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SIMULATION STUDIES OF SOME SUPERSONIC TRANSPORT INSTRUMENTATION REQUIREMENTS AND OPERATING PROBLEMS

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SUMMARY

Results pertinent to some supersonic transport (SST) flight instrumentation requirements and operating problems are presented. The results were obtained during departures and arrivals in simulated operations in air traffic control (ATC) environments representing both present-day systems and future concepts and in some special tests. An SST airplane flight simulator and the Federal Aviation Administration's ATC simulation facilities were used to create the real-time simulations. Airline crews operated the SST simulator and experienced air traffic controllers operated the ATC simulation facilities. The tests were conducted under instrument flight rules (IFR) with two design study configurations of the SST.

In the tests, conventional flight instrumentation was found to be inadequate at supersonic speeds for vertical control in climbs and descents. Provision of a climb schedule mode on the flight director and a more sensitive pitch-attitude indicator were considered to be required improvements. The more sensitive pitch-attitude indicator was also considered to be a requirement for guidance in cruise. In transition from climb to cruise, incorrect thrust reduction techniques were found to result in a serious loss of speed to the extent that only by descending could the SST be accelerated to cruising speed. Provision of an automatic speed control for the transition from climb to cruise appears to be desirable. In the letdown, guidance provided on the flight director reduced the altitude variation at the holding point to less than one-quarter that with conventional guidance. The pilots indicated that the letdown guidance was very helpful. With reference to the problem of estimating time of arrival, a representative vertical wind profile was found to affect descent time by as much as 6 or 7 minutes compared with no-wind conditions. Comparison of the flight paths of an exploratory noise-abatement procedure in which a high climb speed and early flap retraction was used and the conventional noise-abatement procedure indicated that for the exploratory procedure, the level of community noise would be higher up to about 5.5 nautical miles from start of take-off. Beyond this distance, this procedure would result in lower community noise levels.

In SST operations, passengers will be subjected to considerable more time at higher fore-and-aft acceleration levels than in present subsonic jet transport operations; consequently, there may exist an increased stimulation for passenger discomfort effects.

INTRODUCTION

The primary results from a cooperative NASA-FAA simulation program of the supersonic transport (SST) in the air traffic control (ATC) system have been reported in references 1 and 2. The SST-ATC program consisted of a real-time simulation of two design study configurations of the SST in ATC environments representing present-day and future systems in such terminal areas as New York and Los Angeles. Airline crews flew the SST aircraft flight simulator, and experienced air traffic controllers operated the ATC facilities.

During the course of the SST-ATC program, some results pertinent to SST flight instrumentation requirements and operating problems, including flight-path control, were obtained. These results were determined from both climb and descent operations in the SST-ATC program as well as from some special tests. This report presents the results which include pilot evaluation of various types of basic flight instruments; operating problems including flight-path control guidance requirements in subsonic and supersonic speed climbs, in transition from climb to cruise, during cruise, and in descents; and definition of other operating problems involving the effect of wind on descent time, noise-abatement procedures, and fore-and-aft acceleration on passengers.

SYMBOLS

g	acceleration due to gravity, 32.2 ft/sec^2 (9.81 m/sec^2)
M	Mach number
M_{cruise}	cruise Mach number
M_{MO}	maximum operating limit Mach number
Δp	sonic-boom overpressure level, lbf/ft^2 (N/m^2)
V_2	take-off safety speed, knots

α	angle of attack, deg
$(T/W)_{TO}$	thrust-weight ratio at take-off

Notations:

A/B	afterburner
ATC	air traffic control
CRT	cathode ray tube
ETA	estimated time of arrival
FAA	Federal Aviation Administration
IFR	instrument flight rules
KIAS	indicated airspeed, knots
SJT	subsonic jet transport
SST	supersonic transport
VHF	very high frequency
VOR	VHF omni-range radio navigation station

SST SIMULATION

The SST was simulated by use of a fixed-base airplane flight simulator. The flight compartment of the simulator (fig. 1) was representative of current jet transport airplanes, with stations for captain, first officer, and flight engineer. Airplane control was accomplished through conventional control column, rudder pedals, throttles, and trimming arrangements. The flight controls had linear force gradients with positive centering. Because of the lack of acceleration cues in the fixed-base simulator, a flashing red light triggered by a deviation of +0.2g or -0.2g in normal acceleration from the 1.0g unaccelerated flight condition was used on the flight instrument panel to alert the pilot to the onset of undesirable (from a passenger viewpoint) g-level operations.

The basic flight instrumentation was somewhat different for each of the several operating problem investigations reported herein. The instrumentation was varied to reflect improvement suggested by the pilots and to allow study of various arrangements of information content and presentation. Displays having various combinations of drum, counter, and pointer indicators, vertical-scale moving-tape type of instruments, and vertical-scale moving-pointer instruments were utilized. Examples of the various types of displays are shown in the photographs of the captain's and first officer's flight instrument panels (fig. 2). In each case, the flight instrumentation included a modern flight director system. The characteristics of the flight instrumentation shown on the captain's instrument panel in figure 2(a) are given in table I. Special flight instrumentation included

TABLE I.- CHARACTERISTICS OF CAPTAIN'S FLIGHT INSTRUMENTATION

Name of instrument	Type of instrument	Size*		Type indication	Instrument quantity range	Instrument scale	Smallest scale division	Smallest readable increment
		in.	cm					
Airspeed	Round	3	7.62	Pointer Drum	50 to 650 knots 0 to 100 knots	100 knots/1.5 in. 10 knots/0.5 in.	10 knots 2 knots	5 knots 1 knot
Mach meter	Round	3	7.62	Pointer Digital	M = 0 to M = 4.0 M = 0 to M = 4.0	1.0M/1.5 in. 0.00	0.50M 0.01M	0.1M 0.01M
Altimeter	Round	3	7.62	Pointer Counter drum	0 to 99 000 ft 0 to 99.0 ft	100 ft/1.5 in. 00.0 ft × 10^3	20 ft 100 ft	10 ft --------
Vertical velocity	Moving tape	5	12.70	Lubber line	±25 000 ft/min	1000 ft/min/in.	100 ft/min between ±1000 ft/min	50 ft/min
True airspeed	Round	2	5.08	Digital	0 to 9999 knots			
Ground speed	Round	2	5.08	Digital	0 to 2000 knots			
Total air temperature	Round	3	7.62	Pointer	0 to 600° F	100° F/in.	50° F	10° F
Angle of attack	Round	2	5.08	Pointer	-10° to +30°	5°/0.5 in.	1°	0.5°
Drift angle	Round	3	7.62	Pointer	40° left 40° right	10°/in.	2°	1°
Angle of sideslip	Round	2	5.08	Pointer	10° left 10° right	2°/0.5 in.	1°	0.5°
Wing sweep	Round	3	7.62	Pointer	0 to 75° right and left	30°/in.	5°	2°
Longitudinal acceleration	Vertical	3	7.62	Moving index	±0.4g	0.3g/in.	0.05g	0.01
Normal acceleration	Fixed tape	3	7.62	Moving index	-1 to +4g	2.0g/in.	0.5g	0.1g
Slow-up point	Round	3	7.62	Pointer	0 to 100 n. mi.	20 n. mi./in.	5 n. mi.	1 n. mi.
Flight-director attitude indicator:	Round	5	12.70	Horizon lubber line				
(a) Normal mode					±60°	10°/0.5 in.	5°	2.5°
(b) Sensitive mode					±12°	2°/0.5 in.	1°	0.5°

*Diameter of round dial; height of visible tape.

a slow-up point indicator (miles to go to point for reduction in power to flight idle) used as part of the descent guidance in one set of tests, and a wing-sweep angle indicator used in tests of an SST configuration with a variable-sweep wing. For some of the tests, a 5-inch-diameter (12.7 cm) cathode ray tube (CRT) was used to present by means of a moving spot of light the airplane's progress relative to the climb and descent speed schedules. The speed schedules and operating limit boundaries were indicated by means of transparent overlays (fig. 3) mounted on the CRT face. The CRT had a face with a high-persistence coating so that the Mach number-altitude profile history was retained for the duration of the climb or descent. Because of lack of instrument panel space, the CRT was mounted on the glare shield about 6 inches (15.2 cm) to the left of the captain's line of sight when looking directly forward. Also, as indicated in table I, the attitude indicator of each flight director system was modified to allow selection of a sensitive pitch-attitude mode in which the movement of the indicator for each degree of pitch-attitude change was increased by a factor of five. The attitude-indicator face was modified in each case to incorporate dual scales for the normal and sensitive modes similar to the illustration in figure 4.

The characteristics of the SST were programed on five analog computers. Equations for six degrees of freedom were used in the representation of the airplane motions. The characteristics of the engines and other aircraft systems were also programed in the computers for simulation. The United States SST design study configurations considered to be optimum at the time of each investigation were used; therefore, both fixed double-delta wing and variable-sweep wing configurations are represented in these studies. The four engines for each configuration were equipped with thrust augmenters. The ranges of basic airplane characteristic values for the several configurations used are given in table II. The range of $(T/W)_{TO}$ values include only maximum unaugmented thrust conditions for the variable-sweep-wing configurations but include both maximum unaugmented and maximum augmented thrust conditions for the fixed double-delta configurations. The minimum transonic acceleration values given are for maximum augmentation operations along a Mach number-altitude profile dictated by a sonic-boom overpressure limit on the ground of 2.0 lbf/ft^2 (95.7 N/m^2) for domestic configurations and 2.5 lbf/ft^2 (119.7 N/m^2) for international configurations. The wing-loading values are for the take-off condition. For all configurations, the basic aircraft damping was augmented about all three axes to provide satisfactory handling qualities.

TABLE II.- SST CHARACTERISTICS

Basic configuration	$(T/W)_{TO}$	Minimum transonic acceleration*		Wing loading	
		ft/sec^2	m/sec^2	lb/sq ft	kN/m^2
Variable sweep	0.27 to 0.32	1.3 to 3.5	0.40 to 1.07	63 to 107	3.0 to 5.1
Fixed double-delta wing	0.32 to 0.40*	1.4 to 2.3	0.43 to 0.70	47 to 56	2.2 to 2.7

*With full augmentation.

TESTS

Most of the tests were made as a part of the departure and arrival operations in the SST-ATC program (refs. 1 and 2), a simulation program designed to study in real time the problems for the SST in present-day and future ATC systems. In this program, airline crews flew the SST simulator in terminal area environments simulating operations in the air traffic control system under IFR conditions. The tests made as part of this SST-ATC program included a study of the effect of wind on descent time, a study of the effectiveness of a letdown computer coupled to the flight director for descent guidance for a prescribed altitude at a given ground location, and a study and comparison with subsonic jet operations of the fore-and-aft accelerations experienced by the passengers in climb and descent operations. Also during the SST-ATC program, pilot evaluations of various types and arrangements of flight instruments were made. As part of this evaluation, some of the departure and arrival operations were flown from the first officer's seat.

The Mach number-altitude profiles used in the climb and descent operations are given in figures 5 and 6. In the climbs, maximum unaugmented thrust was used for takeoff and climbout. Thrust was reduced following climbout, however, in order to hold the airspeed between 200 and 250 KIAS during the large heading changes and during step-climb operations required in terminal area maneuvering. During the climb, full augmented thrust was applied at about 31 000 feet (9.45 km), was continued until the approach to cruising conditions, and then it was reduced. The descents were made with flight-idle thrust.

Some tests separate from the SST-ATC program were also made. These tests included a study of two noise-abatement procedures, a study of the effectiveness of a sensitive pitch mode on the pitch-attitude indicator for altitude control in cruise, a study of energy management in transition from climb to cruise conditions, and a study of the effectiveness of the flight director for control of the altitude-speed schedule in the supersonic acceleration part of the climb.

For all the tests, manual inputs were used for the control of the flight path. In the tests conducted as part of the SST-ATC program, the basic horizontal and vertical navigation guidance was provided by the flight director system. For vertical guidance along the sonic-boom overpressure-limit boundary, the flight-director command element of the attitude-director indicator was programed to display the pitch input required to guide the aircraft to and maintain the Mach number-altitude schedule.

RESULTS AND DISCUSSION

Flight Instrumentation

The basic flight-path control instrumentation (Mach number, airspeed, altitude, and vertical speed) provided on both the captain's and first officer's panels (fig. 2 and table I) was generally considered to be satisfactory by the pilots for the climb and descent operations performed in the SST-ATC program (refs. 1 and 2). Most of the airline pilots preferred the round-dial displays of the captain's panel (similar to present airline flight instrumentation) to the vertical-scale instrumentation of the first officer's panel. When the pilots were questioned in detail as to the reason for this preference, their general conclusion was that it was due to long training, familiarity with, and use of the round-dial displays compared with the relatively short exposure time and experience with the vertical-scale instruments. Some of the pilots were of the opinion that if the vertical-scale type instrumentation had been developed first and utilized for years as were the round-dial type, the vertical-scale instruments would probably be preferred to the round-dial type, or just opposite the present preference, and for the same reason, that is, long familiarity and use. Of the types of round-dial displays used during the tests, the pilots preferred the drum and pointer or counter and pointer instruments over the simple pointer instruments for displays of the basic flight information because such instruments provided both precise reading on the drum or counter and trend information with the pointer movement. (A counter and pointer instrument for vertical velocity however was not tested.) The vertical-scale (moving-tape) display of vertical velocity shown on the captain's panel (fig. 2(a)) was found to provide both acceptable sensitivity and sufficient range for SST operations. Provision of sufficient range (up to 25 000 ft/min (7.6 km/min)) with acceptable sensitivity (especially near zero reading) on a conventional round display was found to be impractical even with nonlinear scaling. The moving-tape display was generally well liked, except that for rates of climb or descent at which the scale zero was out of sight (above about 2500 ft/min (0.76 km/min)), approximate values could not be ascertained at a glance by noting the relative position of the scale zero to the index as is possible by comparison of needle position with the zero reading in the conventional round-dial display.

For horizontal navigation, the conventional flight-director guidance used on both panels (with inputs from the simulated VOR system) was generally considered to be satisfactory. Because of the large variation in turning radius between subsonic and supersonic speeds, however, it would probably be desirable to provide a variable gain schedule on the lead distance for initiation of a turn which is a function of Mach number in order to prevent large overshoots of the course in turns at supersonic speeds. In addition to the flight-director guidance, a pictorial navigation display was used in some of the departure operations to provide the capability of off-airway navigation (ref. 3). The pilots indicated that this display was an excellent navigation aid.

For vertical flight-path control in climbs and descents, the conventional instrumentation was found to be inadequate. Provision of a climb-schedule mode on the flight director and a more sensitive pitch attitude indicator at supersonic speeds were considered to be required improvements. A CRT display of the airplane's progress relative to the climb and descent schedules and operating limit boundaries (fig. 3) was not considered to be satisfactory as a primary vertical navigation display but was considered to be useful as a backup display for flight-director guidance. The requirements for improved vertical navigation displays as well as for other flight-path control problems are discussed in some of the following sections.

Operating Problems

Flight-path guidance in supersonic speed climb.- The climb schedule for the SST was largely defined by the allowable sonic-boom overpressure level. (See figs. 5 and 6.) For maximum flight efficiency, this schedule must be followed as closely as possible. Flight-path control at these speeds is difficult because the airplane pitch attitude must be controlled more precisely than at subsonic speeds in order to hold or adjust the vertical speed of the aircraft. Further, flight-path changes must be made almost entirely through the interchange of altitude and speed along the climb profile. (The low excess-thrust capability precludes making changes in power for such control.) Vertical flight-path control was also found to be difficult because none of the conventional flight instrument indications are constant for flight along this climb schedule. For guidance, the pilots were first given a series of about a dozen Mach number-altitude points which defined the scheduled profile. With this guidance, the pilots had difficulty following the profile and reported that the workload was too high for routine operations. As a possible means of providing improved flight-path guidance for the supersonic speed climb, the flight-director element of the attitude indicator was programed to display the pitch correction required to guide the airplane to and maintain the Mach number-altitude schedule.

A comparison of the pilots' ability to control the flight path with the two types of guidance is shown in figure 7 for several climbs. The results are presented as the measured deviation in altitude from the scheduled profile over the Mach number range from 1.25 to 2.0. The results show that without flight-director guidance, altitude deviations as large as 2000 feet (609.6 m) occurred and that variations between climbs formed a band of altitude deviation about 1000 feet (304.8 m) wide over most of the Mach number range. Most of the altitude deviations were negative (actual flight path below the intended flight profile). Flight in this region would produce sonic-boom overpressure levels greater than the allowable value. The tendency for the pilots to fly below the profile is believed to be associated with the higher thrust available for acceleration and climb under these conditions. In contrast, the results with flight-director guidance (bottom of fig. 7) show that the altitude deviations never exceeded 600 feet (183 m) and were, on the average, less than ±300 feet (±91.5 m). The somewhat higher altitude deviations at the higher Mach numbers are believed to have occurred because the gain used in the flight-director guidance systems was optimized for the best flight-path control at the lower supersonic Mach numbers where the excess thrust (over drag) characteristics are minimum. The pilots reported that the use of flight-director guidance for vertical flight-path control along a specific profile schedule made the task much easier and that the workload was reduced to a level satisfactory for routine operations.

Transition from climb to cruise.- To effect an acceptable transition from climbing flight to cruising flight for the SST requires control of large amounts of vertical and horizontal momentum in a manner to achieve cruise conditions without large undershoots or overshoots in either altitude or speed. Pitching maneuvers which can be used are limited by acceptable acceleration limits from passenger comfort considerations. Management of the energy involved in this process is affected both by changes in attitude to interchange potential and kinetic energy and by changes in thrust.

An early simulator study of operating problems in connection with the SST mission profile (ref. 4) indicated that when a climb profile was used in which approximately the last 10 000 feet (3048 m) was scheduled to be flown at cruise speed, the excess thrust available with full power resulted in very high rates of climb. Timely reductions of full power to cruise power was necessary about 8000 feet (2438 m) below cruise altitude to prevent overshoot of cruise altitude or cruise speed. The difficulty of effecting the transition from climb to cruise was found to be reduced in the tests of reference 1 by use of an adjusted climb schedule in which the last 13 000 feet (3962 m) to 14 000 feet (4267 m) were flown at the indicated airspeed corresponding to the cruise Mach number at cruise altitude. This procedure reduced the high rates of climb during the transition and provided more time for the transition. Management of the energy was also improved by provision of vertical flight-path guidance. For this guidance, the flight-direction element of the attitude indicator was programed to display the pitch correction required to guide the aircraft to and maintain the Mach number-altitude schedule. With this arrangement, transitions from climb to cruise were made on a routine basis in the tests of references 1 and 2 with overspeeds and overshoots in altitude occurring only infrequently and generally being small in value.

Because of concern over the ability to control the transition from climb to cruise in the case of guidance failure, a few tests were made in which transitions were effected without guidance. Of special concern was the possibility of attaining cruise altitude at a speed so far below cruise speed that the excess thrust available for acceleration was zero or negative because of ram air loss. To examine this operating problem, tests were made without flight-director guidance consisting of transitions initiated at about 60 000 feet

(18.288 km) and M = 2.6 and ending at cruise conditions of 71 000 feet (21.640 km) and M = 2.7. For the tests, the pilot induced high rates of climb or reductions of thrust starting from 3000 feet (914 m) to 6000 feet (1829 m) below cruise altitude in an attempt to simulate overcorrections of an apparent overspeeding situation.

The results of these tests are shown in figure 8 as time histories of altitude, Mach number, rate of climb, and thrust. Examples of results from transitions made with the control of the apparent overspeeding situation attempted by inducing high rates of climb are shown in parts (a), (b), and (c) of figure 8. These results show that for procedures varying from rate-of-climb buildup to 4000 ft/min (1219 m/min) initiated 3000 feet (914 m) below cruise altitude to rate-of-climb buildup to 7000 ft/min (2134 m/min) initiated 5000 feet (1524 m) below cruise altitude, only small reversals in speed buildup and small reductions in speed occurred. In all cases, cruise speed was attained within 1 minute after cruise altitude was reached. These results indicate that in the transition from climb to cruise, serious loss of speed caused by application of unnecessarily high rates of climb does not appear to constitute an operational problem.

An example of a transition with the control of the apparent overspeeding situation attempted by both a moderate rate of climb and a thrust reduction initiated 6000 feet (1829 m) below cruise altitude is shown in figure 8(d). The approximate 1-minute period of thrust reduction resulted in a reversal of speed buildup and loss of speed to a Mach number of about 2.62 at an altitude of about 1000 feet (305 m) below cruise altitude. Although maximum available thrust was reapplied at this time, the airplane could not be significantly accelerated at this altitude. The lower excess thrust capability for this flight condition compared with cruise conditions results from the reduced amount of ram air available to the engines at the lower Mach number. In this situation, only by descending could sufficient excess thrust be developed for acceleration to the speed-altitude climb schedule. The results in figure 8(d) illustrate the importance of insuring correct thrust and speed management during the transition from climb to cruise. In consideration of the number of factors which can affect thrust management in addition to pilot ability such as hot-day conditions, vertical and horizontal temperature gradients, and turbulent air conditions, the provision of automatic speed control for the transition from climb to cruise for the SST appears to be desirable.

Pitch-attitude guidance in cruise.- The problem of maintaining altitude and speed in cruise flight at supersonic speeds under manual control has been noted in a number of instances both in flight and simulator operations. (For example, see refs. 4 and 5.) Almost continual throttle and pitch-attitude control adjustments were required. In the flight operations (ref. 5), the altitude and Mach number varied by as much as 1600 feet (488 m) and 0.14, respectively, from the target value. The variations in altitude and Mach number were attributed to (1) the fact that the airplane pitch attitude must be controlled more precisely than at lower speeds in order to hold or adjust the vertical speed of the airplane, (2) the short-period and phugoid characteristics, (3) atmospheric condition variations, and (4) phasing of the throttle and pitch-attitude control adjustments made by the pilot. The requirement for increased precision in pitch attitude control at cruise speed arises from the fact that the vertical-speed change for a given attitude change is proportional to the airplane forward velocity. For example, a 1° pitch-attitude change results in vertical-velocity changes of about 800 ft/min (244 m/min) at subsonic jet transport cruise speed and about 3000 ft/min (914 m/min) at $M = 3.0$. When it is considered that present attitude indicators have a reading accuracy of the order of $\pm 1^{\circ}$, the need for improved attitude guidance at supersonic speeds is evident.

To study the pitch-attitude guidance requirements for supersonic speeds, some flights at cruising conditions with the special pitch-attitude indicator shown in figure 4 were performed. The right-hand side of this display was scaled for normal movement (1° attitude change equals 1° ball movement) and had 2° markings from 0 to $\pm 30^{\circ}$ and markings at $\pm 60^{\circ}$. The left-hand side of the display was scaled for sensitive-mode indicator movement (1° attitude change equals 5° ball movement) and had 1° markings to $\pm 18^{\circ}$. A toggle switch allowed selection of the normal or sensitive modes of operation, and an indicator light was illuminated with selection of the sensitive mode. Selection of the sensitive mode increased the voltage to the indicator servo-driven motor by a factor of 5. The dual-scale display arrangement shown was used as a matter of convenience and is not considered to be suitable for flight operations.

Comparative results of about 4 minutes cruising flight (Mach number of 3.0 at 70 000 feet (21.34 km)) with normal and sensitive attitude guidance are shown in figure 9 as time histories of the variations in altitude and normal acceleration. The results indicate that with the sensitive attitude display, the pilot was able to control altitude with a fewer number of deviations and with a fewer number and smaller values of normal acceleration inputs than with the normal attitude display. Although the extent of the excursions in altitude was not significantly reduced by use of the sensitive attitude display, the pilot reported that there was considerably less effort required in controlling altitude with the sensitive attitude display.

Use of comparable dual-scale attitude indicators by airline pilots in the SST-ATC program (refs. 1 and 2) developed a number of pilot comments. The pilots generally agreed that a sensitive attitude display was necessary for manual control at supersonic speeds. An arrangement of individual, separately displayed normal and sensitive scales on the attitude indicator rather than the dual-scale arrangement was suggested to avoid reading errors. Possible problems noted in connection with the use of the sensitive attitude display were: (1) loss of good horizon reference on 8-ball type of attitude indicators at high pitch deflections; (2) loss of attitude reference under turbulent air conditions; and

(3) misinterpretation of scale in use leading to errors in pitch attitude effected in such maneuvers as rotation in take-off and rotation for missed approach climbout. For a few tests, a separate moving-tape display alongside the conventional attitude display was used to present a sensitive pitch-attitude indication. This display had a window approximately 3/4 inch wide (1.9 cm) and 5 inches long (12.7 cm) and a tape-movement sensitivity of 1 inch (2.54 cm) for 2° attitude change. Pilot comments were that this arrangement was not as satisfactory as having the sensitive-attitude indication on the basic attitude display because of the additional scanning required in monitoring and effecting small attitude changes.

Letdown guidance.- In the arrival operations in the SST-ATC program, the vertical navigation problem in letdown from cruise conditions to the holding point was found to be more acute for the SST than for subsonic jet transports because of the greater speed and altitude changes which had to be made and the greater distances involved. Some form of letdown guidance appeared to be necessary to aid the pilot in this task and to insure efficient operations. In SST operations, for example, a 1-minute error in initiation of descent (at $M = 2.7$) results in about a 6-minute increase in time proceeding at 250 knots to the holding point for early descent initiation, or orbiting down to the prescribed altitude at the holding point for late descent initiation. The comparative time for a subsonic jet transport is about 2 minutes.

To study the value of letdown guidance for the SST, guidance was supplied in some of the arrival operations made in the SST-ATC program for (1) the initiation of slowup prior to descent and (2) vertical flight-path control to arrive over the holding point at a prescribed altitude. These guidance functions were obtained from a letdown computer programed to calculate the point at which to initiate slowup and to calculate a glide-slope type path for an approximate constant airspeed descent based on inputs from a simulated onboard navigation system. The distance from present position to the holding point and the desired altitude at the holding point were entered by the pilot into the computer, prior to descent, by means of digital-indicating potentiometers. A clock-type indicator on the instrument panel was used to display the distance remaining to the point at which slowup should be initiated (slowup point indicator, fig. 2(a)). Guidance for the letdown following slowup was provided by the flight-director command bar of the attitude indicator.

Results showing the altitude measured at the holding point relative to the prescribed (target) altitude for descents made with conventional guidance and with letdown guidance are given in figure 10. The stippled areas define the range of values obtained in seven conventional guidance and six letdown guidance descents. The results show that with the letdown guidance the altitude variation at the holding point was less than one-quarter that with conventional guidance. For all the descents with letdown guidance, the altitude at the holding point was above the target altitude. Examination of the ground tracks for these descents indicated that the reason was that the actual distance traveled in the descent was shorter than that programed by the pilot because of greater than normal corner cutting at a turn on the airway system.

Pilot comments on the letdown guidance system ranged from "very helpful" to "necessary." In general, variations in airspeed during the descents were smaller for a given run with the letdown guidance than with conventional guidance (fig. 11); thus, the letdown guidance improved the pilots' ability to control the flight path.

Effect of wind on descent time.- Descent times are a factor in the determination of the estimated time of arrival (ETA) used for air-traffic-control traffic sequencing. Discrepancies in ETA are due primarily to inaccuracies in estimating ground speed, which is affected by wind direction and velocity; these quantities vary widely with altitude and latitude. In the north temperate zone, the prevailing wind is westerly, and the wind velocity generally increases with altitude to values as high as 120 knots at about 40 000 feet (12.19 km). Pilots of commercial subsonic aircraft have had no significant difficulty in estimating valid ETA in their normal operating range below about 40 000 feet (12.19 km) with altitude-wind velocity profiles similar to that in the upper part of figure 12. Altitude-wind surveys over the North Atlantic at higher altitudes (ref. 6) have shown that wind velocity generally decreases from the high values at about 40 000 feet (12.19 km) to near zero values at about 80 000 feet (24.38 km). In descents of United States-Europe missions, the SST, therefore, will generally experience increasing wind velocities from a low value at cruise altitude to a maximum value at about 40 000 feet (12.19 km) and then decreasing wind velocities below 40 000 feet (12.19 km). The altitude-wind velocity profile, however, can vary over a wide range of shapes, the maximum easterly value being as much as 50 to 60 knots at about 40 000 feet (12.19 km).

To explore the effect which wind may have on descent times for the SST, some comparative arrival operations were conducted during the SST-ATC program (refs. 1 and 2) under no-wind and wind conditions. Both head-wind and tail-wind conditions were investigated by using the altitude—wind-velocity profile shown in figure 12. The altitude—wind-velocity profile used was representative of a westerly wind profile with a strong wind at 40 000 feet (12.19 km). The results of the measurements of descent times are shown in figure 12, the stippled areas indicating the range of values measured. With no wind, descent times ranged from about 29 to 32 minutes. With wind, descent times, reflecting both head-wind and tail-wind conditions, ranged from about 24 to 38 minutes. The results indicate that these winds can affect descent times when compared with no-wind conditions by as much as 6 or 7 minutes.

Noise abatement.- The noise-abatement tests were made with a variable-sweep wing configuration having a thrust-weight ratio at take-off of 0.27. Take-offs were made with full unaugmented power with inboard and outboard wing flaps set at 20° and 40°, respectively (designated as $20^{\circ}/40^{\circ}$). Two noise-abatement procedures were investigated. Procedure A, similar to present subsonic jet transport practice, involved use of near-minimum speeds, delayed flap retraction, and a power reduction at 1500 feet (457 m) for a low gradient (V_2 + 20 knots, 500 ft/min (152 m/min)) climb over the noise-sensitive area. Procedure B differed from procedure A by use of higher speeds, full-flap retraction before power reduction, and a steeper climb gradient over the noise-sensitive area. In procedure B, power was reduced to the same level (percent rpm) used in procedure A. The details of the procedures and an example of the altitude-distance profile for each case is given in figure 13.

The results shown in figure 13 indicate as would be expected that the use of higher speeds in procedure B results in a lower climb gradient with attendant lower altitude flight over the initial part of the climb and a greater distance covered before power reduction at 1500 feet (457 m) can be effected. With procedure A, the power was reduced at about 3.75 nautical miles; with procedure B, the power was reduced at about 4.25 nautical miles. Because the noise level on the ground is a function of both the distance to the aircraft and the power setting (ref. 7), the community noise level with procedure B would be greater than that with procedure A over the distance up to about 5.5 nautical miles from start to take-off. The noise level with procedure B would be particularly greater between about 3.75 and 4.25 nautical miles because of the higher power setting in use. Community noise levels beyond about 5.5 nautical miles would be less for procedure B because of the higher climb gradient which can be flown with the same power setting with the flaps retracted. The higher climb gradient for procedure B in this condition results in a shorter distance and time required in the reduced power phase of climbout, that is the distance and time required to climb from 1500 feet (457 m) to 3000 feet (914 m). From an operations standpoint, procedure B was preferred by the pilots because the higher operating speeds provided more speed margin for maneuvering, and the higher climb gradient in the reduced-power phase provided more altitude clearance and less time required in the reduced-power condition.

In summary, for SST noise-abatement procedures with power reduction at 1500 feet (457 m), use of higher climb speeds and earlier flap retraction than present procedures resulted in a flight path on which higher levels of community noise would be developed at distances up to about 5.5 nautical miles from start of take-off. Beyond this distance, these procedures would result in lower community noise levels.

Fore-and-aft acceleration on passengers.- Because of its high thrust-weight ratio, the SST will have higher climb and acceleration capability than present subsonic jet transports. This higher performance capability will allow higher fore-and-aft accelerations to be imposed on the passengers than in present operations. This fact appears to be of significance relative to passenger mobility and to the stimulation that combinations of angular and linear accelerations may have in affecting orientation, producing illusions and false perceptions, and producing motion sickness. (See ref. 8.) The combination of the fore-and-aft acceleration with the angular accelerations of head movements in conversing, for example, can be the stimulus for such passenger discomfort. Little is known of these effects except on healthy male adults such as test pilots. Results of fore-and-aft accelerations measured during representative climb and descent operations with a variable-sweep design study configuration of the SST in the SST-ATC program (refs. 1 and 2) are presented in figure 14. Positive values represent accelerations forcing passengers against the back of the seat and arise from increasing speed and airplane nose-up attitude conditions.

During the take-off and climb, the maximum acceleration occurred following brake release. The large and rapid variations in acceleration between ground level and about 8000 feet (2.44 km) were caused by throttle changes required to keep the airspeed low for terminal area maneuvers and required in step-climb type of operations. The increase in acceleration at about 29 000 feet (8.8 km) was caused by the scheduled change from full unaugmented thrust to full augmented thrust. The acceleration value of 0.13g at the top of climb (67 000 feet (20.4 km)) corresponds to a floor angle of 7.5° for initial cruise conditions. The same acceleration was measured at final cruise conditions (71 000 feet (21.6 km)) just prior to descent and indicated that a floor angle of about 7.5° exists for this SST design throughout the cruise phase.

In the descent, the reduction in acceleration to about 0g at 67 500 feet (20.6 km) reflects the effects of partial thrust reduction and pushover for a constant airspeed descent to this altitude. The increase in acceleration to about 0.06g at this altitude resulted from the combined effects of thrust reduction to flight idle condition and the floor angle increase in the slowdown prior to continuing descent. The large changes in acceleration below 10 000 feet (3.05 km) were caused by changes in attitude and thrust for leveling, slowdown, and final descent operations. The results in figure 14 show that exposure of passengers to significant (greater than 0.1g) fore-and-aft accelerations in SST operations apparently needs consideration only for the climb and cruise phases for an SST design of the type investigated.

A comparison of the exposure time of passengers to fore-and-aft accelerations in take-off and climb for the SST and a subsonic jet transport (SJT) is presented in figure 15. The results are shown as the cumulative time at or above 0.1g levels in acceleration. The results for the SST are from an average of four take-offs and climbs similar to the take-off and climb shown in figure 14. The results for the SJT are an average of fore-and-aft acceleration measurements from an equal number of take-offs and climbs of an airline cargo jet transport. The results show that the exposure time at and above all levels of acceleration is much greater for the SST than for the SJT. Exposure time at or above 0g is about 15 minutes more for the SST, almost double the corresponding time for the SJT, and thus reflects the longer time required to climb to cruise conditions. For the SST, the acceleration level was always above 0.1g in the climb (see fig. 14) because of the combined effects of the high thrust-weight ratio and high floor angles; therefore the exposure level at or above 0.1g is the same as at or above 0g. The exposure times at and above acceleration levels of 0.1g, 0.2g, and 0.3g were about 26, 13, and 2 minutes greater, respectively, for the SST than for the SJT. With regard to mobility, the entire climb for the SST was made at an equivalent floor angle greater than 5.8° and the cruise floor angle is 7.5° whereas the maximum floor angle recommended for pedestrian walkways is about 4.8°; these levels indicate possible difficulties for passengers and crew in using the aisle in both climb and cruise.

These results indicate that for the SST, the passengers will be exposed to considerable more time at higher fore-and-aft acceleration levels in climb and cruise operations than in present subsonic jet transport operations; consequently, there may exist an increased stimulation for passenger discomfort effects.

SUMMARY OF RESULTS

Results pertinent to some supersonic transport (SST) flight instrumentation requirements and operating problems have been presented. The results were obtained during departures and arrivals in simulated operations in air traffic control (ATC) environments representing both present-day systems and future concepts and in some special tests. An SST aircraft flight simulator and the Federal Aviation Administration's ATC simulation facilities were used to create the real-time simulations. The aircraft flight simulator was operated by airline crews and the ATC simulation facilities by experienced air traffic controllers. The tests were conducted under instrument flight conditions with two design study configurations of the SST. The principal results are:

1. The conventional flight instrumentation was found to be inadequate at supersonic speeds for vertical navigation in climbs and descents. Provision of a climb schedule mode on the flight director and a more sensitive pitch attitude indicator were considered to be required improvements. The more sensitive pitch-attitude indicator was also considered to be a requirement for guidance in cruise.

2. Incorrect thrust-reduction technique during transition from climb to cruise was found to result in a serious loss of speed to the extent that only by descending could the SST be accelerated to cruise speed. Provision of automatic speed control for the transition from climb to cruise appears to be desirable.

3. Letdown guidance provided on the flight director reduced the altitude variation at the holding point to less than one-quarter that with conventional guidance. In general, the pilots indicated that the letdown guidance was very helpful.

4. In connection with the problem of estimating time of arrival, a representative vertical wind profile was found to affect descent time by as much as 6 or 7 minutes when compared with no-wind conditions.

5. Comparison of the flight paths of an exploratory noise-abatement procedure in which a high climb speed and early flap retraction was used and the conventional noise-abatement procedure indicated that for the exploratory procedure the level of community noise would be higher up to about 5.5 nautical miles from start to take-off. Beyond this distance, this procedure would result in lower community noise levels.

6. Passengers in SST operations will be subjected to considerable more time at higher fore-and-aft acceleration levels than in present subsonic jet transport operations; consequently, there may exist an increased stimulation for passenger discomfort effects.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., April 24, 1969,
720-05-00-04-23.

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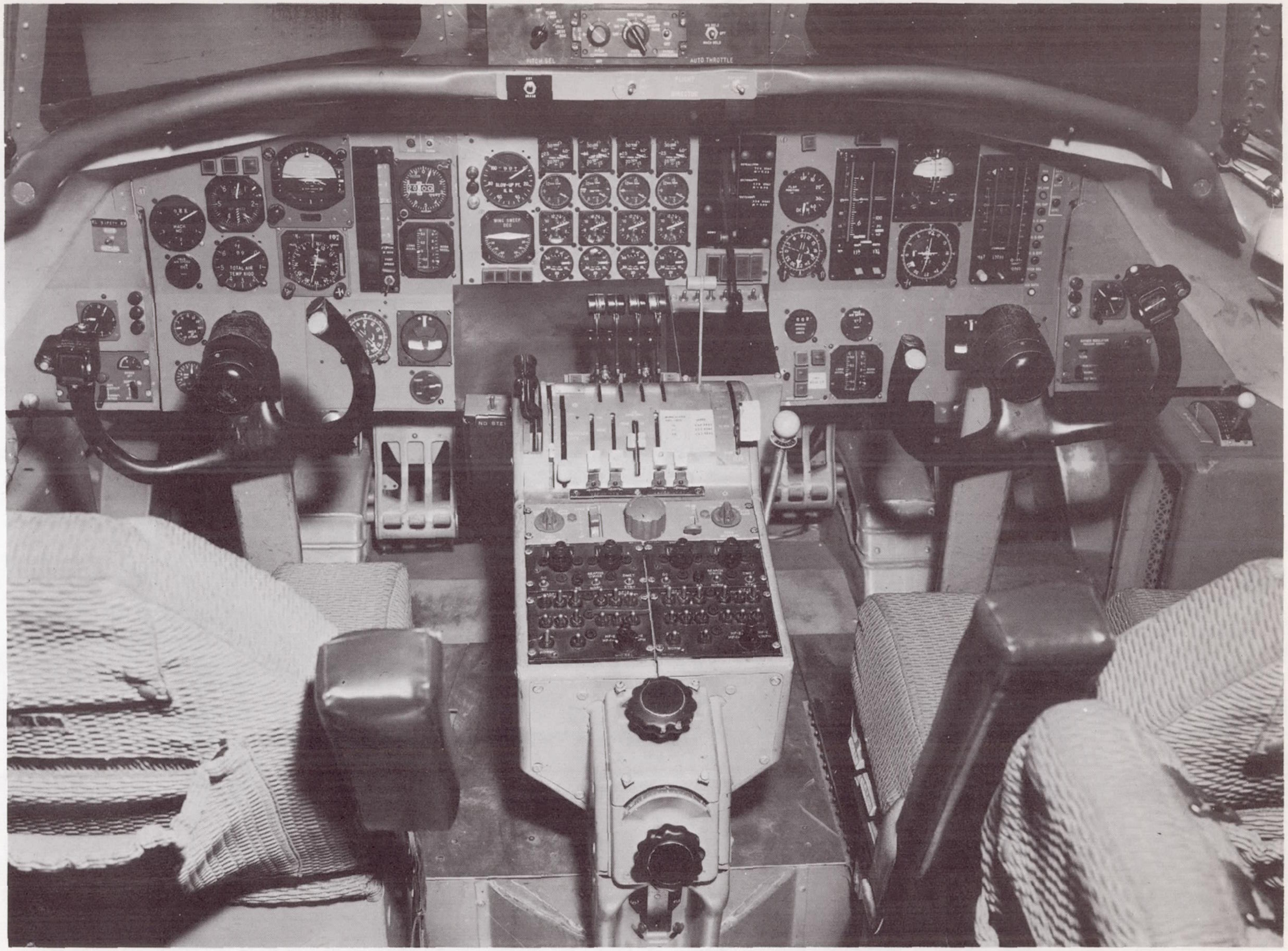
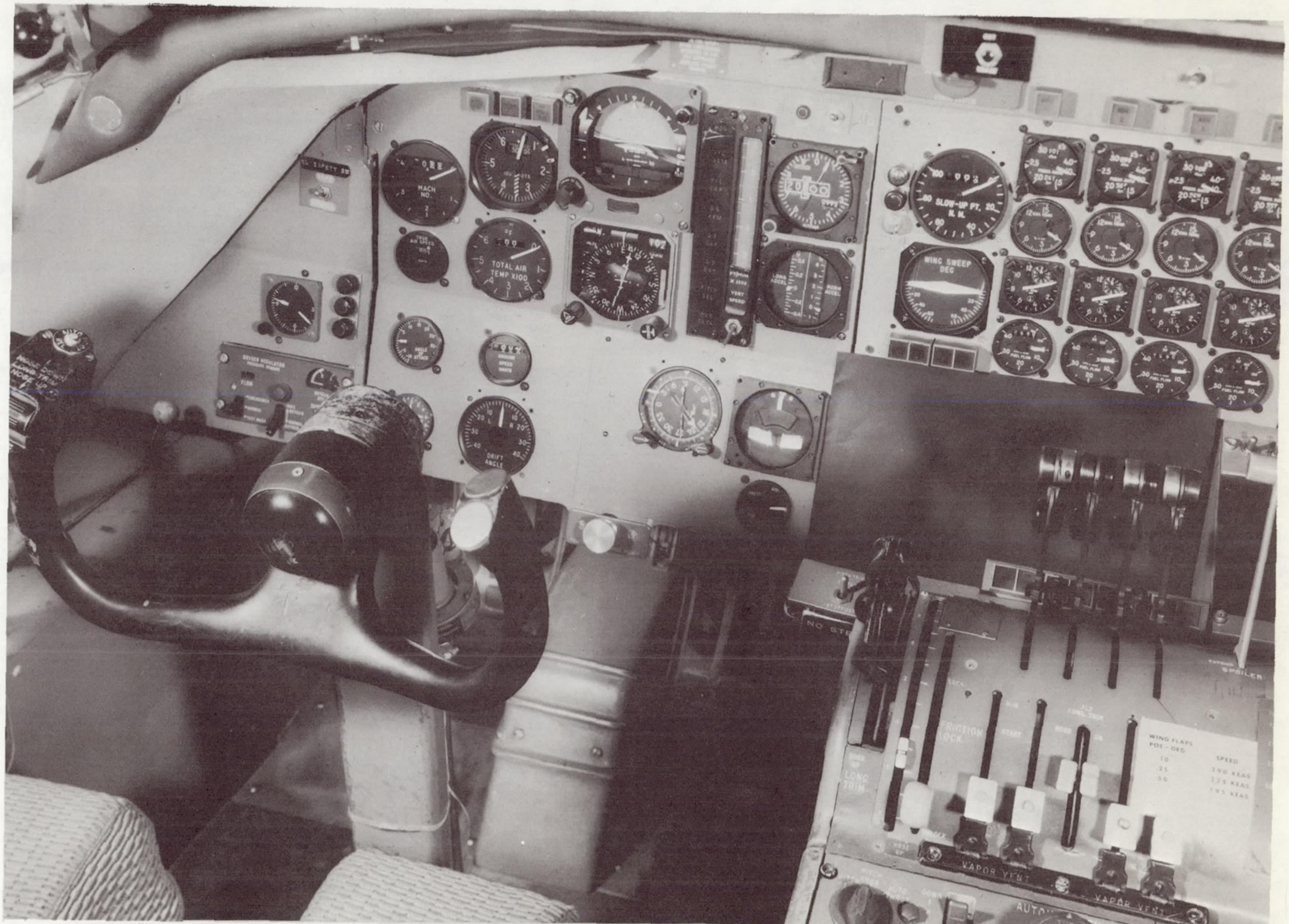


Figure 1.- Fixed-base SST simulator flight compartment.

L-68-4293



(a) Captain's flight instrumentation.

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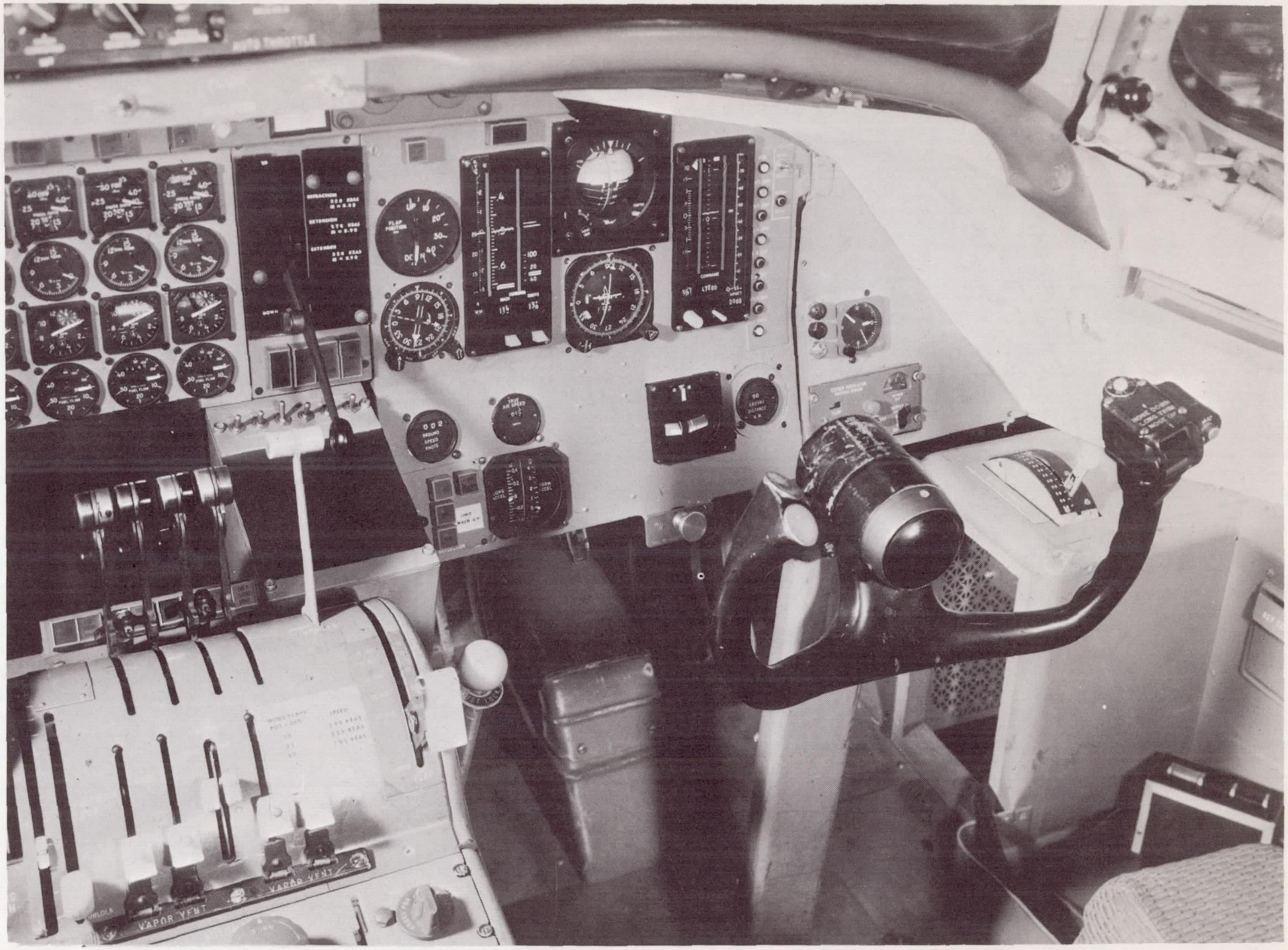
Figure 2.- Instrumentation in SST simulator flight compartment.



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(b) First officer's flight instrumentation.

Figure 2.- Concluded.

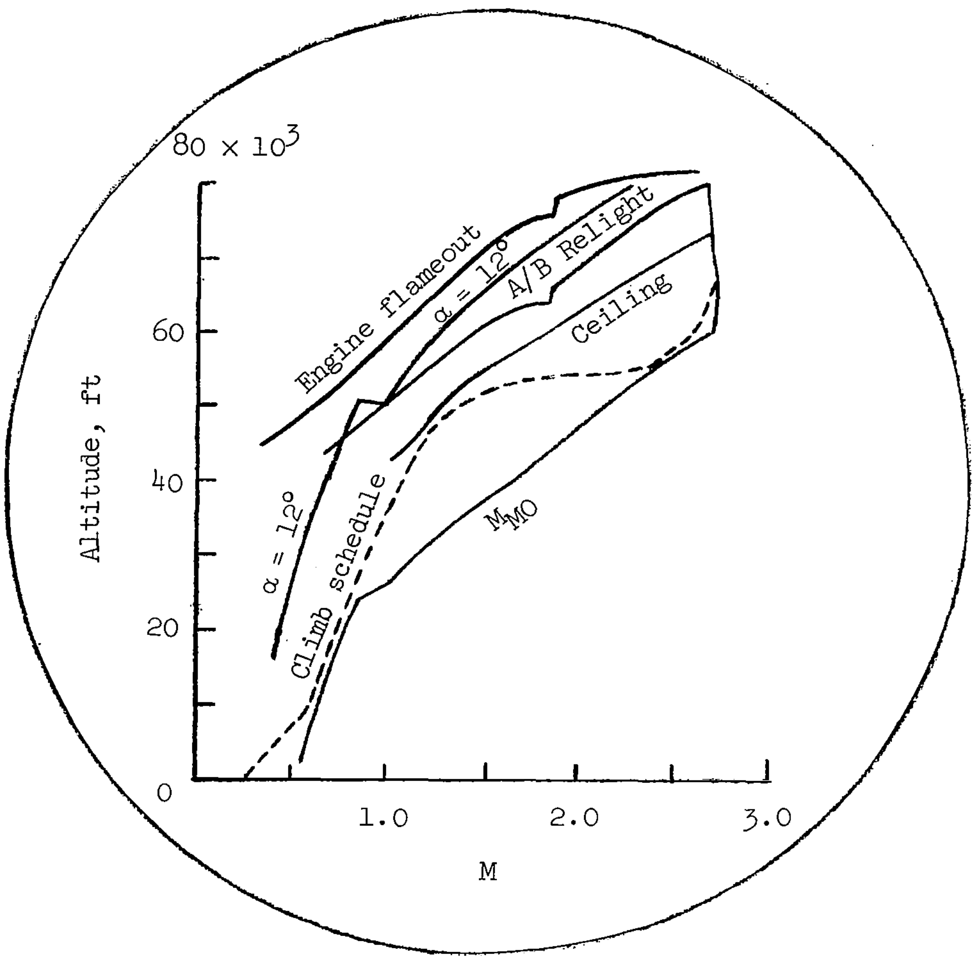


Figure 3.- Full-scale representation of CRT overlay, showing altitude and Mach number scales, climb schedule, and operational limitation curves.

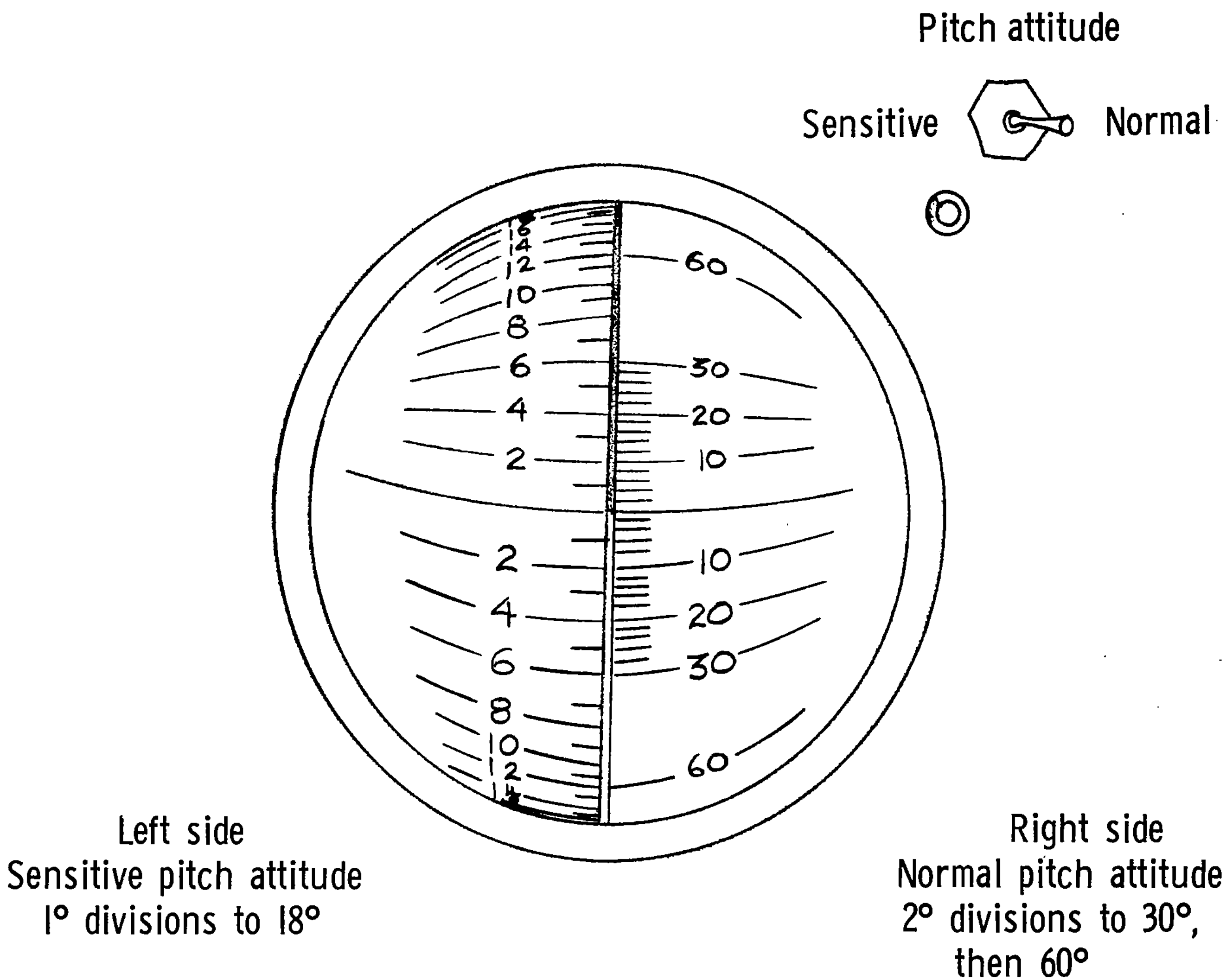
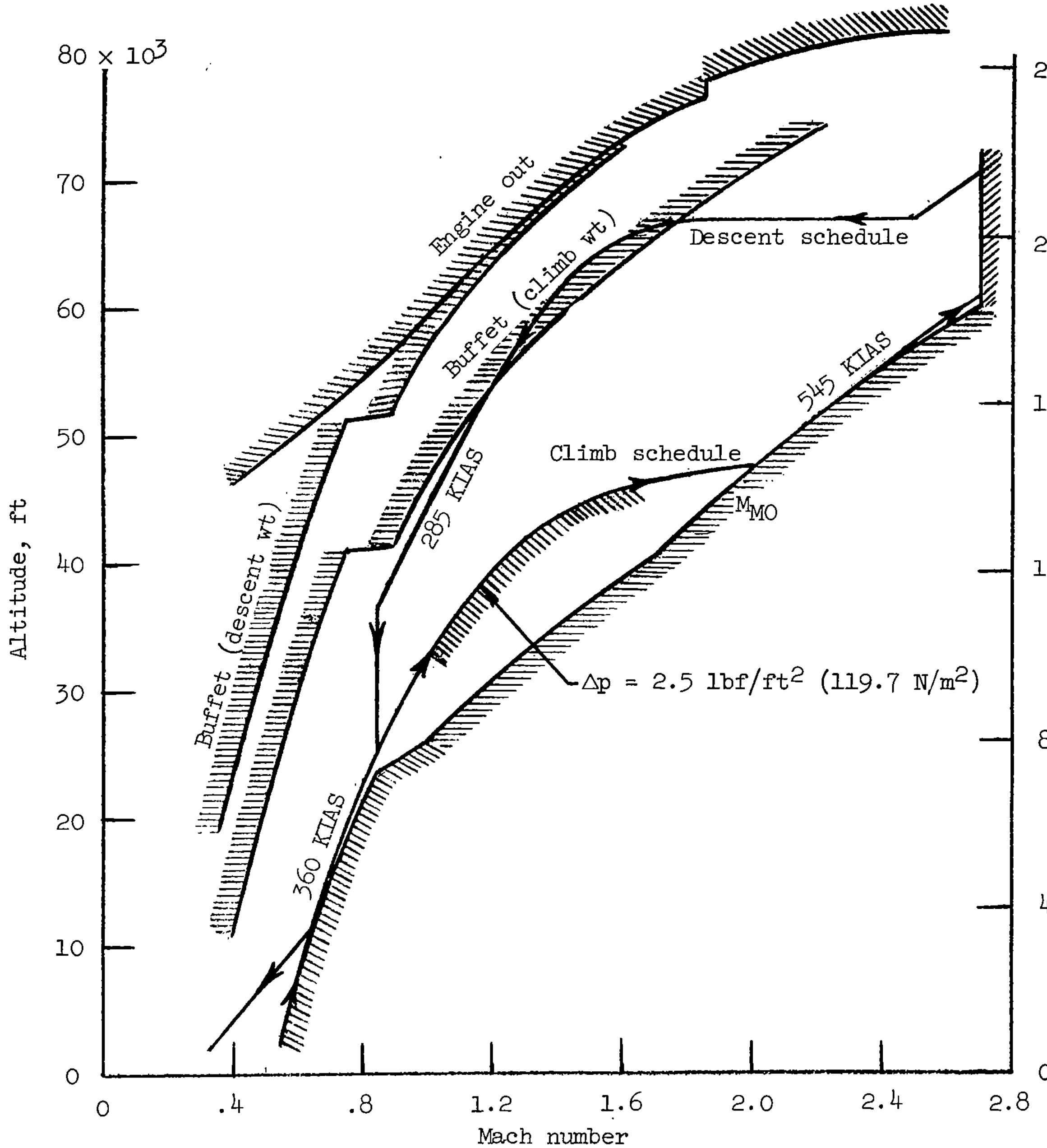
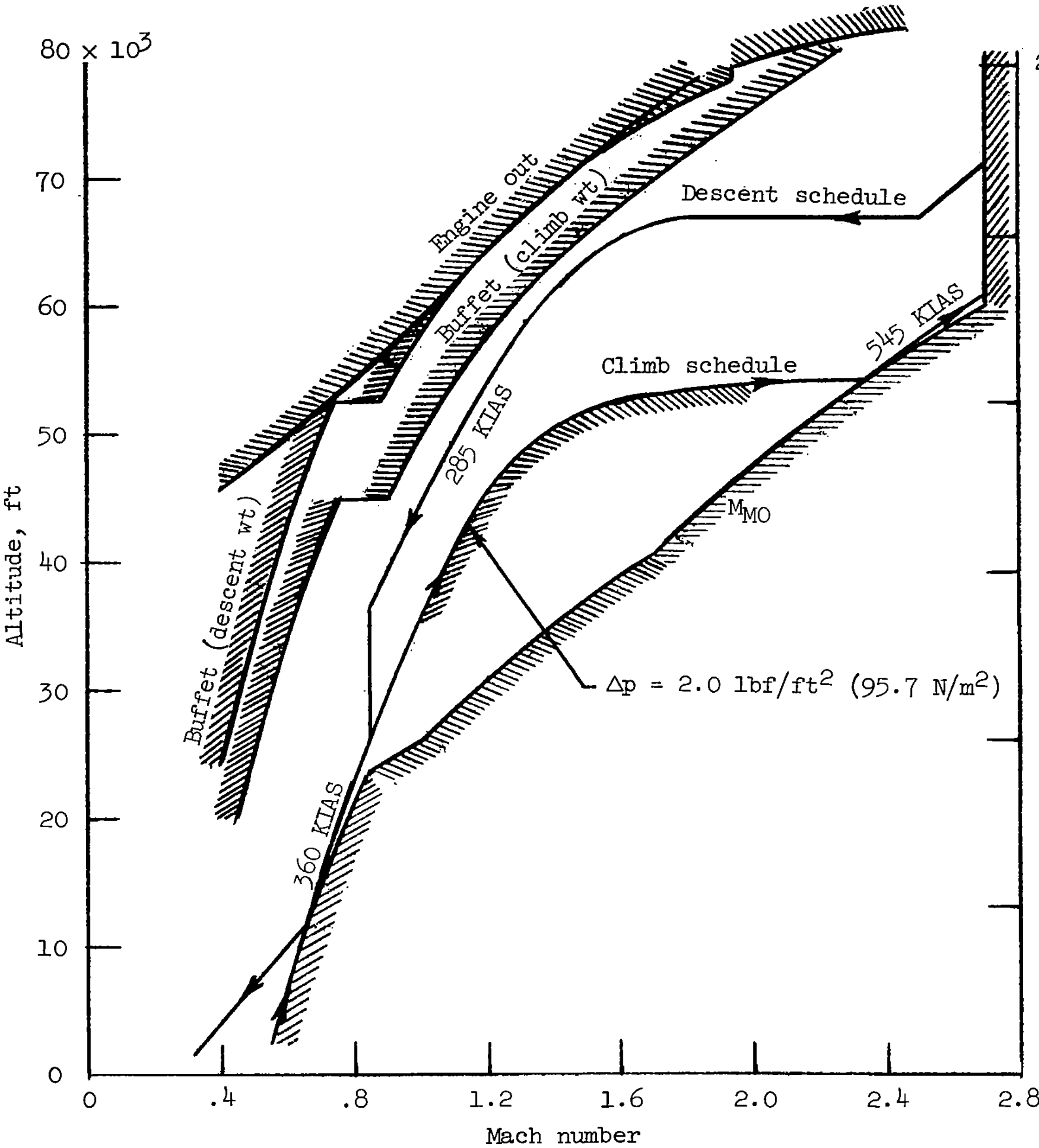


Figure 4.- Full-size sketch of modified pitch attitude indicator; normal display on right, sensitive display on left.



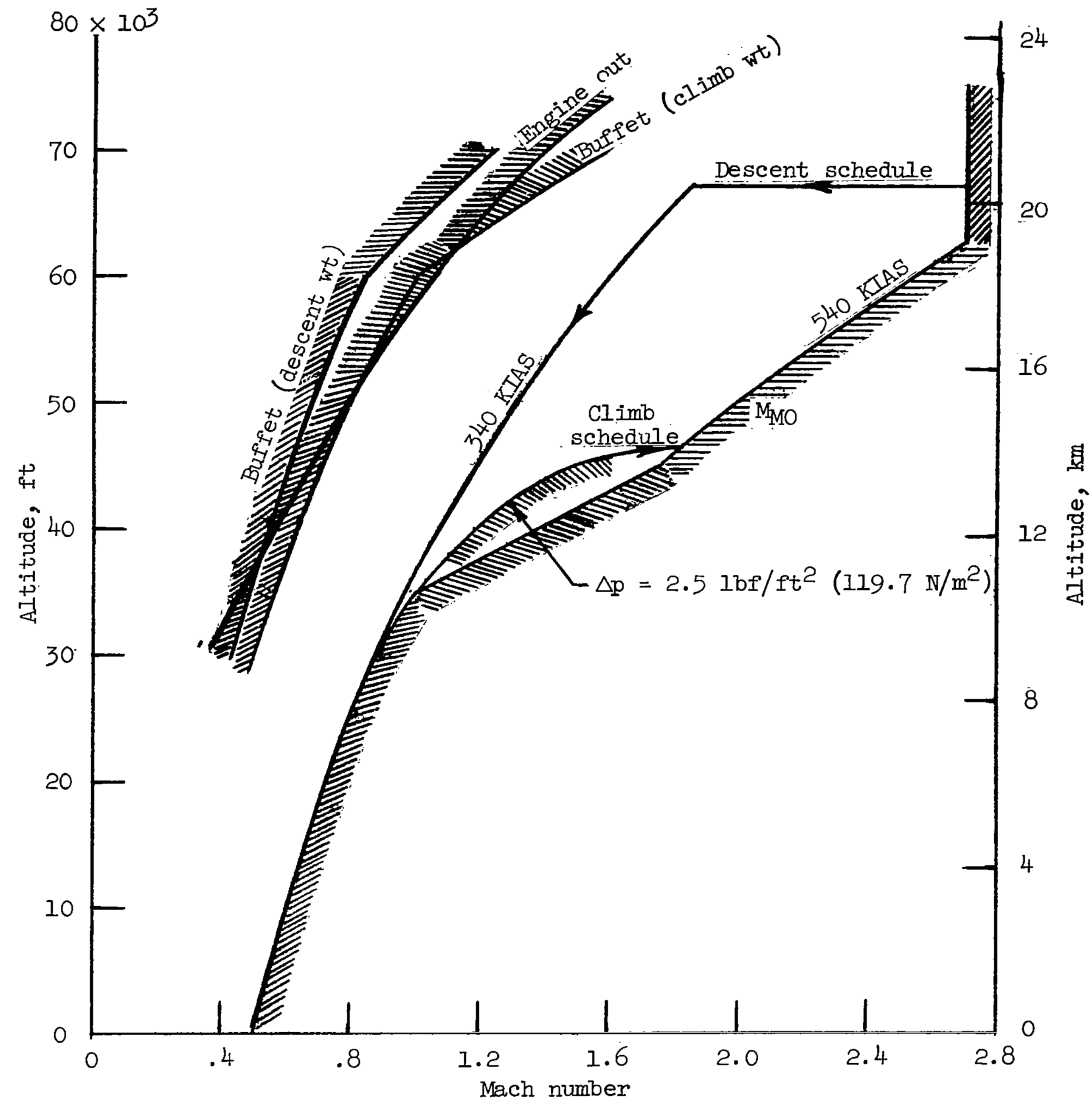
(a) Oceanic operations.

Figure 5.- Climb and descent schedules and flight limit boundaries. Variable-sweep configuration.



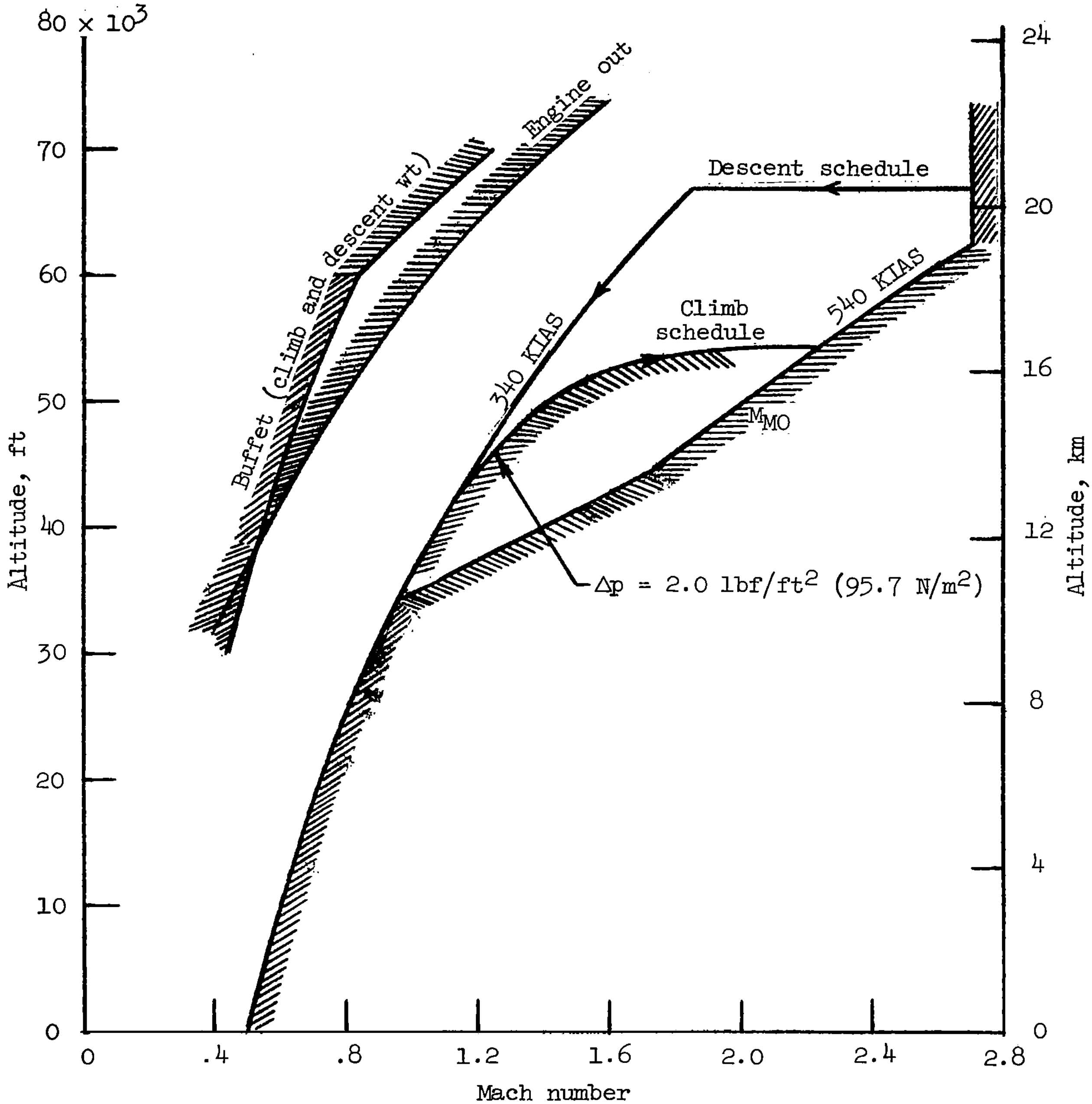
(b) Domestic operations.

Figure 5.- Concluded.



(a) Oceanic operations.

Figure 6.- Climb and descent schedules and flight limit boundaries; fixed double-delta wing configuration.



(b) Domestic operations.

Figure 6.- Concluded.

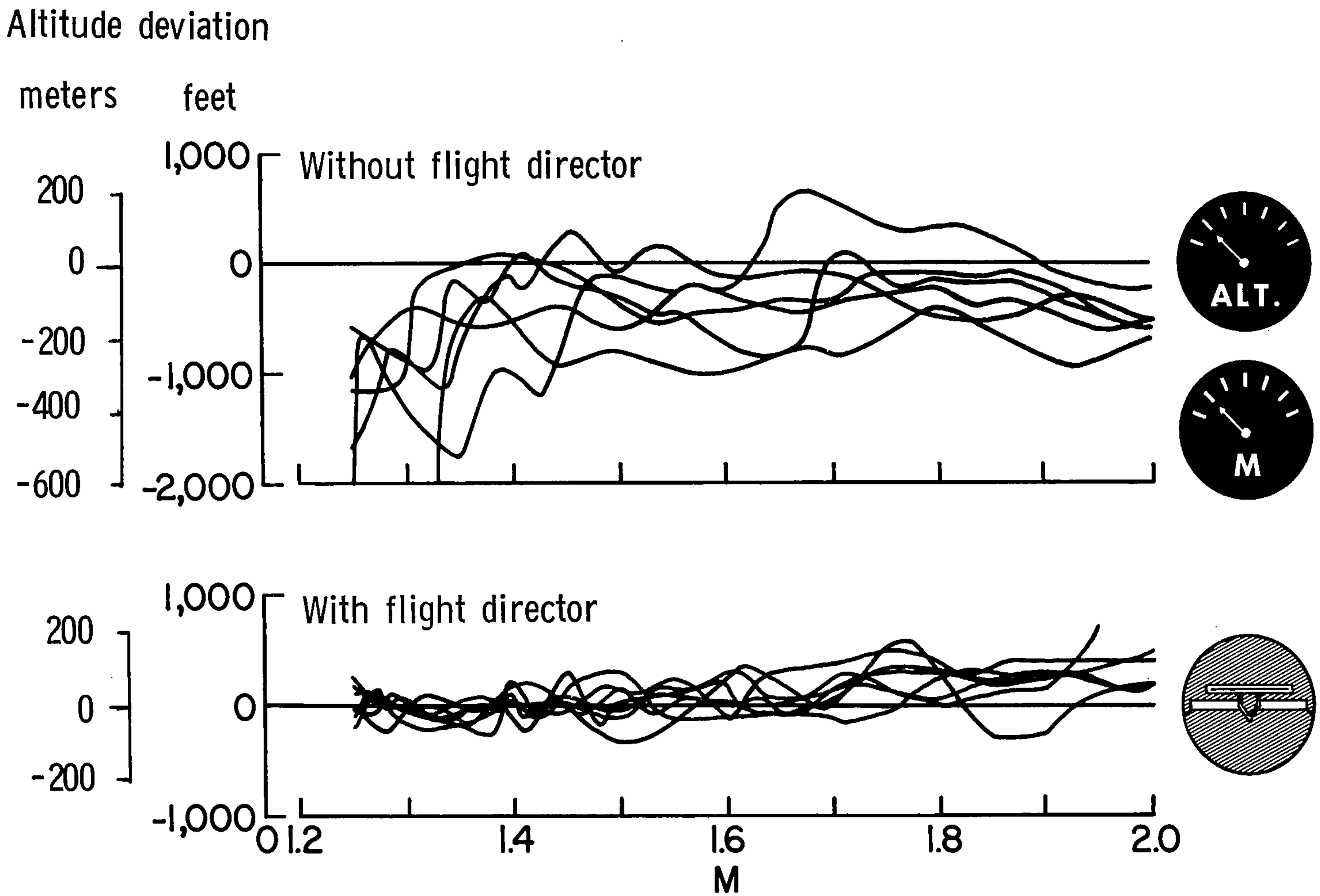
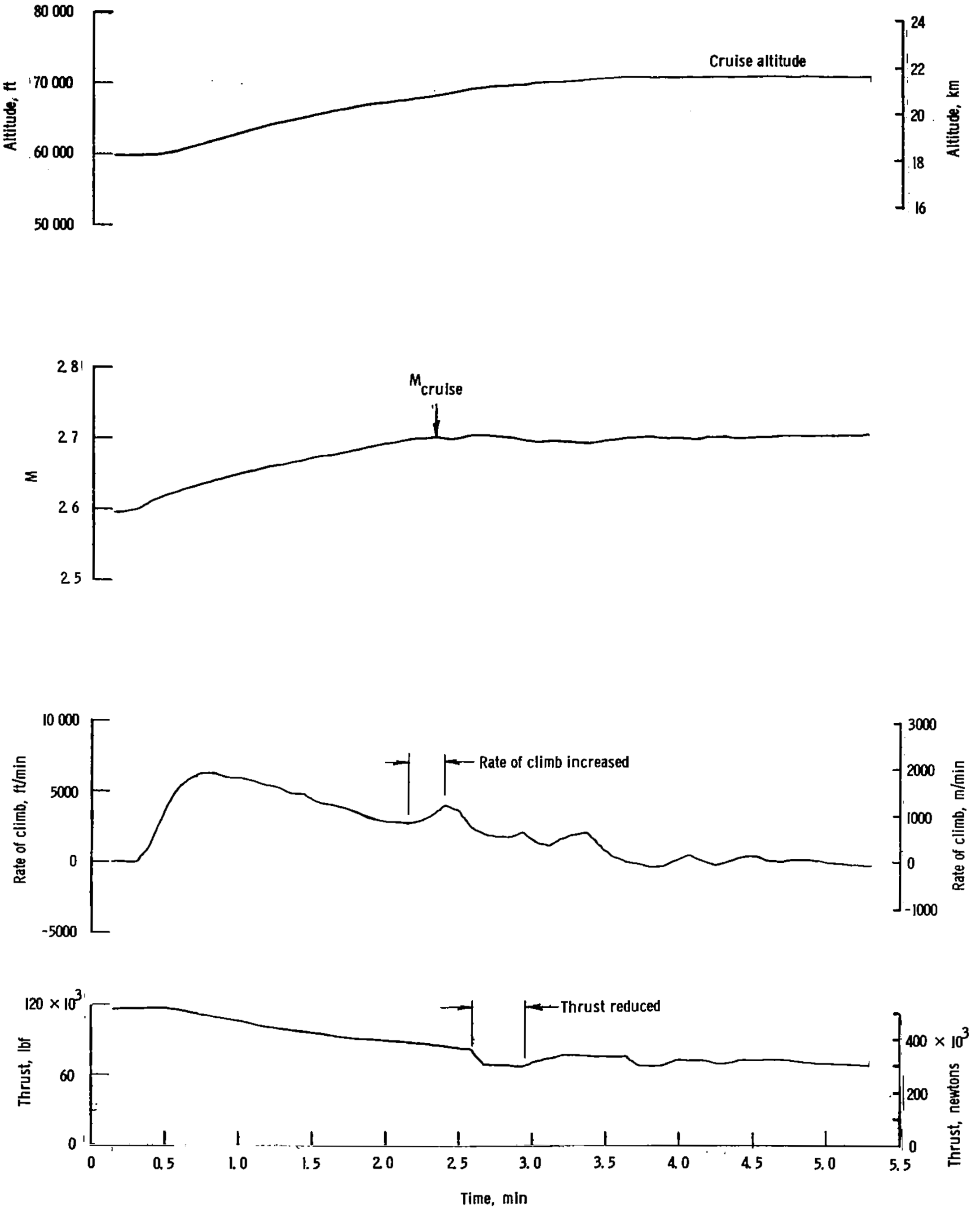
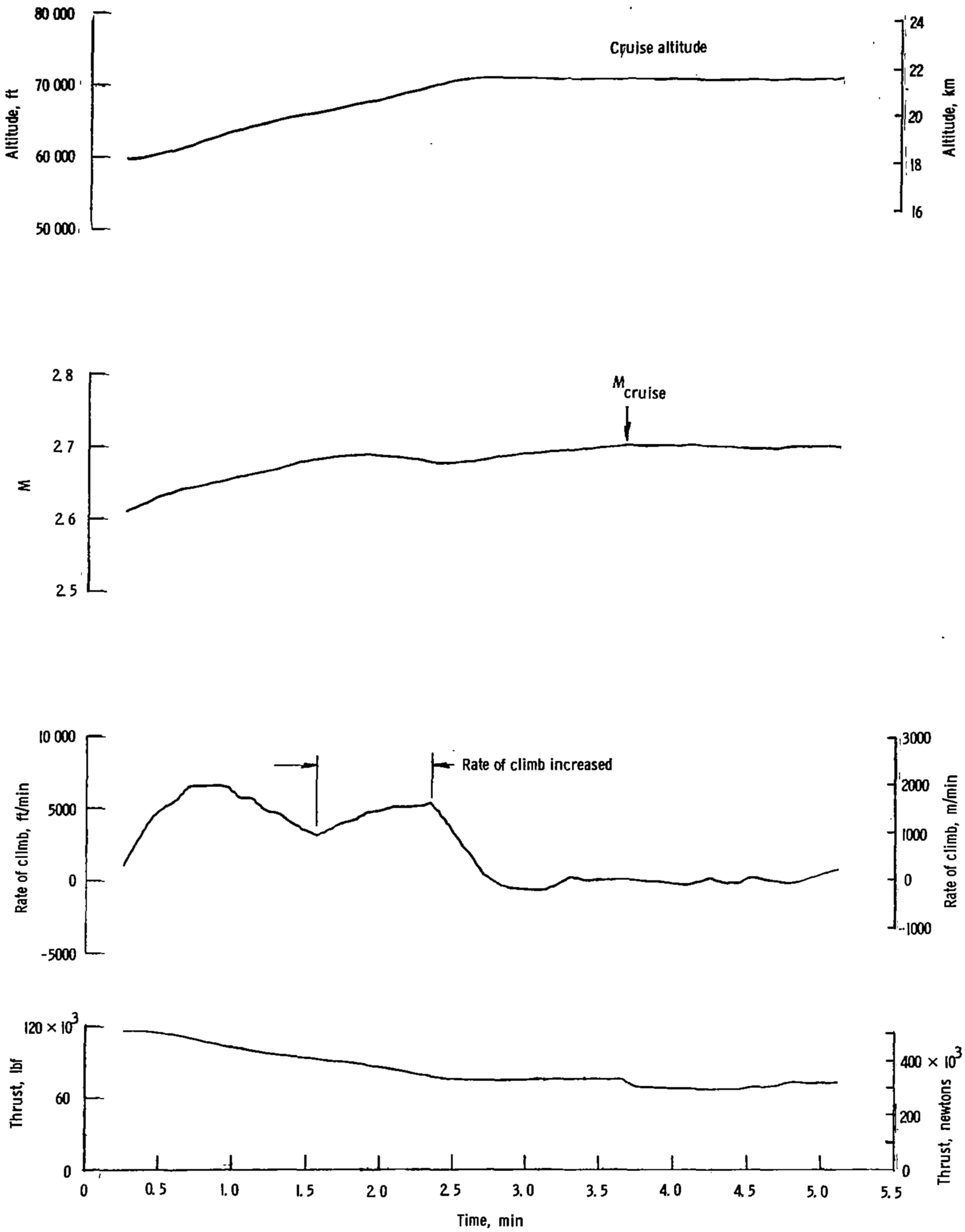


Figure 7.- Altitude deviations in following scheduled profile with and without flight-director guidance.



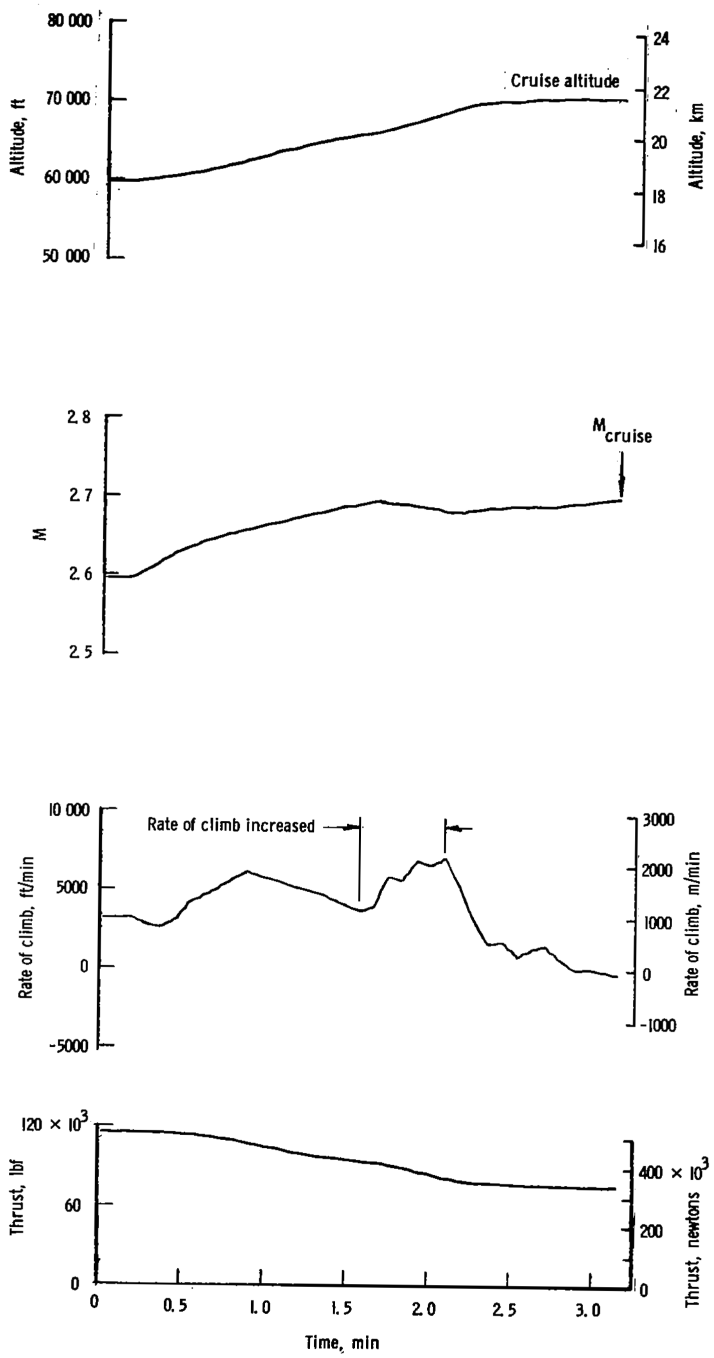
(a) Rate of climb increased followed by thrust reduction.

Figure 8.- Transitions from climbing to cruising flight at M = 2.6 at an altitude of 71 000 feet (21.64 km). No flight-director guidance; variable-sweep-wing configuration.



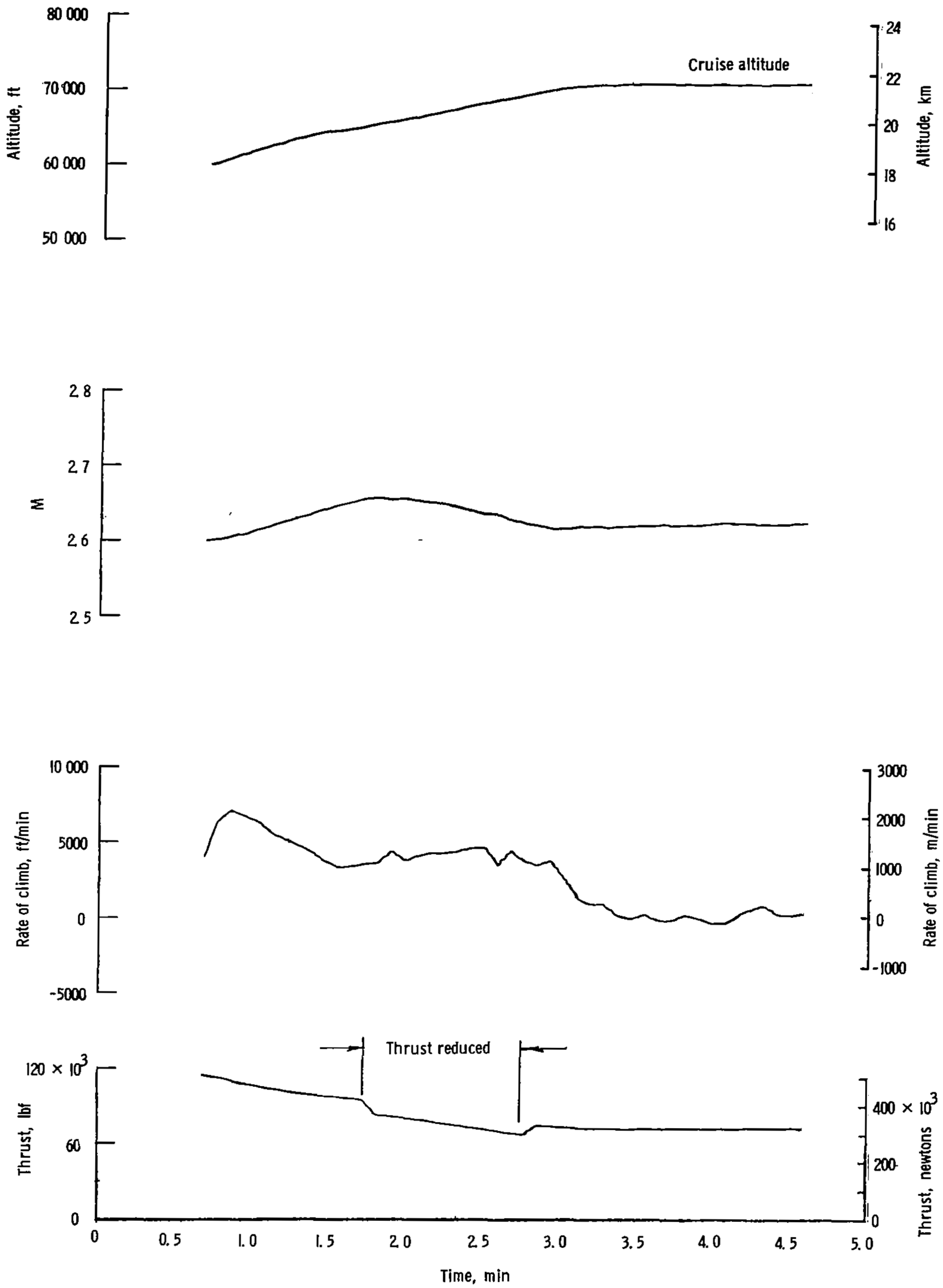
(b) Rate of climb increased; no thrust reduction until cruise condition.

Figure 8.- Continued.



(c) Rate of climb increased; no thrust reduction.

Figure 8.- Continued.



(d) Thrust reduction initiated 6000 feet below cruise altitude.

Figure 8.- Concluded.

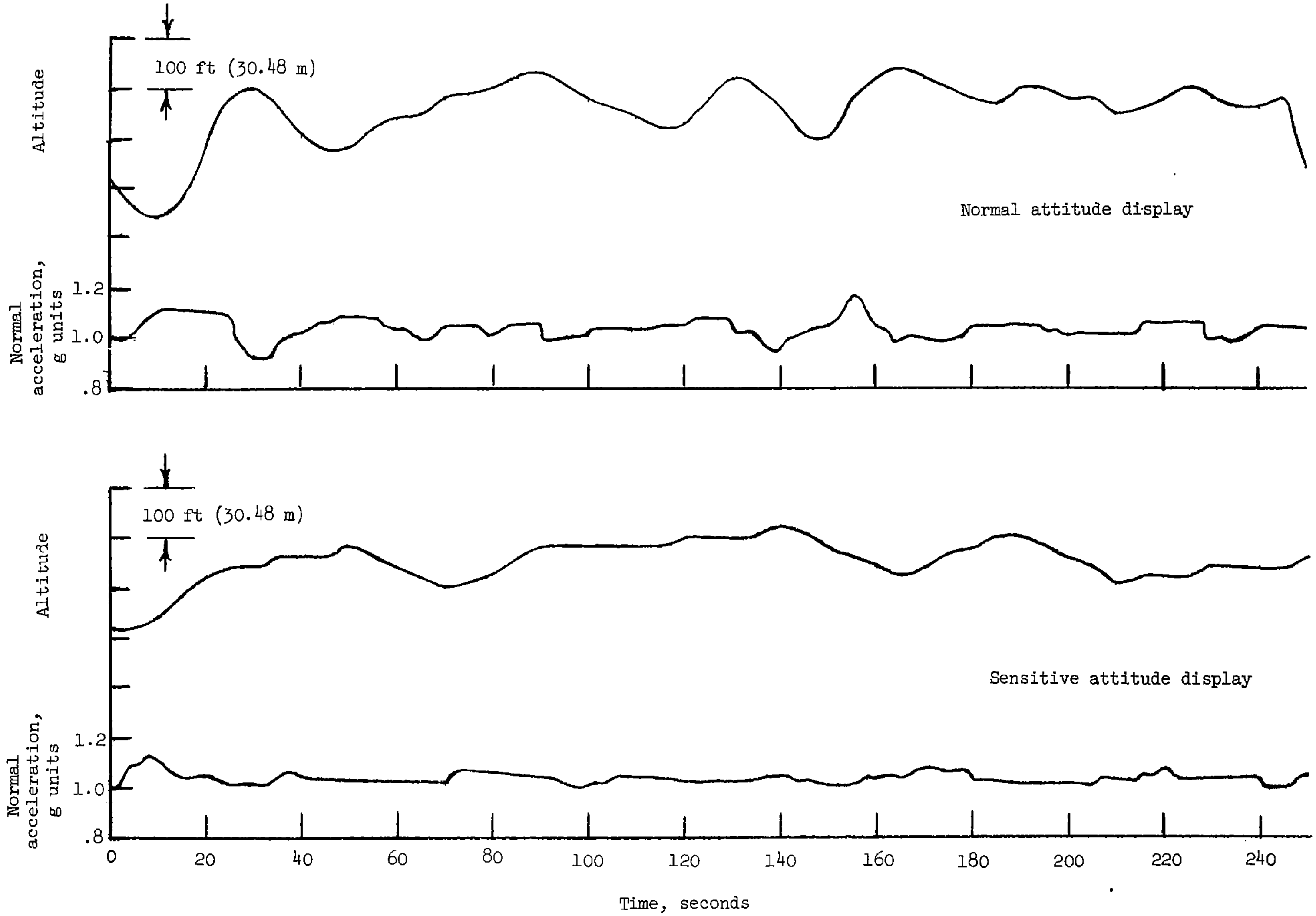


Figure 9.- Variation in altitude and normal acceleration during cruising flight. Altitude near 70 000 feet (21.34 km); M ≈ 3.0.

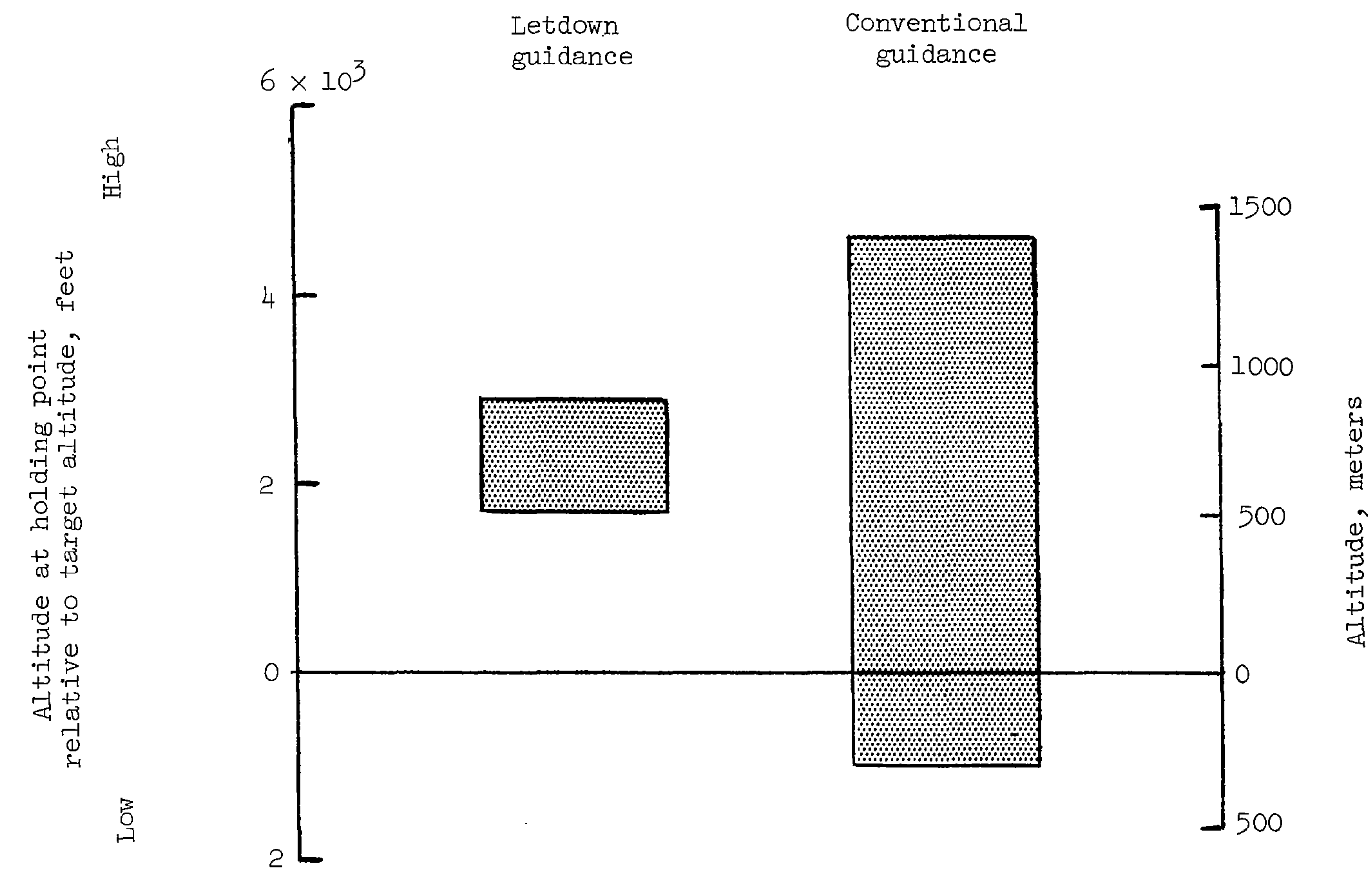
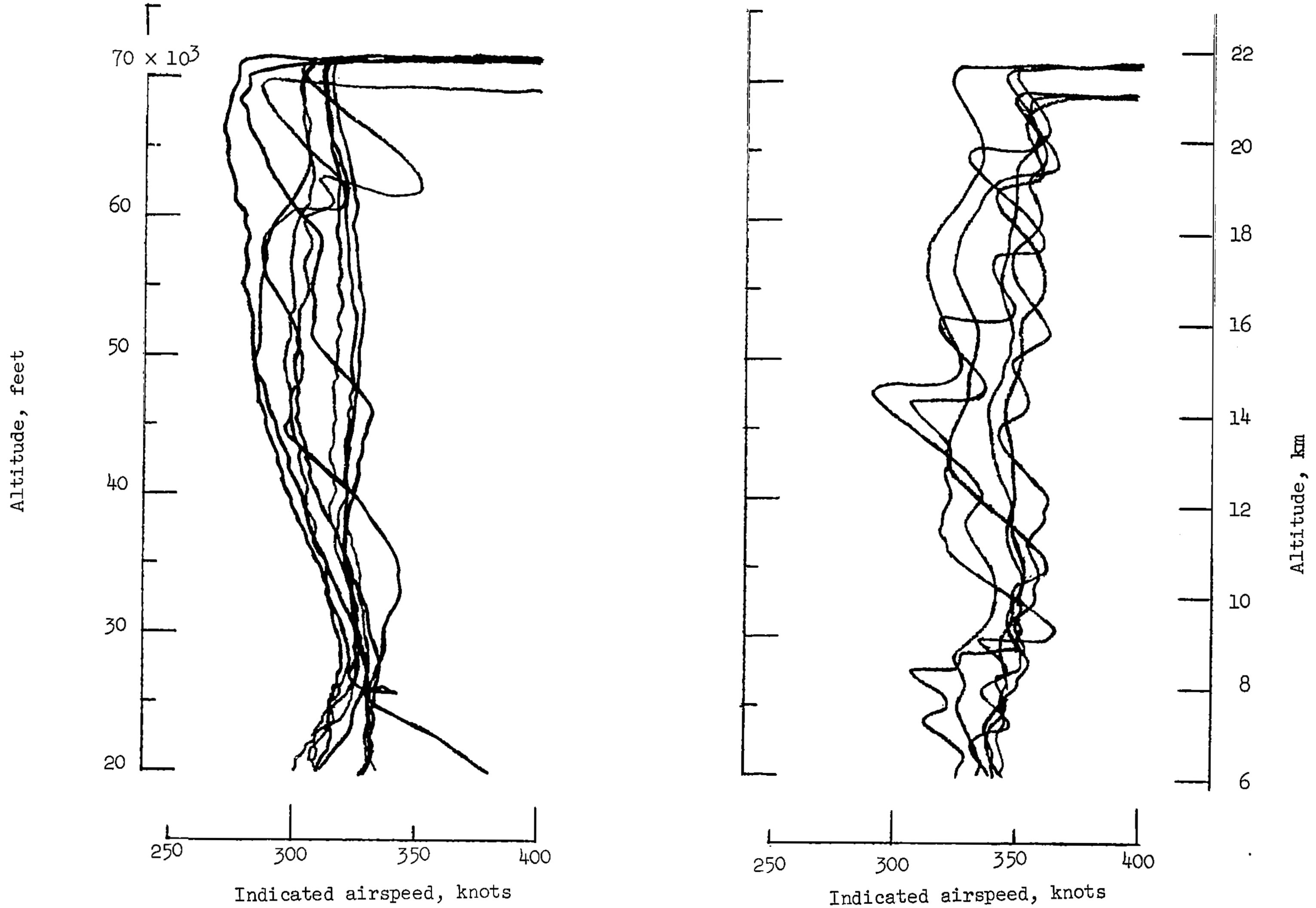


Figure 10.- Range of altitudes measured at arrival over holding point relative to target altitude for both computer and conventional guidance. Seven conventional and six letdown guidance descents.



(a) Letdown guidance.

(b) Conventional guidance.

Figure 11.- Variation of altitude with indicated airspeed during descent with both letdown and conventional guidance.

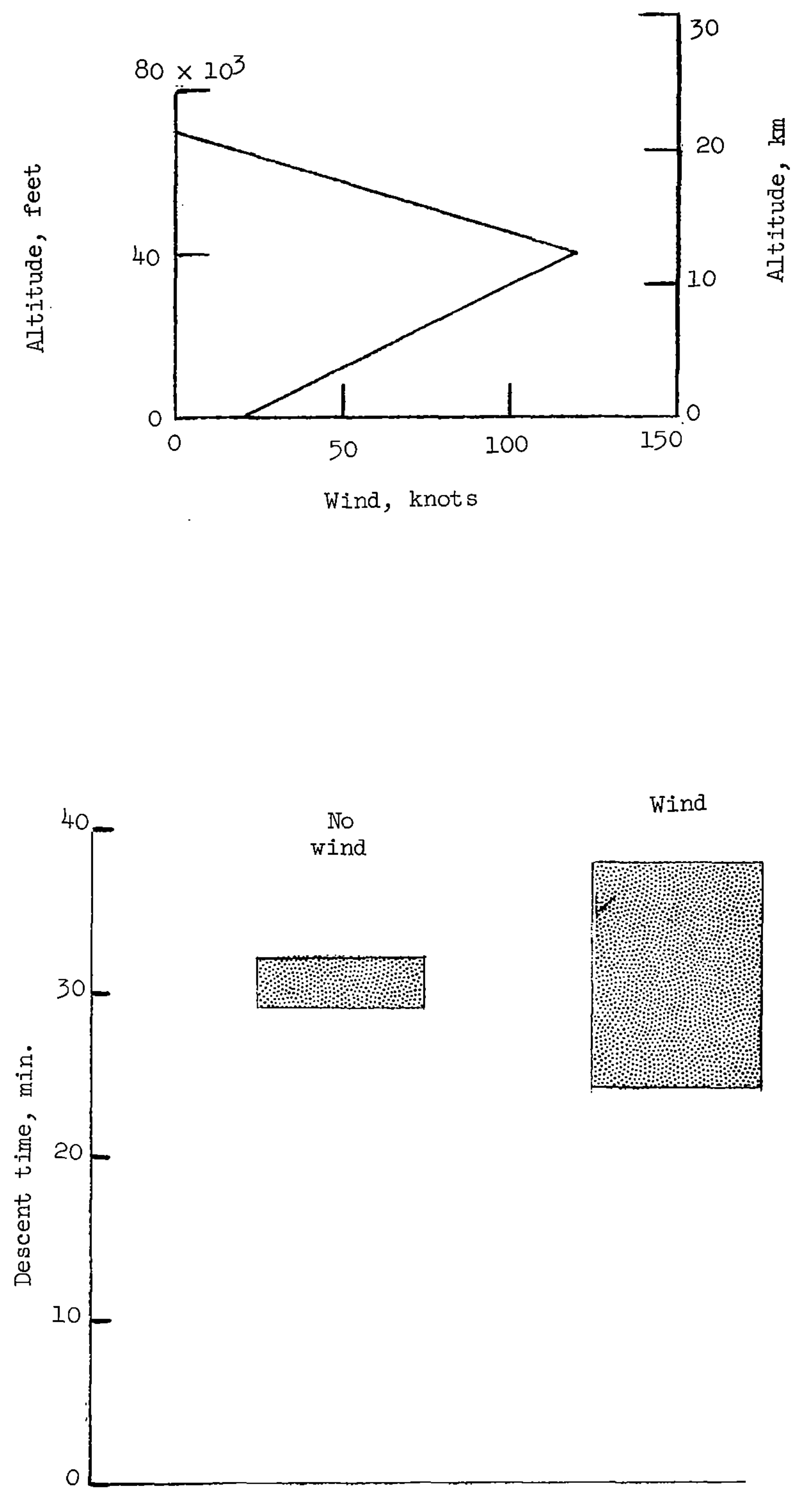


Figure 12.- Range of descent times for conditions of wind and no wind. Wind profile also shown.

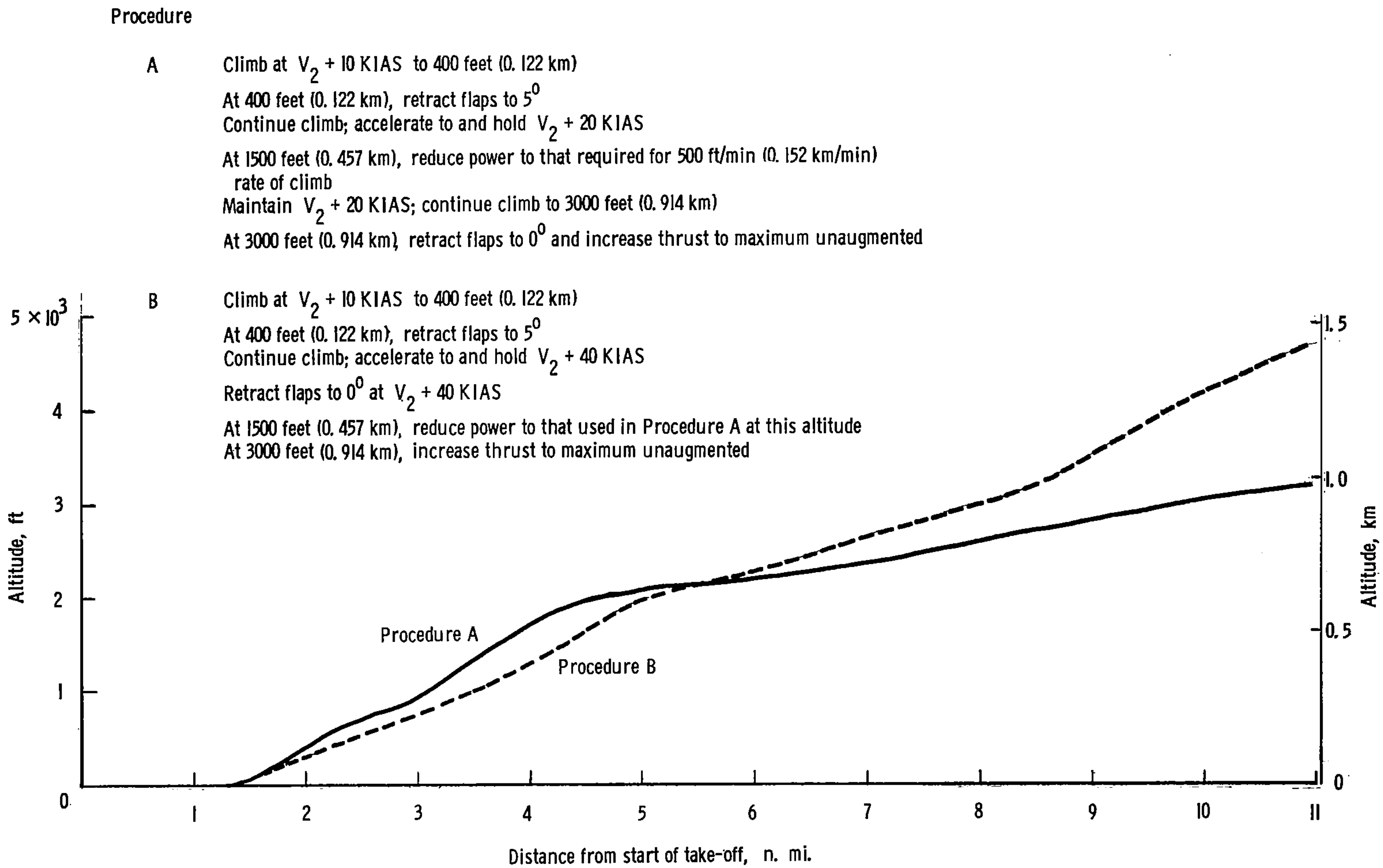


Figure 13.- Altitude-distance profiles for two noise-abatement procedures. SST configuration with variable-sweep wing.

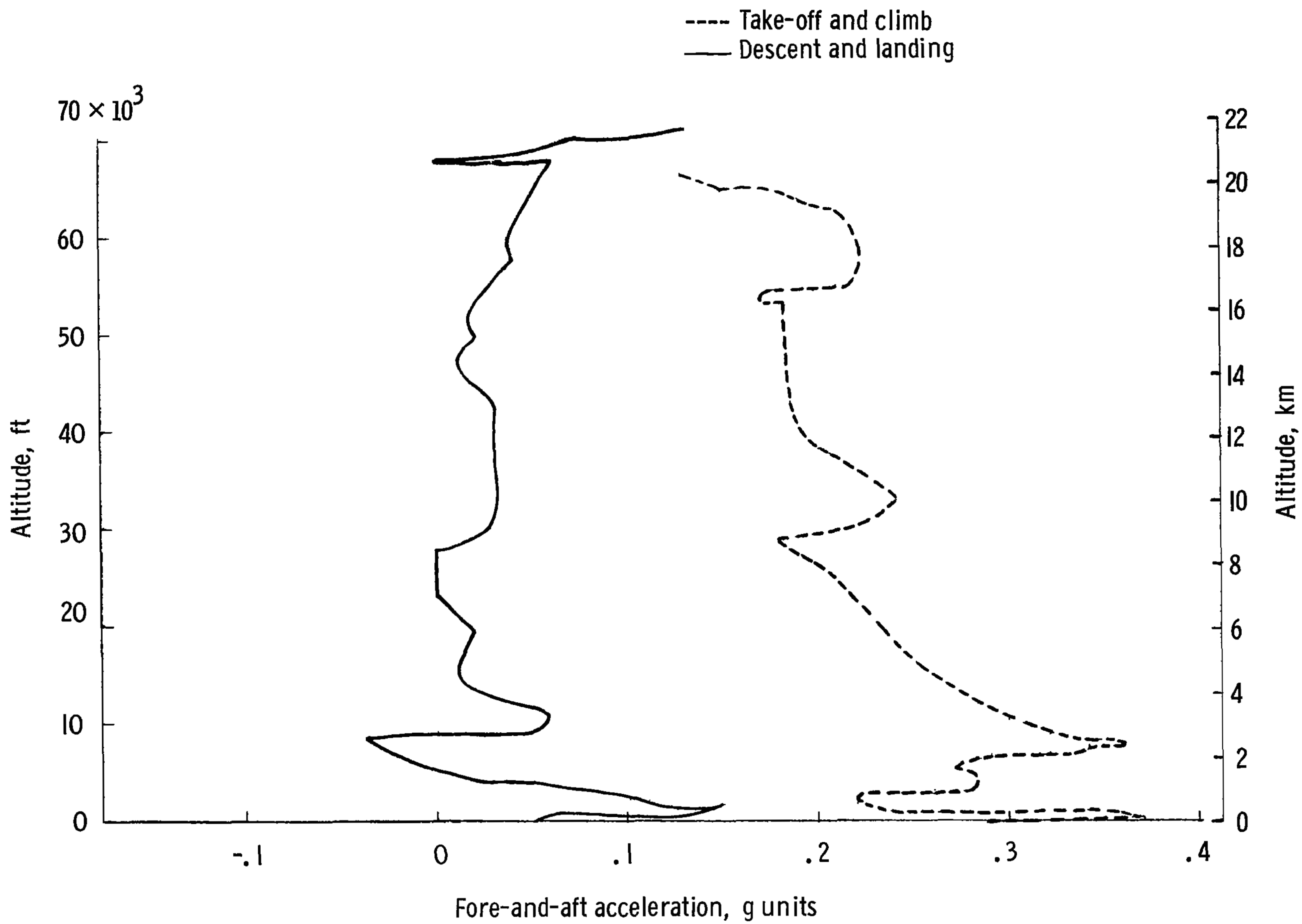


Figure 14.- Variation with altitude of fore-and-aft acceleration for a typical take-off and climb and a typical descent and landing. SST design configuration with variable-sweep wing.

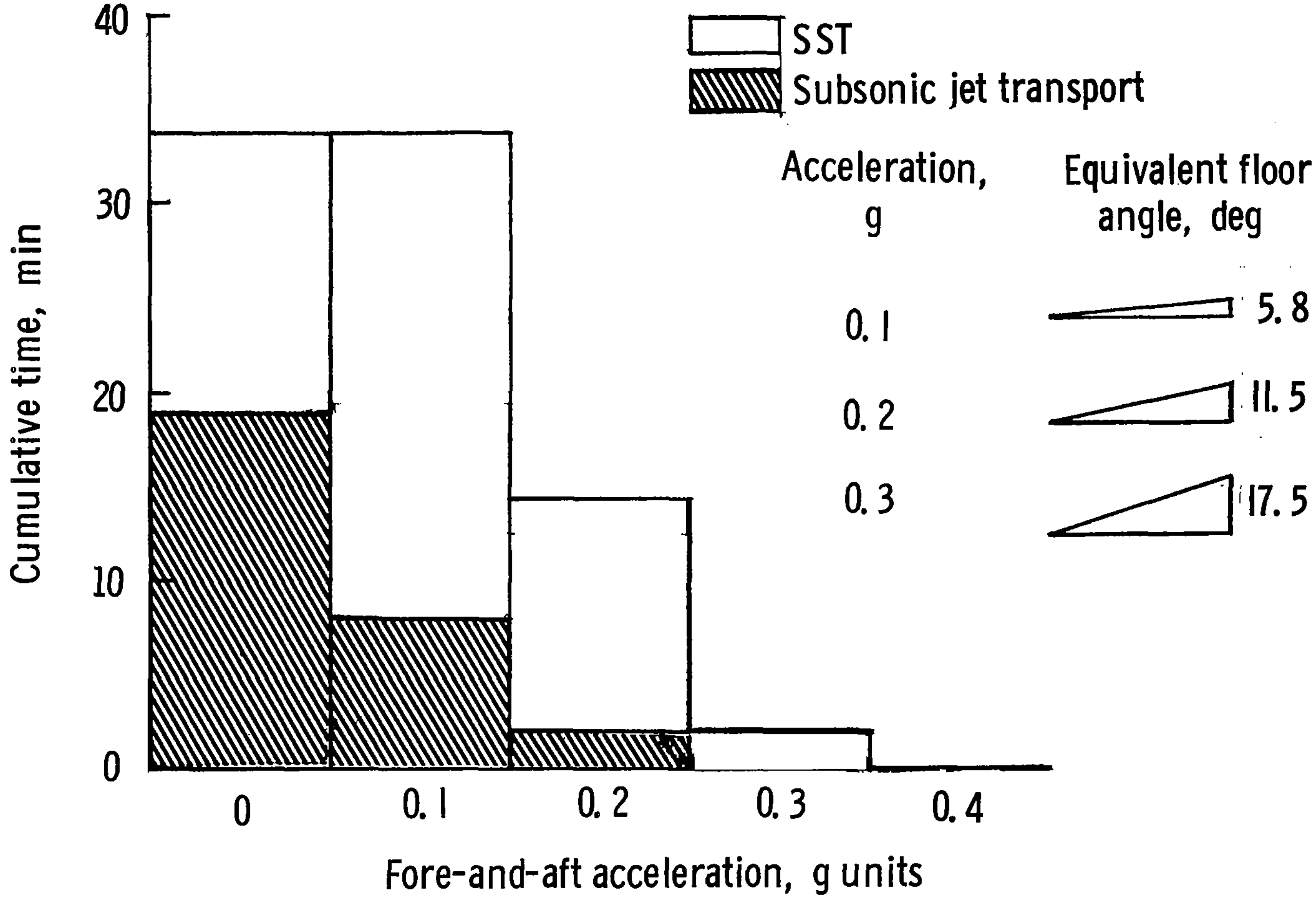


Figure 15.- Comparison of cumulative time at or above 0.1g levels in fore-and-aft acceleration for the supersonic transport and a subsonic jet transport during take-off and climb to cruise conditions.

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