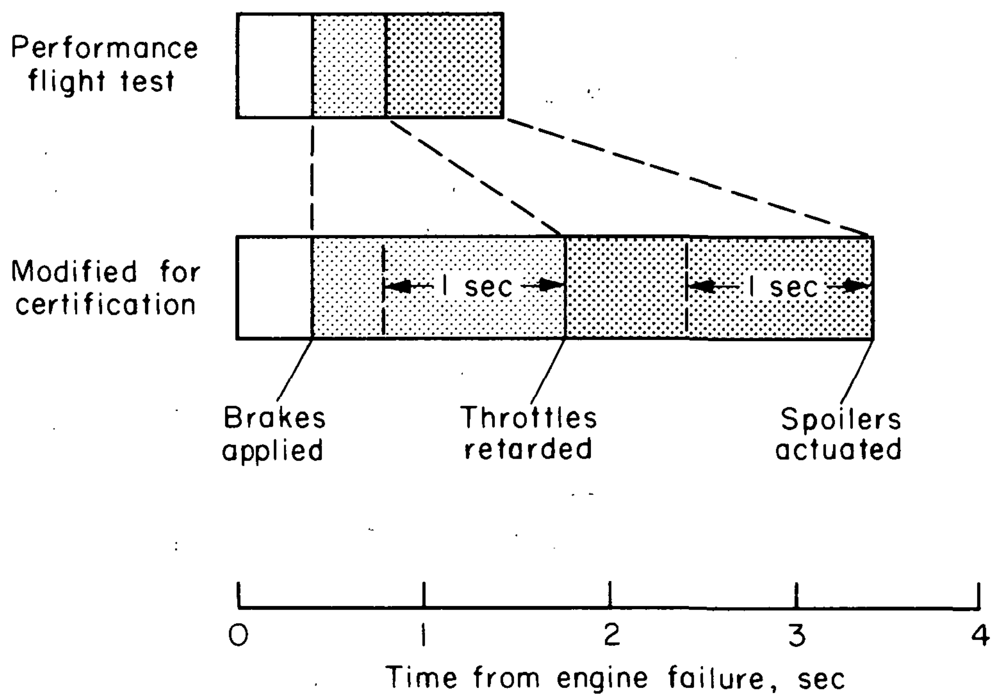


Figure 34.– Accelerate-stop pilot action times. Example of method used in determining transition time during certification.

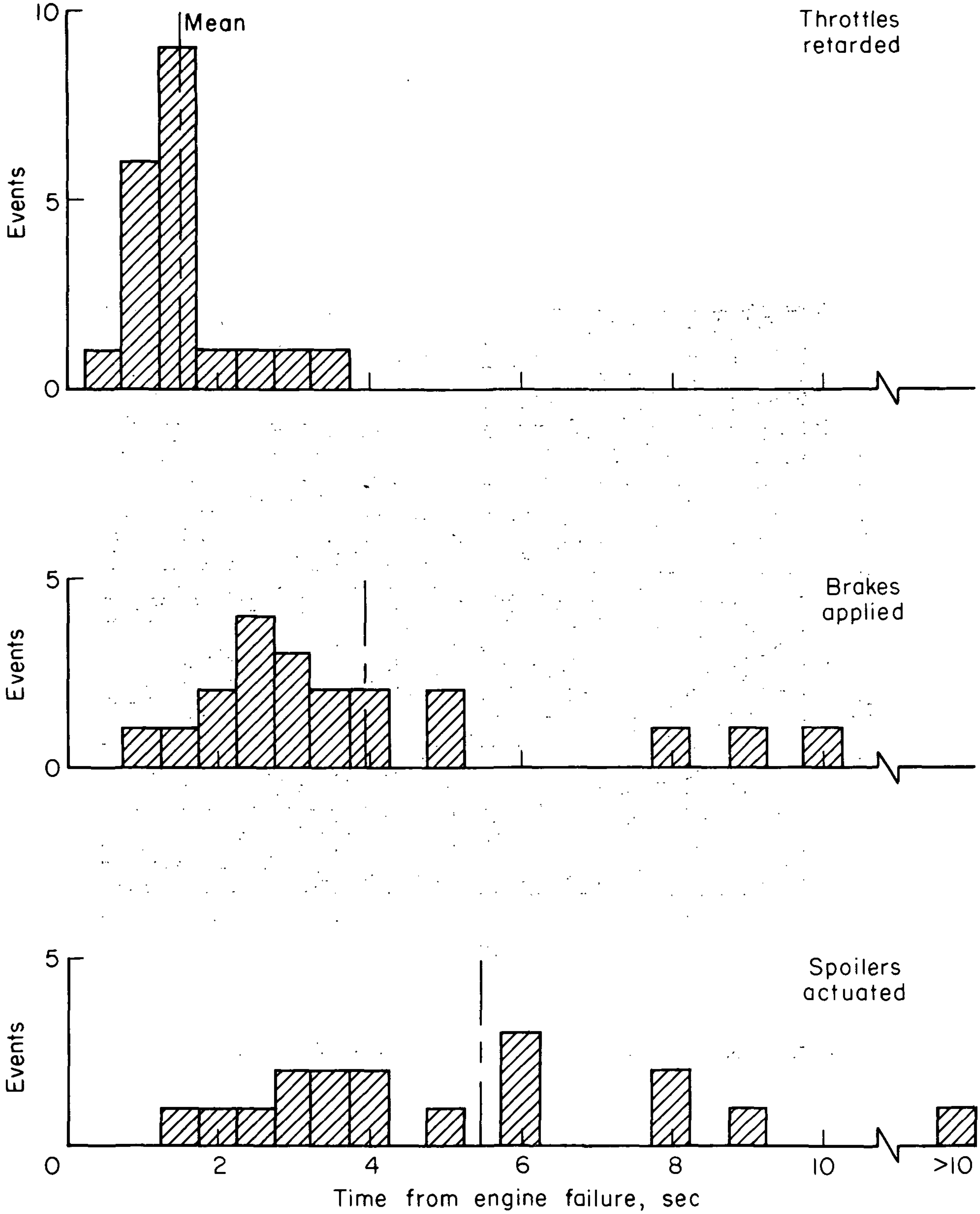


Figure 35.– Timing of pilots' control actions during simulated refused takeoffs.

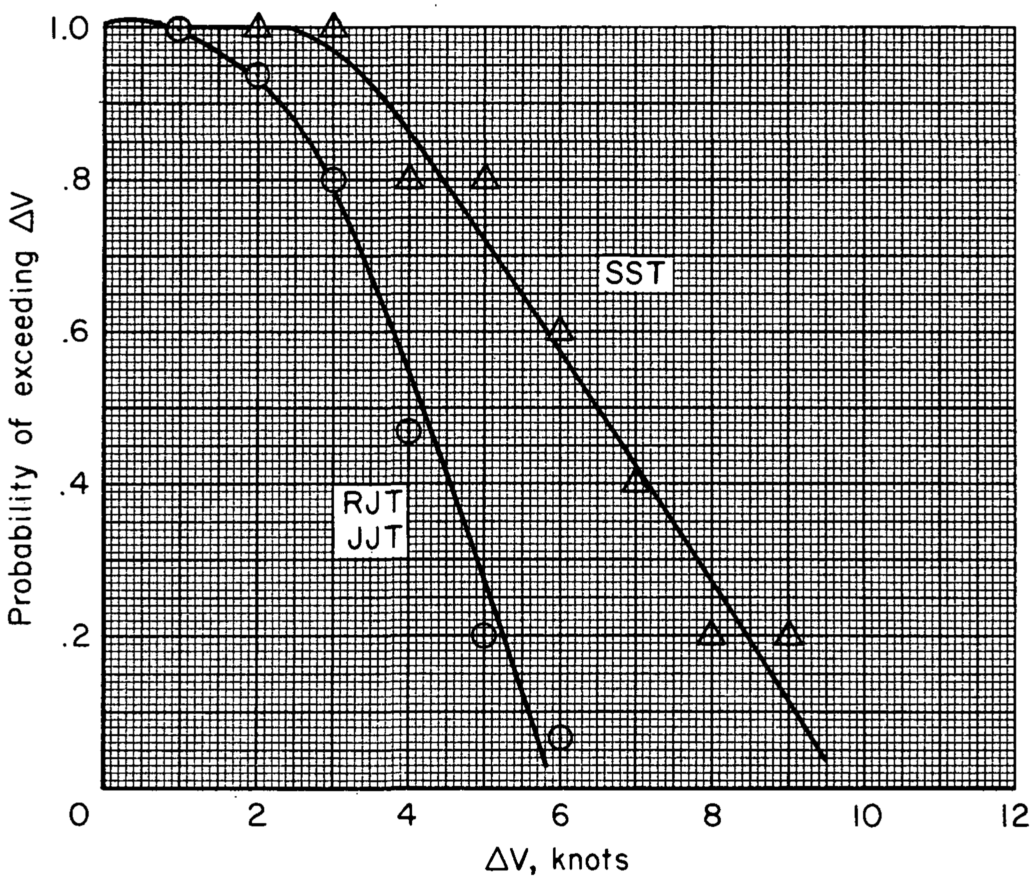


Figure 36.– Speed overshoots after engine failure from simulated refused takeoffs.

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