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MEMORANDUM

FLIGHT MEASUREMENTS OF THE EFFECT OF A CONTROLLABLE THRUST REVERSER ON THE FLIGHT CHARACTERISTICS OF A SINGLE-ENGINE JET AIRPLANE

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SUMMARY

A flight investigation was undertaken to determine the effect of a fully controllable thrust reverser on the flight characteristics of a single-engine jet airplane. Tests were made using a cylindrical target-type reverser actuated by a hydraulic cylinder through a "beep-type" cockpit control mounted at the base of the throttle. The thrust reverser was evaluated as an in-flight decelerating device, as a flight path control and airspeed control in landing approach, and as a braking device during the ground roll.

Full deflection of the reverser for one reverser configuration resulted in a reverse thrust ratio of as much as 85 percent, which at maximum engine power corresponded to a reversed thrust of 5100 pounds. Use of the reverser in landing approach made possible a wide selection of approach angles, a large reduction in approach speed at steep approach angles, improved control of flight path angle, and more accuracy in hitting a given touchdown point. The use of the reverser as a speed brake at lower airspeeds was compromised by a longitudinal trim change. At the lower airspeeds and higher engine powers there was insufficient elevator power to overcome the nose-down trim change at full reverser deflection.

INTRODUCTION

Recent experience with landings of jet aircraft has indicated a need for improved thrust response, particularly where steep approaches are made at low engine rpm with high-aspect-ratio, low-drag-type aircraft. Pilots have tended to compensate for poor thrust response by increasing approach speeds with a consequent increase in overshoot-type accidents.

One means of improving the thrust response of a jet engine is to use a fully controllable thrust reverser. The use of in-flight thrust modulation combined with the capability of immediate full reverse thrust after touchdown offers safer operation, particularly in poor weather. In addition, the thrust reverser by virtue of its ability to change the effective lift-drag ratio of an airplane can be used as a glide path control as well as a speed brake.

The feasibility of several thrust reversing principles has been demonstrated with aircraft during taxi tests (refs. 1 and 2). The results of an earlier attempt to use in-flight thrust modulation are given in reference 3. In order to investigate further the in-flight and ground use of a fully modulating thrust reverser, the Ames Research Center installed a reverser on a modified F-94C airplane. The reverser was of the cylindrical target type, actuated hydraulically, and controlled by means of a "beep switch" mounted on the throttle. The geometric details for size and spacing relative to the engine tail pipe were obtained from small-scale tests with unheated air conducted at the Lewis Research Center (ref. 4).

Tests were made for the most part in the landing-approach configuration at speeds below 200 knots. Measurements were made to document the effect of the reverser on glide path control, landing performance, and low-speed flying qualities. The effect of pilot technique on the operational use of the reverser is included herein. In addition, a 16mm sound film describing the construction, ground testing, and flight use of the reverser has been prepared as a supplement to this report.

NOTATION

A_x	longitudinal acceleration, g
A_z	vertical acceleration, g
F_G	engine gross thrust, lb
h	altitude, ft
N	engine speed, percent rpm
V_i	indicated airspeed, knots
W	airplane gross weight, lb
α	angle of attack, deg
γ	flight path angle, positive for descending flight, deg
δ_e	elevator deflection angle, positive for upward deflection, deg
δ_{rev}	reverser position, fraction of total actuator travel (see fig. 4(b))

δ_T	throttle position for given engine speed, percent rpm
η_{rev}	reverser effectiveness, percent of forward gross thrust
θ	airplane attitude angle, deg

DESCRIPTION OF EQUIPMENT

Airplane

The installation of the reverser was made on an F-94C airplane. A two-view drawing of the test airplane is shown in figure 1. Pertinent dimensions of the airplane are given in table I. A general view of the airplane is given in figure 2. Removal of the afterburner facilitated reverser installation and in addition reduced any center-of-gravity shift.

Reverser

The reverser was of the cylindrical target type and is shown in a close-up view in figure 3. A drawing giving pertinent dimensions is presented in figure 4. Various reverser end plates tested are shown in figure 5. The relationship between angular deflection and actuator travel is shown in figure 6. Materials for the reverser consisted of Hastalloy B for the reverser faces and stiffening ribs, stainless steel type 321 for cover plates, and 4130 steel for the tubular structure used to transmit loads from the reverser to the rear fuselage bulkhead. A thin stainless steel doubler was used to cover 2024-T aluminum fuselage skin in areas subjected to high temperature during operation in reverse thrust. The reverser was positioned 8.5 inches downstream of the plane of the tail-pipe exit giving a spacing ratio (length/tail-pipe diameter) of 0.39. The reverser was actuated by a hydraulic cylinder mounted in an enclosed compartment in the lower portion of the fuselage.[1] Connection to the reverser was made by stainless steel rods attached to the lower part of the reverser by rod end spherical bearings. Positioning of the reverser was controlled from the cockpit by means of a toggle switch at the base of the throttle which formerly had been used for the speed brake control. This beep-type control supplied electrical signals to a four-way valve which permitted continuous adjustment of the reverser position.

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[1] A schematic diagram of the hydraulic system is shown in figure 7. Two rates of actuation could be selected by the pilot: a fast rate of 4.0 seconds to go from full forward thrust to full reverse thrust and 2.5 to recover full forward thrust; and a slower rate of 10 seconds for full travel for finer control.

Several safety features were incorporated, among them an accumulator system designed to provide safe operation in the event of a hydraulic or electrical failure. A microswitch was used to prevent reverser deflections greater than approximately 0.6 which cause large longitudinal trim changes at low speeds. This switch could be bypassed for higher speed flight where it was desired to use the reverser as a speed brake. Upon ground contact a microswitch on the landing gear allowed full deflection of the reverser for maximum braking effectiveness. In order to avoid possible structural failure to the fuselage skin due to overheating a light was installed in the cockpit to warn the pilot not to apply full engine power unless the reverser was fully deflected.

Instrumentation

Standard NASA instruments were used to record airspeed, altitude, rates of roll and pitch, accelerations, angle of attack, and control positions and forces. Temperatures were measured in 15 locations on the fuselage and tail surfaces. These temperature values were used only as a monitor for safety of flight and are not reported in detail herein.

TESTS

Thrust reverser effectiveness was measured in flight over a range of airspeeds and engine power settings which would be useful to a pilot making landing approaches. The airspeed range covered was 130, 150, and 170 knots indicated airspeed at engine speeds of 65-, 75-, and 85-percent rpm, with the airplane in the landing configuration. Effectiveness was measured in flight up to a maximum engine speed of 85-percent rpm.

Effectiveness tests were conducted at an average altitude of 10,000 feet. With engine speed constant at 65-, 75-, or 85-percent rpm, the reverser doors were brought from full forward to full reverse position in small increments while indicated airspeed was held constant. Measurements of the change in flight path angle obtained in deflecting the reverser from the full forward thrust position were used to determine the effectiveness for a particular indicated airspeed and engine rpm (see appendix A).

For the flight measurements of effectiveness the average wing loading and center-of-gravity location were 70 pounds per square foot and 0.30 mean aerodynamic chord, respectively. For approach and landing the wing loading was 65 pounds per square foot. The data presented in the figures are for the landing condition with the flap and gear down.

RESULTS AND DISCUSSION

Operational Use of Thrust Reverser

A fully controllable thrust reverser can be used as a drag device for decelerating and for emergency letdown in cruising flight, for flight path control during landing approach, and as a decelerating device on the ground either after touchdown or in the event of a refused take-off. In the present investigation, use in the landing approach is considered in the most detail.

Landing-approach procedure with reverser.- The manner in which thrust is used in landing approach depends on the type of approach pattern and the pilot control technique. As discussed more completely in reference 5, two general types of patterns are used: the constant speed, constant flight path angle approach (carrier, ILS, GCA types), and the tactical approach in which neither speed nor flight path angle is held constant. Control technique is the manner in which the pilot uses thrust and elevator variations to control flight path angle and/or airspeed. The use of thrust as the primary flight path control has generally been associated with the constant speed, constant flight path angle type approach, particularly the carrier approach, and with airplanes having low lift-drag ratios. Elevator control of flight path is most generally associated with the tactical approach and with aircraft having high lift-drag ratios. Under these conditions thrust is used for airspeed control.

When the thrust reverser is used for flight path control, engine rpm is maintained constant at 85 percent (slightly more than power for level flight in the final approach speed). The reverser is deflected to decelerate first to the gear and flap down speeds and then to the desired approach speed, for example, 140 knots. With the airplane trimmed at the approach speed, flight path adjustments are made by positioning the reverser; the flight path and airspeed are maintained constant until touchdown. When the reverser is used for speed control, the initial procedure for decelerating to gear down speed is similar to that previously described; however, faster approach speeds are used (150-170 knots) and the airplane is aimed at a point short of the intended touchdown point, and the elevator is used to control flight path and flare. Upon completion of the flare, reverser deflection is increased and airspeed is reduced to touchdown at the desired speed (approximately 130 knots).

Use of reverser for flight path control.- Several factors enhanced the use of the reverser for flight path control during landing approach. These were an increase in the usable range of approach angles for a given approach speed, increased thrust response, and the presence of a favorable nose-down trim change when forward thrust was decreased by reverser deflection.

The flight path angle as a function of thrust obtained by reverser deflection or throttle movement for a constant airspeed is presented in figure 8. Indicated on the figure are the maximum usable flight path angles in landing approaches with reverser and throttle. Note that the range of approach angles with the reverser is increased 2.5-fold over that obtained with the throttle.

Although flight path angles considerably greater than 4° are possible with idle engine thrust (up to 12°), this increased range of flight path angles was not usable in landing approach because of the poor engine response in the lower rpm range. A time history comparing thrust response for reverser and throttle operation is presented in figure 9. The increased response shown for the reverser made it possible to adjust flight path angle more rapidly and accurately and thus utilize a larger range of flight path angles.

Values of flight path angle greater than 10° were obtainable with the reverser but were not useful in landing approach primarily because of an increased nose-down trim change induced by reverser deflection. An example of a typical variation in trim is shown in figure 10 in which elevator angle to maintain a constant airspeed is plotted as a function of reverser deflection. It can be noted that the rate of change of elevator angle with reverser deflection increased with the reverser deflection. The lower range of reverser deflection, up to 0.5, was considered by the pilots to be a region of favorable nose-down trim change, where the elevator movements and associated control forces were small. At the higher reverser deflections elevator control power was marginal and the trim change was therefore considered unacceptable. Because the longitudinal trim change became excessive at the higher reverser deflection, 0.6 deflection was the maximum which could be used in landing approach.

Normally, pilots who use thrust for flight path control will tend to rely on elevator control for making final adjustments to the flight path prior to touchdown or for the flare maneuver. The magnitude and rapidity with which flight path changes could be made with the reverser minimized the need to use the elevator for other than speed control and thus simplified control technique.

Use of reverser for speed control in landing approach.- In the standard tactical type approach without a reverser, speed is gradually reduced from a relatively high pattern penetration speed (300 knots) to that used at touchdown by means of speed brakes and low engine power. As a result, the airplane arrives at the flare position with low engine power and consequently poor response in a region where thrust adjustments may be required to assist the flare or stretch the glide. The tendency has been for pilots to compensate for poor engine response by increasing approach speed; this decreases their ability to control the touchdown point and the touchdown speed.

For the reverser to be most effective as a speed control device in landing approach, increased reverser deflection should result in a nose-up trim change with a negligible change in flight path angle. This type of trim variation was obtained for only one reverser configuration (fig. 11) and over a restricted deflection range (0.4 to 0.6). Use of the reverser in this range made it possible to reduce relatively high approach speeds (170 knots) to acceptable values (130 knots) at touchdown. Floating tendencies were reduced and improved control over touchdown point was obtained. While the pilots felt that more thrust reduction could have been used, the rate of speed bleed-off with the reverser deflection of 0.60 and 85-percent rpm was beginning to force the pilot to monitor airspeed more closely prior to touchdown.

With the trim characteristics which were previously pointed out to be favorable for flight path control (see fig. 10) the reverser could still be used for speed control. To reduce speed at a constant flight path angle it was necessary to increase elevator deflection above that required to offset the nose-down trim change which occurred with increased reverser deflection. In landing approaches where speed corrections with the reverser are made around a constant approach speed which is being maintained with the elevator, this coordination was handled satisfactorily. In tactical approaches where airspeed is reduced continuously throughout the approach, and the elevator is already used to control flight path, the combined use of elevator and reverser for speed control becomes more difficult. This emphasizes the fact that changes in trim with thrust influence pilot control technique.

The advantages of reverser control over throttle control were found to be more pronounced the larger the corrections required in either flight path angle or airspeed. This was brought out in GCA, ILS, and mirror approaches in which the glide path was intercepted with 15 knots excess airspeed. When the reverser was used, the airspeed was reduced from 155 knots to 140 knots quite rapidly, leaving the pilot free to devote his attention to other tasks during the rest of the approach. When the throttle was used, particularly in mirror and ILS approaches where the time is shorter, it was necessary to retard the throttle to idle to decelerate to 140 knots prior to touchdown. Because of the poor thrust response in the low engine rpm range, the pilot was reluctant to do this; consequently, touchdown was made at a higher speed than desired and an undue amount of pilot attention was required to monitor airspeed during the long speed transition period.

Several of the points which have been discussed in the comparisons of the use of throttle and of reverser during the landing approach are shown in time histories (fig. 12) in which normal throttle control and reverser were used in an attempt to establish and fly an 8° approach at 140 knots. As may be seen in figure 12(b), the throttle was retarded too slowly to keep airspeed from increasing. The speed increase was checked at 150 knots, however, and a further throttle cut was made to idle rpm in order to reduce airspeed toward the desired 140 knots at about 400 feet altitude.[2] The throttle was then advanced to increase the engine speed to approximately 60 percent; the airspeed increased to slightly in excess of 140 knots and variations in flight path angle of $\pm 2^{\circ}$ occurred.

When the reverser was used, flight path angle was increased more rapidly to 8° by increasing the reverser deflection from 0.40 to 0.48. As speed was high (145 knots) at the start of the run, the elevator was used to reduce it to 140 knots. At 140 knots reverser deflection was decreased in conjunction with a decrease in angle of attack to stabilize speed at 140 knots while maintaining the 8° approach. Abrupt jogs in elevator position were associated with the trim change with reverser deflection. The reverser configuration used has the trim characteristics shown in figure 11 and required considerably use of the elevator. Even with these trim characteristics, improvements in the control of both flight path angle and airspeed may be noted.

Effect of reverser on approach speed.- As indicated previously, thrust response was one of the factors influencing the choice of minimum comfortable approach speed. It would be expected that in regions where thrust response of the reverser was greater than that of the throttle, reductions in approach speed would occur. This was found to be the case as indicated by figure 13 which was based on actual landing approaches. It can be seen that the magnitude of the reduction in approach speed varied with the steepness of the flight path angle since steeper approach angles require greater reductions in engine thrust with resultant poorer engine thrust response. Normally, any increase in approach angle will be accompanied by some increase in approach speed in order to maintain a safe margin for flare. It is seen, however, that with the reverser it was possible to approach at angles up to 10° with only small increases in approach speed. This was possible at the steeper angles only because the thrust could be rapidly increased to prevent excessive speed loss in the flare. Such steep approaches were not considered possible by the pilots without the rapid thrust control provided by the reverser. For low approach angles where engine thrust is at a high enough value to give satisfactory thrust response, no reductions in approach speed were realized.

Effect of reverser on wave-off.- One of the most impressive improvements through the use of the thrust reverser was in wave-off. As noted previously, power slightly in excess of that required for level flight was set initially during the approach and the flight path angle desired for descent was adjusted by the thrust reverser. In the event of a wave-off, power for level flight can be obtained in 1 second. By virtue of the fact that the engine is already at a high enough speed to provide rapid acceleration characteristics, full forward thrust can be obtained in but

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[2] If the airspeed had been reduced too far at this altitude the airplane could have undershot the runway because a rapid increase in thrust was impossible.

slightly over 1 second. In addition, the airplane by virtue of the trim change immediately rotates toward the optimum climb-out angle with minimum use of the elevator. This simplified considerably the pilot's task during wave-off and reduced the chance of inadvertently exceeding the angle of attack for stall. While acceptable trim change characteristics existed only during a portion of the deflection range of the reverser, they fortuitously generally coincided with the range used during a normal landing approach. In the pilots' opinion the wave-off characteristics were improved as a result.

Use of reverser for in-flight deceleration and emergency descent.- Two uses of the thrust reverser are in-flight deceleration (holding altitude constant) from cruise or high-speed flight and emergency descent to lose altitude rapidly without exceeding an airspeed limit. Tests were made comparing deceleration characteristics between a throttle cut and reverser deflection starting from a speed of 300 knots. These data indicate that deceleration is increased from 2.5 knots per second when the throttle is used to 7.5 knots per second when the reverser and 85-percent engine rpm are used. Formation flights with an airplane of similar gross weight with aerodynamic speed brakes were made to evaluate the relative merits of the reverser and speed brakes at a speed of 200 knots. At this speed reverser effectiveness equal to the speed brakes was obtained at a reverser deflection of 0.6 and 85-percent engine rpm.

Simulated emergency descents were made from 26,000 to 15,000 feet using idle power with no reverser and full reverse thrust at an airspeed limit of 250 knots. It took 76 seconds to lose altitude using the reverser and 233 seconds using the throttle.

Ground operation.- The majority of touchdowns were made with engine rpm at 85 percent and with the reverser deflected approximately 0.4. As soon as all three wheels were on the runway the reverser was fully deflected and then engine rpm was increased to 100 percent. A typical time history is shown in figure 14. About 0.3g deceleration was obtained without using wheel brakes from touchdown speed to a speed of 50 knots where forward thrust and idle power were selected. Slower speeds under full reverse thrust operation were not used in order to avoid the possibility of exceeding maximum allowable skin temperatures over the rear fuselage area. Using the reverser in this manner reduced the landing roll to approximately one half of that for wheel brakes. The light airplane buffet and moderate elevator buffet which occurred with full reverse thrust as speed decreased was not considered objectionable. During the landing rollout there was no difficulty in maintaining a straight path even in a substantial cross wind. The nose-down trim change previously mentioned was present on the ground, loading the nose wheel. The nose-down load which was not considered detrimental decreased as speed was reduced. The reverser configuration which produced a nose-up tendency in flight in the intermediate deflection range, also tended to lift the nose wheel off the runway. This undesirable characteristic was noticeable only when the reverser was deflected at the higher engine powers above 85-percent rpm.

The pilots experimented with the use of reverse thrust during taxiing. It was felt to be practical only for an emergency (icy taxiway or loss of wheel brakes) because of the high engine rpm required.

Refused take-offs were made at speeds up to 120 knots. A short time was required (reverser going from full open to full closed in 4 seconds) to obtain full reverse thrust due to the fact that engine rpm did not have to be reduced. Even more rapid actuation would have been desirable under this condition of refused take-off.

Effect of type of cockpit reverser control.- For reasons of simplicity the initial flight tests were conducted with a beep-type control since it was felt that such a system would be entirely compatible with the pilots present use of speed brakes as a speed control device. With the use of beep-type control for flight path control two rates of actuation were required: a slow rate (10 sec for full travel) for precision control and a fast rate (2.5 sec) for emergency, during wave-off, or when maximum reverse thrust was required during ground operation. Little opportunity was afforded to investigate a variety of actuating speeds during this initial evaluation; however, the slow rate was generally adequate for controlling flight path angle although there was some tendency to over-control during attempts to establish a precise angle of approach. Either a slower rate or a proportional type control would have been more desirable under these conditions. For wave-off a rate of 2.5 seconds for full travel was satisfactory but does not represent the maximum rate that the pilot could utilize assuming that trim changes remain within satisfactory limits.

Though the pilots found that the fast rate was desirable in producing rapid speed changes, they found it difficult to return the reverser to the correct setting for a given approach speed. In spite of the foregoing, the over-all response in terms of ability to change airplane speed and flight path were so much improved over the use of throttle alone that the pilots accepted the overcontrolling without serious objection. The accumulator button placed on top of the control stick was originally considered as an emergency device; however, the increased response available together with the simplicity of the device caused it to become the primary wave-off control. The reverser position indicator was useful as a reference for making deflection changes and in avoiding the high reverser deflections with the accompanying severe trim change.

When the reverser was used for maximum braking during the ground roll, the reverser control was held back to change reverser position from that used in the approach (approximately 0.4) to full reverse and then the throttle was moved forward to change rpm from 85 percent, used in the approach, to 100 percent for maximum reverse thrust. This change in direction of control was considered awkward to make and therefore unsatisfactory for operational use.

From the experience gained with the beep-type control it was the pilots' opinion that this type of control would be satisfactory if the reverser were used only as a replacement for speed brakes, but the broader possibility of its use for flight path control would indicate that some form of a proportional type control would be more desirable. Such a control would overcome most of the shortcomings noted with the beep control. First of all vernier type control would be available through minute deflections of the control lever while maximum rates could still be obtained through large momentary deflections of the control. In addition, a single lever proportional type control could be designed so that the proper sense of motion is retained. For example, the control would always provide increasing thrust when moved forward and decreasing thrust when moved aft.

Requirements for ideal reverser.- From the discussion on the operational uses of the reverser it may be concluded that the ideal reverser should be such that if the pilot chose to use the reverser exclusively for flight path control, deflection of the reverser would produce only a change in flight path angle with a negligible change in airspeed. On the other hand, if the airplane were on the desired flight path but at an airspeed other than that desired, reverser deflection would change only airspeed. Obviously, these two conditions are not compatible with a simple system and a choice must be made. From the experience gained in these tests it is felt that it would be preferable to have the reverser supply the proper trim variation for flight path control, thereby compromising its use as a pure speed control. Included in this ideal reverser system would be a reverser cockpit control integrated with the throttle such that forward throttle motion would decrease reverse thrust at a constant engine rpm as desired.

It should be noted that in the design of a reverser for satisfactory flight path control, it appears desirable to provide a mild nose-down moment with increasing reverser deflection so that the airplane rotates toward a steeper flight path angle to correspond to a reduction in thrust. Thus the pilot would be given an immediate indication of the direction of the flight path angle change; however, the proper elevator control input must be supplied to maintain airspeed constant. Because of the complex flow field produced by the reverser in the vicinity of the horizontal tail, it is not likely that one reverser configuration could be designed to produce a flight path angle change with only a negligible airspeed change under various engine thrust values and over a large airspeed range. It is felt, however, that if the longitudinal trim change induced by reverser deflection is in a nose-down direction with decreasing thrust, is linear over the reverser deflection range, and is of small enough magnitude to be well within the elevator control power, satisfatory operational flight path control will result.

Effect of Reverser on Aerodynamic Characteristics

Trim change.- The large longitudinal trim change at the larger reverser deflections was the most serious aerodynamic problem arising during the program. Unpublished wind-tunnel data indicate that the trim change is associated with an increase in upwash at the horizontal tail due to the blocking action of the reverser. The trim change was more severe at lower airspeeds and higher engine thrust as shown by the data in figures 10 and 11. It can be noted in general that the trim change was reduced somewhat at the full reverse position. Even at full reverse the trim change increased considerably with engine rpm (fig. 15). Tuft studies of the rear fuselage area disclosed that the largest trim change corresponded to the greatest amount of flow attachment to the fuselage in the area ahead of the reverser. One method tested to alleviate the trim change was to vary the end plate size and shape since the results in reference 3 indicated these changes would vary the exhaust gas flow angle and velocity distribution. The results of the test are summarized in figure 16. In general, these data indicate that the trim change below 0.6 reverser deflection is changed very little by end plate geometry. In contrast, changing the amount of top and bottom cover plate area caused a considerable variation in trim change below 0.6 deflection as shown in figure 17. It should be noted, however, that although the trim change was reduced in the reverser range below 0.6, the inflections in the curves around 0.4 deflection were disconcerting to the pilot.

Lateral-directional characteristics.- In order to investigate for possible deterioration in the lateral-directional stability caused by the reverser the damping was measured at three airspeeds. Although the damping was slightly less at the lower airspeeds, there appeared to be no marked effect of the reverser on the damping for the range of reverser positions tested. In steady sideslip tests there appeared to be no effect of reverse thrust on the directional stability over the speed range from 130 to 170 knots. The pitching moment due to sideslip was not affected appreciably by reverser deflection.

Stalling and minimum speed.- In general there was no effect of the reverser on the airplane motions at the stall. Because of the increasing amounts of up-elevator deflection required for trim with increasing reverser deflection, the minimum speed (determined by maximum up-elevator deflection) is increased. The reduction in available control was not particularly bothersome to the pilot in landing approach since the flight path response with the reverser was considered excellent.

Effect of Reverser on Miscellaneous Characteristics

Reverse thrust.- A comparison of reverse thrust effectiveness for static, in-flight, and small-scale cold air tests is shown in figure 18. The results shown in figure 19 for various end plates indicate that reducing the end plates to one-half normal size reduced the maximum reverse effectiveness approximately 25 percent, while doubling the end plate size over normal resulted in further reductions in effectiveness. It is believed that with the larger end plates the flow was turned more directly into the blunt rear-fuselage fairing which forced flow out the top and bottom of the reverser. Installing top and bottom cover plates resulted in reverser effectiveness as high as 85 percent at maximum deflection as shown in figure 20. This produced a reverse thrust of 5100 pounds. It should be noted that since increases in reverse thrust effectiveness, such as that provided by the top and bottom cover plates, resulted in a more pronounced nose-down trim change (fig. 17), the flight evaluation tests were conducted with a reverser configuration which produced a reverser effectiveness of 60 percent. The data in figure 21 show the effect of engine rpm on reverse thrust effectiveness. The increase in effectiveness with increase in rpm is believed to result from a greater turning tendency due to flow attachment to the rear fuselage areas. A similar effect was noted in the small-scale tests of reference 3. Installation of the reverser had no effect on maximum forward thrust nor was there any significant increase in tail-pipe temperature with increase in reverser deflection.

Buffet.- Buffet induced by the reversed exhaust gases was a mild shaking of the airplane and elevator and rudder controls in flight, increasing to moderate amplitude shaking during ground rolls with maximum reverse thrust. No evidence of large amplitude cyclic buffeting of the airplane was found over the speed range tested. It is felt that with an aft location of the reverser such as that used on the test airplane, buffeting effects would be minimized compared to a reverser location on wing pods or to a reversible propeller system. Buffeting was most intense in the intermediate reverser deflection range where tuft pictures showed attachment of exhaust flow to the fuselage skin ahead of the reverser.

Temperature.- Temperature measurements over the rear fuselage area and tail surfaces disclosed that the bluff area immediately ahead of the reverser experienced the greatest temperature rise. A maximum temperature of 1100° F was measured in this area during ground roll at maximum reverse thrust. No increase in temperature was measured on the tail surfaces during flight nor was any reduction in dynamic pressure at the tail measured. During the ground roll at maximum reverse thrust the maximum temperature measured on the lower surface of the inboard portion of the elevator was 125° F. It is noteworthy that the maximum fuselage skin temperatures were less at full reverser deflection where the flow was directed more outboard. There appeared to be no increase in engine inlet temperature down to the lowest test speed of 50 knots. The engine inlet was 31 feet ahead of the reverser.

Structural skin failures.- Structural skin failures occurred on the rear portion of the fuselage during the early part of the program. For the most part these failures were confined to cracks emanating from rivet joints in the areas of direct impingement of the reversed exhaust gases. In one case a 5-inch diameter hole was burned in the rear fuselage 2024-T aluminum skin 18 inches ahead of the reverser during a ground roll. In this case maximum engine thrust had been inadvertently applied with the reverser at 0.6 of maximum reverser deflection. In these critical areas a thin doubler skin of stainless steel eliminated additional structural difficulties.

CONCLUSIONS

The following conclusions are based on the investigation of a modulating thrust reverser on the F-94C airplane.

1. Use of the reverser in the landing approach resulted in improved control over a relatively large range of flight path angles for a given approach speed. Large reductions in approach speed were realized when the reverser rather that the throttle was used in executing steep approaches.

2. Improved control of flight path angle was made possible by the rapidity with which large thrust changes could be made with the reverser; this improvement resulted in increased accuracy in selecting the touchdown point in both carrier and tactical type approaches. Some of the improved flight path control resulted from a nose-down trim change with decreasing forward thrust induced by the reverser.

3. The nose-down trim change induced by the reverser compromised the use of the reverser for speed control in landing approach. The use of full reverser deflection with maximum engine power for deceleration at high speeds or as an emergency let-down device was considered practical due to a smaller trim change.

4. The rate of change of elevator angle with reverser deflection increased with increases in reverser deflection at a given airspeed. At the lower airspeeds and higher engine powers there was insufficient elevator power to overcome the nose-down trim change which occurred at the higher values of reverser deflection.

5. The wave-off characteristics of the airplane were improved by the rapid thrust response and nose-up trim change produced by reverser retraction.

6. Deceleration values of approximately 0.3g were obtained with full reverse thrust during the landing roll, resulting in reductions in landing roll of the order of one-half that for brakes alone.

7. Changing end plate geometry on the reverser had little effect on the nose-down longitudinal trim change. Removing the cover plate above the reverser had the effect of inducing a nose-up trim change with increasing reverser deflection over the intermediate reverser position range.

8. There were no marked changes in the lateral-directional dynamic stability characteristics, the static directional stability, or the stalling behavior due to use of the reverser.

9. Full deflection of the reverser resulted in a reverse thrust ratio of as much as 85 percent for one reverser configuration, thus producing a maximum reversed thrust of 5100 pounds. A change in end plate size or top and bottom cover plates had a powerful effect on the magnitude of reverse thrust.

10. The reversed flow resulted in mild buffet of the airplane and controls.

11. Structural heating effects of the blunt rear fuselage fairing restricted reverser use at full engine power to speeds greater than 50 knots. There was no increase in engine inlet temperature down to the lowest test speed of 50 knots when full reverse thrust was used.

12. The beep-type control employed in these tests was satisfactory for research purposes, but several limitations were noted which indicated that a proportional type control would be desirable for operational use.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., Jan. 27, 1959

APPENDIX A

THRUST REVERSER EFFECTIVENESS MEASURED IN FLIGHT

Flight path angle, γ, was obtained by the accelerometer method:

$$\sin \gamma = A_z \sin \alpha - A_x \cos \alpha$$

Increase in effective drag, ΔD, assuming no change in engine output and airspeed, was determined for the full range of reverser deflections:

$$\Delta D = W(\sin \gamma - \sin \gamma_o)$$

where

W	gross weight of the airplane, lb
$\sin \gamma$	sine of flight path angle for some reverser position
$\sin \gamma_o$	sine of flight path angle for full forward thrust

Thrust reverser effectiveness, η_{rev}, in percent of forward gross thrust, assuming no changes in engine output due to reverser deflection, and constant airspeed:

$$\eta_{rev} = \frac{F_G - \Delta D / \cos \alpha}{F_G} \cdot 100$$

where

F_G	gross thrust, lb

REFERENCES

1. Kohl, Robert C.: Performance and Operational Studies of a Full-Scale Jet-Engine Thrust Reverser. NACA TN 3665, 1956.

2. Kohl, Robert C., and Algrante, Joseph S.: Investigation of a Full-Scale, Cascade Type Thrust Reverser. NACA TN 3975, 1957.

3. Polak, I. P.: Development of Turbo-Jet Engine Thrust Destroying and Reversing Nozzle No. A.E.L. 102, Rep. A.E.L. 1108, Naval Air Experimental Station, Philadelphia, Jan. 1950.

4. Povolny, John H., Steffen, Fred W., and McArdle, Jack G.: Summary of Scale-Model Thrust-Reverser Investigation. NACA TN 3664, 1957.

5. Drinkwater, Fred J., III, Cooper, George E., and White, Maurice D.: An Evaluation of the Factors Which Influence the Selection of the Landing Approach Speeds. Paper presented to Flight-Test Panel of AGARD, Copenhagen, Denmark, Oct. 20-24, 1958.

TABLE I.- DIMENSIONS OF TEST AIRPLANE

Wing	
Total wing area, sq ft	232.8
Span, ft	42.58
Aspect ratio	6.1
Mean aerodynamic chord, in	80.6
Leading-edge sweepback	$9^{\circ}18'$
Fuselage	
Length, ft	44.72
Depth (max.), in	56
Width (max.), in	56
Horizontal tail	
Area, sq ft (total)	59.5
Elevator, sq ft	7.81

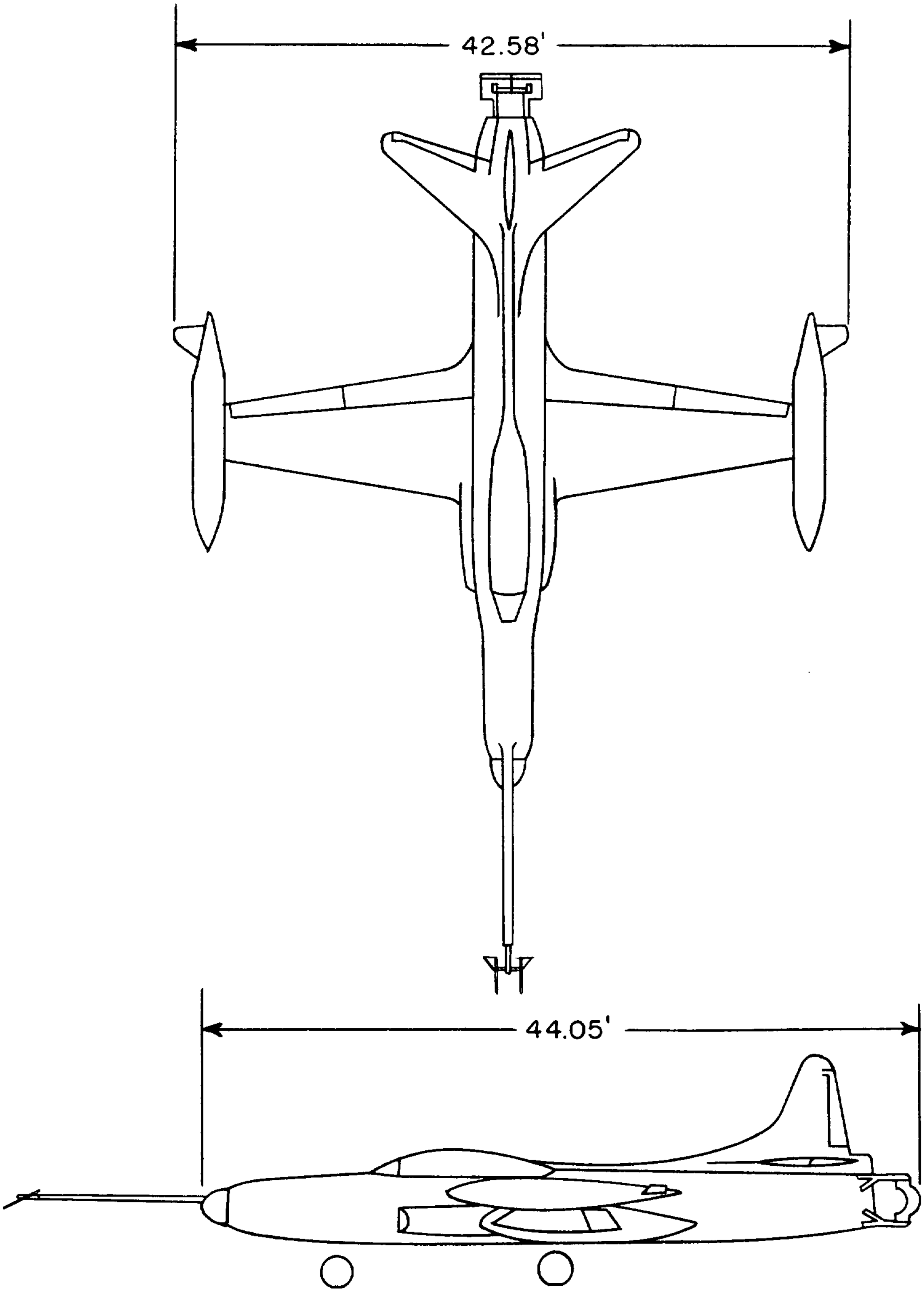

Figure 1.- Two-view drawing of test airplane.

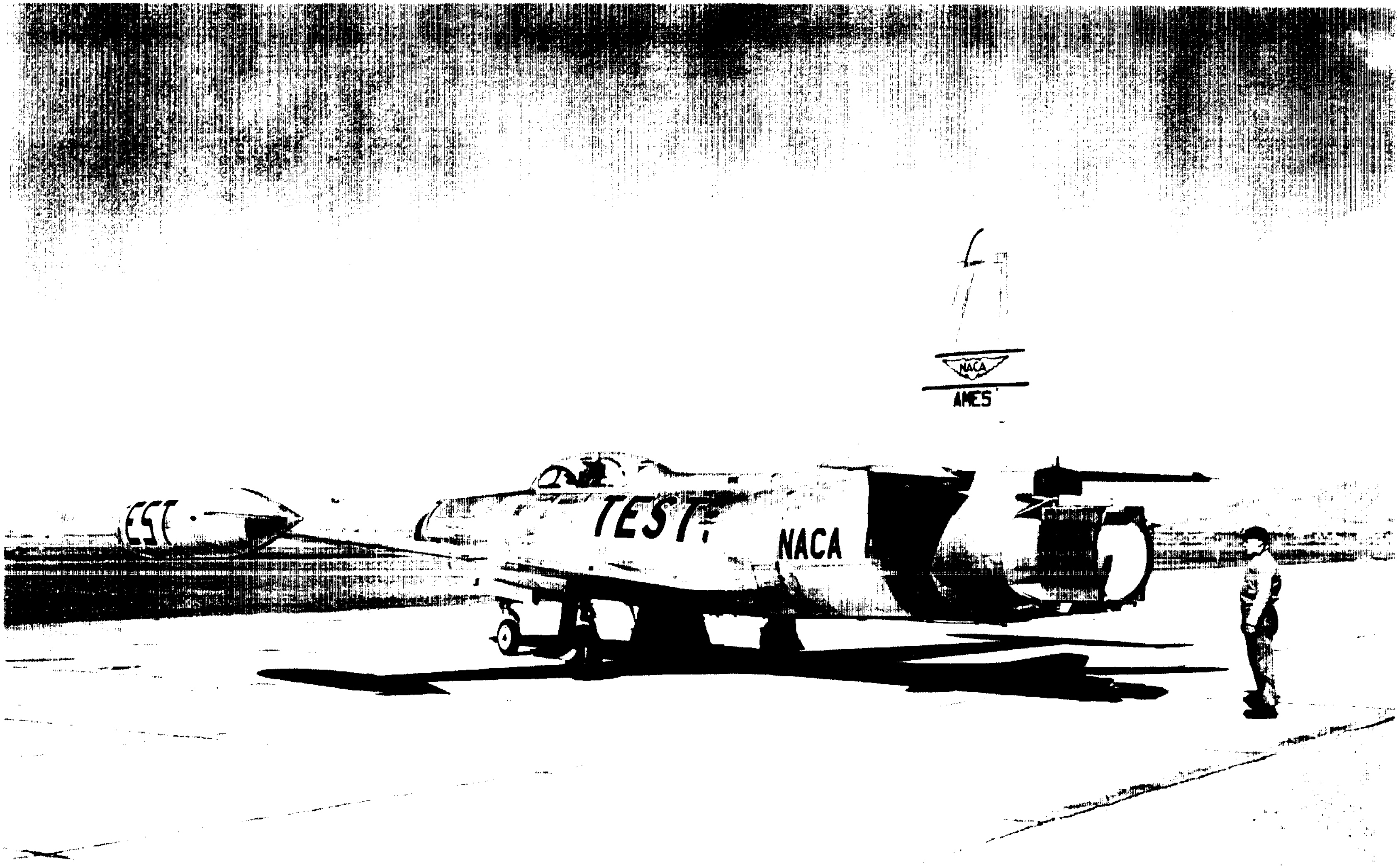

Figure 2.- General view of the test airplane.

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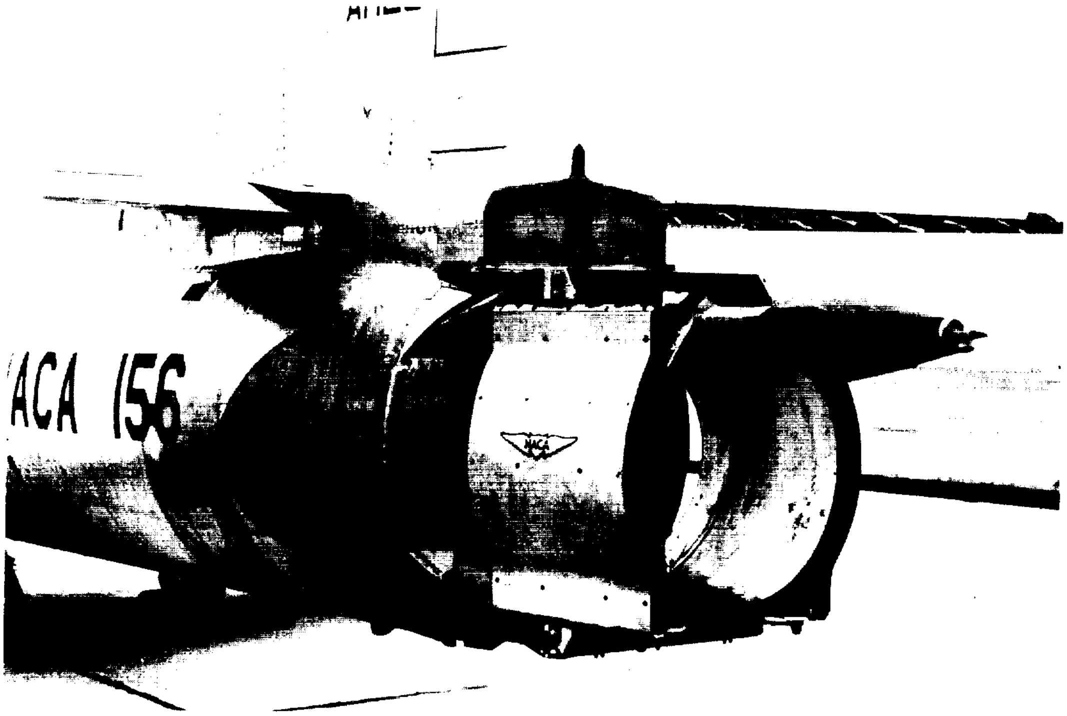

(a) Full forward thrust position.

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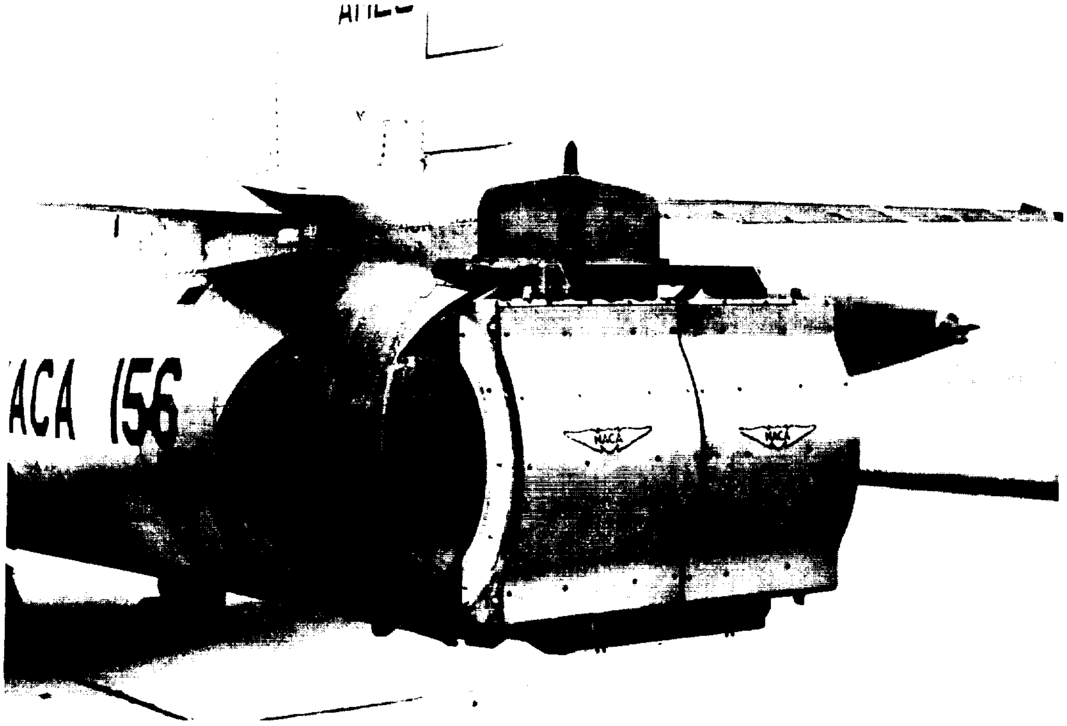

(b) Full reverse thrust position.

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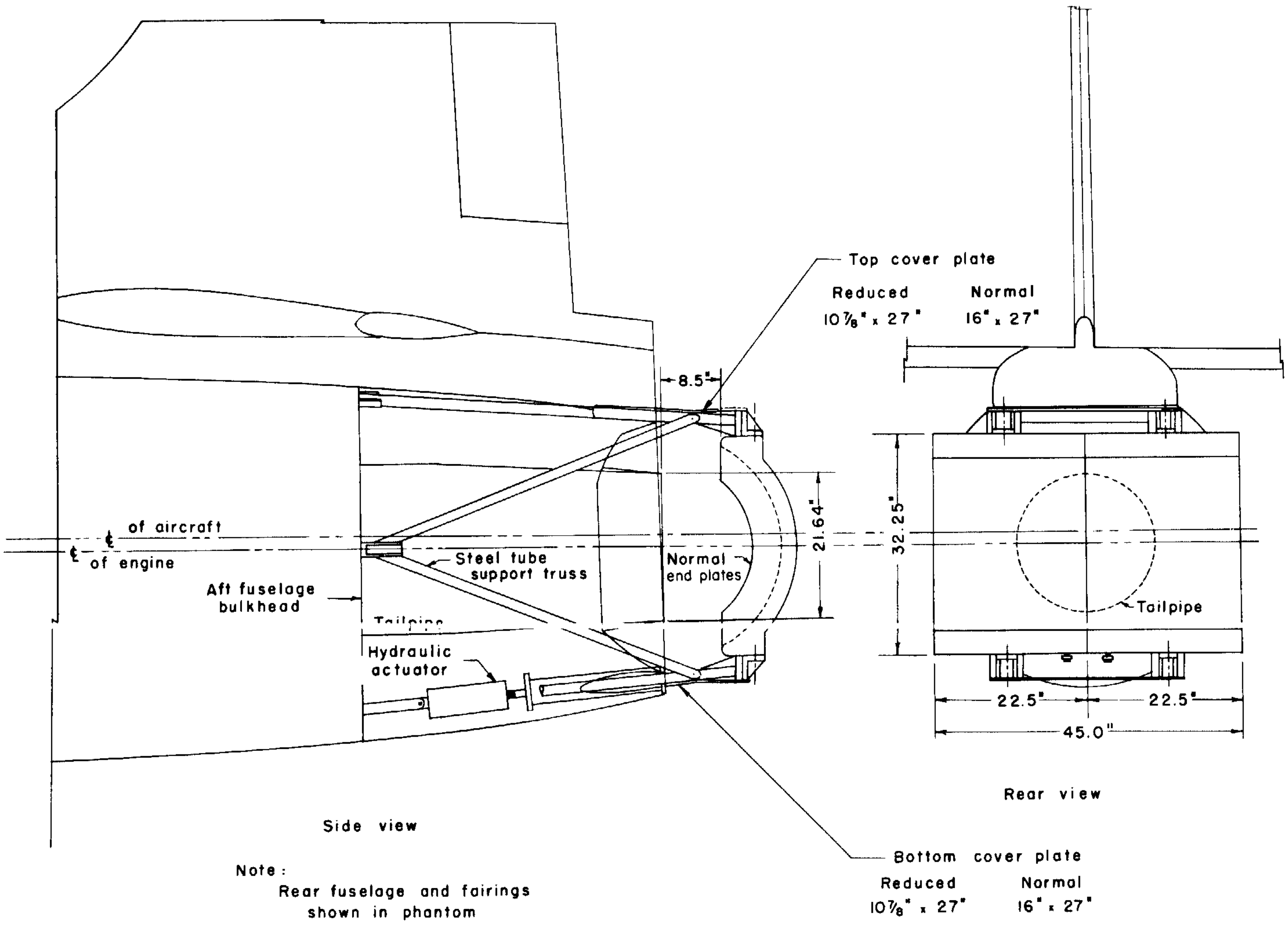
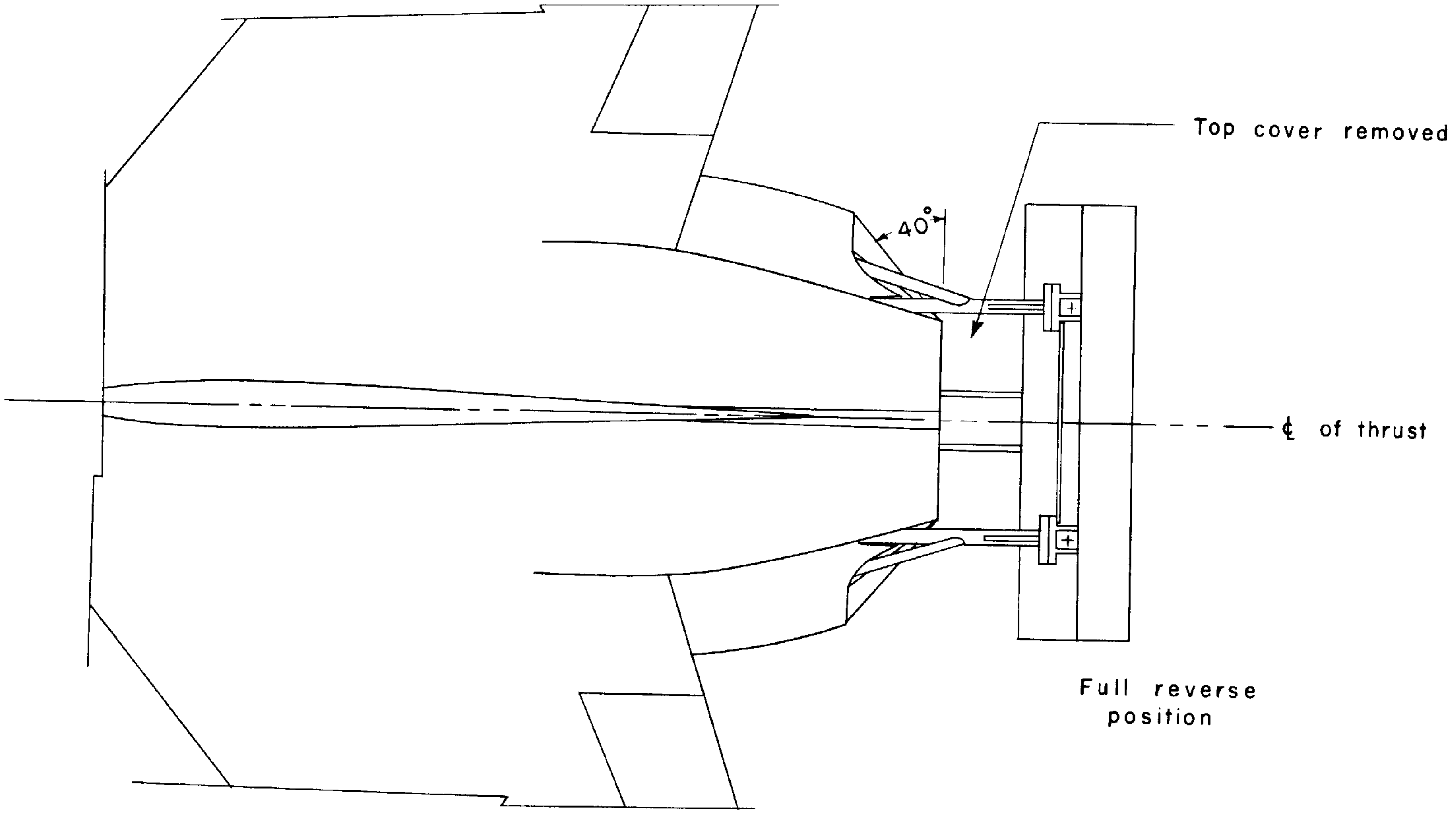
Figure 3.- Close-up view of the thrust reverser installation.



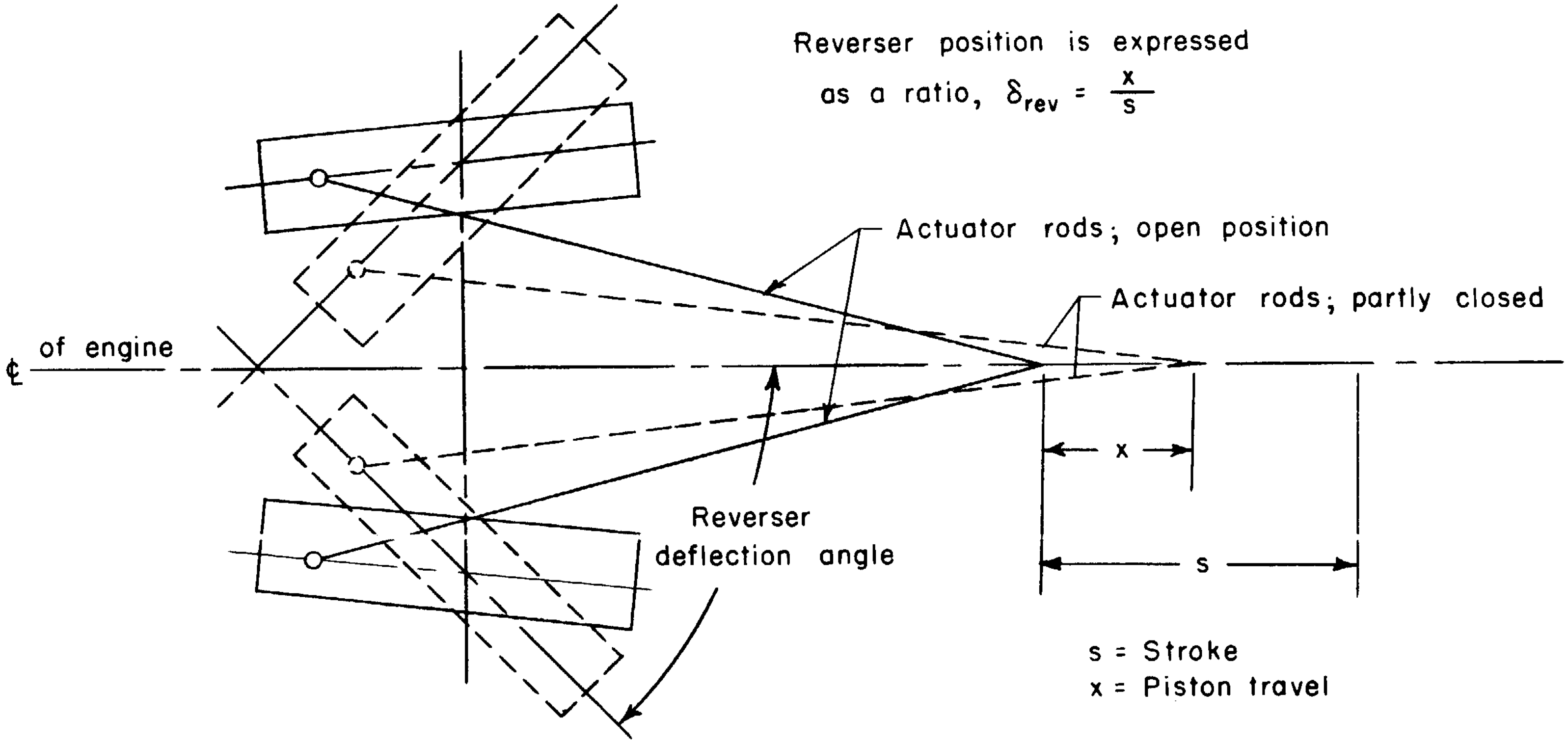
(a) Side and rear view.

Figure 4.- Details of F94-C Thrust Reverser.



(b) Plan view.

Figure 4.- Continued.



(c) Schematic diagram of reverser actuation.

Figure 4.- Concluded.

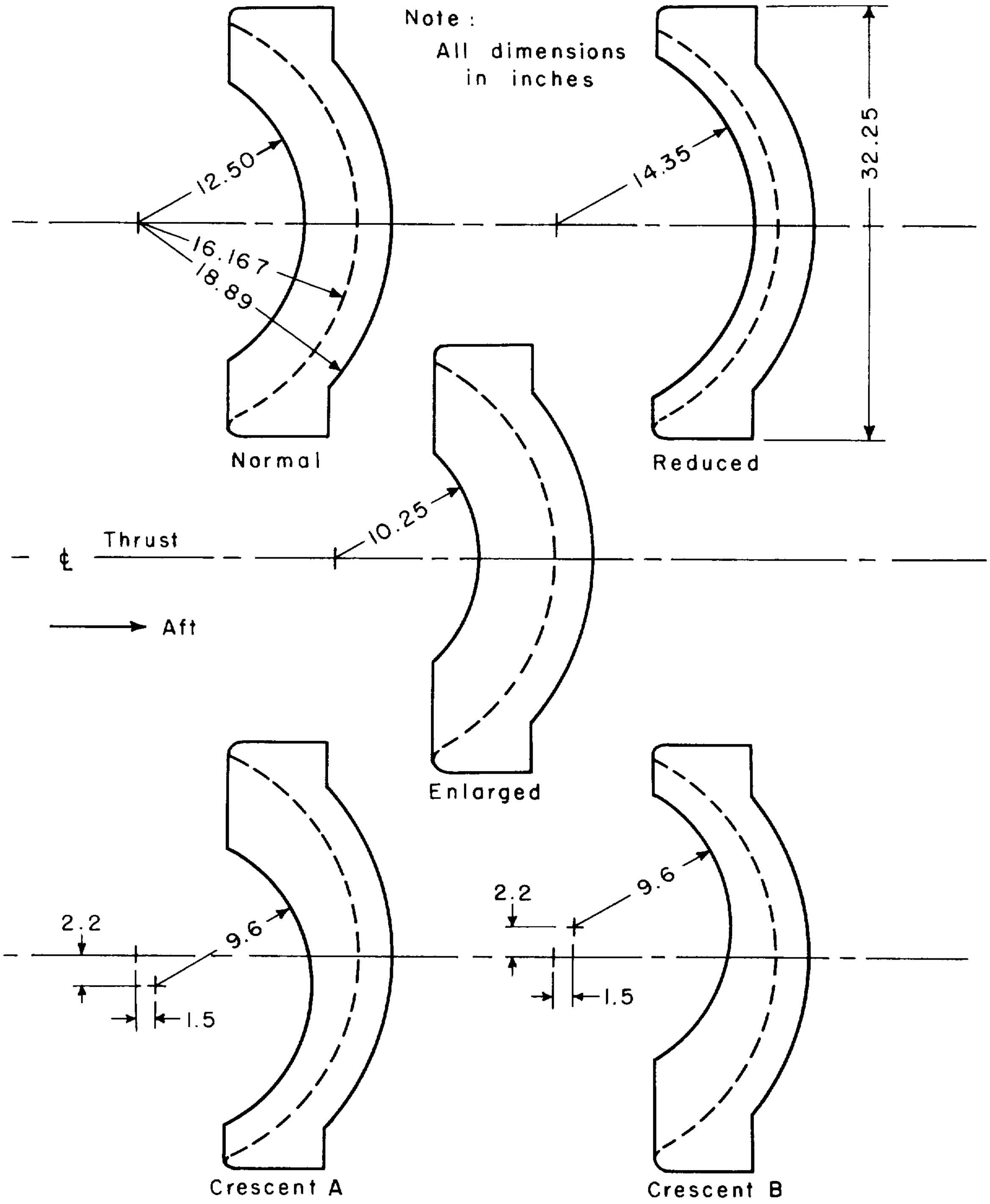


Figure 5.- Various reverser end plate configurations.

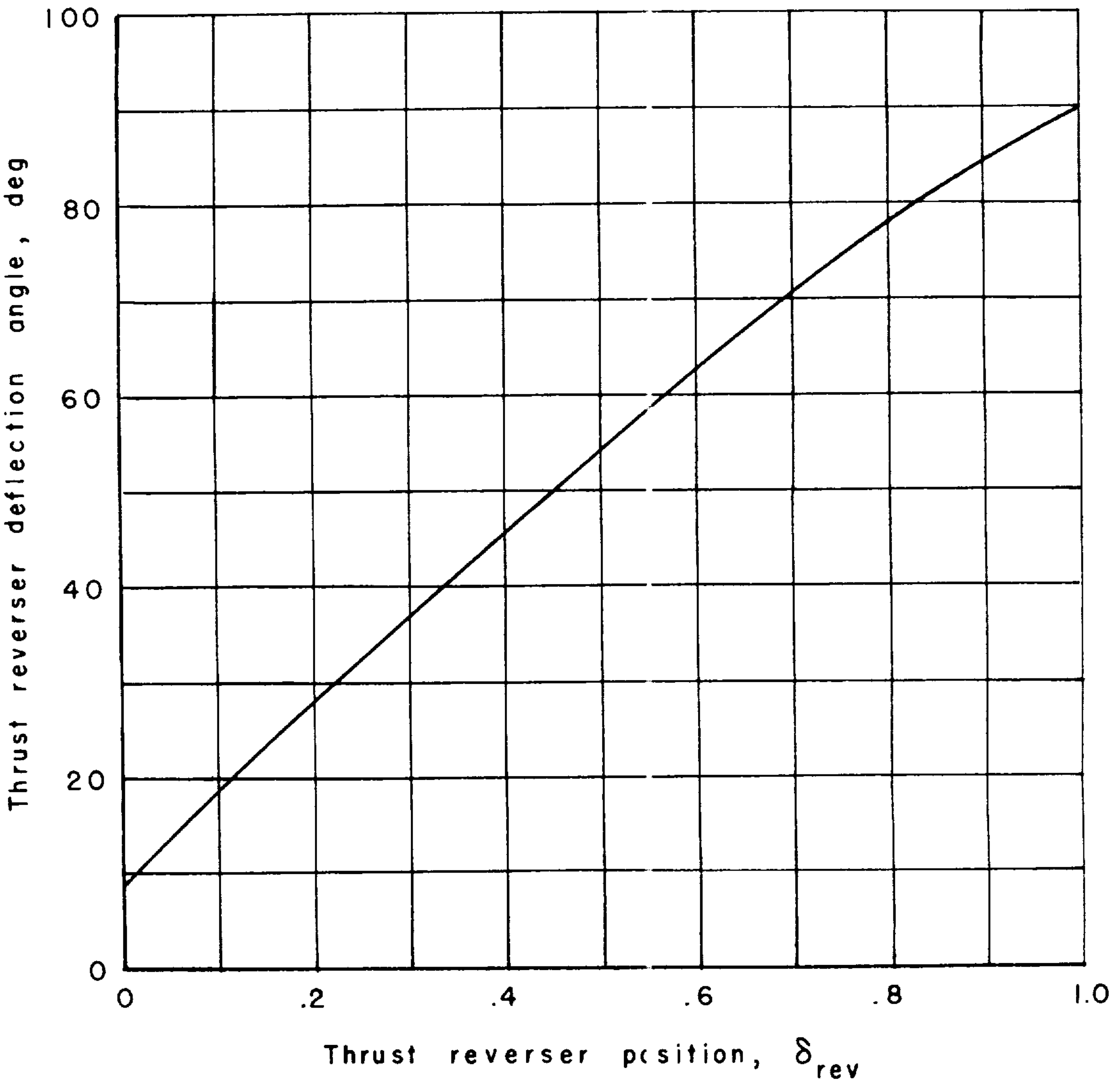
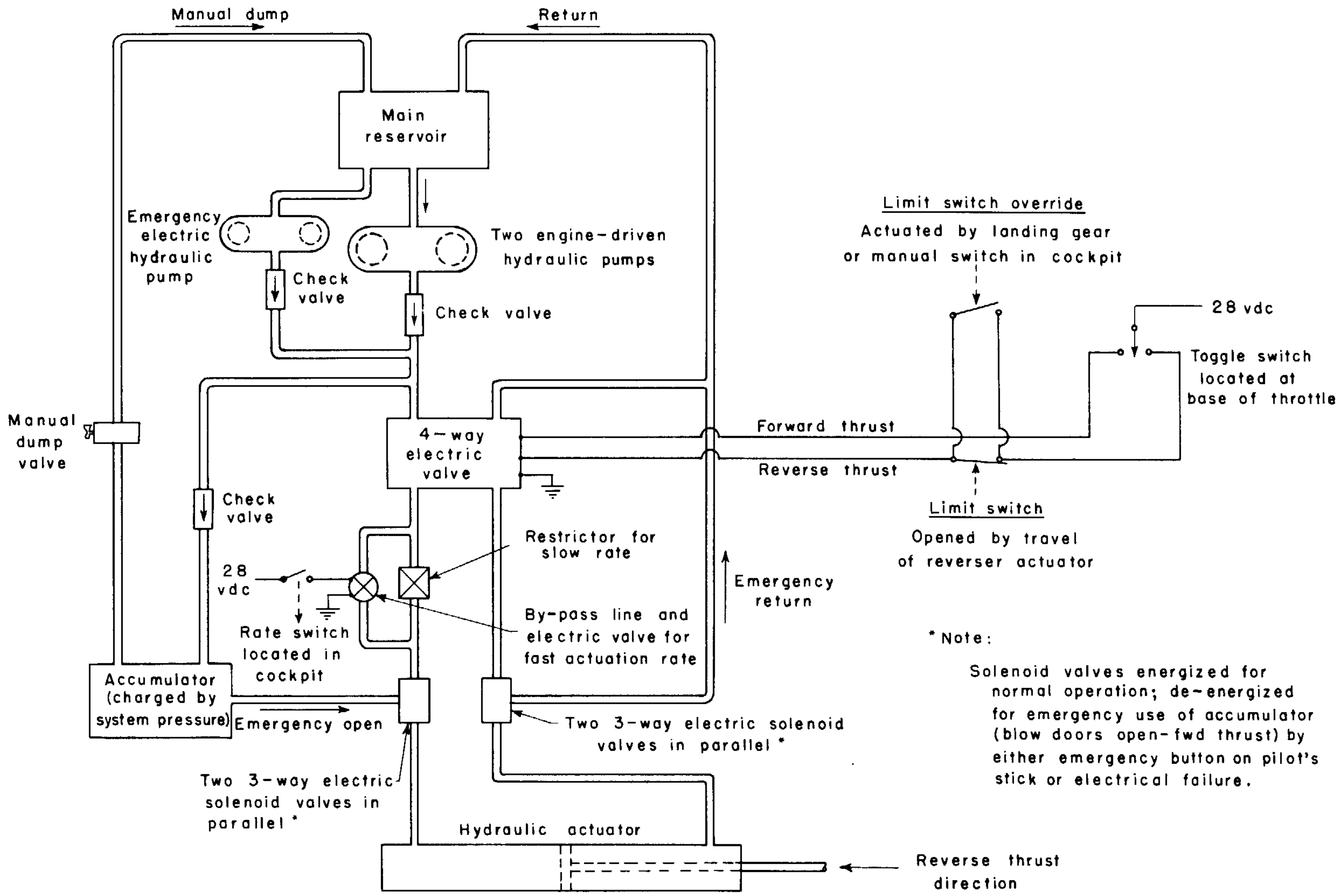


Figure 6.- Variation of angular deflection of reverser with reverser position.



*Note:

Solenoid valves energized for normal operation; de-energized for emergency use of accumulator (blow doors open-fwd thrust) by either emergency button on pilot's stick or electrical failure.

Figure 7.- Schematic diagram of hydraulic system used for reverser (beep control).

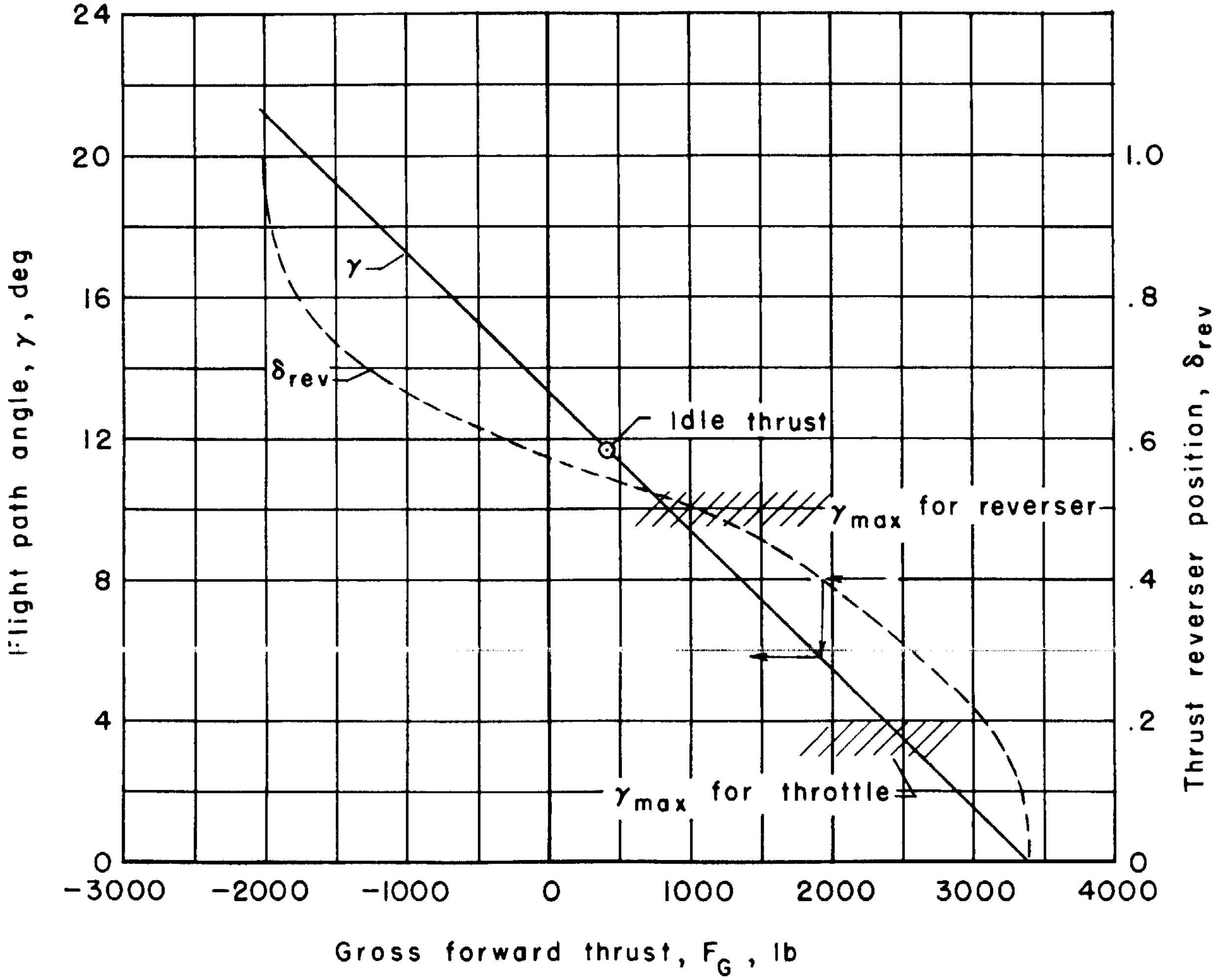
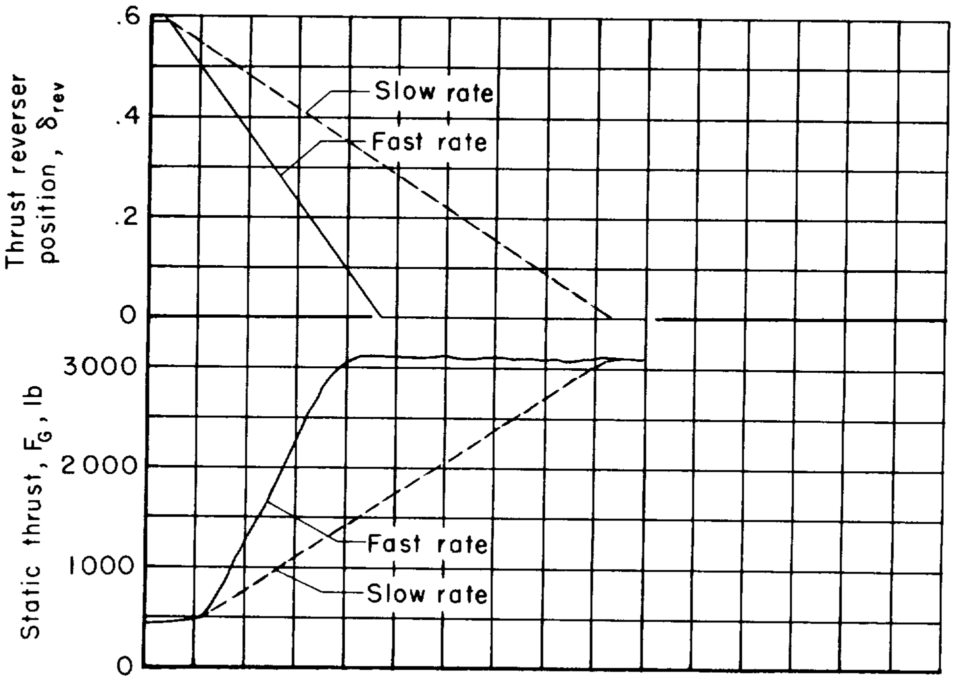
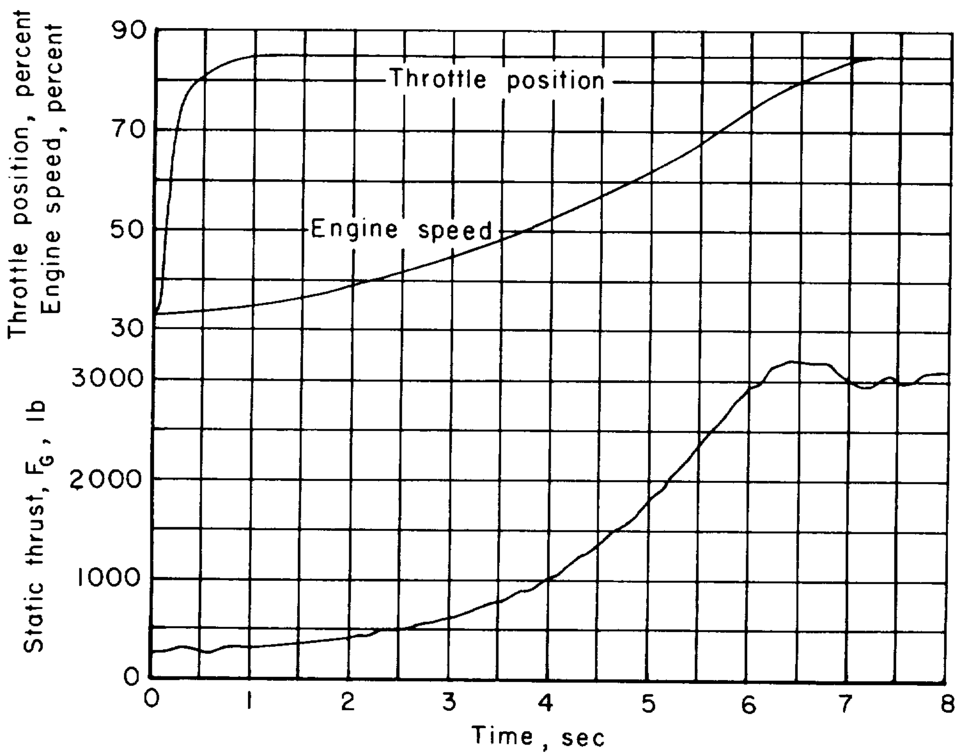


Figure 8.- Comparison of landing-approach flight path angles available for throttle movement and for constant engine speed (N = 85 percent) with thrust reversal; W = 15,000 pounds; V_i = 140 knots; sea level conditions.



(a) Thrust reverser only.



(b) Throttle only.

Figure 9.- Comparison of thrust response using reverser and throttle.

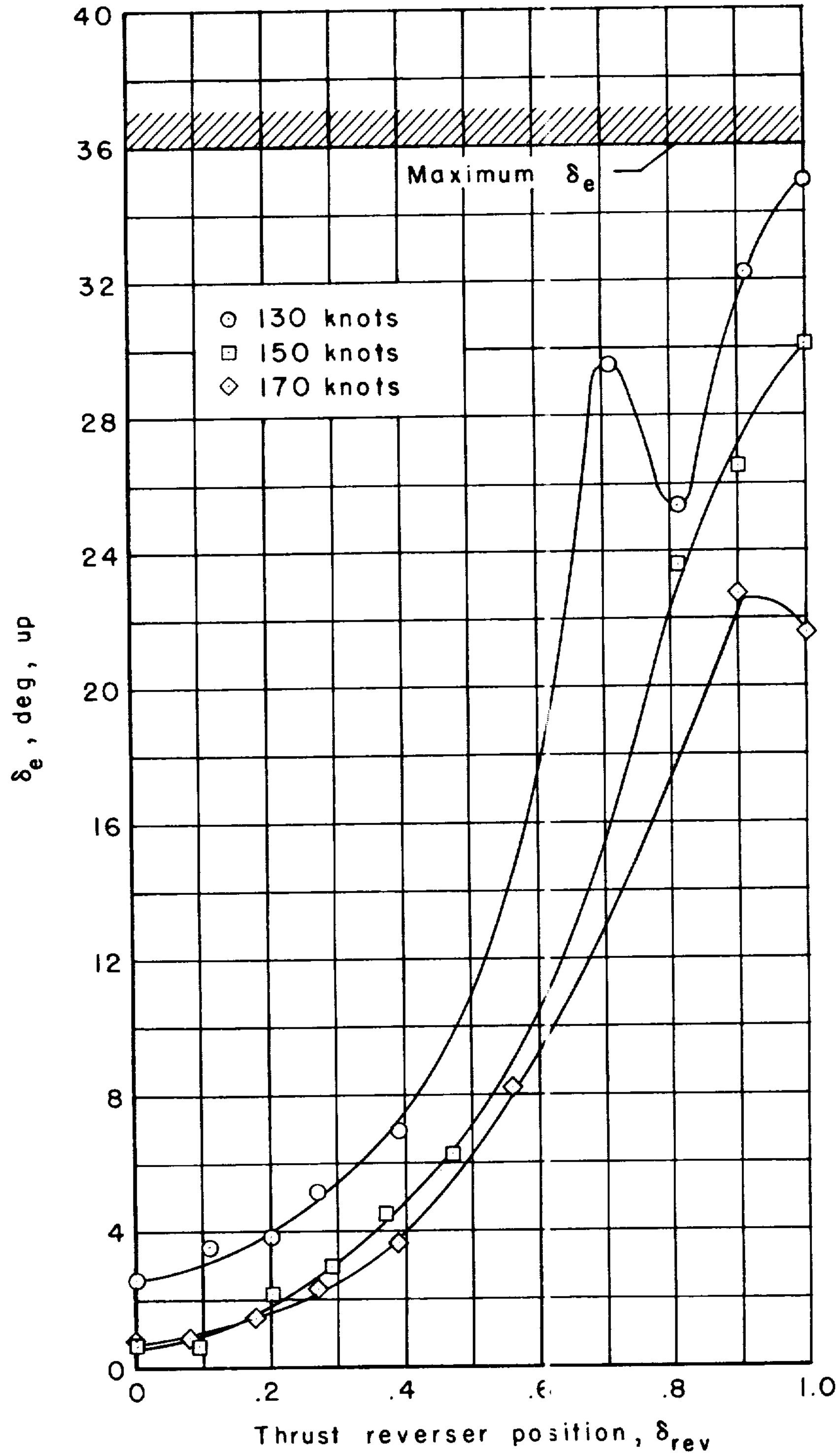


Figure 10.- Variation of δ_e required with reverser deflection at various constant values of airspeed. Reduced end plate. N = 85 percent.

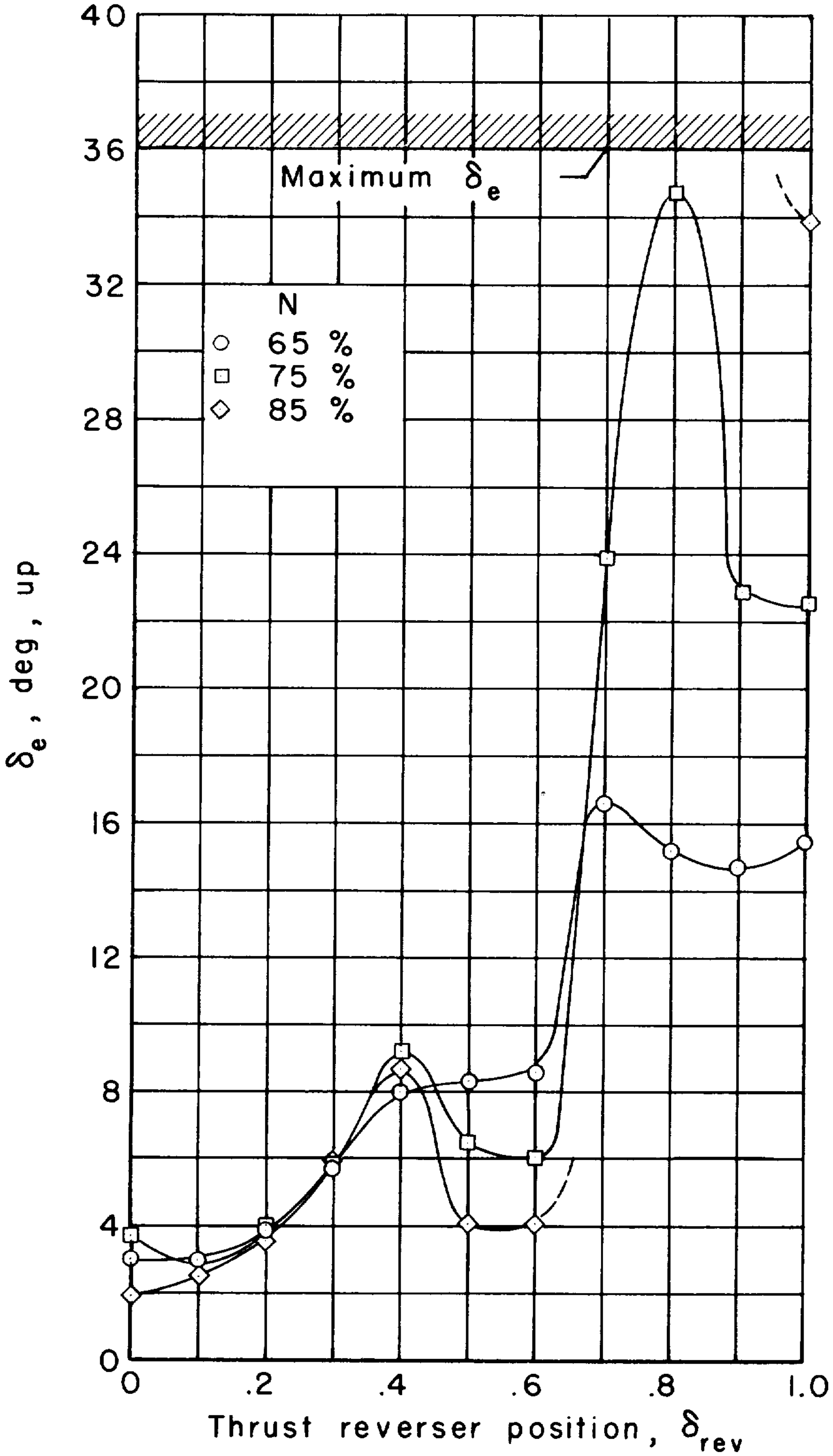
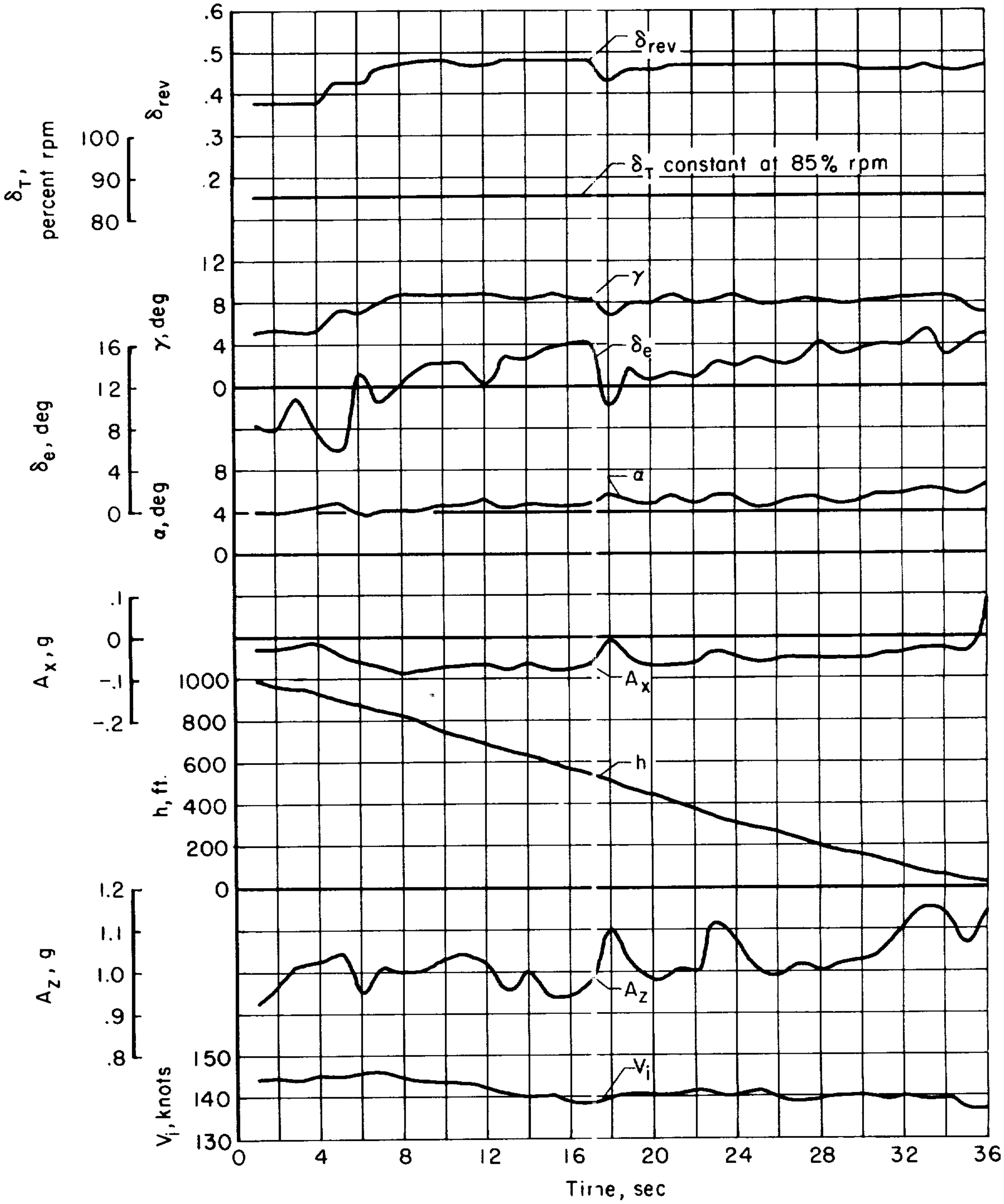
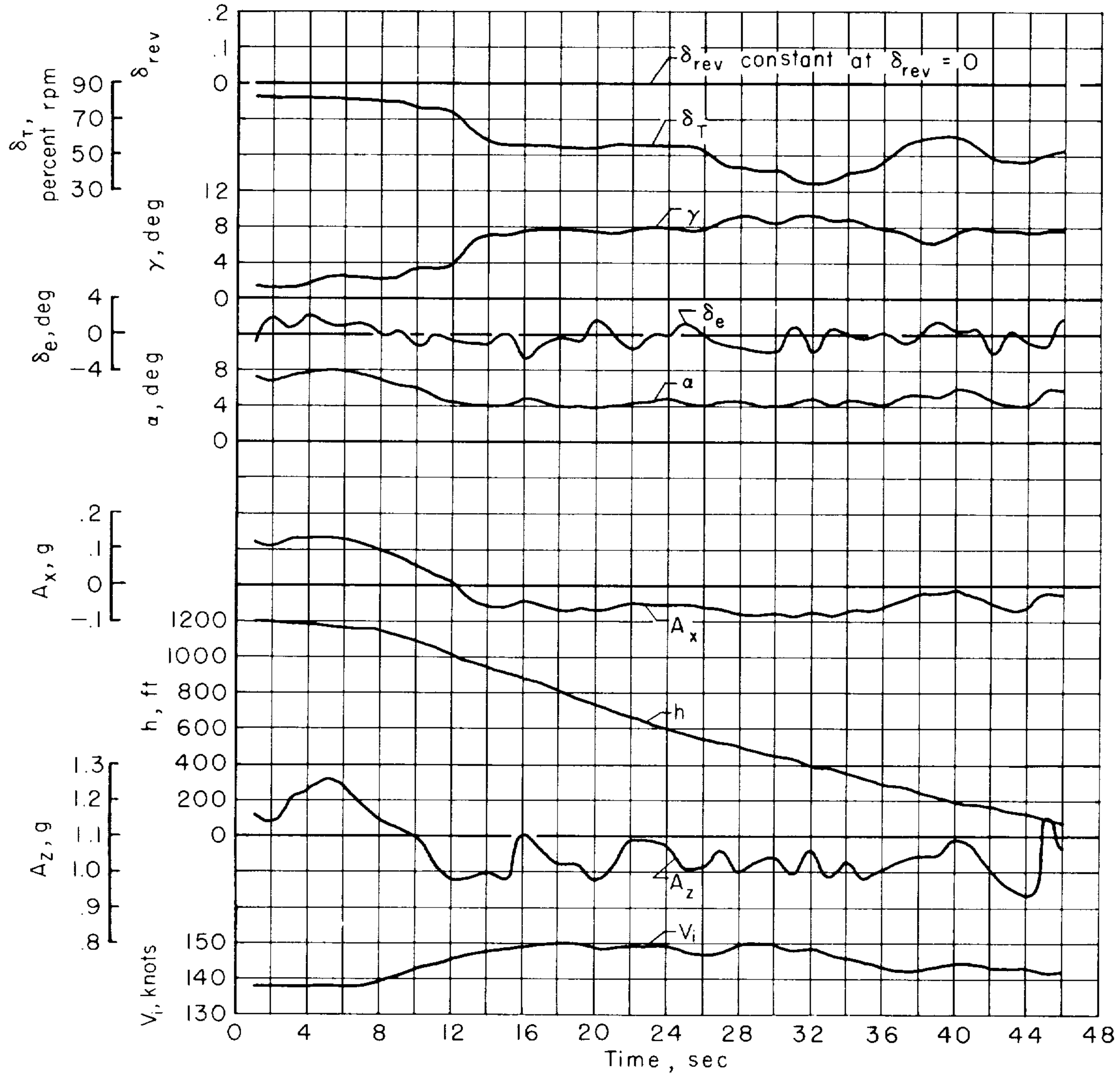


Figure 11.- Variation of δ_e with δ_{rev} for various engine speeds with normal bottom cover and reduced top cover plates; V_i = 150 knots.



(a) Thrust reverser only.

Figure 12.- Time history of 8° approach.



(b) Throttle only.

Figure 12.- Concluded.

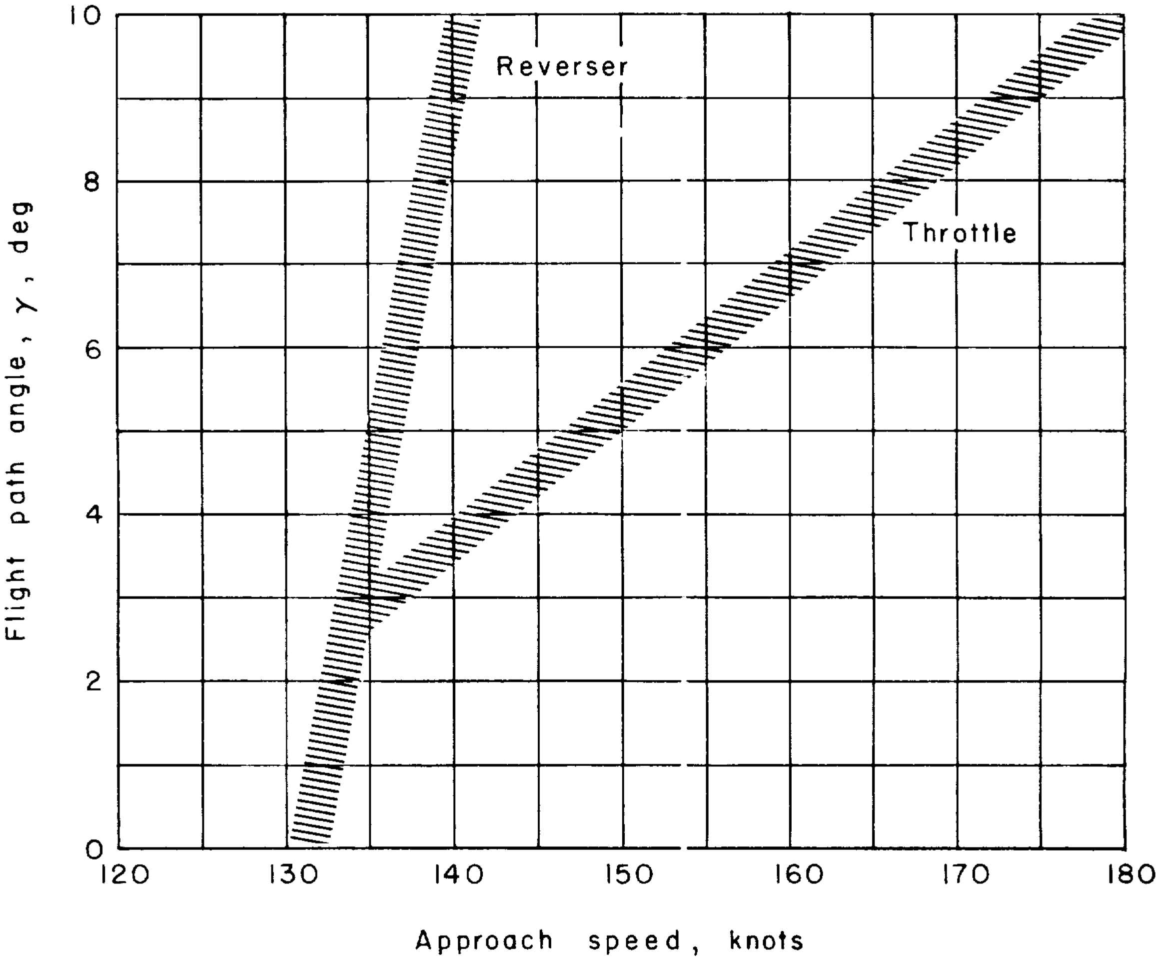


Figure 13.- Variation of flight path angle with approach speed with reverser and throttle.

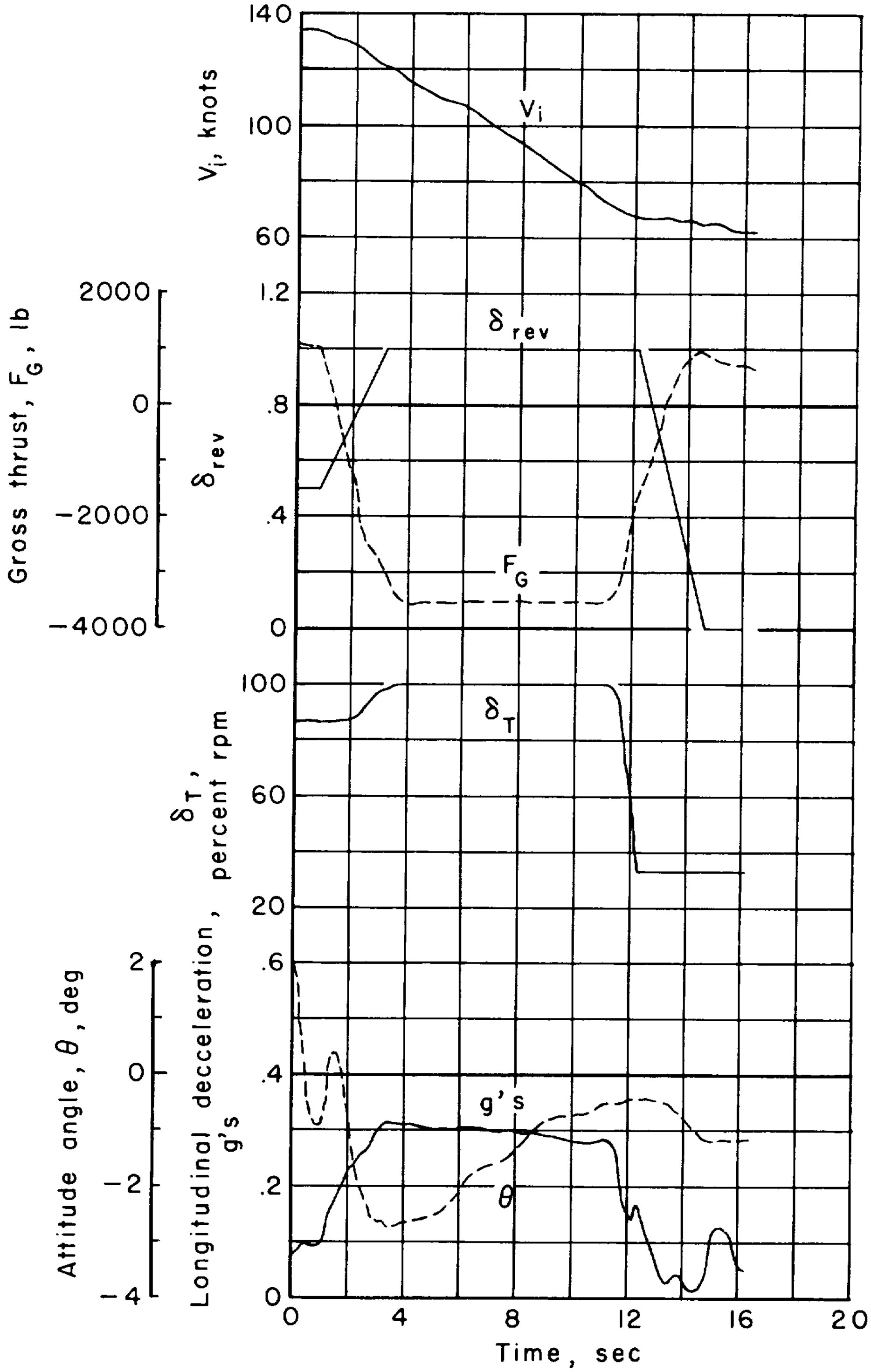


Figure 14.- Time history of landing deceleration using thrust reversal after touchdown on the runway. Touchdown point at time = 0.

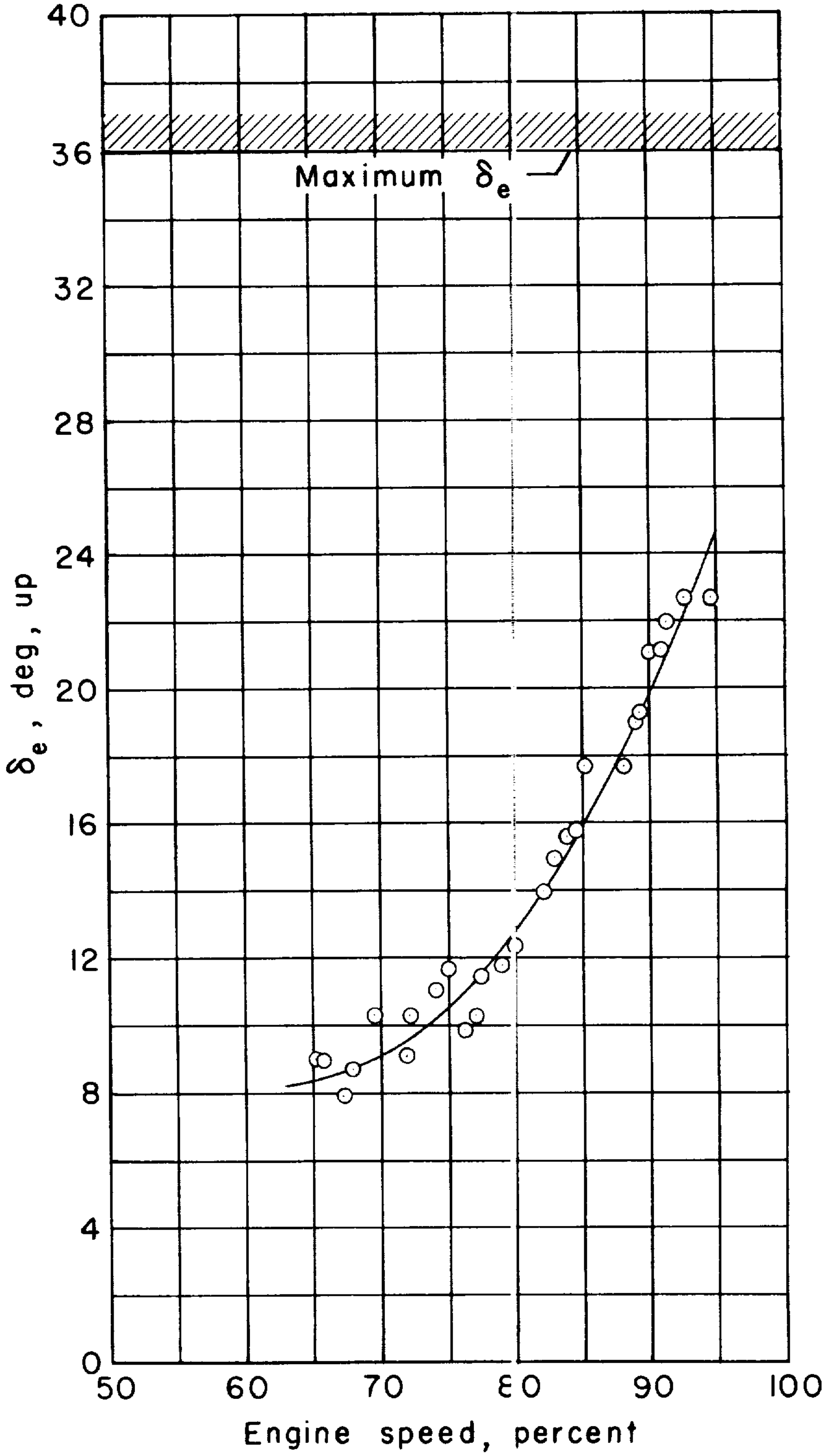
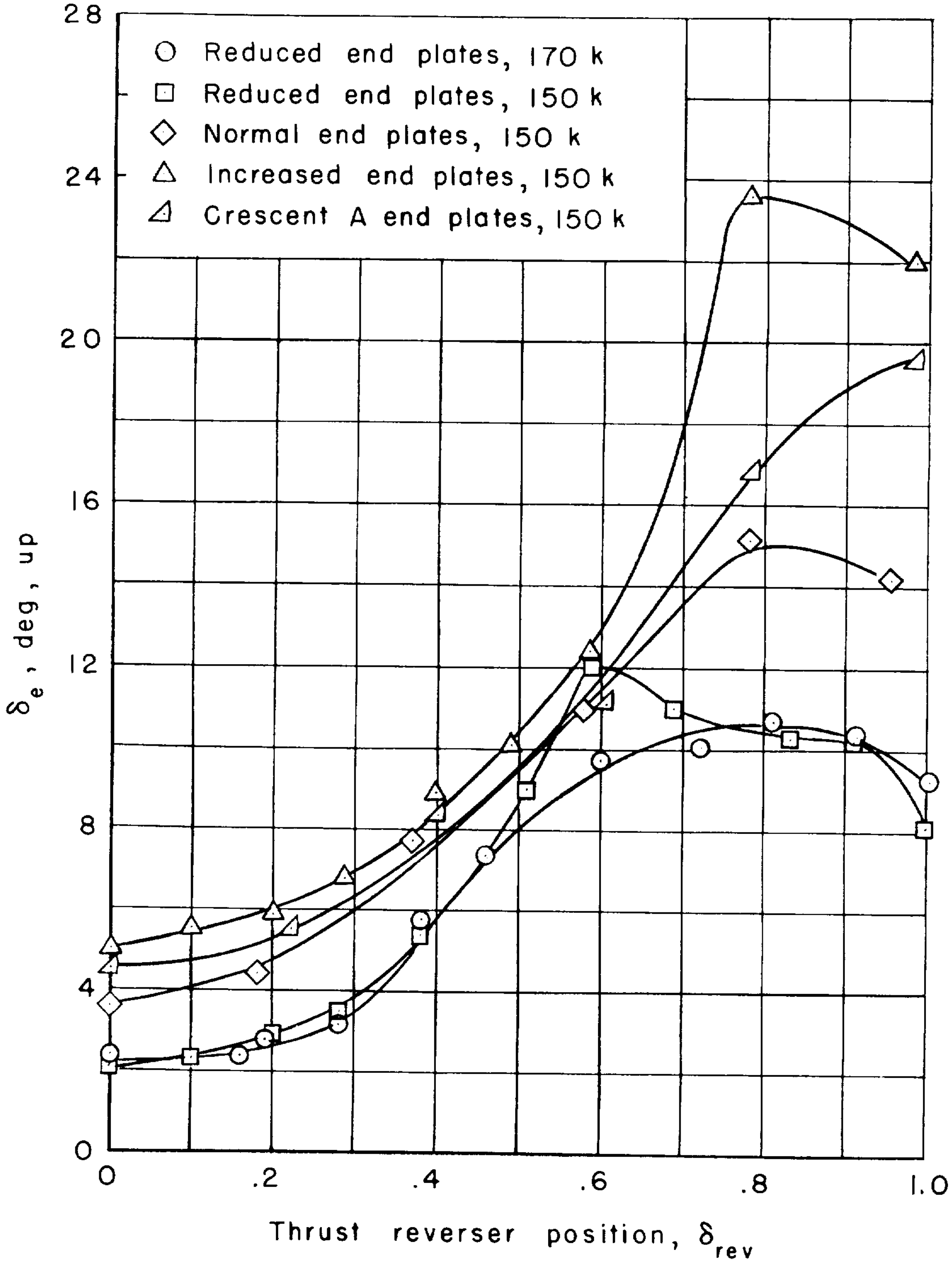
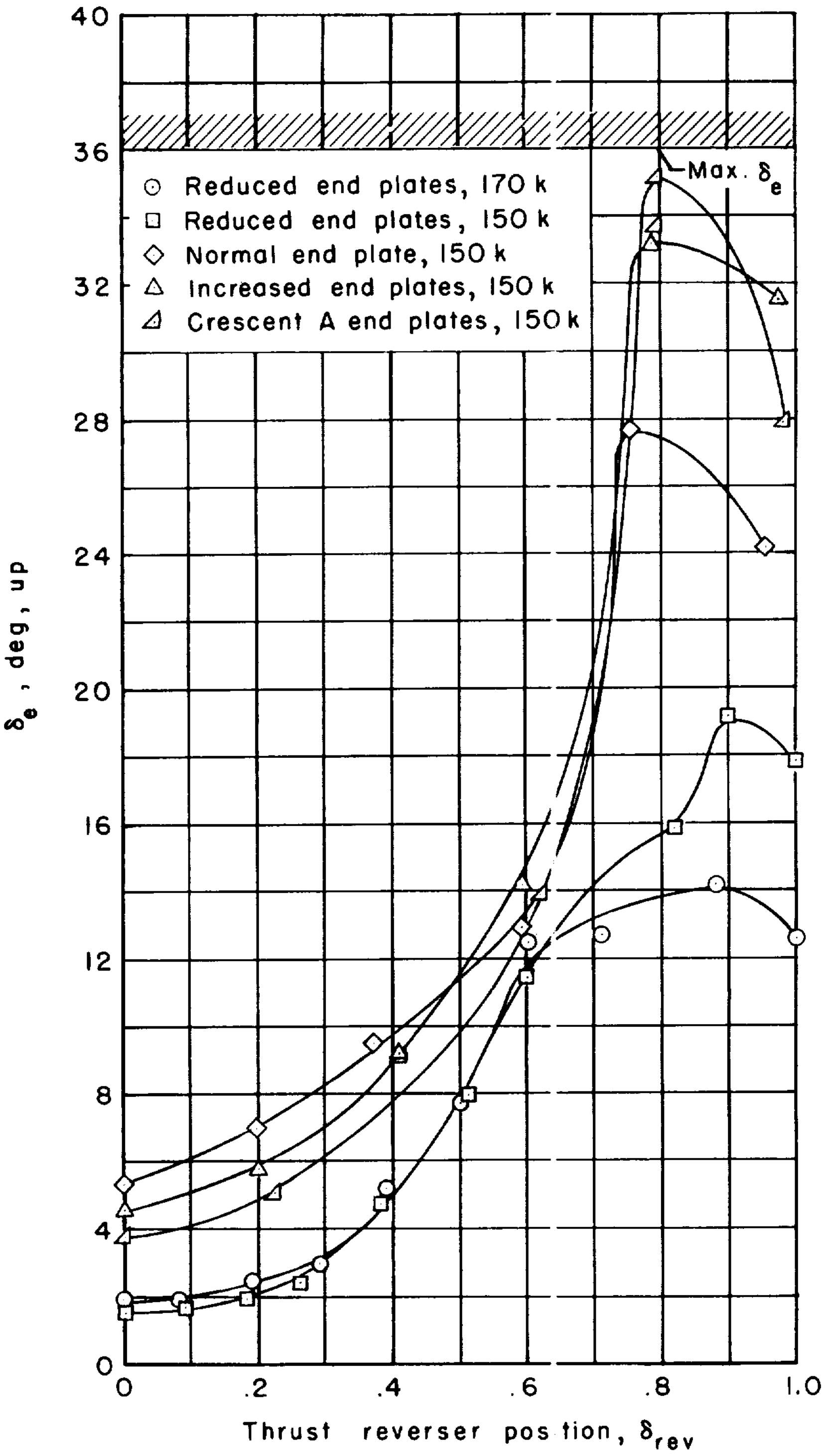


Figure 15.- Variation of δ_e with engine speed at full reverser deflection. No top cover, reduced bottom cover; V_i = 150 knots.



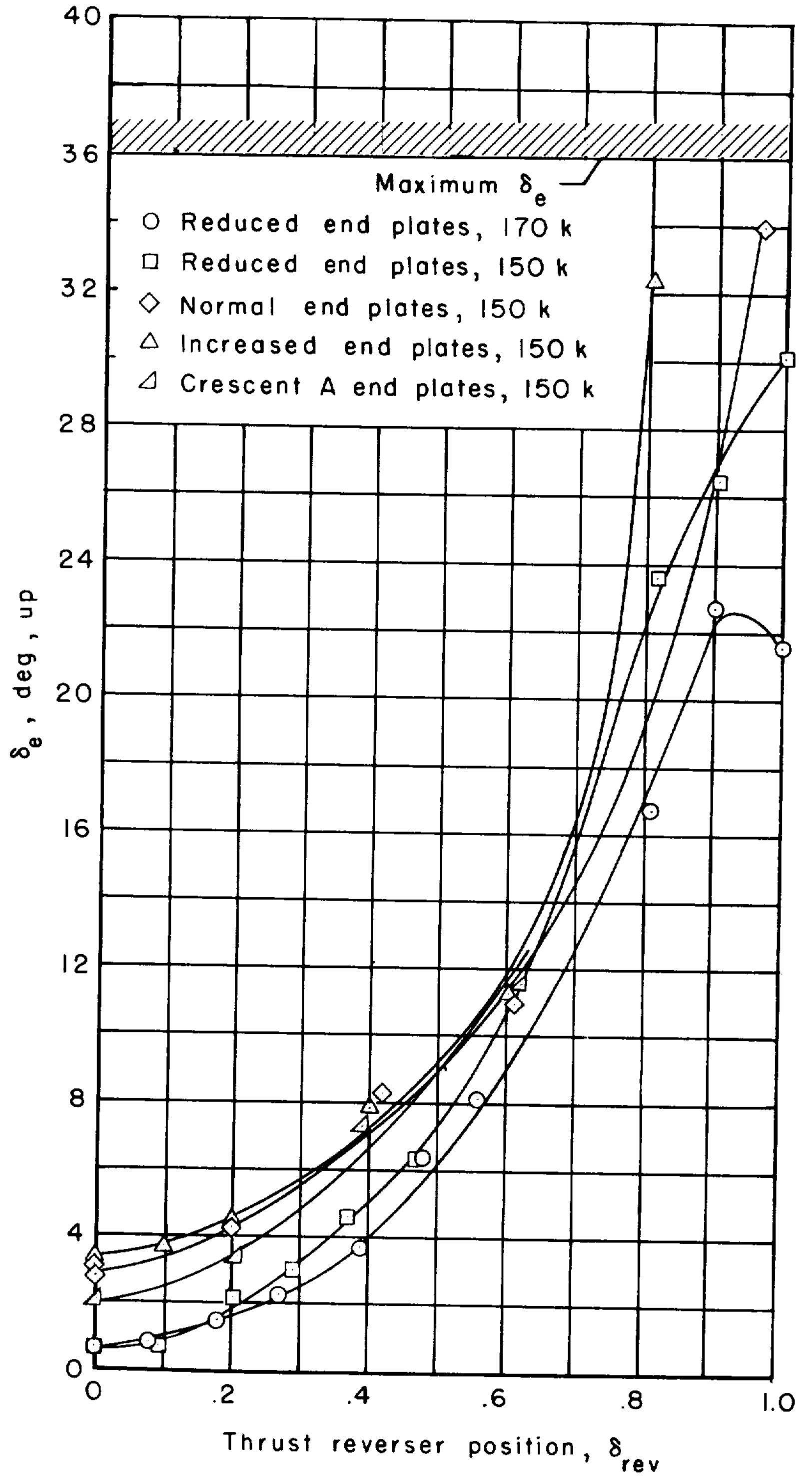
(a) N = 65 percent.

Figure 16.- Variation of elevator angle with reverser position for various engine speeds, airspeeds, and end plates; reduced top and bottom cover plates.



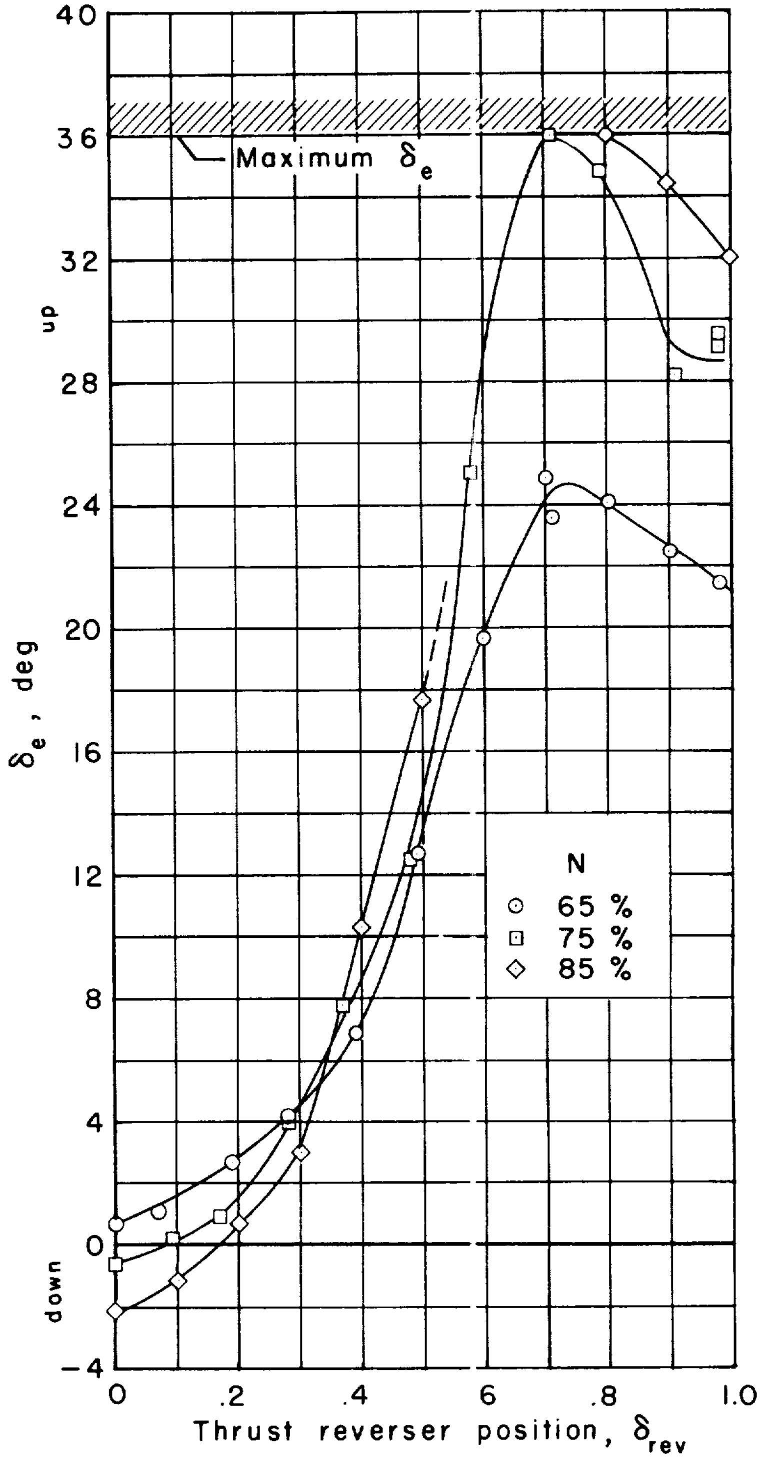
(b) N = 75 percent.

Figure 16.- Continued.



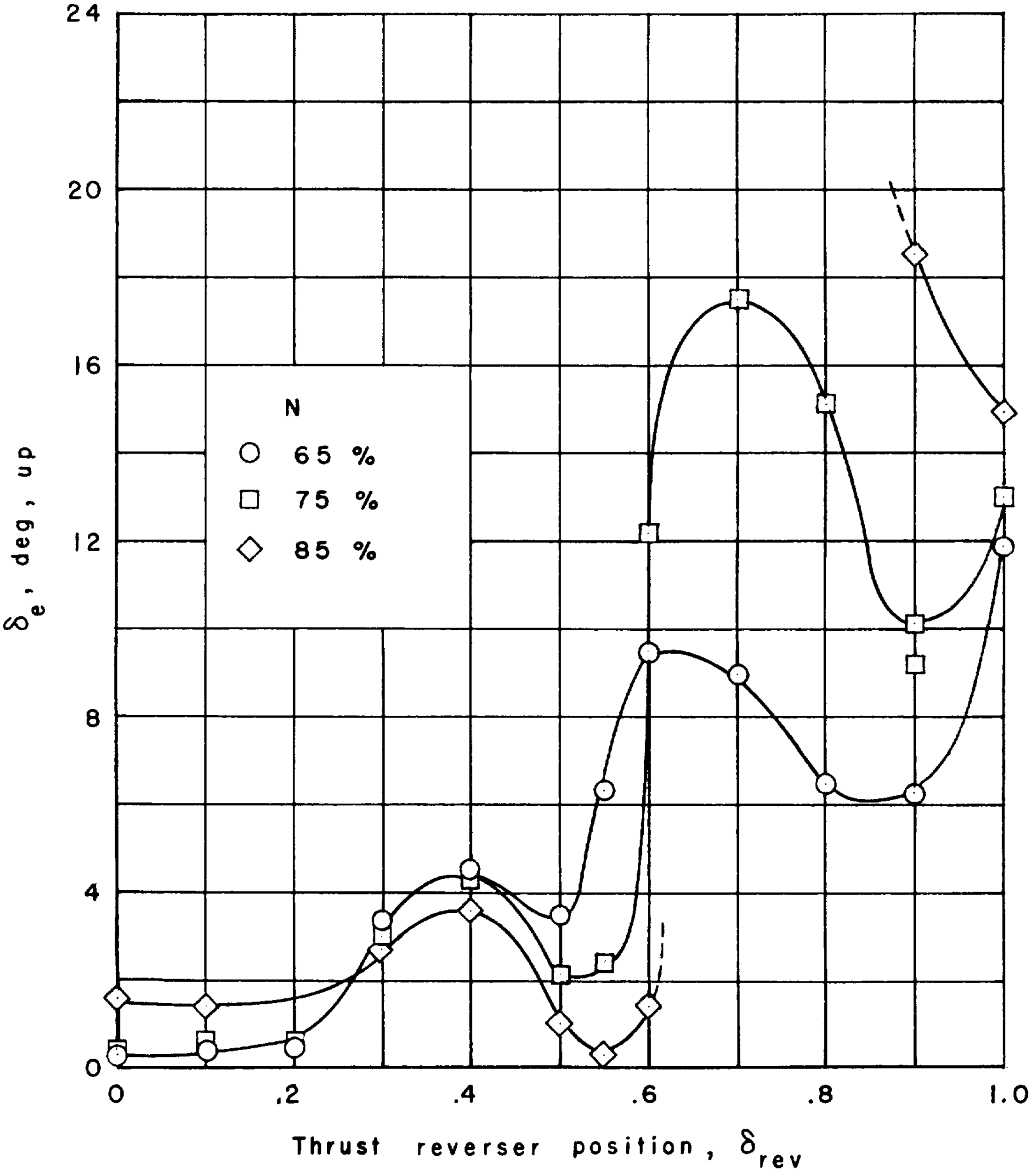
(c) N = 85 percent.

Figure 16.- Concluded.



(a) Normal top and bottom plates installed.

Figure 17.- Effect of cover plates on trim with normal end plates for various engine speeds; V_i = 150 knots.



(b) Top plate removed.

Figure 17.- Concluded.

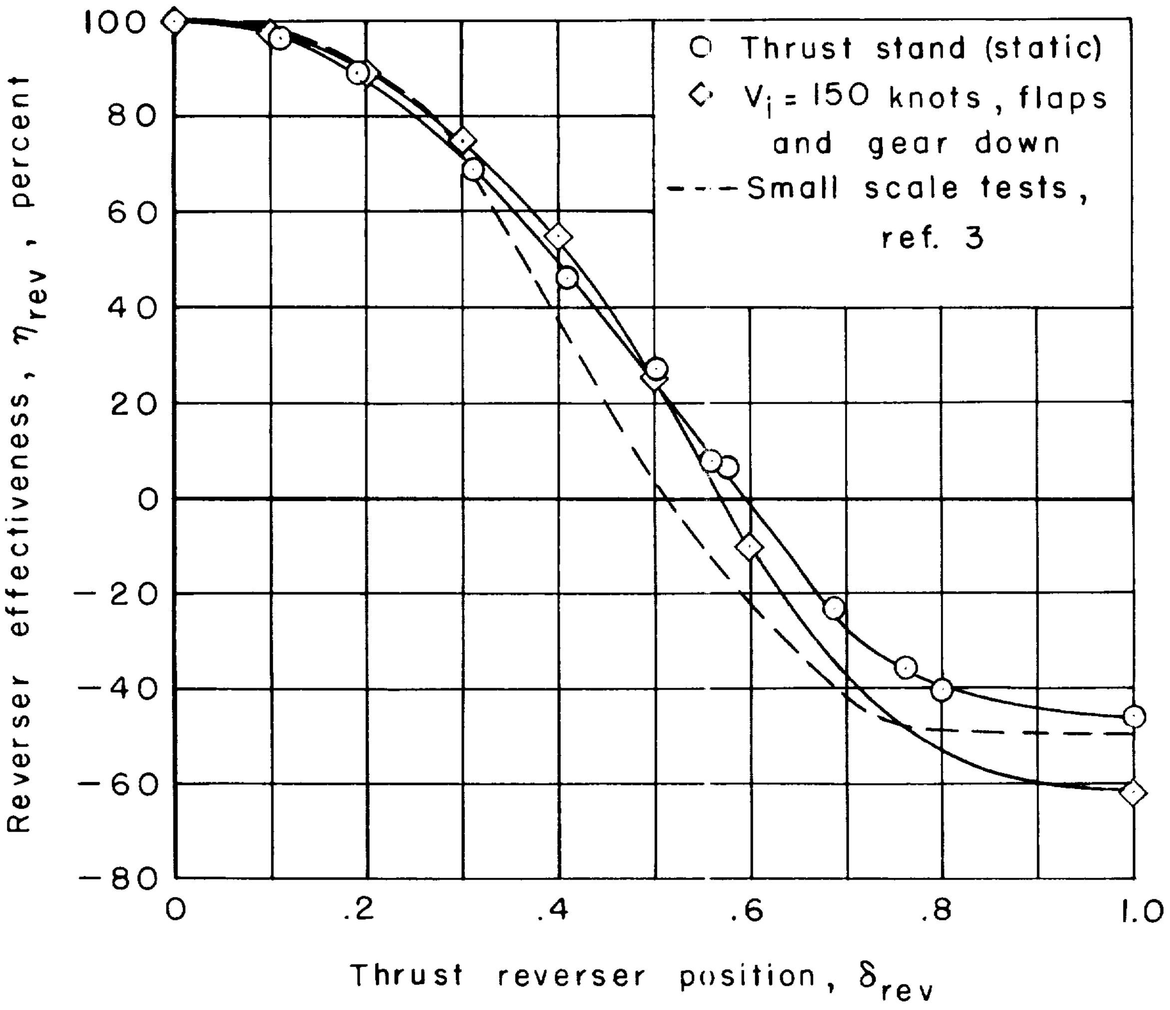


Figure 18.- Variation of reverse thrust ratio with reverser position. Normal end plates and normal bottom cover plate; reduced top cover plate.

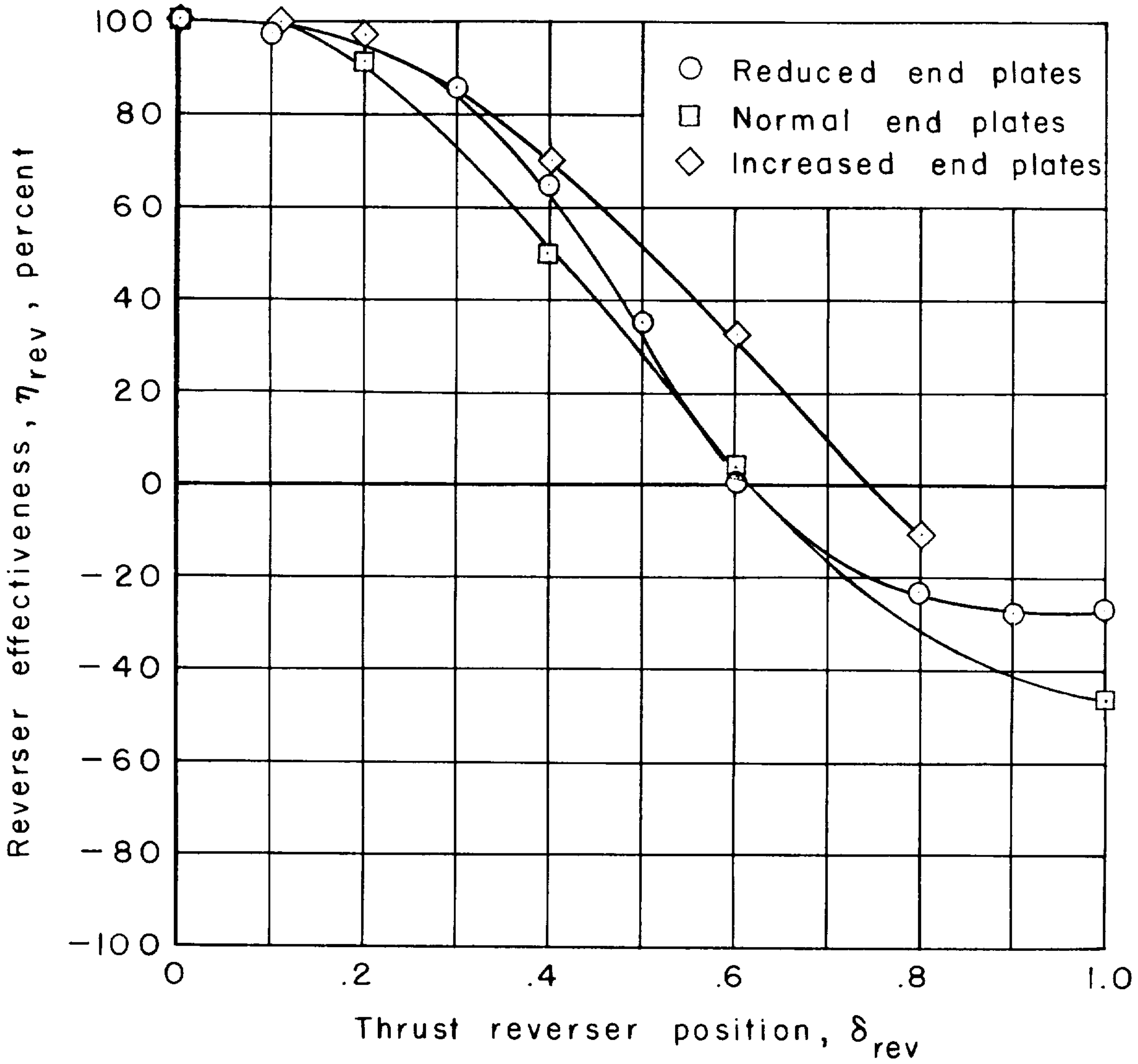


Figure 19.- Variation of reverse thrust ratio with reverser position for various end plates. Reduced top and bottom cover plates; V_i = 150 knots; N = 85 percent.

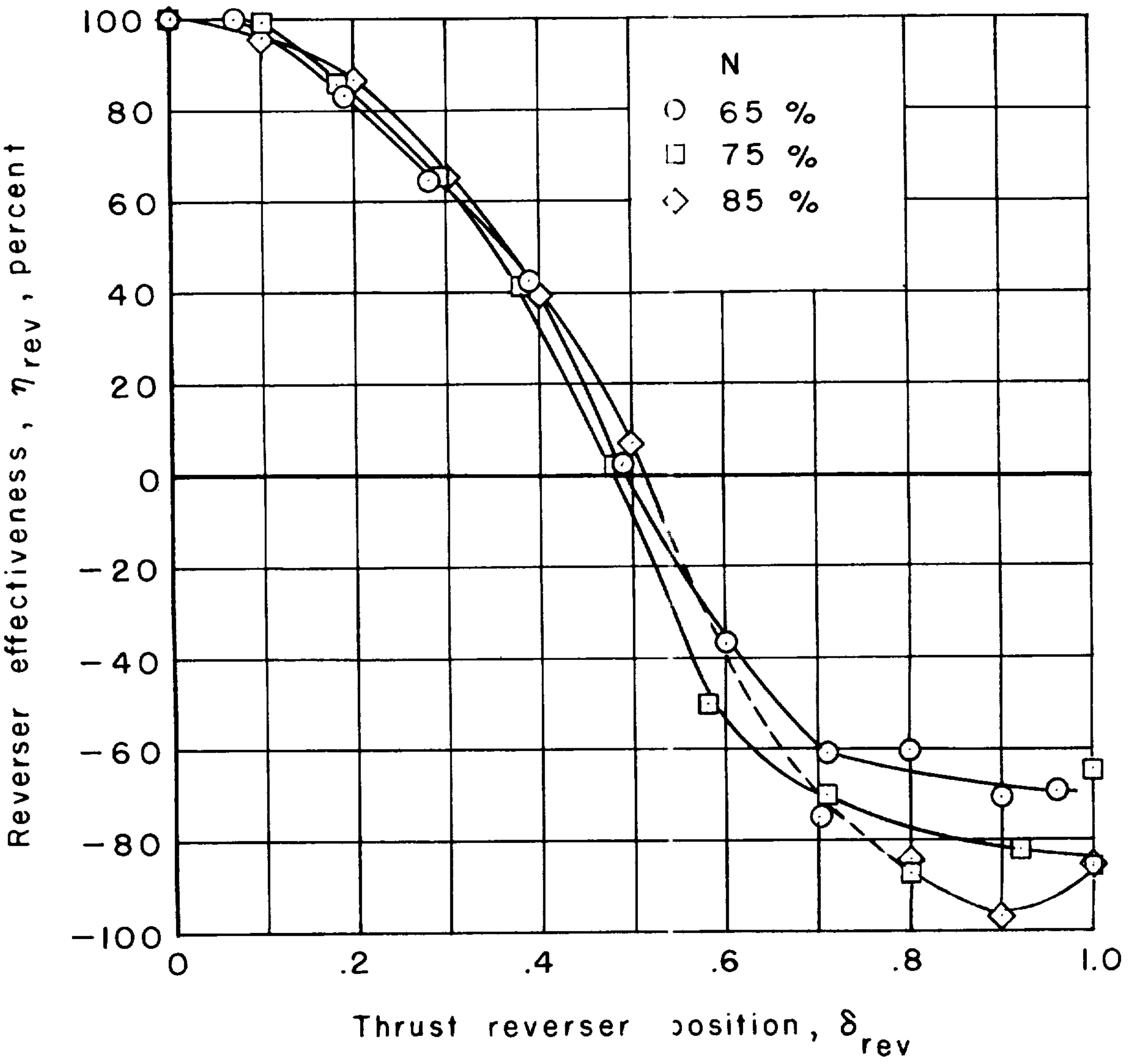


Figure 20.- Variation of reverse thrust ratio with reverser position with increased top and bottom cover plates. Normal end plates; V_i = 150 knots.

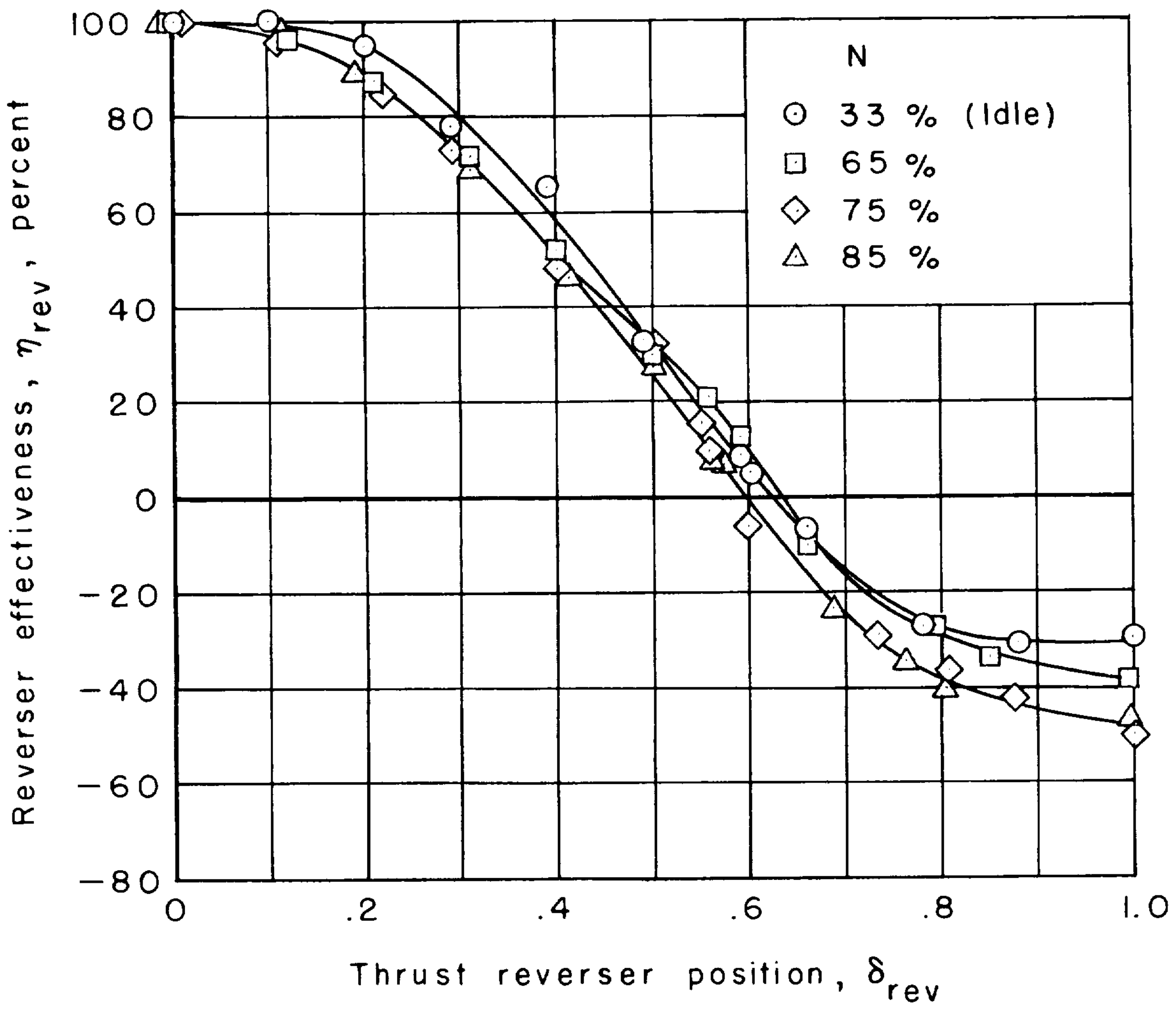


Figure 21.- Variation of reverse thrust ratio with reverser position measured on thrust stand for various engine rpm. Normal bottom cover plate; reduced top cover plate.