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INVESTIGATION OF A FULL-SCALE, CASCADE-TYPE THRUST REVERSER

By Robert C. Kohl and Joseph S. Algranti

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

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SUMMARY

A cascade-type thrust reverser was installed in a single-engine, fighter-type, turbojet airplane. A reverse-thrust ratio of about 35 percent was obtained at full engine speed. Reverse-thrust ratios up to 56 percent were obtained by increasing the thrust-reverser inlet velocity.

Supplementary scale-model, unheated-air tests indicated a 3 percent loss of forward thrust due to stowage of the turning vanes inside the tailpipe. The effect of turning-vane spacing on thrust-reverser performance and on tailpipe blockage was also determined by means of scale-model tests.

Taxi tests on a dry asphalt-macadam runway indicated that the average airplane deceleration was about 0.11 g's when using either wheel brakes only or thrust reverser only. When the wheel brakes and thrust reverser were used in combination, the average deceleration was doubled.

INTRODUCTION

Reversing the jet thrust offers a means for decelerating turbojet-powered aircraft. Many types of thrust reversers have been investigated by testing scale models using unheated air, and several promising configurations have been developed. However, some of the problems associated with the installation and use of a thrust reverser can be studied only in full scale.

The NACA Lewis laboratory has therefore conducted an investigation of a full-scale jet-thrust reverser. The investigation was limited to stationary and taxi tests. The airplane was not flown. The thrust-reverser system was installed in a single-engine, fighter-type, turbojet airplane, and consisted of a twin set of movable vanes stowed inside the engine tailpipe upstream of the nozzle. The thrust-reverser installation was designed to fit into the existing airplane with a minimum of structural modification or change of the fuselage contour. Reverse thrust was produced by opening the tailpipe and moving the vanes outward to form cascades that intercepted the rearward gas flow and turned it through approximately 150°. Variation of the forward and reverse thrust with engine speed was measured with the airplane held stationary. Taxi tests were conducted on a dry asphalt-macadam runway in order to provide data with which to compare the distances required to bring the airplane to a stop using (1) wheel brakes only, (2) reverse thrust only, and (3) a combination of wheel brakes and reverse thrust.

Supplementary tests were conducted using a three-tenths scale model with unheated flow to determine the effect of turning-vane spacing in the double cascade on thrust-reverser performance and tailpipe blockage. The scale model was also used to isolate the forward-thrust losses due to vane stowage inside the tailpipe.

In addition to presenting performance data, the report contains a detailed description of the full-scale, thrust-reverser installation together with a resumé of the operating experience.

APPARATUS

Airplane

The airplane used for this investigation was a single-engine, subsonic, turbojet fighter. The nonafterburning, axial-flow jet engine powerplant has an installed rating of 3750 pounds static sea-level thrust. Before the installation of the thrust reverser, the airplane basic weight was 10,249 pounds. Basic weight includes the weight of the ballast, but excludes the weight of fuel, oil, and pilot. With the thrust reverser installed, and additional ballast added in the nose compartment, together with instrumentation and smoke-generating apparatus, the airplane basic weight was 11,337 pounds. For the taxi runs, the gross operating weight was 14,342 pounds. In a flight-type version of a similar thrust reverser, considerable weight reduction could be effected in such items as the actuation system, cooling-air ejector, and structural supports.

Thrust Reverser

Installation. - An over-all view of the airplane with the thrust reverser installed is shown in figure 1. A comparison of the shape of the rear fuselage before and after the thrust reverser was installed is shown in figure 2. Additional external views of the thrust reverser in the forward- and reverse-thrust positions are shown in figure 3. Figure 4 is a three-dimensional cutaway view of the installation showing the various components of the thrust reverser.

Reverse thrust is produced by a twin set of turning vanes which deflect the engine exhaust gas. Turning-vane details are shown in figure 5. In order to obtain more operating clearance, the sharp leading and trailing edges of the turning vanes were cut back to form a more blunt shape, shown by the solid lines in figure 5. During forward thrust, these vanes are stowed inside the exhaust duct in the form of a vertical strut. In order to produce reverse thrust, each of the movable tailpipe sections and turning-vane assemblies are rotated outward through an arc of 30° to form a V-shaped double cascade, which intercepts the exhaust-gas flow discharging from the adapter section.

Actuation time required to open or close the thrust reverser was less than 1 second. Figure 6 shows the thrust reverser removed from the airplane, in the forward- and reverse-thrust positions.

The exhaust-gas flow patterns during forward and reverse thrust were made visible by injecting a low-viscosity lubricating oil into the tailpipe through four 60 gallon-per-hour, 200-pound-per-square-inch spray nozzles mounted along the trailing edge of one of the engine tailcone support struts. The 9-gallon oil reservoir and pump were located in the nose-wheel well. Oil-injection rates of 9 gallons per minute and less, depending on engine speed, were sufficient to produce a dense white smoke that could be photographed with a motion-picture camera. A portion of one such motion-picture record is reproduced in figure 7. The sequence, starting in the upper left frame and ending in the lower right frame, shows the transition from forward to reverse thrust with the airplane held stationary.

In the forward-thrust position, the flow in the tailpipe is divided upstream of the movable reverser section by a vertically positioned, fixed splitter vane. The turning vanes are nested in the wake of the splitter vane and form a vertical strut across the tailpipe. In the exhaust-nozzle section downstream of the nested turning vanes, the strut is reduced to zero thickness by a rear-fairing section (see figs. 3 and 4), which terminates at the plane of the nozzle exit. This rear fairing is so contoured that the tailpipe flow-area contraction rate is equivalent to that of a right circular cone having a 6° half-angle.

To provide adjustment of the engine tailpipe temperature to rated conditions during forward-thrust operation (675° C at full corrected engine speed), the nozzle was constructed slightly oversize, and tapered blocks, which can be seen in figure 3(b), were installed inside the nozzle to reduce the flow area until rated conditions were obtained. During reverse thrust, the strut rear fairing is moved rearward (see figs. 3 and 4) to avoid interference with the moving turning vanes and tailpipe walls. Because the thrust reverser was mounted aft of the last fuselage main-frame assembly, it was necessary to pass the engine tailpipe and tailpipe cooling-air shroud through this main-frame assembly in such a way as to leave space for the upper- and lower-thrust-reverser hydraulic actuators. The space required for the hydraulic actuators was obtained by reducing the flow area of the engine tailpipe some distance upstream of the fixed splitter vane. Figure 8 shows a cross-sectional plan view of the tailpipe arrangement before and after modification. Also shown on figure 8 are plots of the design values of the exhaust-gas Mach number variation within the tailpipe for the case with forward thrust at full corrected engine speed for both forms of the tailpipe.

Figure 9 is an elevation view of the fuselage shape and tailpipe arrangement before and after installation of the thrust reverser.

Ejector cooling. - Installation of the thrust reverser required alteration to the tailpipe cooling-air system. The cooling-air shroud which surrounds the engine tailpipe in the rear-fuselage section was terminated ahead of the movable reverser sections (fig. 4). In the forward-thrust position, cooling air was drawn through passages in the movable reverser sections. These cooling air passages consisted of holes in the sheet-metal stiffeners between the outer-fuselage skin and the exhaust-duct walls. During the early test runs overheating of the rear fuselage was encountered during stationary forward-thrust operation. The overheating was caused by leakage of the hot exhaust gas through the various thrust-reverser tailpipe seals. To counteract this overheating, progressively larger cooling-air ejectors were installed and tested until the temperature inside the rear fuselage, as measured in the vicinity of the upper thrust-reverser hydraulic actuator, was stabilized at an acceptable value. The ejector ultimately selected had an elliptical cross section throughout. The cross-sectional discharge flow area at the plane of the ejector outlet was 1.4 times that of the exhaust-nozzle area. The plane of the ejector exit was 1 nozzle diameter downstream of the jet nozzle.

Model Tests

The essential elements of the full-scale thrust reverser, with the exception of the cooling-air ejector, were duplicated in a three-tenths unheated-air test model (fig. 10). The model was tested in the unheated-air test facility described in reference 1. The discharge end of the unheated-air supply duct (fig. 10(b)) simulated the adaptor section and exhaust pipe of the full-scale installation and was equipped with a fixed splitter vane. The model thrust reverser was not actuated, but could be assembled in either the forward- or reverse-thrust position. By altering the spacing between the turning vanes, the solidity (ratio of the turning-vane chord to distance between similar points on adjacent turning vanes (fig. 5)) could be varied between 0.50 and 1.40.

INSTRUMENTATION OF FULL-SCALE THRUST REVERSER

The system used to measure the forward and reverse net thrust during stationary operation is shown in figure 11. A calibrated strain-gage load cell was used to measure the tension in a steel cable that tethered the airplane to a tie-down ring. The cable was attached to each of the main landing-gear struts. Thrust was indicated on a calibrated strain analyzer. Zero readings were taken before starting and after engine shutdown.

Static and total pressures were measured in the divided section of the tailpipe upstream of the movable thrust-reverser sections. Tailpipe pressures were not measured during the tests with the unmodified tailpipe. The exhaust-gas temperature was obtained from the standard airplane temperature-measuring system, which consisted of four equally spaced thermocouples connected in parallel and mounted in the engine tailcone. Temperature drop between the tailcone and the pressure-measuring station was measured with a single exhaust-gas thermocouple probe installed in the tailpipe at the same axial station as the pressure instrumentation. Ambient pressure and temperature were obtained before each test run.

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During the taxi runs, the actual ground speed and elapsed distance were measured by means of a bicycle wheel attached to the left landing gear (fig. 12). Positive contact with the runway surface was maintained by spring loading the bicycle-wheel suspension system in a downward direction using elastic shock cord. A small conductor plate, attached to the spokes of the bicycle wheel, made contact with a pair of spring leaves and completed an electric circuit with each wheel revolution. This electric impulse was converted into a telemeter signal which was broadcast to a receiving station where the signal was recorded on photographic strip chart. Also recorded on the chart was a time-reference pulse. The bicycle-wheel system was selected because of the negligible variation of the tire diameter with airplane ground speed.

PROCEDURE

Full-Scale Tests

The full-scale tests were conducted in the following six phases:

(1) The forward thrust was measured over a range of engine speeds with the airplane in the as-received condition. Subsequent inspection of the engine revealed that the combustor liners were in poor condition during the tests, and the measured thrust values may have been substandard. Modifications of the fuselage aft section had already been completed when the faulty liners were discovered, so that the tests could not be repeated. The combustor liners were replaced before proceeding with phase (2).

(2) The thrust loss due to the pumping action of the unmodified cooling-air ejector was determined by repeating the forward-thrust measurements over a range of engine speeds with the standard tailpipe extension and nozzle, but with the rear fuselage section and cooling-air ejector removed. The difference between the measured forward thrust with the ejector installed and with the ejector removed was the unmodified ejector-pumping loss.

(3) The forward thrust was measured over a range of engine speeds with the thrust reverser installed. In this test, the cooling-air ejector supporting structure terminated 2 inches downstream from the plane of the jet-nozzle exit so that there was little or no cooling-air flow and cooling-air pumping loss.

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(4) The forward thrust was measured over a range of engine speeds with the thrust reverser installed, and for this test the largest of the series of experimental cooling-air ejectors, mentioned earlier in this report, was installed so that the thrust data obtained included the ejector-pumping loss.

(5) Measurements were made of the reverse thrust developed over a range of engine speeds. Included in this test was a reverse-thrust calibration with the thrust-reverser upstream splitter vane widened beyond the design width so that limiting exhaust-gas temperature was obtained at the downstream end of the tailpipe-adapter section (thrust-reverser inlet) at full engine speed.

(6) Airplane stopping distances on a dry asphalt-macadam runway were measured using (a) wheel brakes only, (b) reverse thrust only (no wheel brakes), and (c) a combination of reverse thrust and wheel brakes. The length of the runway (6200 ft) determined the maximum ground speed to which the airplane could be accelerated before braking was applied. For the runs when the thrust reverser was used, the airplane was accelerated for approximately 20 seconds using full engine speed. The engine speed was then reduced to 70 percent of full engine speed and reverse thrust was applied. As soon as the thrust reverser was opened, the engine speed was increased to full speed. Full engine speed was maintained until the airplane was brought to a stop. The engine speed was reduced to 70 percent of full speed before applying reverse thrust in order to simulate the engine speed setting at touchdown. The 70-percent-speed setting was arbitrarily chosen as a compromise to permit a reasonably short engine-reacceleration time.

For the runs in which the wheel brakes were used, intermittent braking was applied in order to obtain maximum braking action without skidding or brake fade due to overheating of the brake disks. This intermittent braking procedure corresponds to maximum braking effort commensurate with normal service usage. The wheel brakes were inspected and serviced prior to each taxi run to ensure maximum brake performance.

Scale-Model Tests

Scale-model configurations were tested using unheated air with the nozzle exhausting to ambient conditions. Data points were obtained over a range of tailpipe total-to-ambient-pressure ratios from 1.1 to 2.1. Forward thrust was obtained with the turning vanes installed in the stowed position as well as with the turning vanes and upstream splitter vane removed. Reverse thrust was obtained for a range of turning-vane solidities from 0.50 to 1.40. In two of the tests, the leading and trailing edges of the turning vanes were rounded to simulate more exactly the turning vanes used in the full-scale device (see fig. 5). This modification was tested at solidity values of 0.89 and 0.69. The solidity value of 0.89 duplicated the solidity of the full-scale installation for which performance data is herein presented. The solidity value of 0.69 is of significance in that it represents the maximum solidity value that could be used without swiveling the turning vanes during opening and closing of the thrust reverser. The 0.69 solidity configuration was not tested in full scale.

RESULTS AND DISCUSSION

Full-Scale Performance

Forward-thrust characteristics. - Static, sea-level forward net thrust, corrected for barometric pressure, is plotted against corrected engine speed in figure 13 for the unmodified airplane and for the airplane with thrust reverser installed. Net thrust includes the installation losses, which consist of the engine-inlet-duct loss, the tailpipe loss, and the losses associated with the operation of the cooling-air ejector. At full corrected engine speed the thrust was 3450 pounds for the unmodified airplane, and 3130 pounds for the modified version. The difference between these thrust values represents an aggregate forward-thrust loss of 320 pounds which is associated with the thrust-reverser installation. Insofar as possible, the individual forward-thrust losses contributing to the aggregate loss are identified and examined separately.

Installation of the thrust reverser necessitated the use of a different cooling-air ejector than that used with the unmodified airplane. In order to eliminate the discrepancy in the forward net thrust caused by the different ejectors, the thrust measurements were repeated with the ejectors removed. The results are shown in figure 13(b). With the unmodified cooling-air ejector removed, a corrected thrust of 3555 pounds at full engine speed was obtained with the unmodified nozzle. When the modified ejector was removed from the thrust-reverser installation, a corrected forward thrust of 3200 pounds was obtained at full engine speed. These measurements indicate that at full engine speed the forward-thrust loss due to the presence of the cooling-air ejector was 105 pounds with the unmodified arrangement, and 70 pounds with the modified version. An unknown portion of the 105-pound thrust loss may be due to substandard engine performance during the tests with the unmodified cooling-air ejector installed.

The remaining difference in thrust levels between the modified and unmodified version of the airplane represents the aggregate of several types of loss, among which are internal flow losses due to the presence of the stowed vanes, leakage losses through the tailpipe and thrust-reverser seals, and nozzle losses. The loss of forward thrust associated with internal-vane stowage is estimated to be in the order of 3 percent at full engine speed. This estimate is based on scale-model test data which will be discussed in a subsequent section of the report.

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With the thrust reverser in the forward-thrust position, the exhaust-gas leakage through the tailpipe and thrust-reverser seals upstream of the exhaust nozzle results in a thrust loss. This loss can be estimated with the aid of figure 14 which is a cross plot of figure 6, reference 2. In figure 14 the ratio of the net forward thrust with leakage to the net forward thrust without leakage is plotted against the tailpipe gas-leakage ratio. Curves of net thrust ratio are presented for two values of engine speed. It will be recalled that after the thrust reverser was installed, the engine tailpipe temperature was adjusted to the rated value (675° C) at rated speed (full engine speed) with the thrust reverser in the forward-thrust position and with some unknown amount of leakage present. This tailpipe-temperature adjustment was equivalent to maintaining a constant fraction of rated turbine-inlet temperature ratio $(T_4/T_2)/(T_4/T_2)_r$ (see ref. 2). Thus, both curves in figure 14 represent the case where tailpipe-temperature adjustment was made to allow for leakage. Figure 14 indicates that there is almost a one-to-one correspondence between thrust loss and tailpipe leakage, provided that the exhaust-nozzle area is resized to compensate for the leakage. Thus, for example, a 5-percent loss of thrust will occur at full engine speed with a tailpipe-leakage ratio of 0.05.

Another source of the thrust decrement might be attributed to losses in the exhaust nozzle and to the fact that the thrust measurements of the modified airplane tended to be slightly low because of required test procedure. Operation of the engine without an ejector was relatively simple for the case with the unmodified airplane. It consisted of removing the entire fuselage aft section and providing a support for the projecting tailpipe and nozzle during engine operation. For the case with the thrust reverser installed, it was not possible to remove the fuselage aft section because portions of the modified tailpipe were directly attached to it. Without the cooling-air ejector, the fuselage aft section tended to overheat during engine operation because of a lack of ventilation. Stationary performance runs were limited to short runs from engine ignition to full speed, pausing at each of the preselected engine-speed settings only long enough to obtain instrument readings. Upon reaching full speed, the engine was shut down immediately after the readings were obtained.

In the course of stationary testing, a discrepancy was observed in the thrust-speed relation. If the engine was started and immediately accelerated to full speed without allowing the temperature throughout the engine to become stabilized, the thrust produced during this first acceleration tended to be lower than the thrust produced during subsequent reaccelerations. This discrepancy in thrust was particularly evident in the lower engine-speed range between 50 and 90 percent of full speed. Because it was not possible to stabilize temperatures throughout the engine at each speed setting, the thrust values obtained for the modified airplane may be slightly low.

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Reverse-thrust characteristics. - The net reverse thrust, corrected for barometric pressure, is plotted against corrected engine speed in figure 15. The maximum reverse thrust produced during normal operation (solid line) was 1100 pounds at full engine speed.

In designing the thrust reverser, it was necessary to arrive at a compromise value for the flow velocity at the thrust-reverser inlet. High flow velocities in the tailpipe were required to reduce the diameter of the tailpipe and cooling-air shroud sufficiently to fit inside the fuselage structure, whereas low flow velocities were desirable in order to keep to a minimum the flow losses resulting from internal-vane stowage. With these requirements in mind, a design Mach number of 0.70 at the thrust-reverser inlet was selected. The design Mach number variation in the tailpipe is shown in figure 8. Experimental results obtained with unheated-air models of cascade-type and target-type thrust reversers (see ref. 1) indicate that optimum reverse thrust is obtained when the inlet velocity is high (on the order of Mach 1.0). For this reason an attempt was made to improve the reverse thrust by raising the thrust-reverser inlet velocity by increasing the thickness of the upstream splitter vane. The thrust reverser was removed from the airplane, and the thickness of the fixed splitter vane at the downstream end was progressively increased from the design thickness of 2.34 inches until the rated tailpipe temperature of 675° C was obtained at full engine speed at a splitter-vane thickness of 4.38 inches. The thrust reverser was reinstalled and the reverse thrust was measured over a range of engine speeds. These data are shown as the dashed line in figure 15. The reverse thrust was significantly increased throughout the speed range over which data were obtained.

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At 90 percent of maximum engine speed some of the turning vanes failed. The failure, which occurred in the welds along the leading and trailing edges of the turning vanes, was not altogether unexpected since the vanes were not designed to withstand the inlet velocities to which they were subjected during these tests.

Reverse-thrust ratio. - The reverse-thrust ratio is herein defined as the ratio, expressed as a percentage, of the measured net reverse thrust, corrected for barometric pressure at any corrected engine speed, to the measured forward net thrust, corrected for barometric pressure at the same value of corrected engine speed. The forward net thrust used is that obtained with the modified airplane with the thrust reverser installed (dashed curve, fig. 13). Reverse-thrust ratios for splitter-vane thicknesses of 2.34 and 4.38 inches are plotted as a function of corrected engine speed in figure 16. A maximum reverse-thrust ratio of about 35 percent at full engine speed was obtained with a splitter-vane width at the design value of 2.34 inches (solid line). With the splitter vane widened sufficiently to produce limiting tailpipe temperature at the thrust-reverser inlet at full engine speed, a maximum reverse-thrust ratio of 56 percent was obtained at 78 percent of full engine speed. The reduction of reverse-thrust ratio at the higher engine speeds is caused by the straight-line reverse-thrust characteristic (shown by the dashed line in fig. 15) as opposed to the rising forward-thrust characteristic shown by the dashed line in figure 13. Although a higher value of reverse-thrust ratio was obtained for the case with the widened splitter vane, such a configuration would further penalize the forward thrust. This forward-thrust penalty was confirmed by a full-scale measurement of the forward thrust with the splitter vane widened and the thrust reverser removed. The results showed that such a configuration produced less forward thrust than the thin-splitter-vane - exhaust-nozzle combination.

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Effect on engine performance. - The installation of a thrust reverser should not result in tailpipe blockage. Tailpipe blockage during either forward or reverse thrust can result in turbine overtemperature or compressor stall. The existence of tailpipe blockage is indicated by engine tailpipe temperatures greater than those used in normal operation. A comparison of the tailpipe temperatures before and after installation of the thrust reverser is shown in figure 17. Measured tailpipe temperatures are plotted against corrected engine speed for the unmodified configuration, and for the thrust reverser installed and positioned for forward and reverse thrust. The data in figure 17 indicate that the thrust-reverser installation caused less tailpipe blockage than the unmodified configuration. Ideally, the thrust-reverser and the unmodified configurations should have the same tailpipe temperature - engine speed characteristic. The lower temperatures obtained with the thrust reverser installed and in the forward-thrust position are attributed to leakage of the exhaust gas through the tailpipe seals. Tailpipe leakage affects the tailpipe temperature in much the same way as enlarging the jet nozzle. In both cases, the pressure drop across the turbine is increased and, for a given engine speed, the turbine temperature levels are reduced. Although the exhaust-nozzle area was adjusted so that the rated tailpipe temperature was obtained at full engine speed, the adjustment did not fully compensate for the leakage at lower engine speeds. The lowest tailpipe temperatures were obtained during reverse-thrust operation, which indicates either excessive flow area in the turning-vane passages or leakage of the exhaust gas around the thrust reverser or both.

Motion pictures of the smoke flow issuing from the thrust reverser during the transition from forward to reverse thrust revealed that shortly after reverse thrust is established the reversed flow becomes stabilized and, thereafter, the small portion of the exhaust gas that escapes rearward appears to be of such low velocity that it has only a small effect on performance. This point is illustrated in figure 18, which is a reproduction of a single motion-picture frame. The main-reversed exhaust-gas flow issues from the thrust reverser with considerable velocity, whereas the leakage flow escaping rearward billows out of the ejector with a low rearward velocity and accumulates at the rear of the airplane. This accumulation of visible leakage flow tends to create an erroneous impression of the magnitude of the rearward leakage.

The tailpipe pressure ratio is shown as a function of the engine speed in figure 19 for forward and reverse thrust. Each type of symbol represents a separate test operation. Tailpipe pressure ratio was not obtained during operation with the unmodified tailpipe and nozzle. In the forward-thrust position the tailpipe pressure ratio developed at full engine speed is 1.71. In the reverse-thrust position the effective flow area in the tailpipe is increased, and the tailpipe pressure ratio is lowered to a value of 1.55 at full engine speed. An increase in reverse thrust should be gained by reducing the gross flow-passage area through the turning vanes.

The thrust-reverser performance data obtained from scale models using unheated air are usually expressed as a function of the tailpipe pressure ratio, and the measured thrust and airflow quantities obtained in model tests are corrected for the pressures and temperatures just upstream of the thrust reverser (see ref. 1). Comparison between full-scale and unheated-model thrust-reverser data required that the full-scale data be corrected for the thrust-reverser-inlet total pressure and temperature and plotted against the tailpipe total-pressure ratio, instead of being corrected for ambient static pressure and plotted against corrected engine speed. The full-scale forward- and reverse-thrust characteristics, corrected for reverser-inlet conditions, are plotted against the tailpipe total-pressure ratio in figure 20. The reverse-thrust ratio will be higher when based on thrust values corrected for tailpipe pressure, because for the same value of corrected engine speed, the tailpipe total pressure is greater during forward thrust than during reverse-thrust operation. This difference in reverse-thrust ratio occurs when the tailpipe conditions change from forward to reverse thrust and is of importance only when comparisons are being made between model and full-scale test results. The net reverse thrust which is available as an airplane braking force consists of the reverse thrust corrected for the engine-inlet pressure and is shown in figure 15.

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Unheated-Air Scale-Model Tests

Forward- and reverse-thrust characteristics. - For a given tailpipe total-pressure ratio, turning-vane shape, and over-all cascade dimensions, the amount of reverse thrust developed depends on the solidity (ratio of turning-vane chord to distance between similar points on adjacent turning vanes). More effective turning of the exhaust-gas flow will be obtained at the higher solidities. Ultimately, a solidity is reached at which the flow velocity in the cascade passages becomes maximum. Further increases in the solidity are accompanied by a reduction of the exhaust-gas weight flow through the cascade and a diminishing of reverse thrust. It is also true that at the lower solidities where the weight flow is unrestricted, poor turning effectiveness causes a reduction of the reverse thrust.

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In order to determine the optimum combination of turning effectiveness, exhaust-gas weight flow, and vane-stowage losses, unheated-air tests were conducted using a scale model of the engine tailpipe and thrust-reverser configuration (fig. 10). The variation of reverse thrust with tailpipe pressure ratio was obtained for six solidity values using vane shapes having sharp leading and trailing edges. Two additional reverse-thrust configurations were tested in which the cascades were made up of turning vanes with the leading and trailing edges blunted as in the full-scale vanes (see fig. 5).

The forward and reverse thrust, corrected for total pressure at the thrust-reverser inlet, is plotted against the tailpipe pressure ratio in figure 21 for all the scale-model configurations. The forward-thrust penalty resulting from stowage of the vanes inside the tailpipe was determined by measuring the forward thrust with and without the stowed vanes installed. This forward-thrust loss amounts to about 3 percent, and, percentage wise, does not appear to vary significantly with tailpipe pressure ratio in the range of tailpipe pressure ratios corresponding to engine operation during takeoff and cruise. Cascades having intermediate values of solidity (0.75 to 0.94) developed the largest amounts of reverse thrust. Reverse-thrust ratio is plotted against tailpipe pressure ratio in figure 22. The forward thrust of the model with vanes and splitter installed, which was used in the computation of the reverse-thrust ratio, appears to be practically insensitive to tailpipe pressure ratio.

Because of the spacing between adjacent turning vanes required for stowage during forward thrust, it was not possible to incorporate sufficient solidity in the cascade to achieve the desired exhaust-gas turning angle of 150°. The design turning angle in the cascades was 140°. The balance of the exhaust-gas turning was accomplished by impingement on the inside walls of the movable-tailpipe sections. The exhaust gas was discharged in a forward direction at an angle of 30° to each side of the fuselage centerline.

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In the model tests the ratio of corrected reverse-thrust weight flow to corrected forward-thrust weight flow at the same tailpipe pressure ratio is defined as the weight-flow ratio and is indicative of the effect of thrust-reverser operation on engine performance. Weight-flow ratios less than unity denote tailpipe blockage. In figure 23 the weight-flow ratio, expressed as a percentage, is plotted against tailpipe pressure ratio for each of the thrust-reverser model configurations. Tailpipe blockage is almost independent of the tailpipe pressure ratio but varies considerably with solidity. The effect of solidity on the weight-flow ratio is more clearly shown in figure 24 where the data of figure 23 have been cross-plotted for a tailpipe pressure ratio of 1.55. This pressure ratio of 1.55 corresponds to that obtained in the full-scale engine during reverse thrust at maximum engine speed. Because there was no leakage around the thrust-reverser cascade in the model tests, the weight-flow ratio drops below 100 percent for solidities greater than 0.84. The two cascades containing the blunted turning vanes pass a slightly larger weight flow during reverse thrust, but appear to follow the same trend.

The results of the model tests are summarized in figure 25 where the reverse-thrust ratios (not based on unit weight flow) shown in figure 22, are plotted against cascade solidity for a tailpipe pressure ratio of 1.55. Figure 25 shows that the optimum cascade solidity is on the order of 0.80. At values of solidity less than 0.76, the reverse-thrust ratio diminishes because of poor turning effectiveness. At values of solidity higher than 0.80, restriction of the weight flow causes a reduction of reverse-thrust ratio. The performance obtained with the unheated-air model of the full-scale configuration, indicated by the circular data point, appears to be close to the optimum arrangement. The unheated-air model of the thrust reverser requiring no vane rotation during actuation (solidity, 0.69), shown by the triangular data point, produces about seven percentage points less reverse-thrust ratio.

In figure 26 the effect of weight flow has been eliminated by expressing the reverse-thrust ratio on a unit weight flow basis. This procedure singles out the effect of solidity on reverse thrust, and is also useful when comparing model and full-scale performance data.

Reverse-thrust ratio per unit weight flow (fig. 26) is cross-plotted against solidity in figure 27 for a tailpipe pressure ratio of 1.55. A plateau of fairly constant performance exists between solidities of 0.90 and 1.20. This is another indication that, for the particular turning-vane shape and arrangement used, the cascade solidity of 0.89, selected for the full-scale thrust reverser, was close to optimum.

Comparison of model and full-scale performance. - The forward and reverse net thrust per pound of corrected weight flow and corrected for tailpipe total pressure and temperature is shown in figure 28 for the full-scale thrust reverser (solid line) and for the unheated-air scale model (dashed line). The difference in forward net thrust is attributed to the tailpipe leakage and cooling-air-ejector pumping losses in the full-scale thrust reverser not present in the scale-model tests. Exhaust-gas leakage through the thrust-reverser seals and operating clearances is also considered to be the cause of the lower full-scale reverse-thrust performance.

A comparison of the reverse-thrust ratio per pound of corrected weight flow is made in figure 29 between the unheated-air model (dashed line) and the full-scale thrust reverser (solid line). At a pressure ratio of 1.55 (max. engine speed) the curves are in good agreement. However, in the model tests, optimum reverse-thrust ratio was maintained to lower values of tailpipe pressure ratio. 4018

It should be noted that when a thrust reverser is located upstream of the jet nozzle, the exhaust-gas weight flow and reverser-inlet Mach number during forward and reverse thrust can be quite different for equal values of tailpipe pressure ratio, as they were for the configuration reported herein. Thus, it is not strictly correct to compute reverse-thrust ratio from the forward- and reverse-thrust values obtained at the same tailpipe pressure ratio. The procedure is valid, however, when the tailpipe pressure ratio and Mach number are unaltered during the transition from forward to reverse thrust, as was the case in reference 3. The reverse-thrust ratio based on the forward and reverse thrust obtained at constant values of engine speed (see fig. 16) has more physical significance with regard to actual airplane braking force. The model testing technique, however, does not offer a straight forward method for comparing forward and reverse thrust at simulated values of constant engine speed. Therefore, the reverse-thrust ratio has been presented as a function of the tailpipe pressure ratio and comparisons between full-scale and scale-model, unheated-air-test results (figs. 28 and 29) were made accordingly. If the reverse-thrust flow area were sized to maintain constant tailpipe total-pressure ratio during both forward- and reverse-thrust operation, the reverse-thrust ratio presented in figure 29 is representative of the performance that would be obtained. At maximum engine speed a maximum reverse-thrust ratio of 43 percent is indicated.

Thrust-Reverser Braking Effectiveness

In addition to the stationary performance tests, the braking effectiveness of the thrust reverser was measured in a series of taxi runs. The results of these taxi tests are presented in figure 30. The airplane ground speed is plotted against elapsed distance, measured from the start of roll, for the following cases: (1) the unmodified airplane using wheel brakes only, (2) the modified airplane using the thrust reverser only, and (3) the modified airplane using both the thrust reverser and wheel brakes. Because this thrust reverser is nonmodulating (which means that it is incapable of operation at other than the full-forward- or full-reverse-thrust positions) the transition from forward to reverse thrust during a landing would be accomplished after touchdown while the engine was at idle speed. In order to simulate this condition during the taxi runs, it was necessary to reduce the engine speed to 70 percent after attaining maximum ground speed and before applying reverse thrust. Changes in the throttle setting and the thrust-reverser position are indicated in figure 30.

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From a peak ground speed of 85 knots the unmodified airplane required 2680 feet to stop. This corresponds to an average deceleration of 0.12 g's.

For the run with thrust-reverser braking only (no wheel brakes), the peak ground speed was 78 knots and 2460 feet were required to stop. The average deceleration was 0.11 g's. Minimum stopping distance was obtained for the run using both wheel brakes and thrust reverser. From a peak ground speed of 73 knots the airplane was brought to a stop in 1090 feet, the average deceleration was 0.216 g's, which indicates that the wheel brake and thrust-reverser combination gave about twice the braking effectiveness of wheel brakes only. This is a conservative estimate because in the latter case, the wheel brakes were not used until near the end of the run when the thrust reverser was operating with full engine speed.

In reference 4 mention is made of an analysis which indicated that reverse thrust in the order of 40 percent of maximum forward thrust, when used together with wheel brakes, is sufficient to stop an airplane on an icy runway in the same distance required to stop the airplane on a dry runway with the wheel brakes alone. If the airplane deceleration force contributed by wheel braking on an icy runway is assumed to be small, the results of the analysis are verified by the taxi tests where the over-all airplane deceleration rate obtained with wheel brakes only compares quite favorably with that obtained for the thrust reverser only.

Operating Experience

During periods of reverse thrust with the airplane stationary, the exhaust gas emitting from the reverser engulfed the wing surfaces from the inboard edge of the ailerons outward to the wing tips (see fig. 7). There appeared to be considerable turbulent mixing of the exhaust gas with the ambient air so that by the time the mixture reached the wing surfaces it was sufficiently cooled and caused no appreciable heating of the wing surfaces. Some aileron buffeting was observed at the higher engine speeds, but moderate stick forces were sufficient to hold the ailerons steady. There was no attachment of the reversed flow to the fuselage surface, and no reingestion of the exhaust gas at the engine inlet was experienced. It was possible for an observer to stand on the wing next to the cockpit during reverse thrust at full engine speed.

Motion pictures of the smoke-flow patterns were taken during the taxi runs. These films showed that the exhaust gas discharging from the reverser during reverse thrust was immediately washed rearward. The forward penetration of the exhaust gas was very slight at ground speeds above approximately 20 knots. Part of one such motion-picture record of a taxi run is reproduced in figure 31. The sequence, starting in the upper left frame, shows the transition from forward to reverse thrust at an average ground speed of 72 knots. The engine-speed setting during the transition was 70 percent of full speed. It can be seen that the reversed exhaust gas does not penetrate beyond the leading edge of the horizontal stabilizer.

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During reverse-thrust operation the cooling-air ejector was inoperative. If the airplane was stationary, the flow of cooling air over the tailpipe was interrupted. Prolonged engine operation without cooling airflow caused the aft fuselage section to overheat. During stationary operation, thrust reversal at full engine speed could be maintained for a period of approximately 2 minutes before an overheat condition in the aft fuselage section was indicated by the airplane overtemperature warning system. The duration of reverse-thrust operation required for braking to a stop after touchdown is estimated to be in the order of 30 seconds. Fuselage overheating should not occur within this period of time, particularly since the forward movement of the airplane will supply some ram cooling.

When the thrust reverser is located at the rear extremity of the airplane, as in the installation investigated herein, the effect of the added weight on the airplane center of gravity is greatly magnified. In order to keep the center of gravity within the specified flight limits, a large amount of ballast must be installed in the forward end of the fuselage. Relocation of armament and accessories might accomplish the equivalent effect.

Considerable development was required before thrust-reverser actuation was achieved at the elevated tailpipe temperatures (400° to 700° C) associated with normal engine operation. The high turning-vane solidity needed for optimum thrust reversal made it necessary to swivel the turning vanes in order to stow them in the form of a strut. The resulting mechanical complexity added weight to the thrust-reverser installation and reduced the operational reliability. Although actuation at ambient tailpipe temperatures (engine not operating) was trouble free, the addition of heat caused changes in the operating clearances and also weakened certain mechanical parts - particularly the turning-vane crank arms (item Q, fig. 4).

No appreciable change in noise level was evident during reverse-thrust operation. Sound measurements were not made; however, it was the opinion of observers that although the sound field was redistributed, the maximum sound intensity was not increased appreciably.

SUMMARY OF RESULTS

An investigation of a full-scale, cascade-type, thrust reverser installed in a single-engine, fighter-type jet airplane produced the following results:

1. Reverse-thrust ratio increased with corrected engine speed. A reverse-thrust ratio of about 35 percent was obtained at full corrected engine speed. A reverse-thrust ratio of 43 percent is obtainable, if the engine-tailpipe total-pressure ratio is not reduced during reverse-thrust operation.

2. Increasing the exhaust-gas velocity at the thrust-reverser inlet produced additional reverse thrust. A peak reverse-thrust ratio of 56 percent was obtained when the tailpipe flow area at the thrust-reverser inlet was sized for limiting tailpipe temperature at full engine speed.

3. Stowage of the turning vanes inside the tailpipe causes an estimated 3 percent loss of forward thrust. This estimate is based on data obtained in scale-model, unheated-air tests where tailpipe leakage and cooling-air pumping losses, which tend to mask out the vane-stowage loss, were not present. Leakage of exhaust gas through the tailpipe seals is another source of forward-thrust loss. This leakage also tends to overheat the fuselage aft section.

4. Scale-model, unheated-air tests indicated that the optimum cascade solidity was in the order of 0.80 for the turning vanes used in the thrust reverser. At lower solidities the performance was impaired by the reduced turning effectiveness, while at higher solidities the flow through the thrust reverser was restricted.

5. Taxi tests on a dry runway indicated that the average deceleration was about 0.11 g's when using either the thrust reverser or wheel brakes to stop the airplane. When the thrust reverser and wheel brakes were used in combination, the average airplane deceleration was almost doubled.

6. Only slight heating and buffeting of the airplane external surfaces by the reversed exhaust gas was encountered during stationary operation. At ground speeds greater than approximately 20 knots the reversed flow was washed rearward before striking a surface. Stationary reverse-thrust operation for periods greater than approximately 2 minutes caused the aft fuselage section to overheat because of a lack of cooling airflow over the tailpipe. This length of time, however, is well in excess of that estimated as being required to bring the airplane to a stop after touchdown.

CL-3

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7. No appreciable change in noise level was evident during reverse-thrust operation. Sound measurements were not made; however, it was the opinion of observers that, although the sound field was redistributed, the maximum sound intensity was not increased appreciably.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, January 24, 1957

APPENDIX - SYMBOLS

F_n net thrust, lb

P total pressure, lb/sq ft

p static pressure, lb/sq ft

T total temperature, ^{o}R

t strut thickness, in.

w gas weight flow, lb/sec

η_R reverse-thrust ratio

δ ratio of tailpipe total pressure to NACA standard sea-level pressure, $P_6/2116$

θ ratio of total temperature to NACA standard sea-level temperature, T/519

Subscripts:

F forward

R reverse

r rated value or value obtained when operating with NACA standard sea-level static inlet conditions at rated engine speed and rated turbine-inlet temperature

0 ambient

2 compressor inlet

4 turbine inlet

6 tailpipe

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2. Koutz, Stanley L.: Effect of Heat and Power Extraction on Turbojet-Engine Performance. IV - Analytical Determination of Effects of Hot-Gas Bleed. NACA TN 2304, 1951.

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

4. Sutter, Joseph: Reverse Thrust for Jet Transports. Paper presented at meeting SAE, New York (N.Y.), Apr. 12-15, 1954.

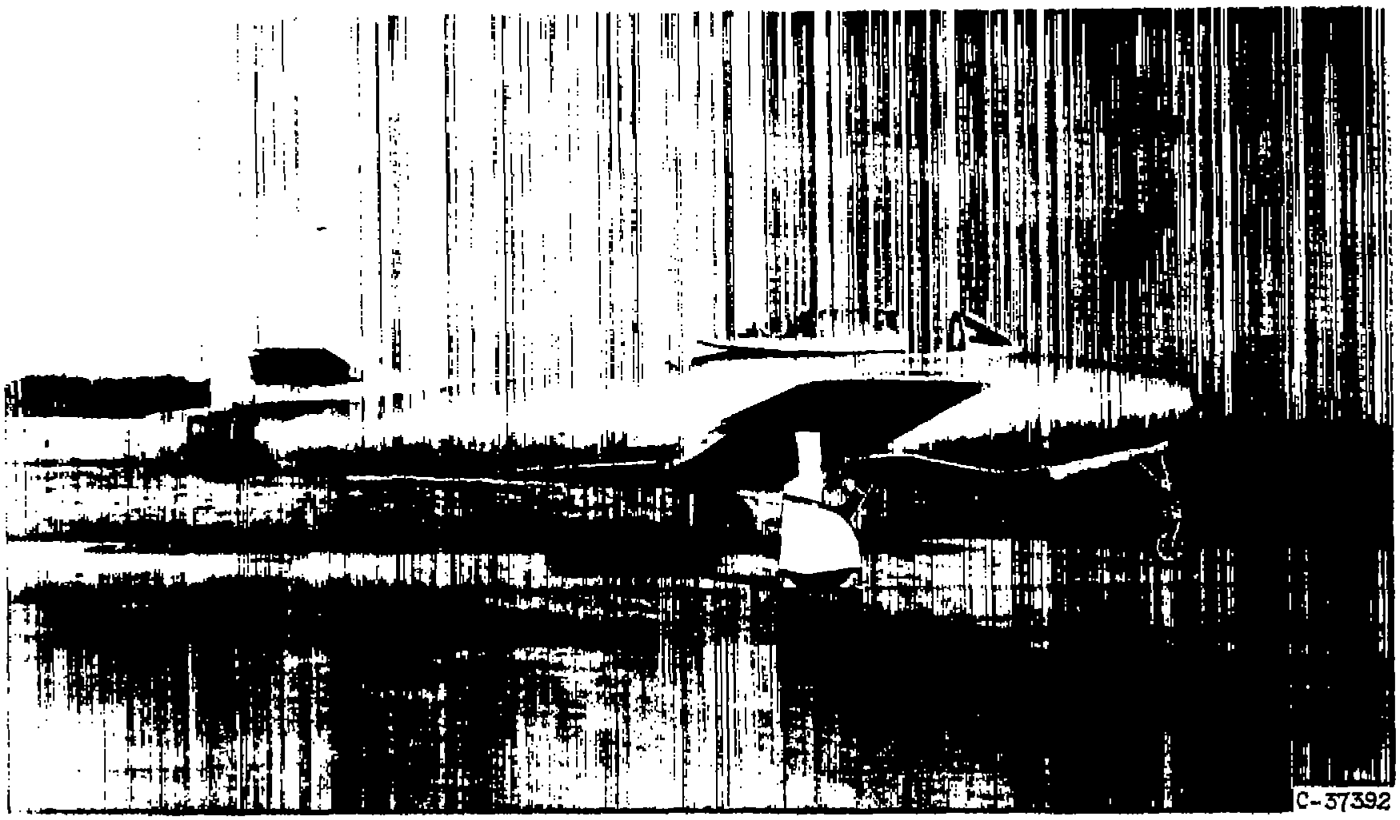

Figure 1. - Over-all view of airplane with thrust reverser installed.

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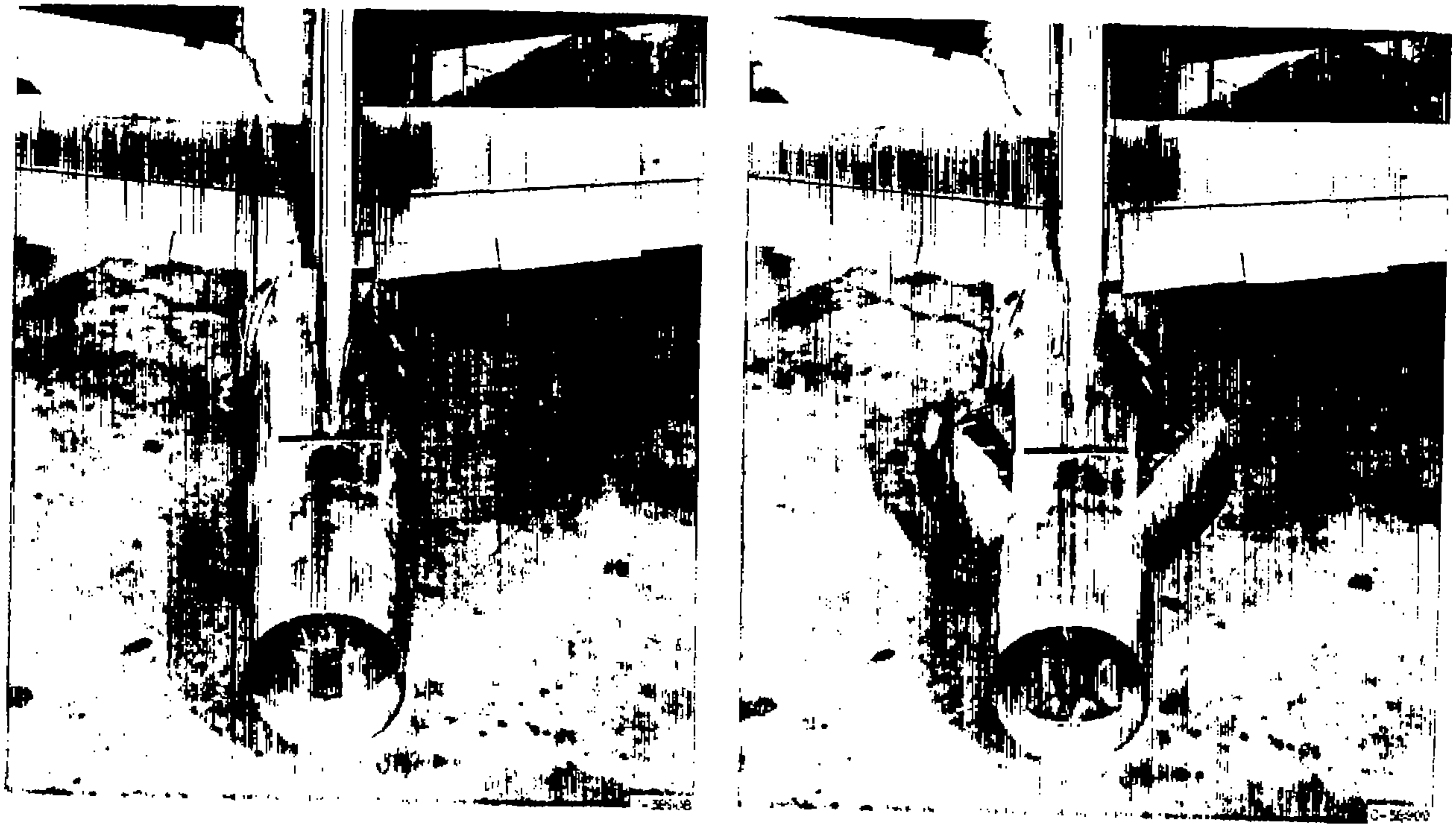
(a) Before modification.

(b) After modification.

Figure 2. - Comparison of airplane rear-fuselage shape before and after thrust-reverser installation.

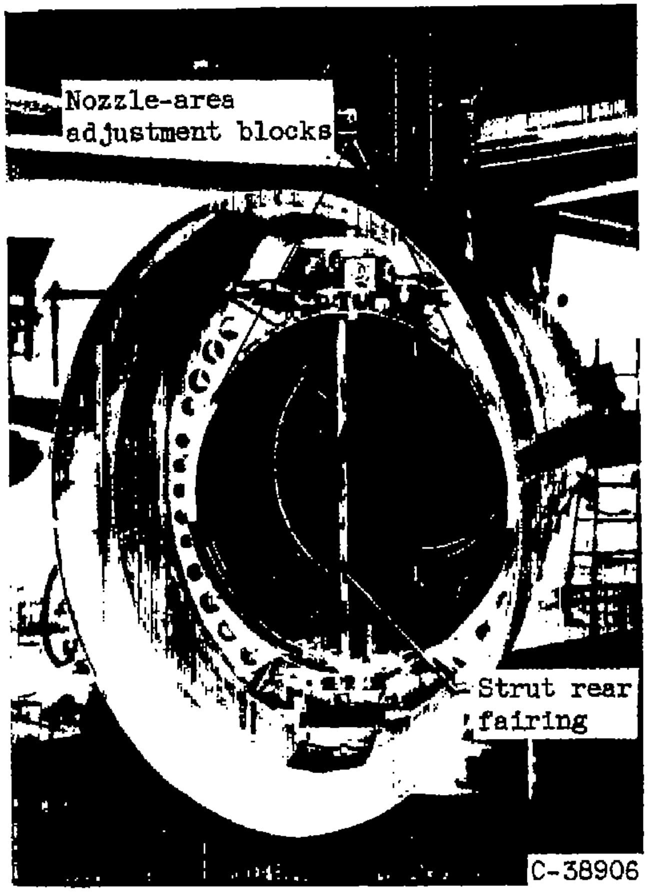


Forward-thrust position

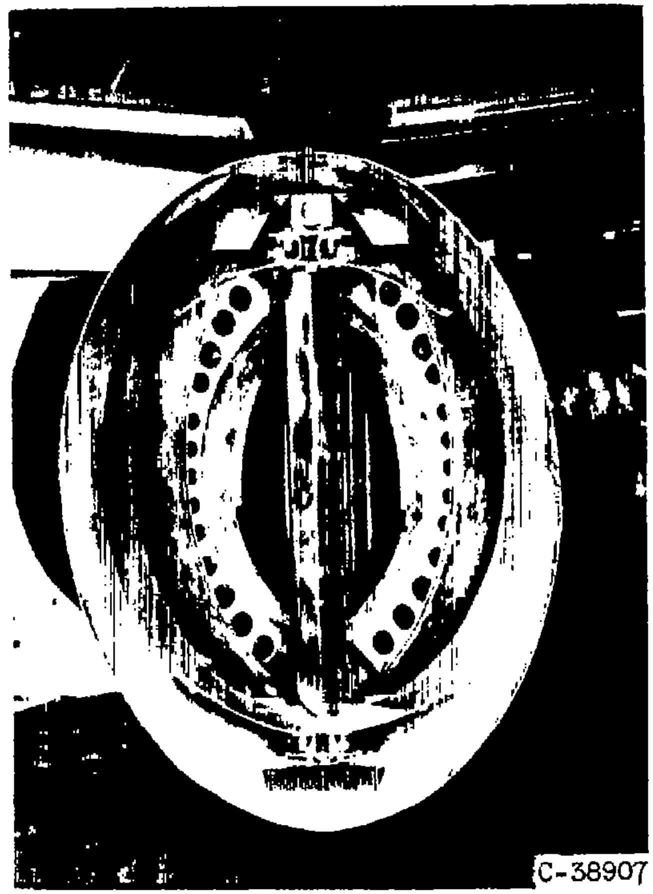
Reverse-thrust position

(a) Overhead view from rear.

Figure 3. - Vane-type thrust-reverser installation on fighter-type jet airplane.



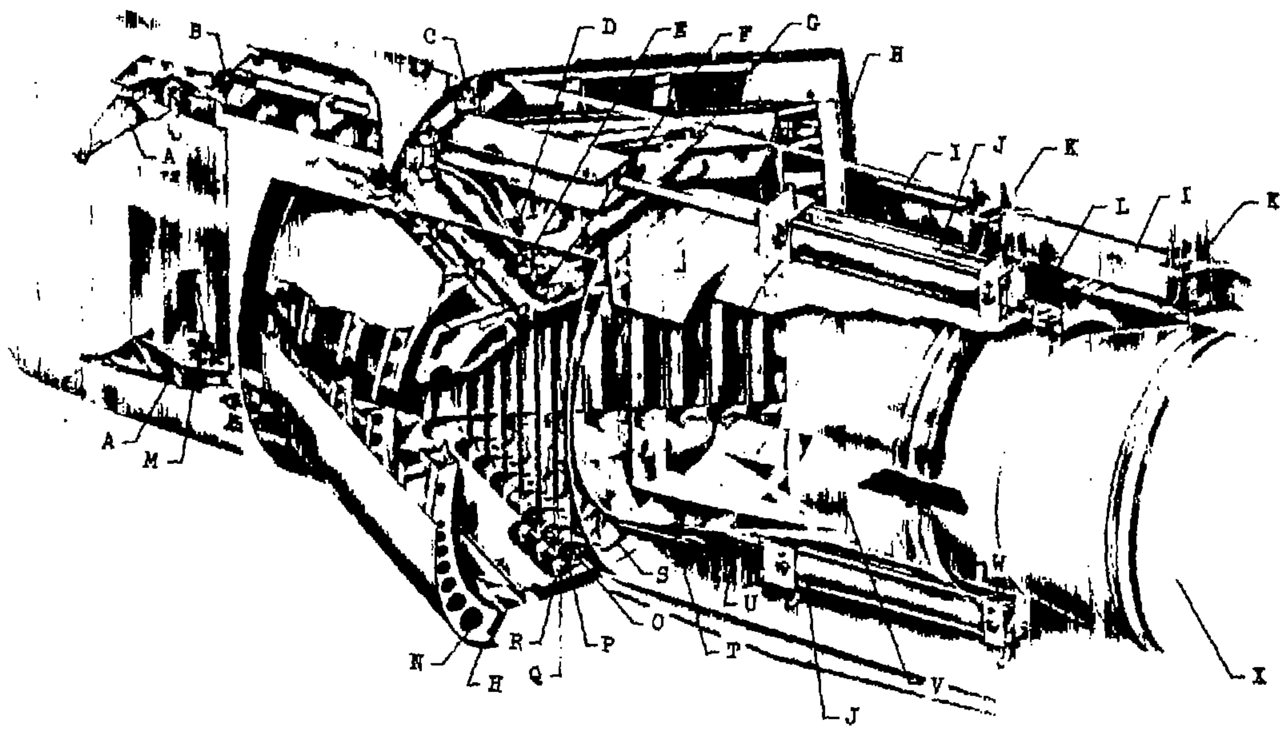
Forward-thrust position



Reverse-thrust position

(b) Rear view looking into tailpipe.

Figure 3. - Concluded. Vane-type thrust-reverser installation on fighter-type jet airplane.



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A	Jet-nozzle segment	M	Movable-strut rear fairing section
B	Cam-plate axial-position adjustment	N	Cooling-air flow passage
C	Movable tailpipe section pivot	O	Turning vane
D	Cam-plate groove	P	Turning-vane pivot
E	Cam follower pin	Q	Turning-vane crank arm
F	Turning-vane crank-arm stop	R	Turning-vane crank pin
G	Cam plate	S	Turning-vane crank-pin guide slot
H	Movable tailpipe section	T	Blast shield
I	Reverse-thrust load distributing member	U	Tailpipe adaptor section
J	Hydraulic actuator	V	Upstream splitter vane
K	Fuselage structural member	W	Tailpipe expansion joint
L	Cooling-air shroud	X	Engine tailpipe

Figure 4. - Cutaway view of thrust-reverser installation.

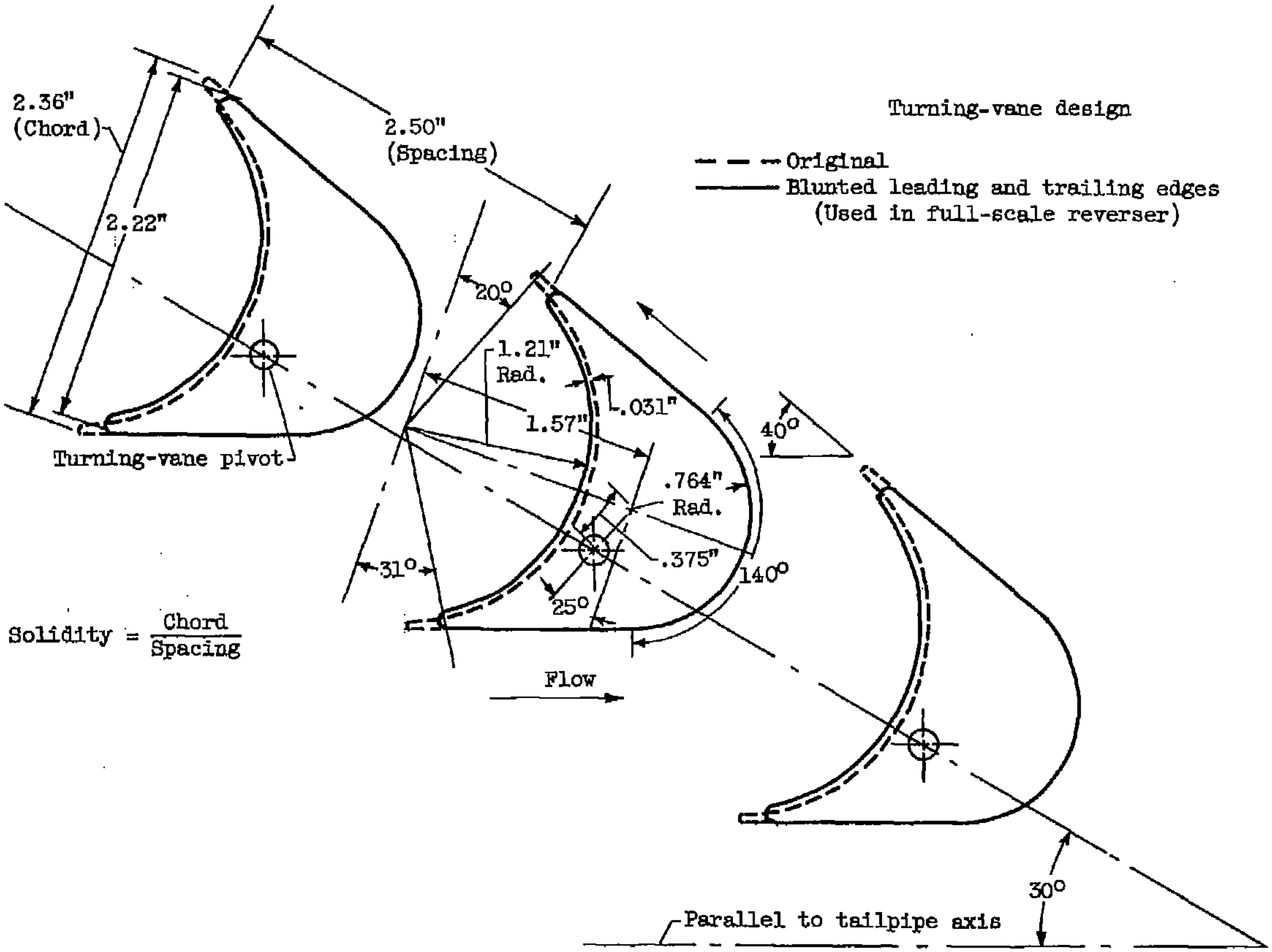

Figure 5. - Thrust-reverser turning-vane details.

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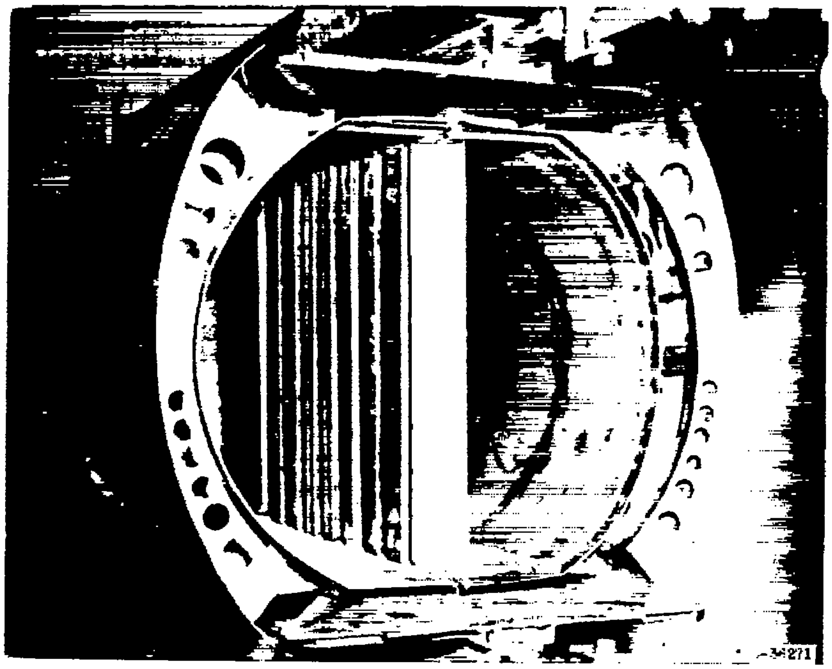
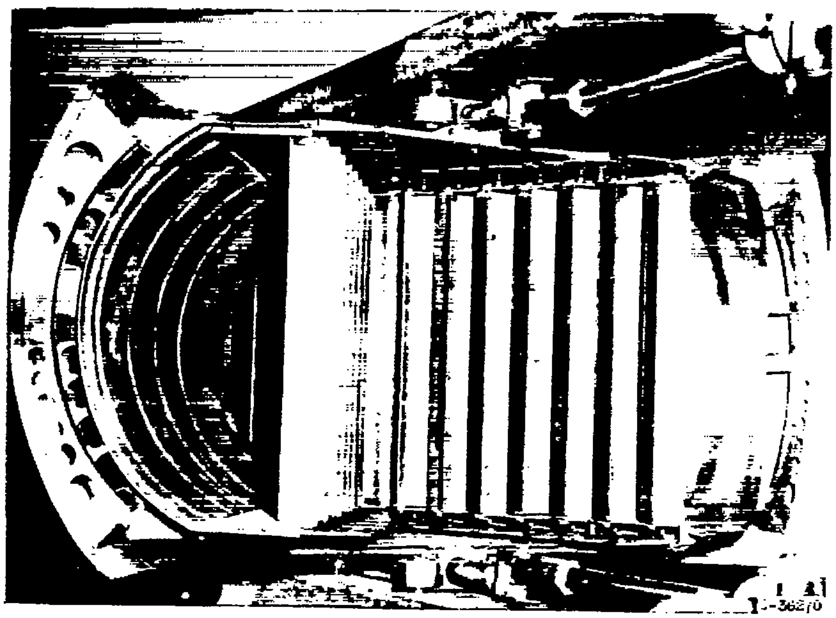
CL-4 back



(a) Forward-thrust position.



(b) Reverse-thrust position.

Figure 6. - Upstream view of thrust reverser (removed from airplane) showing forward- and reverse-thrust position.

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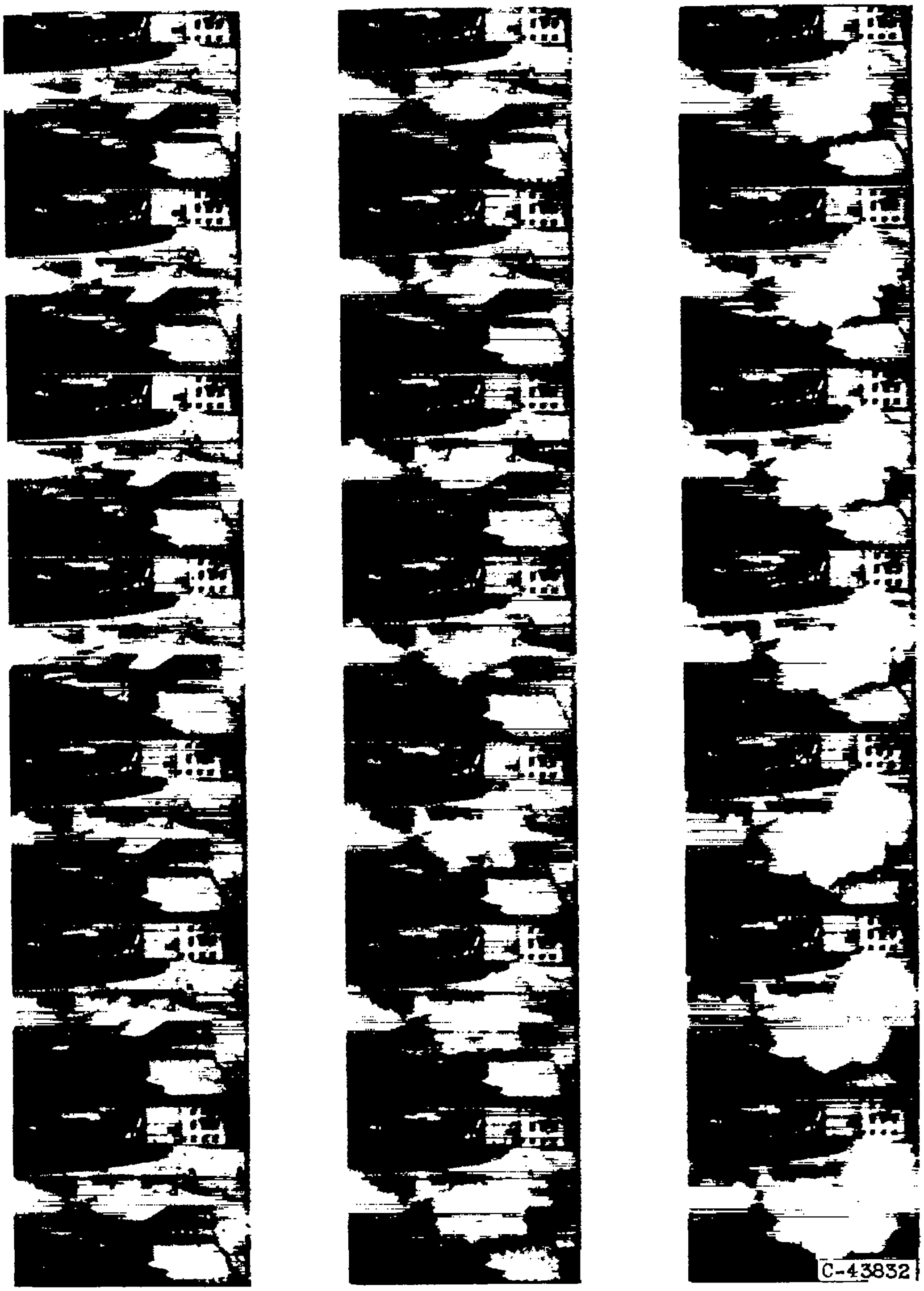

Figure 7. - Motion-picture sequence showing transition from forward to reverse thrust during stationary operation.

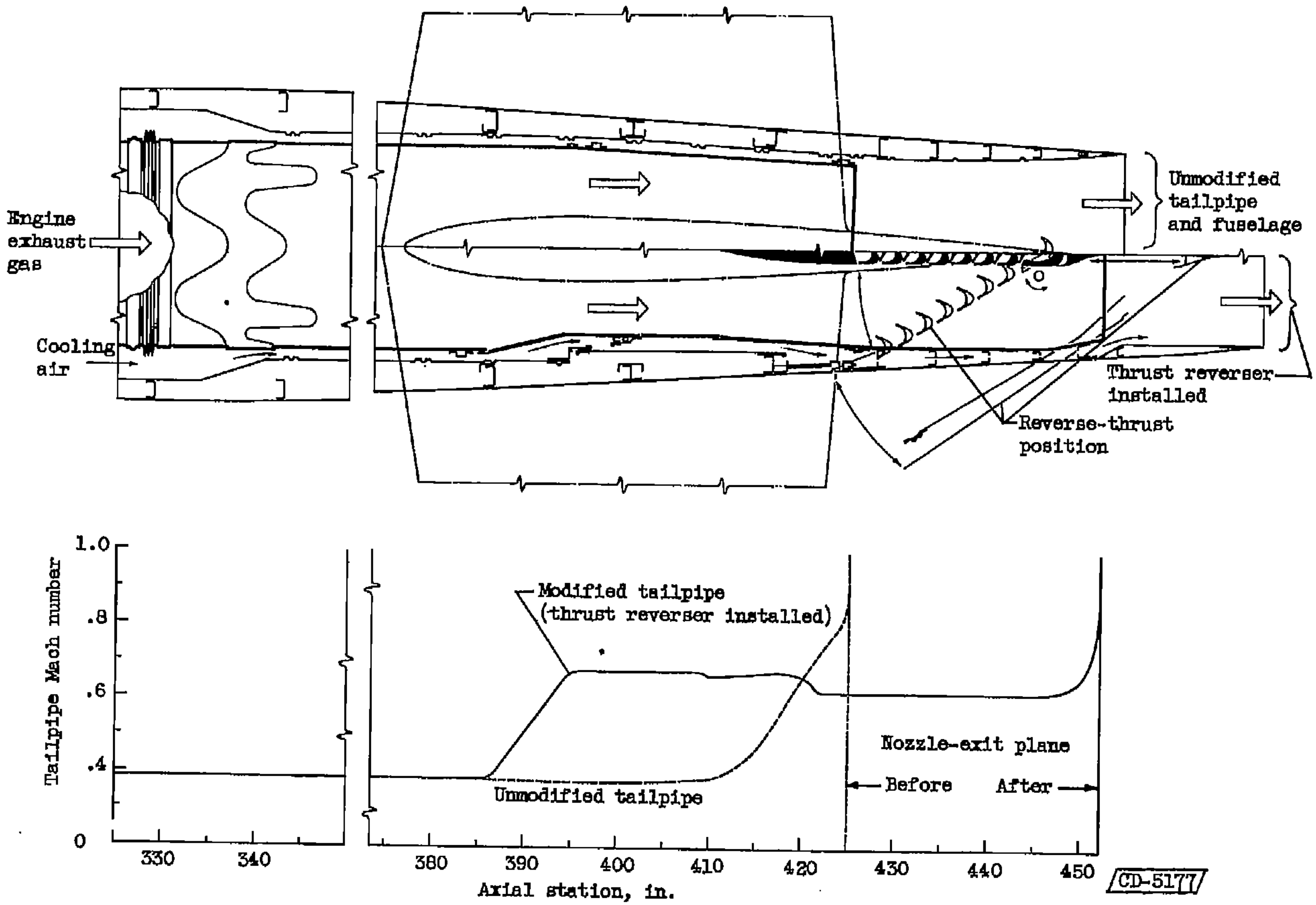

Figure 8. - Plan view of airplane tailpipe configurations and design tailpipe Mach number before and after thrust-reverser installation.

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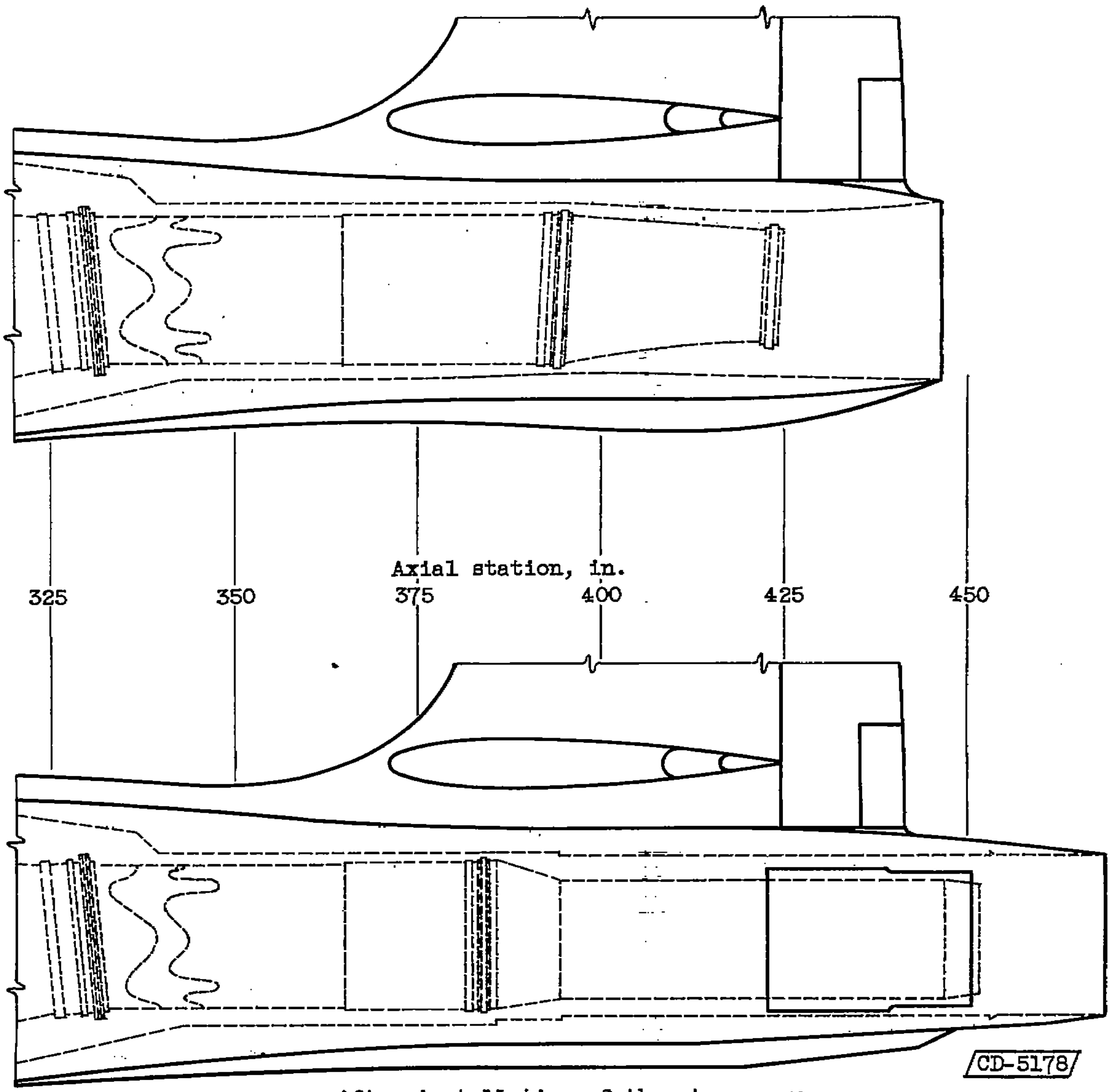

After installation of thrust reverser

Figure 9. - Elevation view of fuselage aft section and tailpipe configurations before and after thrust-reverser installation.

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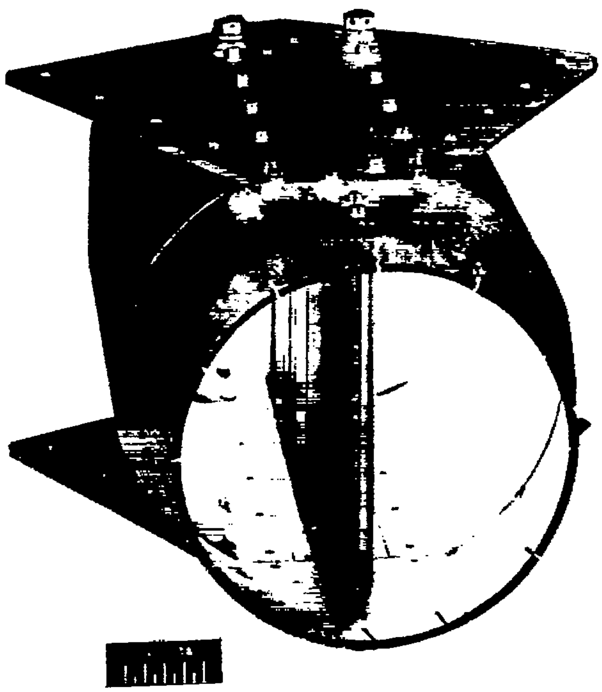

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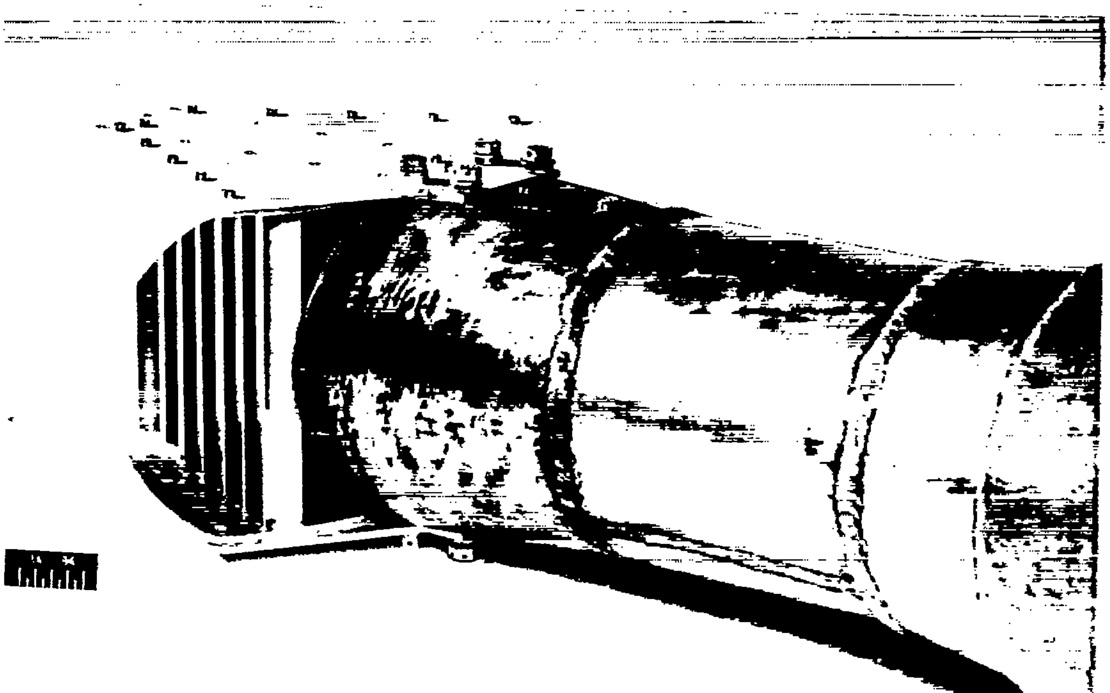
(a) Forward thrust.



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(b) Reverse thrust.

Figure 10. - One-third scale unheated-air model of vane-type thrust reverser.

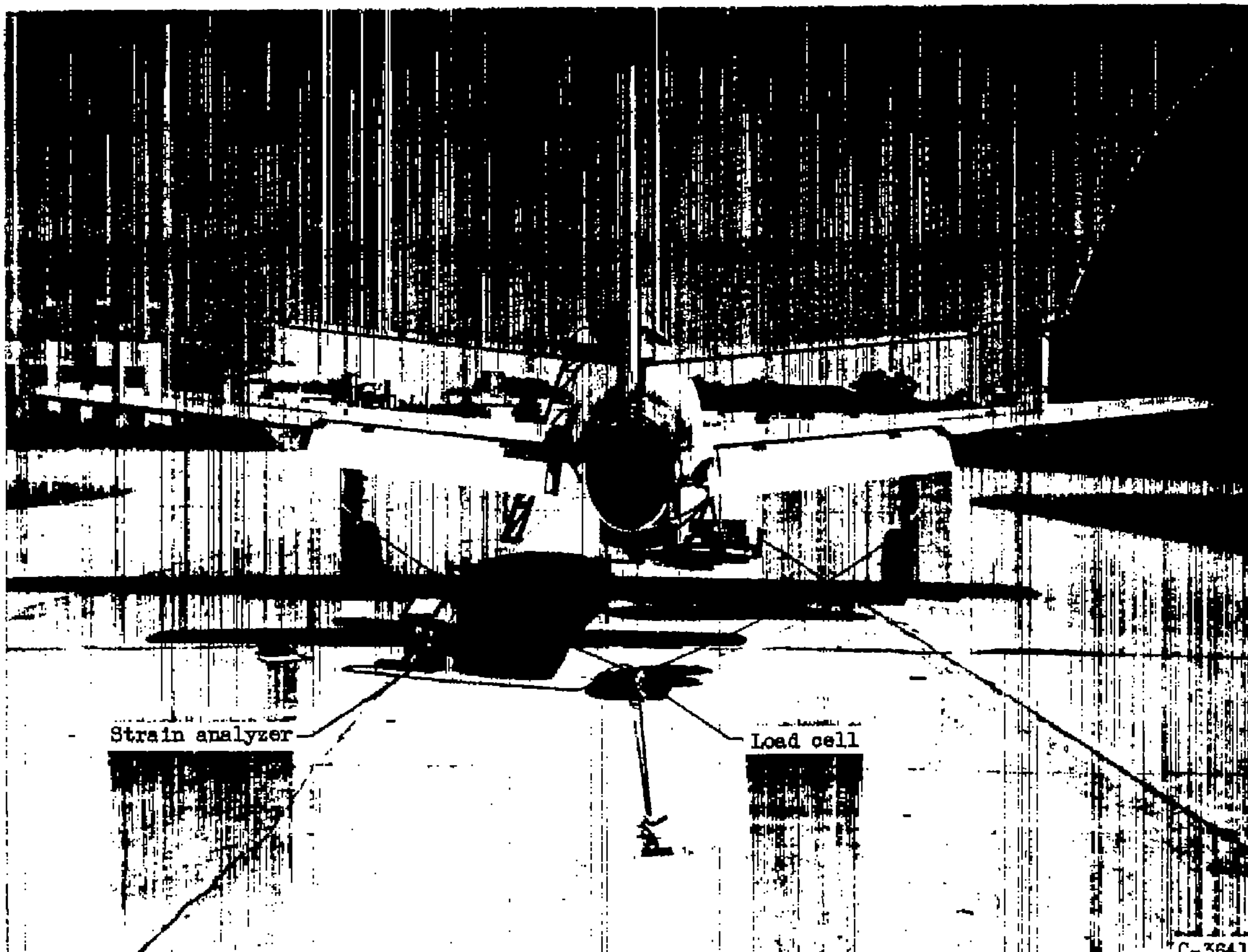

Figure 11. - Tethering cable arrangement used to measure thrust.

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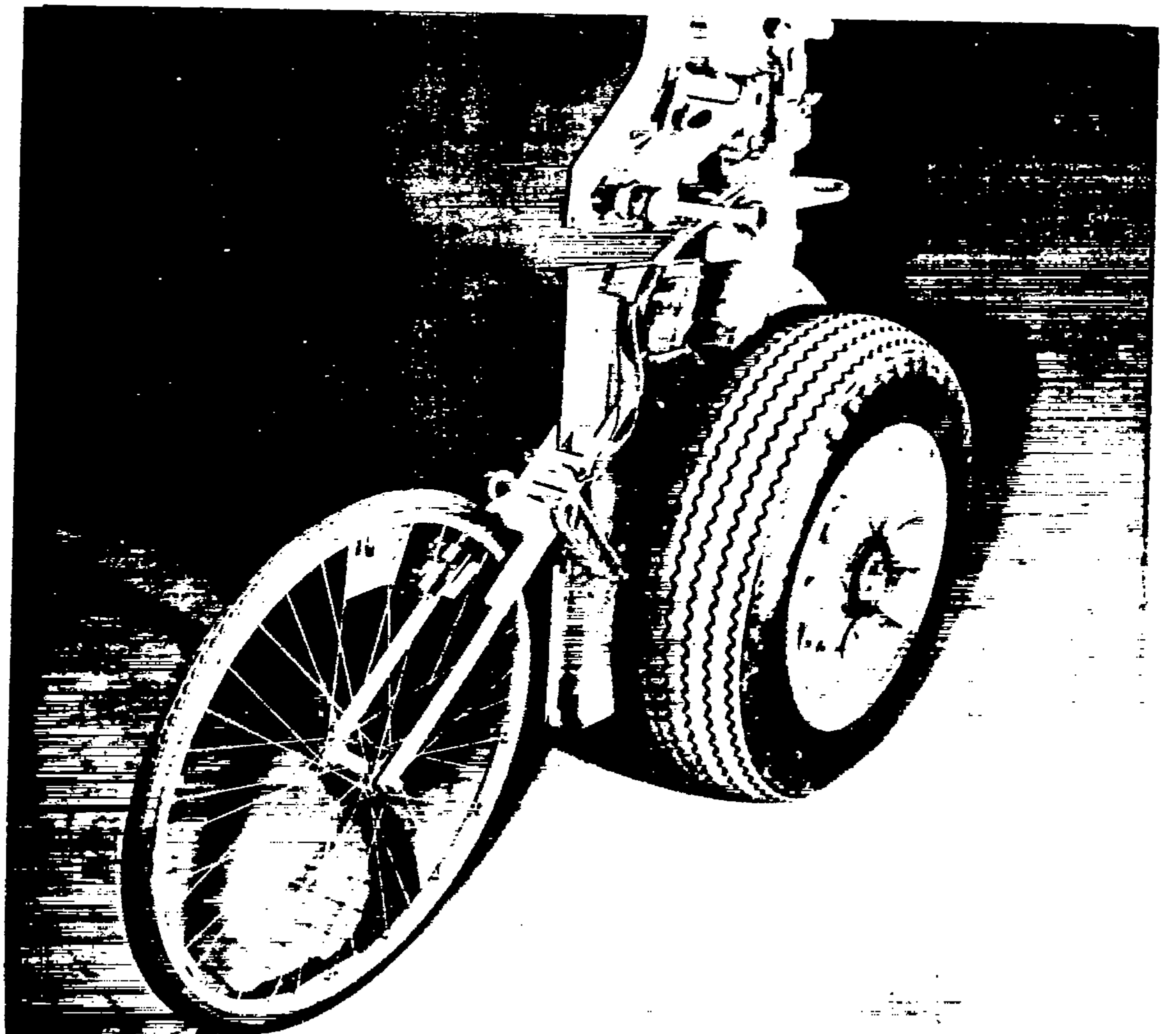

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Figure 12. - Bicycle-wheel arrangement used to measure ground speed and elapsed distance during airplane taxi runs.

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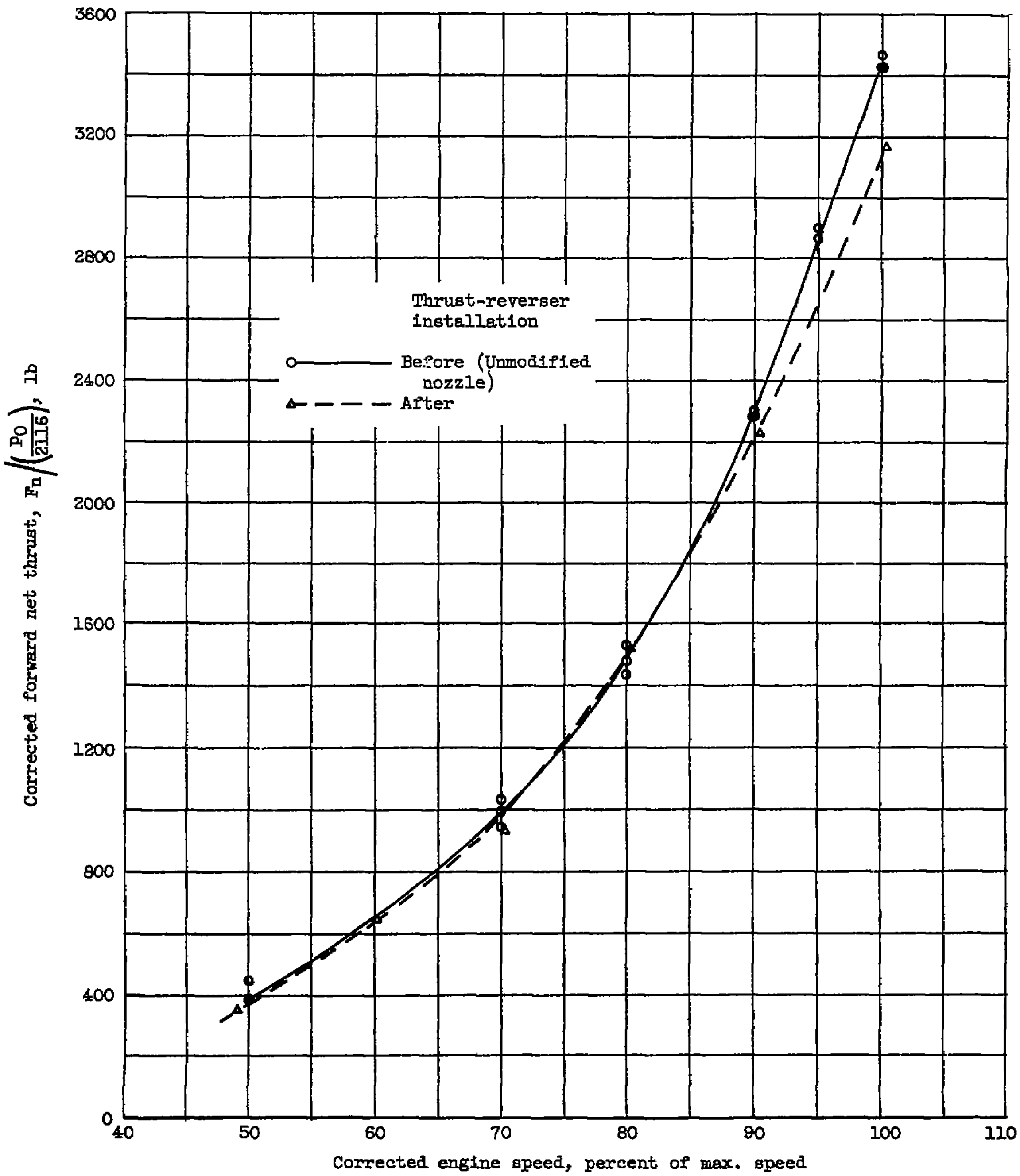

(a) With cooling-air ejector.

Figure 13. - Comparison of forward net thrust before and after thrust-reverser installation.

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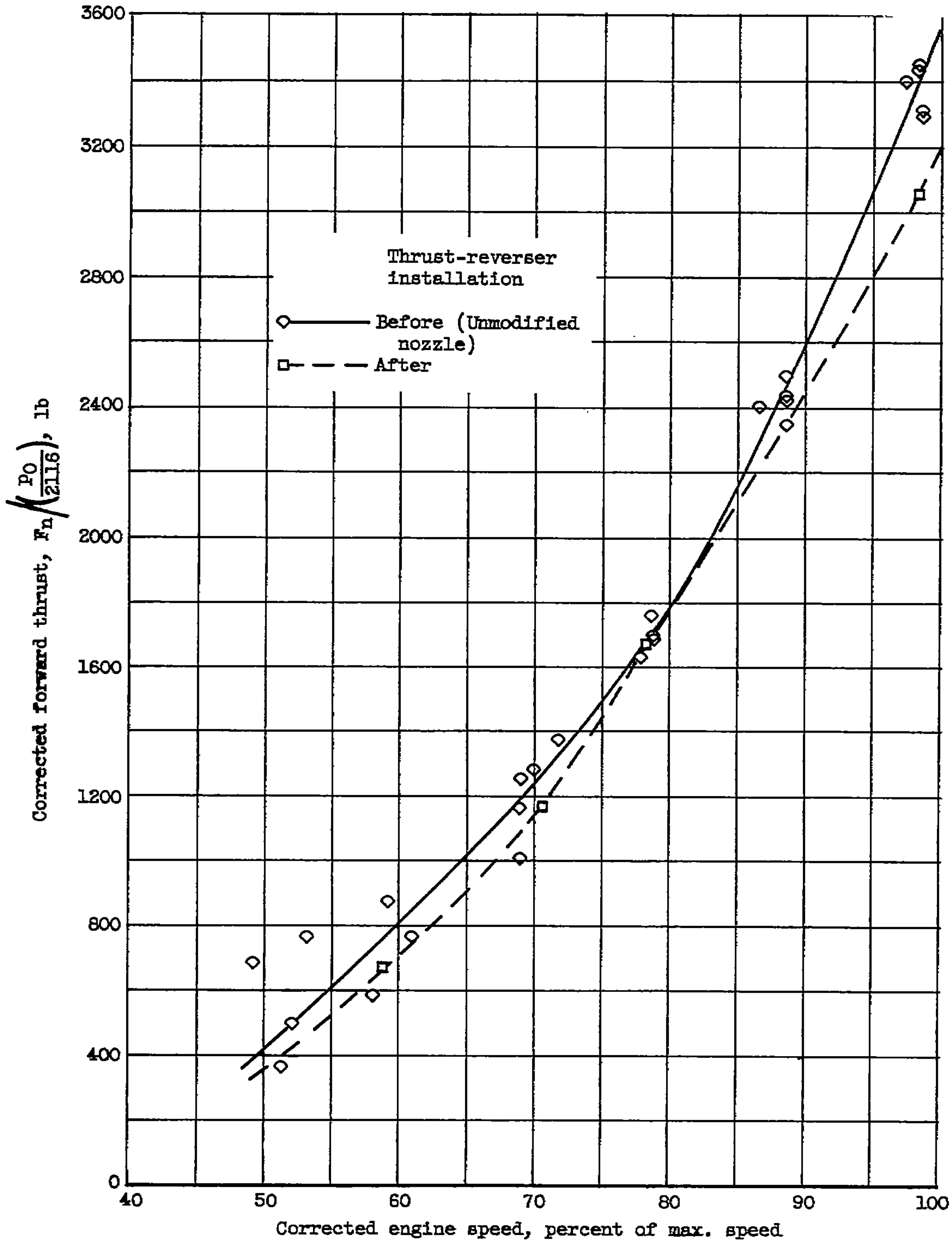
CL-5 back



(b) Without cooling-air ejector.

Figure 13. - Concluded. Comparison of forward net thrust before and after thrust-reverser installation.

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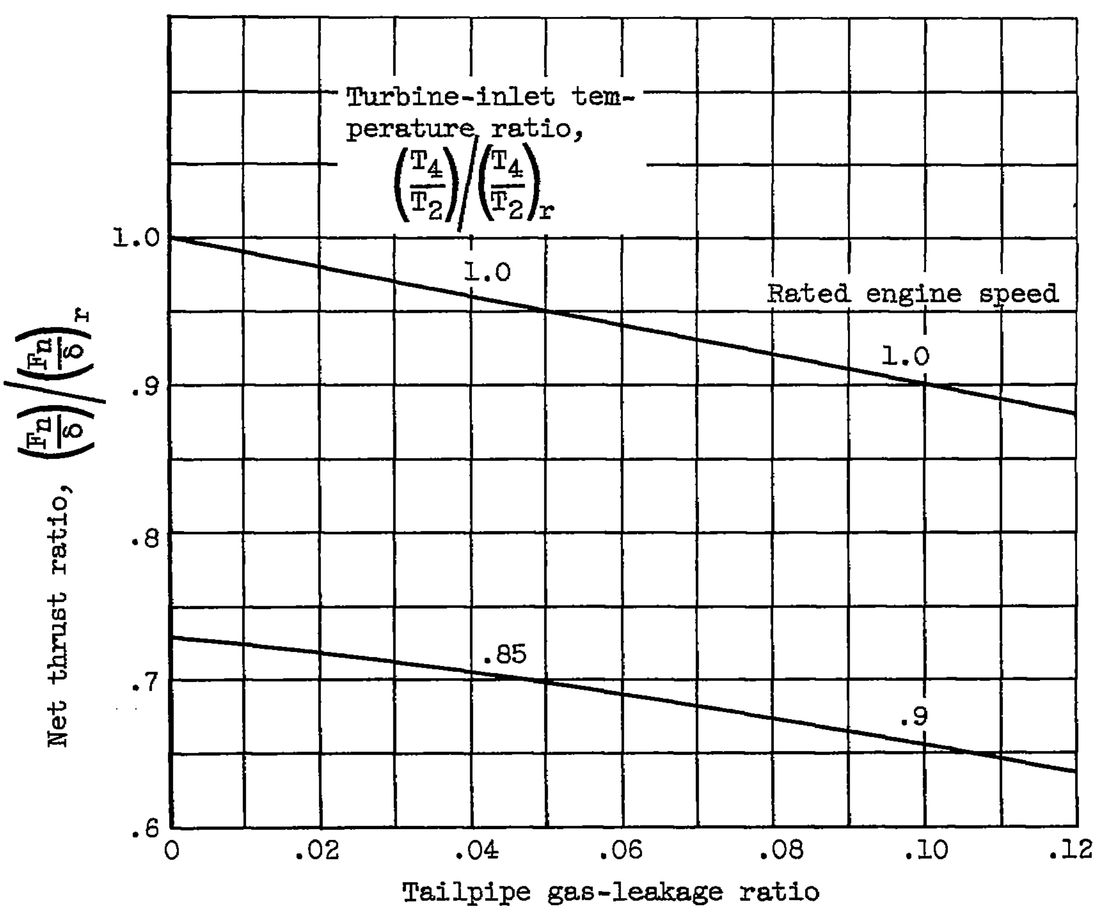

Figure 14. - Effect of tailpipe gas leakage on engine net thrust.

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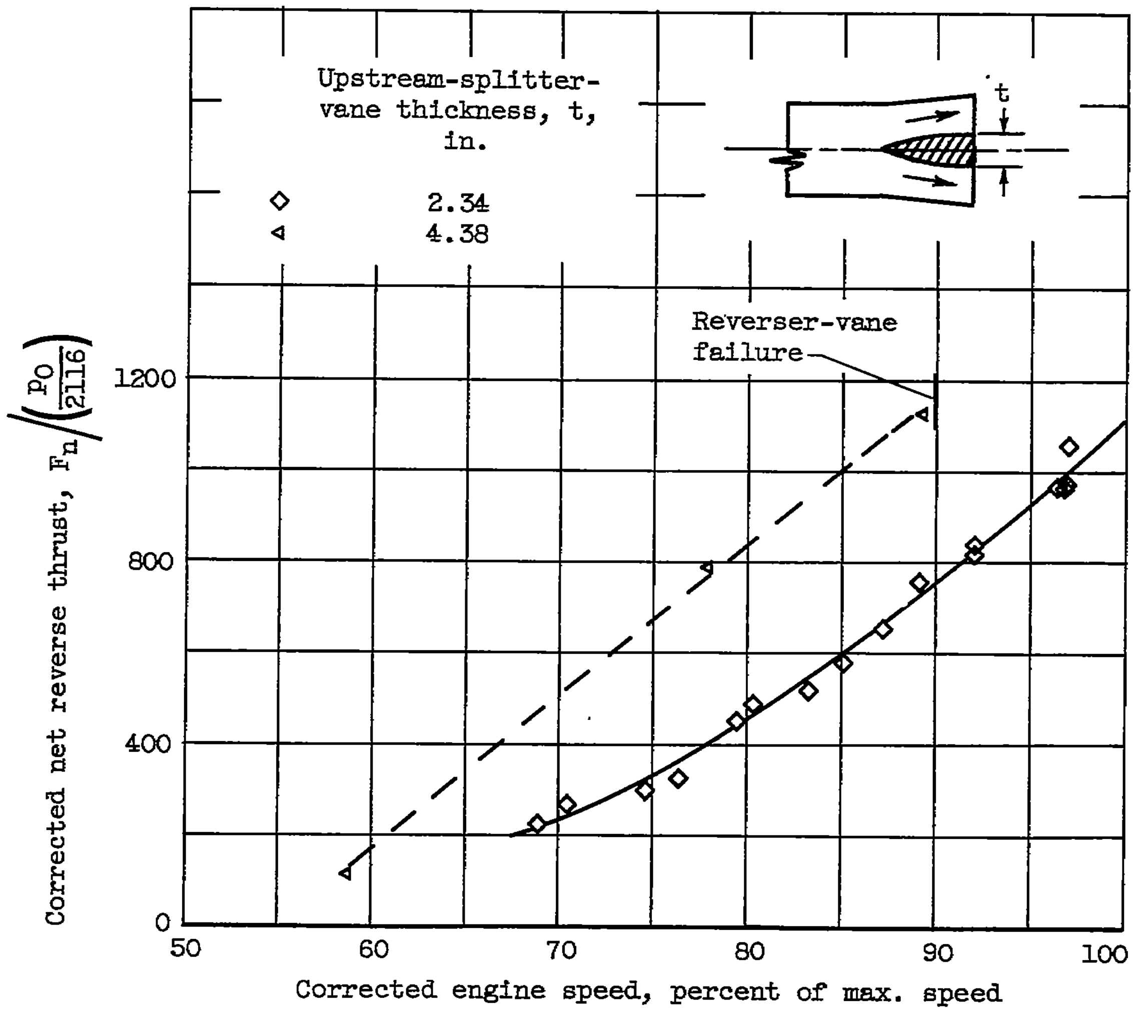

Figure 15. - Variation of reverse thrust with engine speed.

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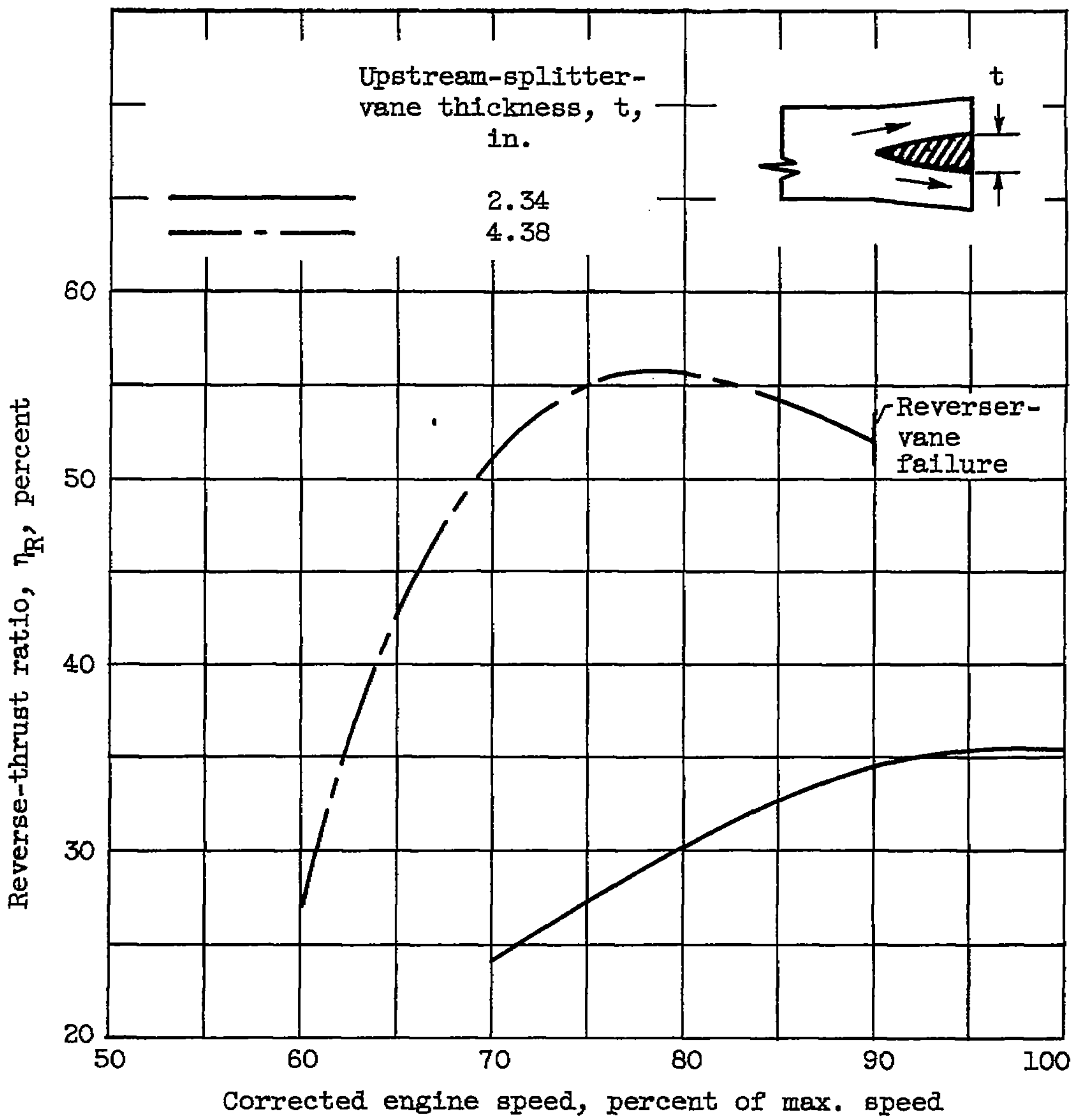

Figure 16. - Variation of reverse-thrust ratio with engine speed.

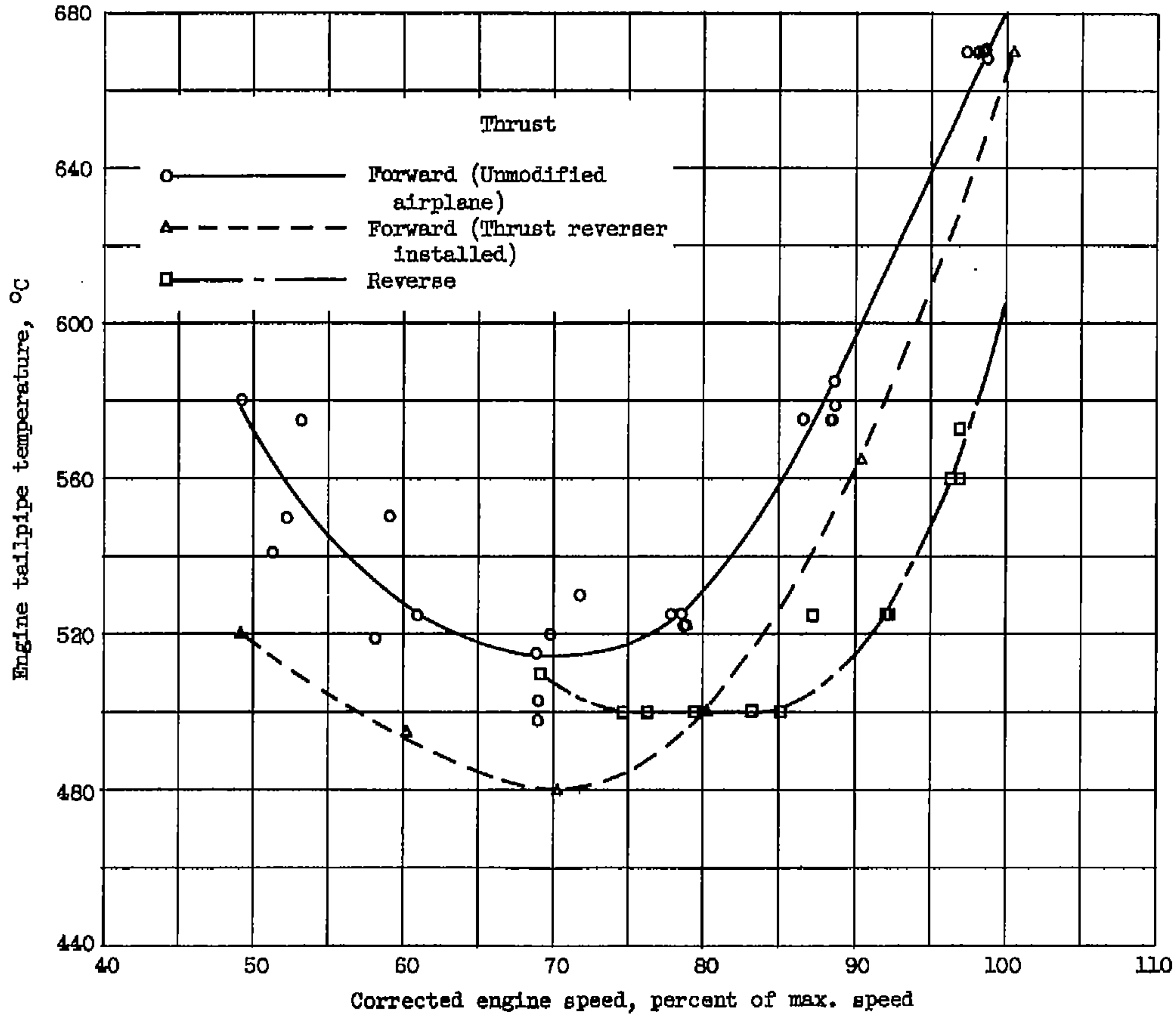

Figure 17. - Comparison of engine tailpipe temperatures before and after thrust-reverser installation.

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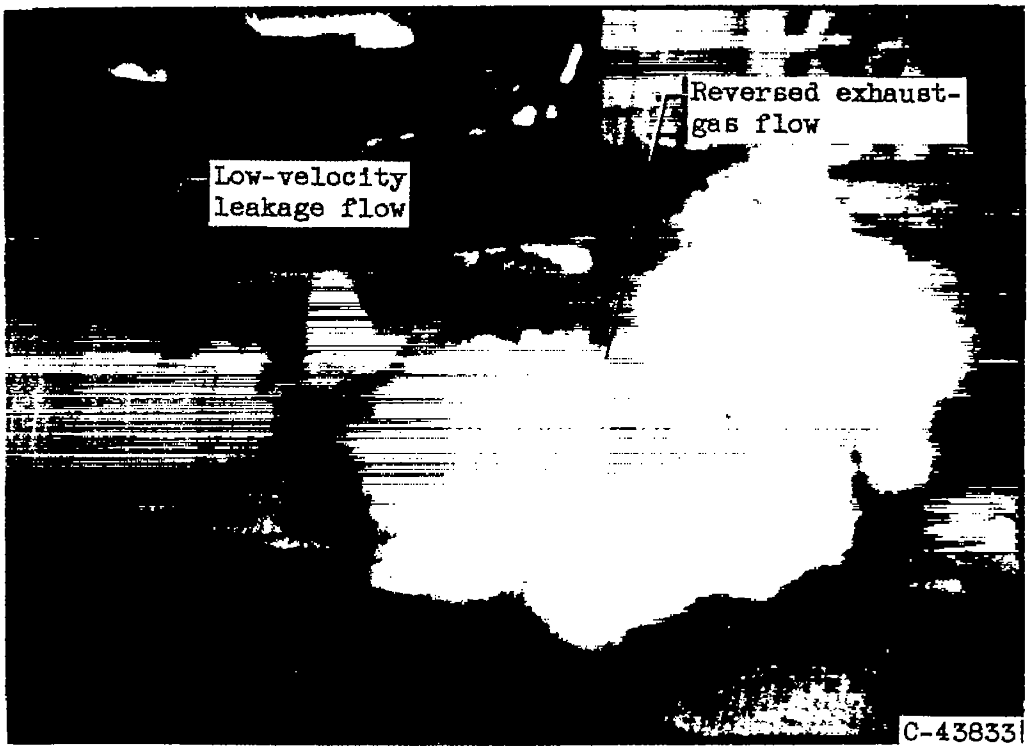

Figure 18. - Exhaust-gas smoke-flow pattern during reverse-thrust operation with airplane stationary.

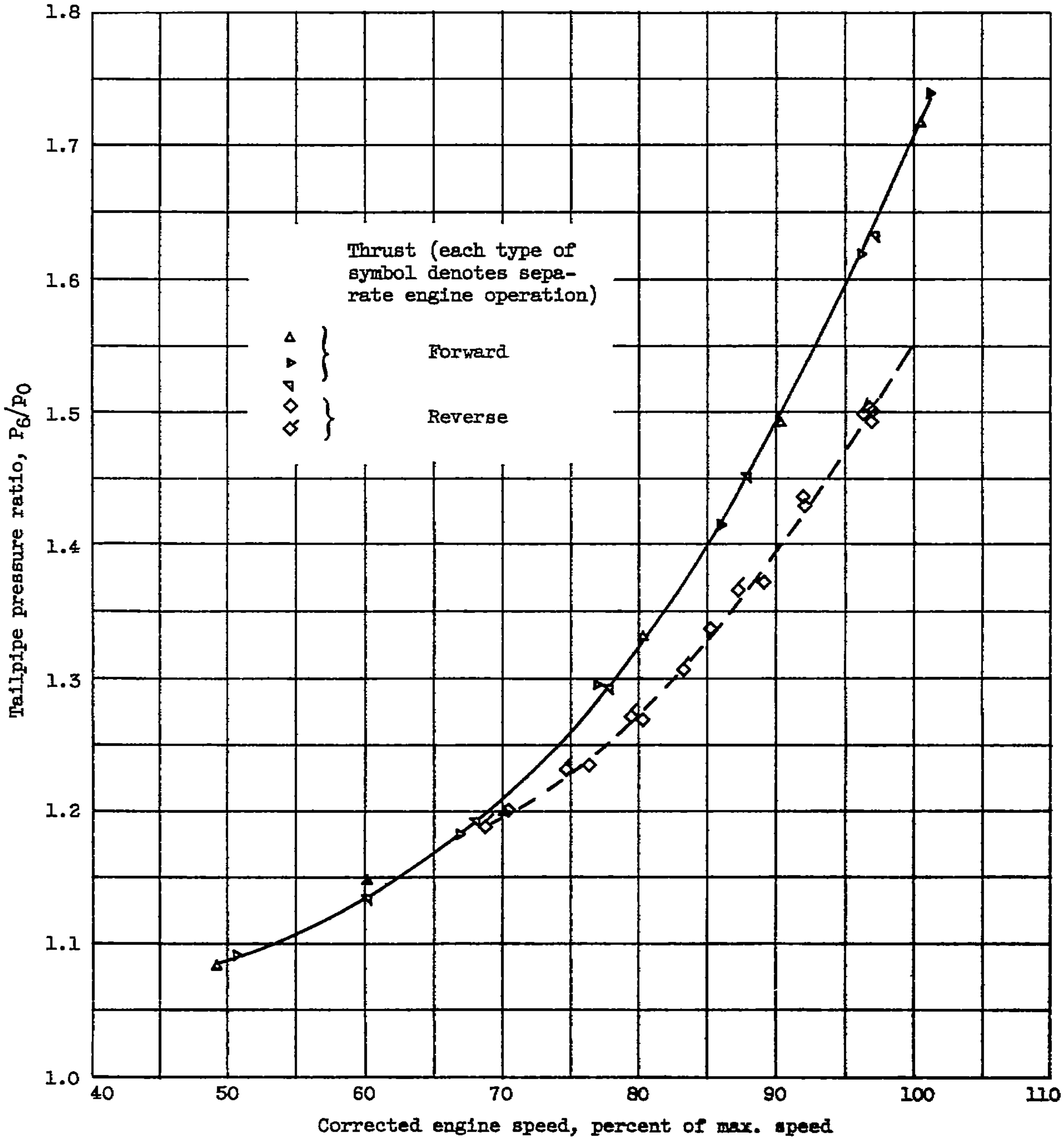

Figure 19. - Variation of tailpipe pressure ratio with engine speed during forward- and reverse-thrust operation.

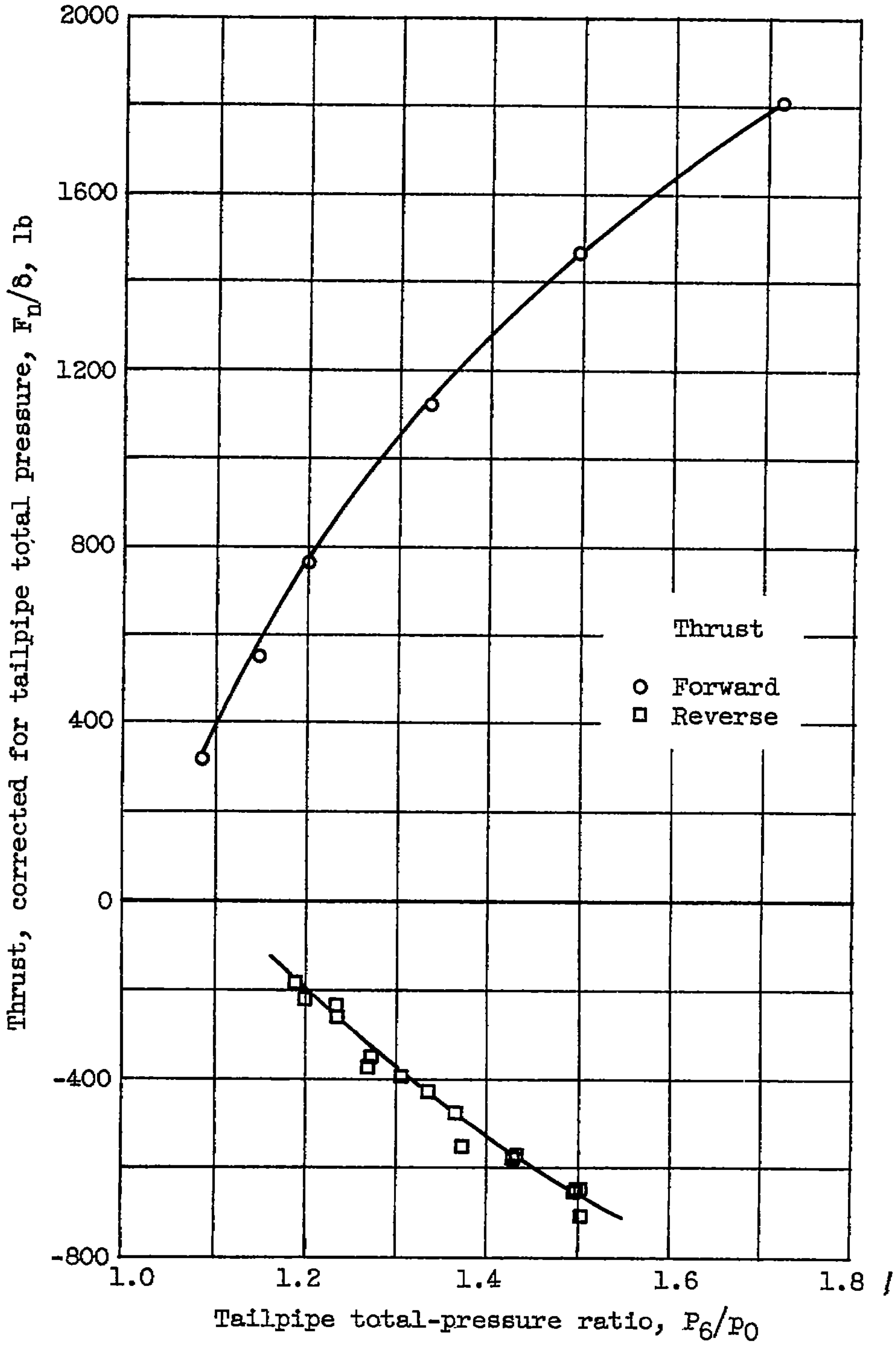

Figure 20. - Full-scale forward- and reverse-thrust characteristics corrected for thrust-reverser inlet pressure.

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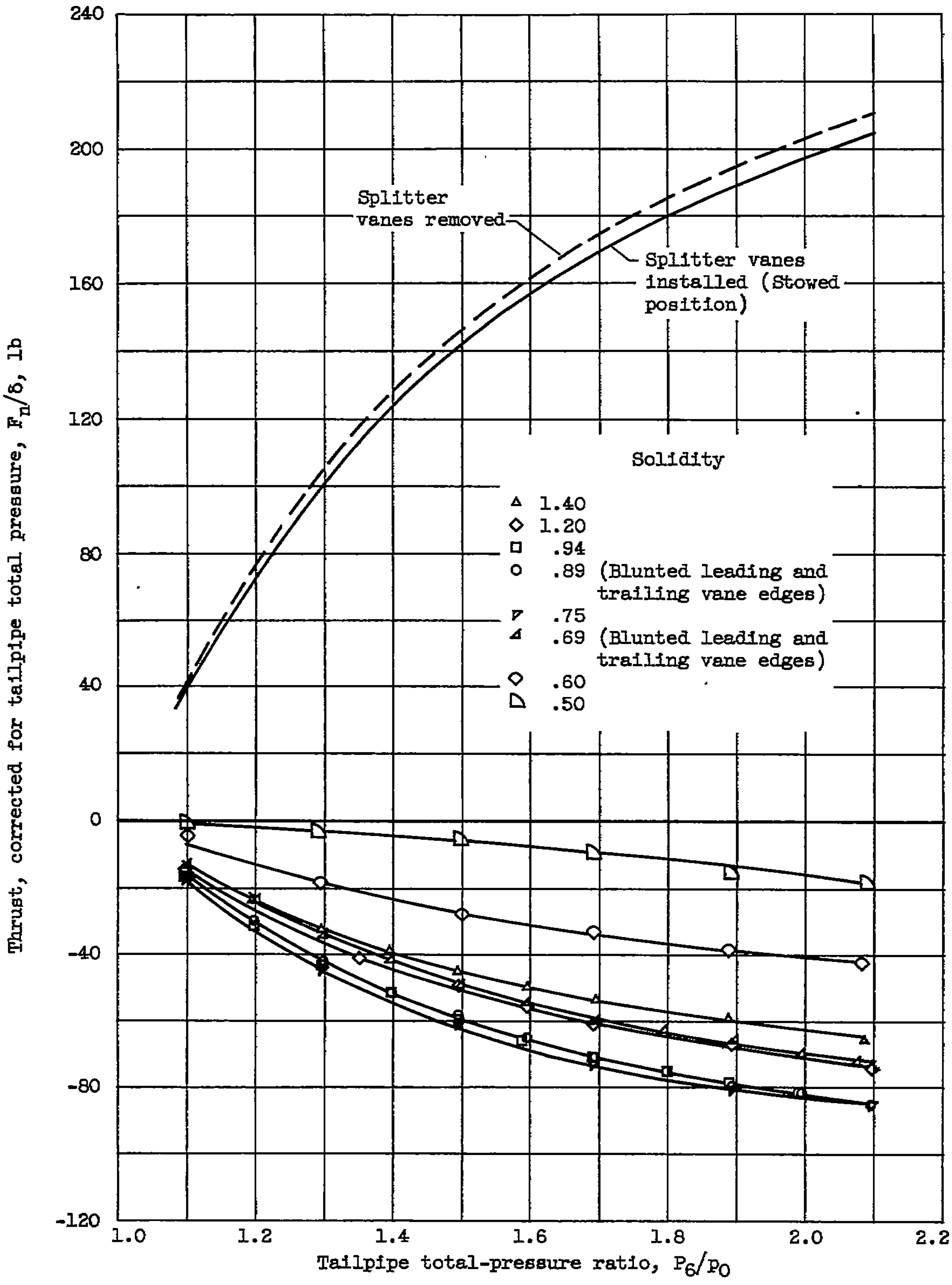

Figure 21. - Variation of forward- and reverse-thrust with tailpipe total-pressure ratio. Scale-model, unheated-air tests.

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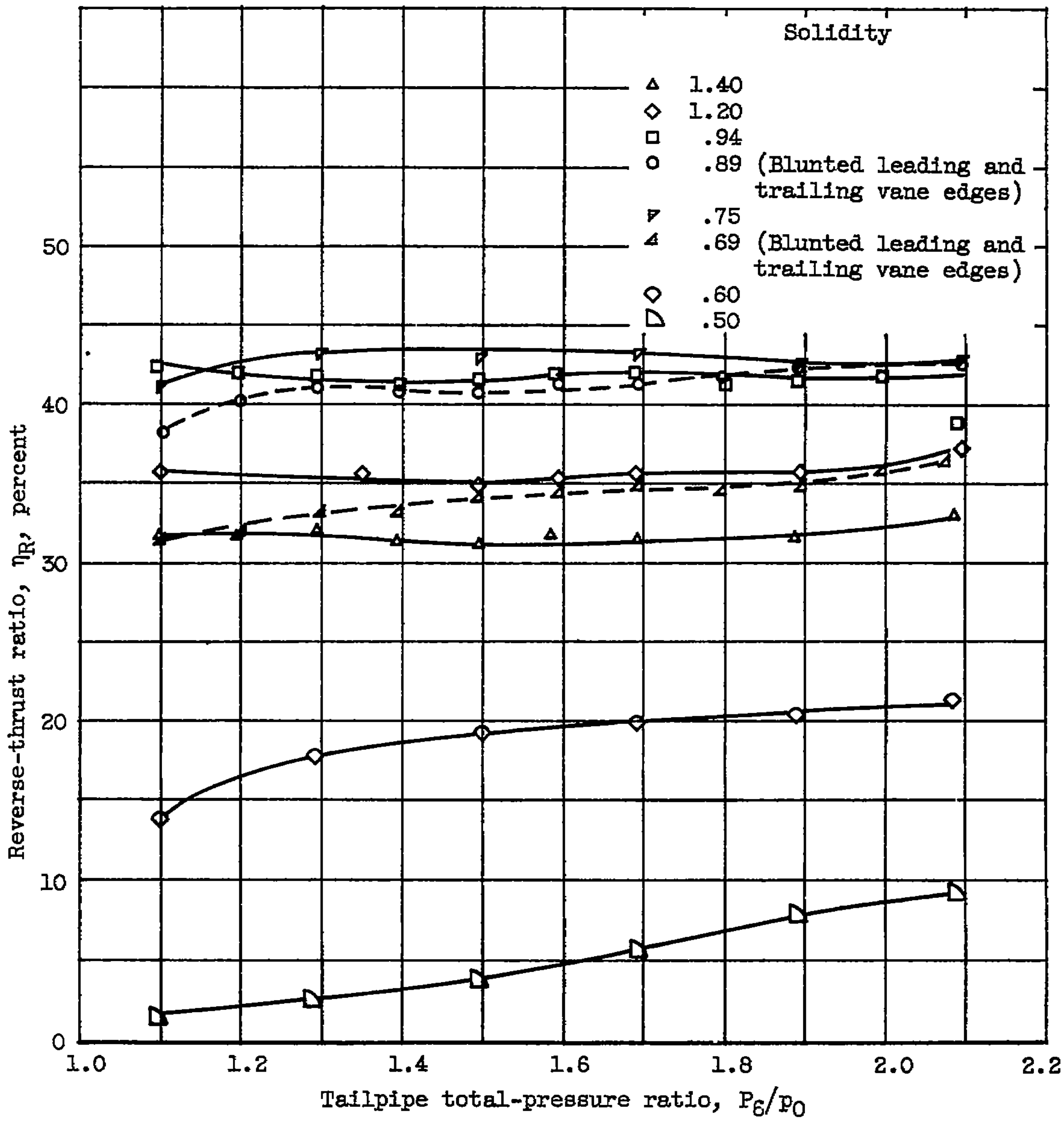

Figure 22. - Variation of reverse-thrust ratio with tailpipe total-pressure ratio in scale-model, unheated-air tests.

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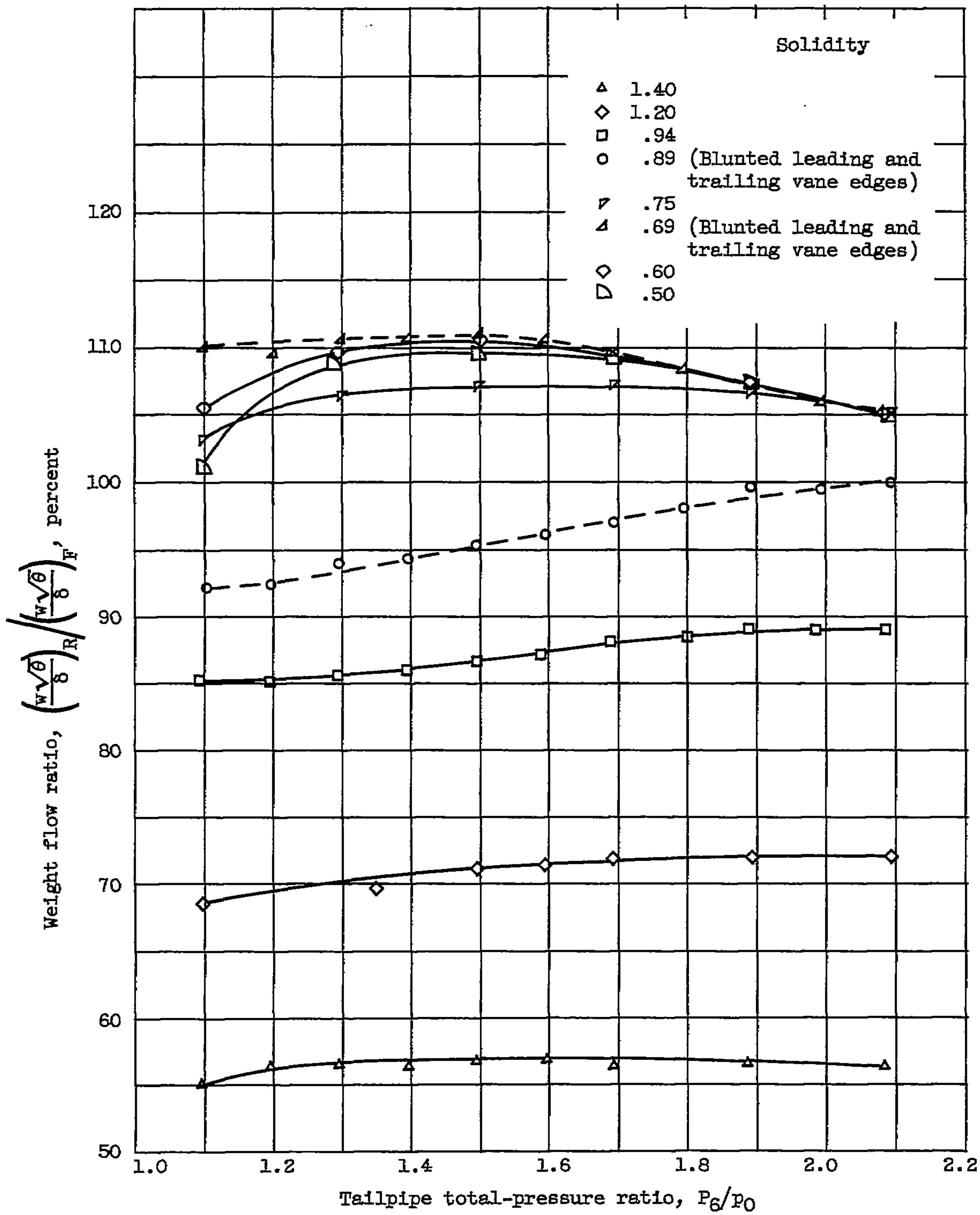

Figure 23. - Variation of weight-flow ratio with tailpipe total-pressure ratio in scale-model, unheated-air tests.

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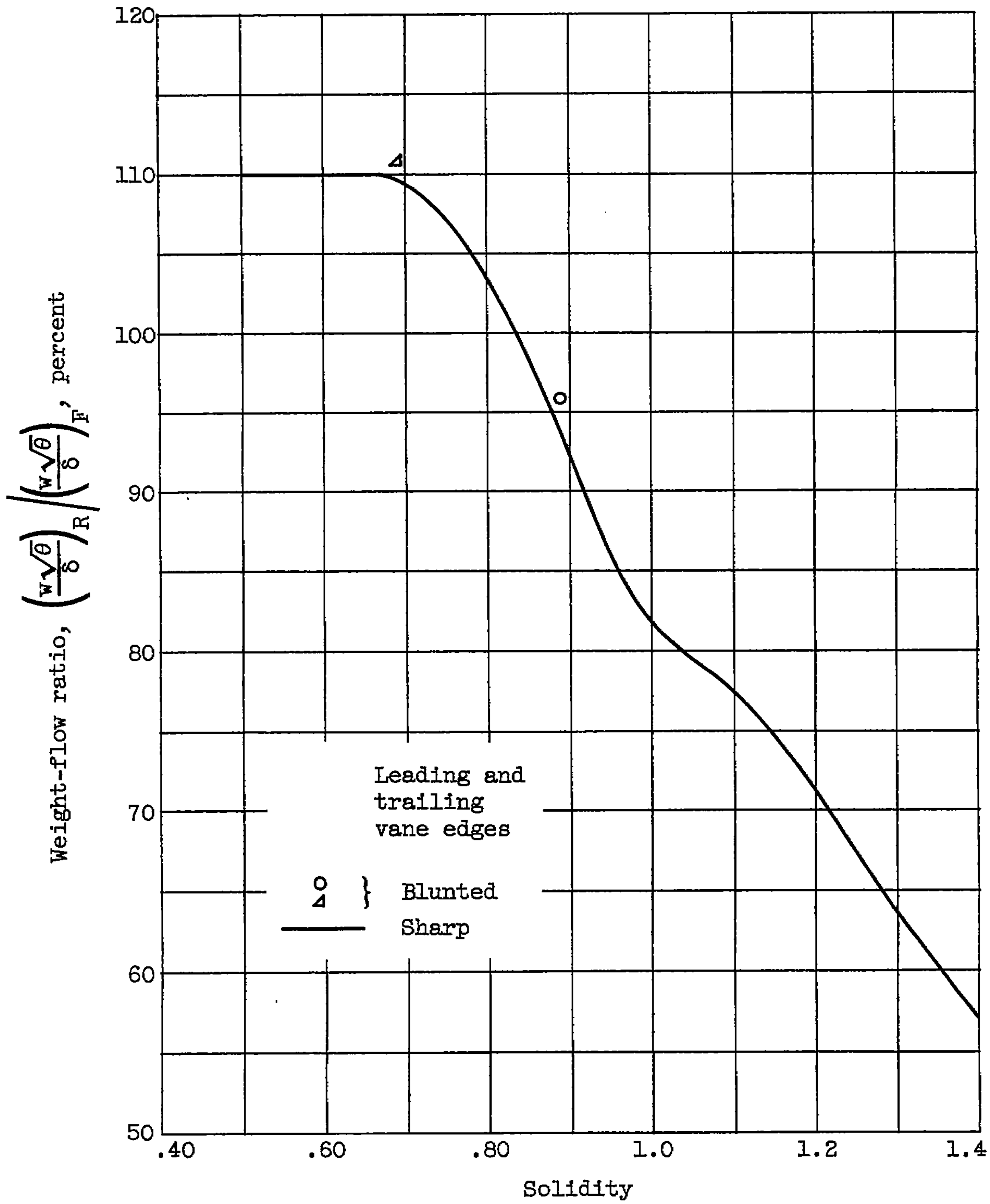

Figure 24. - Variation of weight-flow ratio with solidity at a tailpipe total-pressure ratio of 1.55 in scale-model unheated-air tests.

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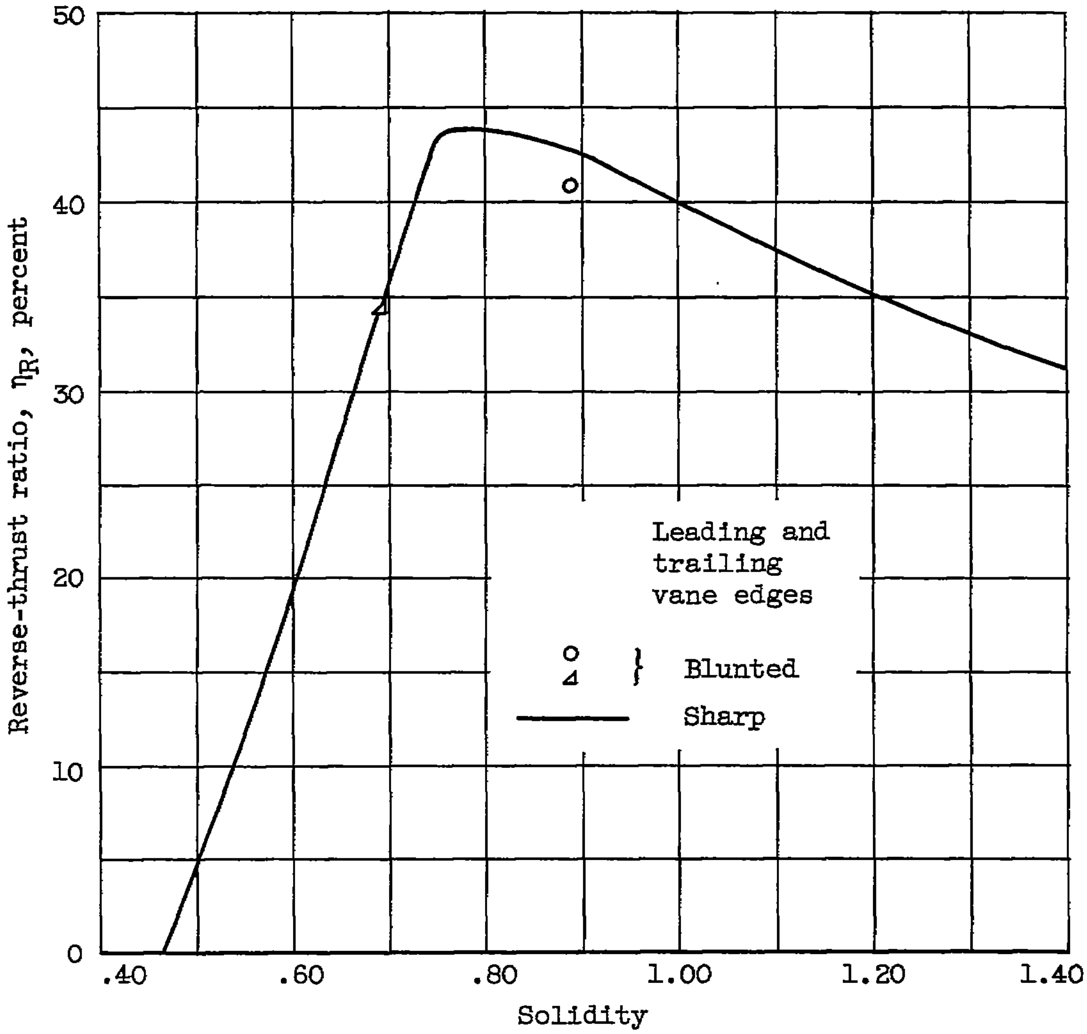

Figure 25. - Summary of scale-model, unheated-air test results showing effect of solidity on reverse-thrust ratio at constant tailpipe total-pressure-ratio of 1.55.

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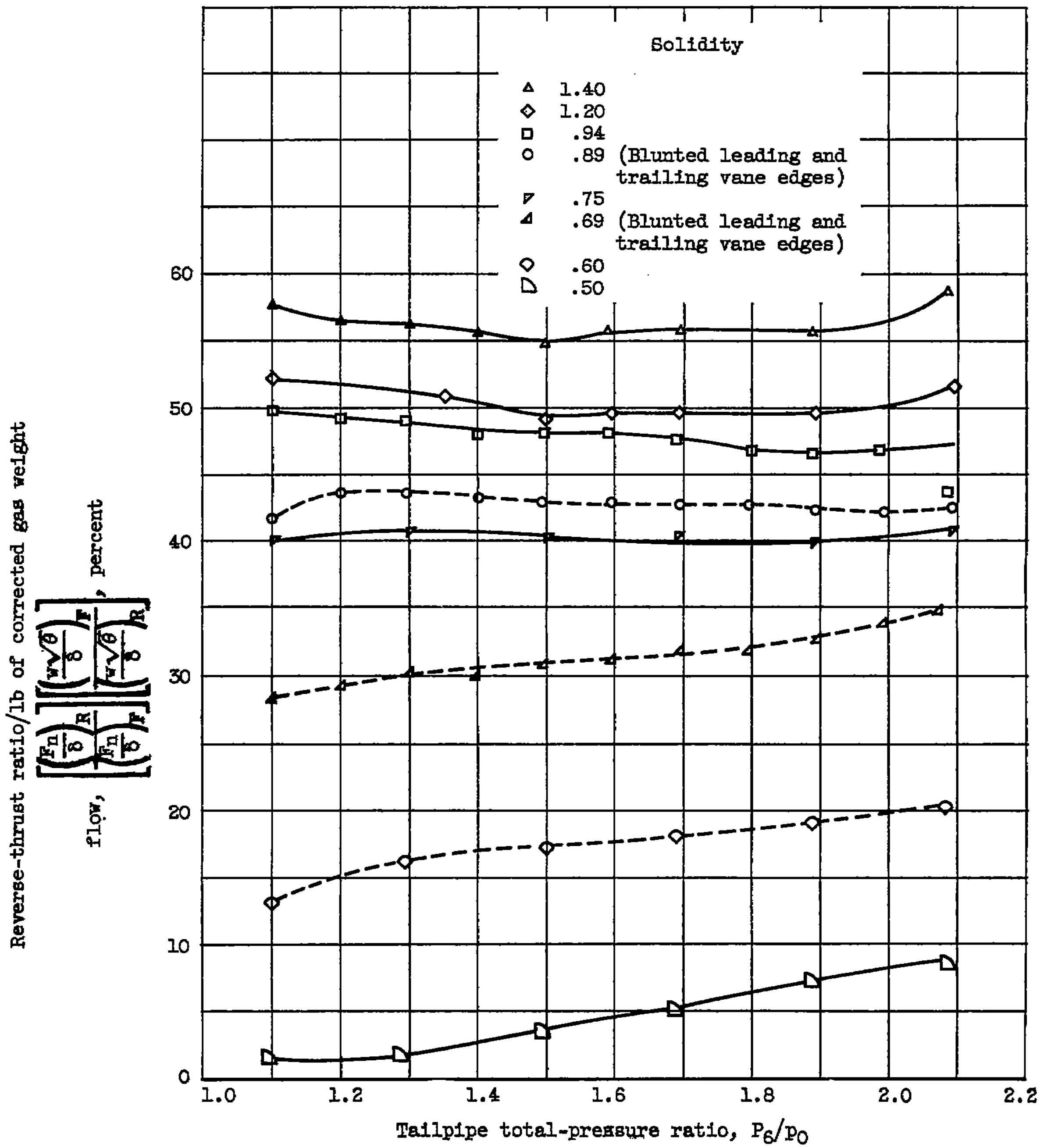

Figure 26. - Variation of reverse-thrust ratio per pound of corrected airflow with tailpipe total-pressure ratio in scale-model unheated-air tests.

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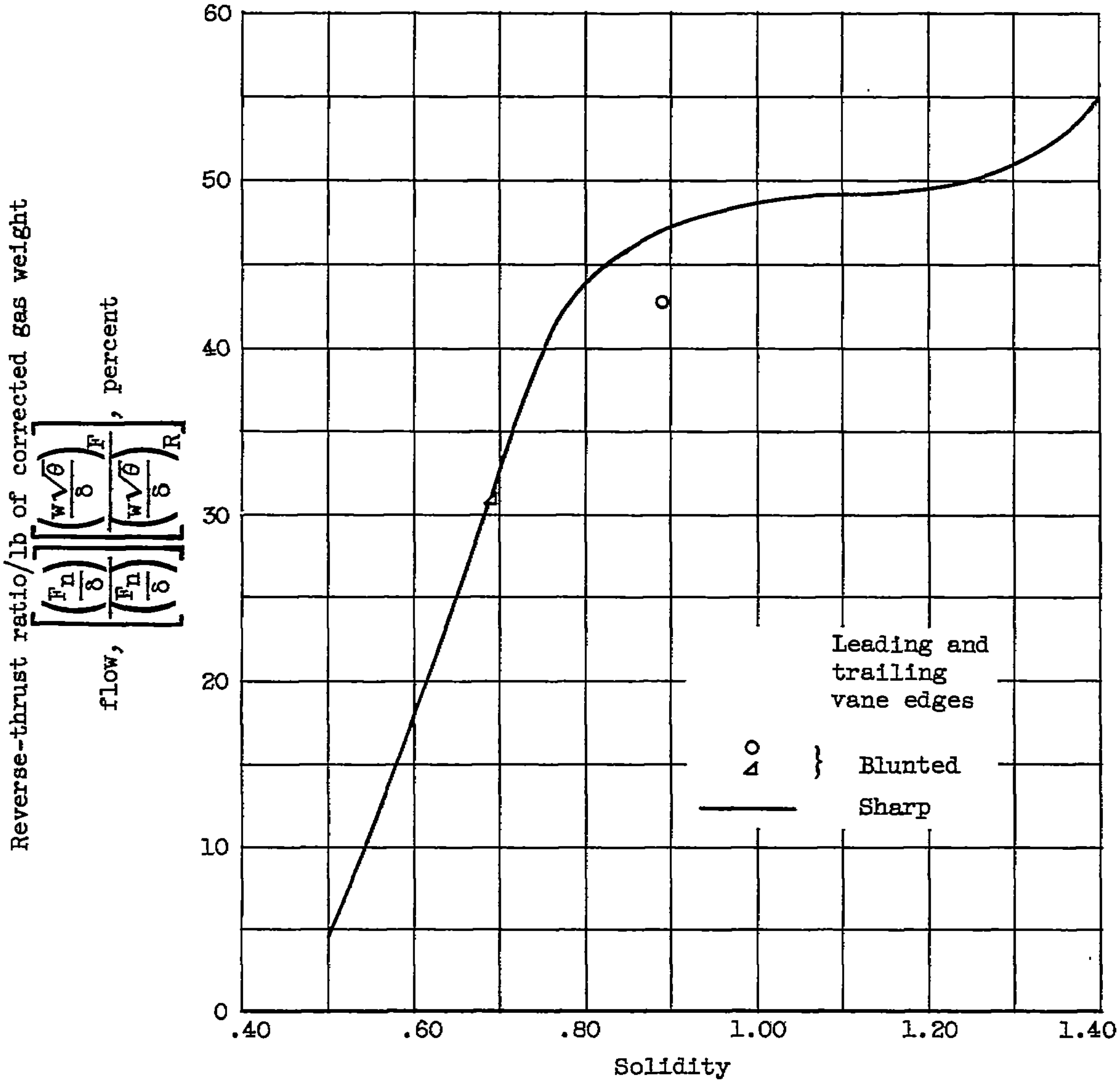

Figure 27. - Summary of scale-model, unheated-air test results showing effect of solidity on reverse-thrust ratio per pound of corrected gas weight flow at constant total-pressure ratio of 1.55.

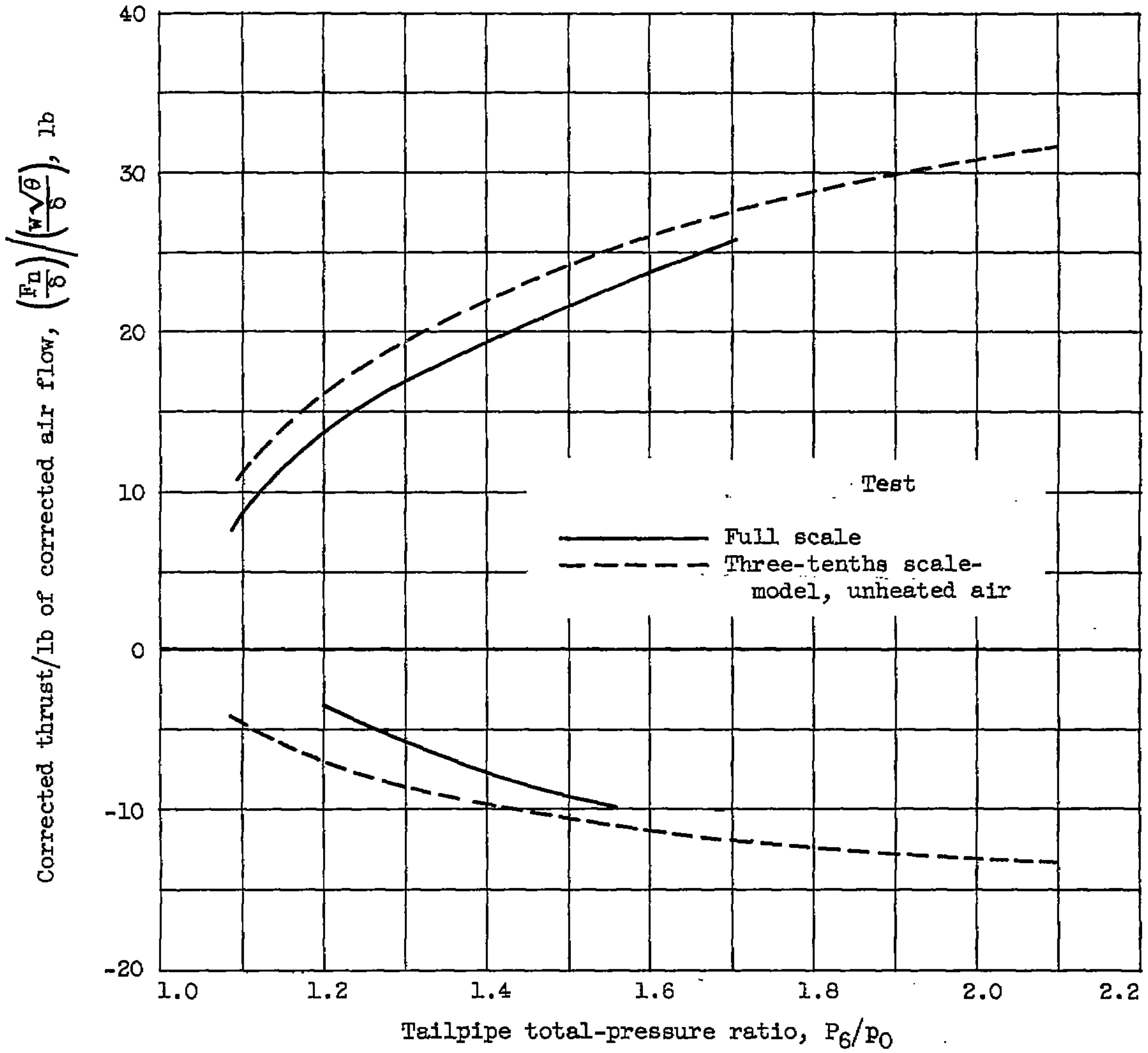

Figure 28. - Comparison of corrected forward and reverse thrust per pound of corrected weight flow in full-scale and scale-model, unheated-air tests.

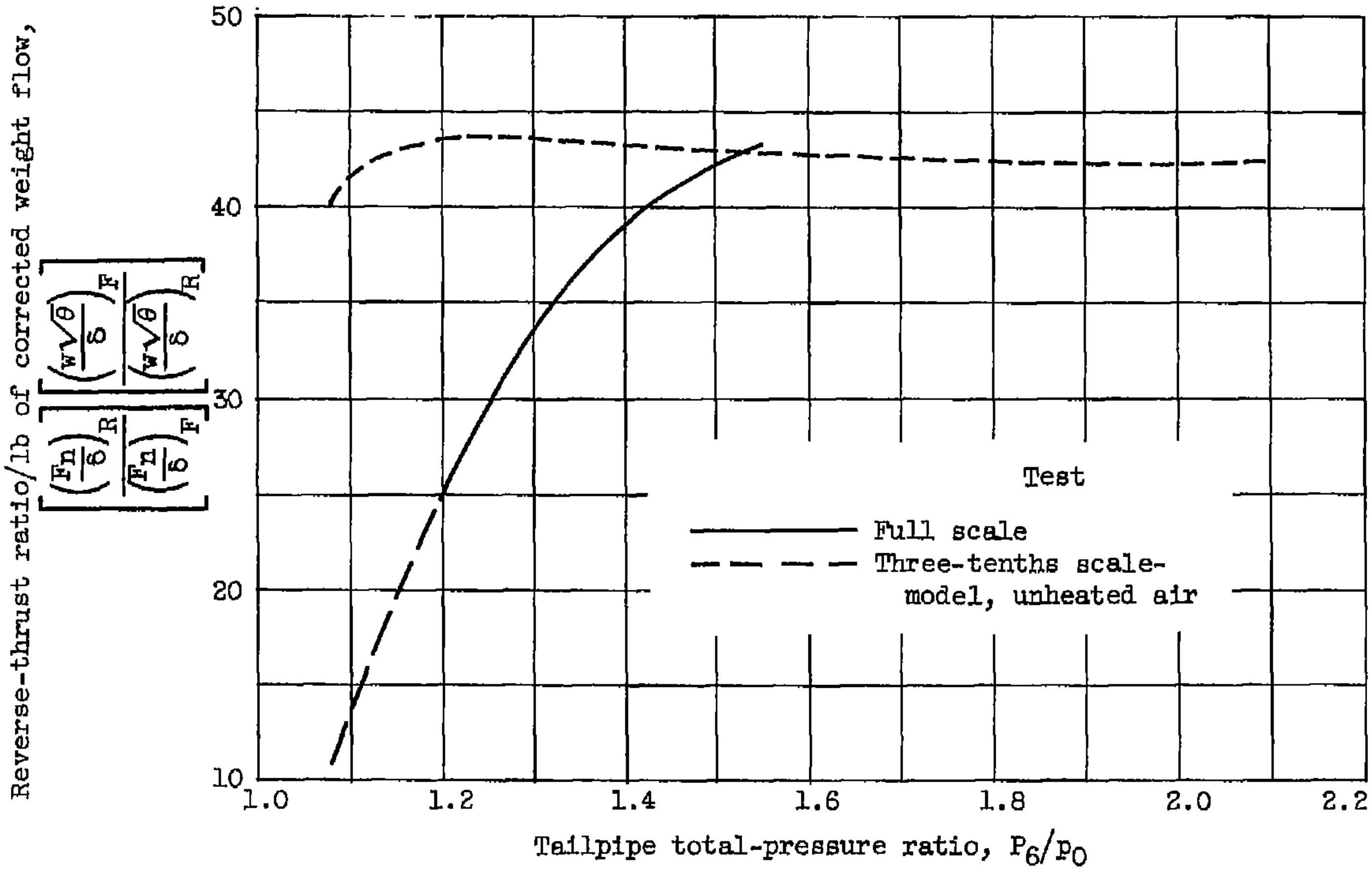

Figure 29. - Comparison of reverse-thrust ratio per pound of corrected weight flow in full-scale and scale-model, unheated-air tests.

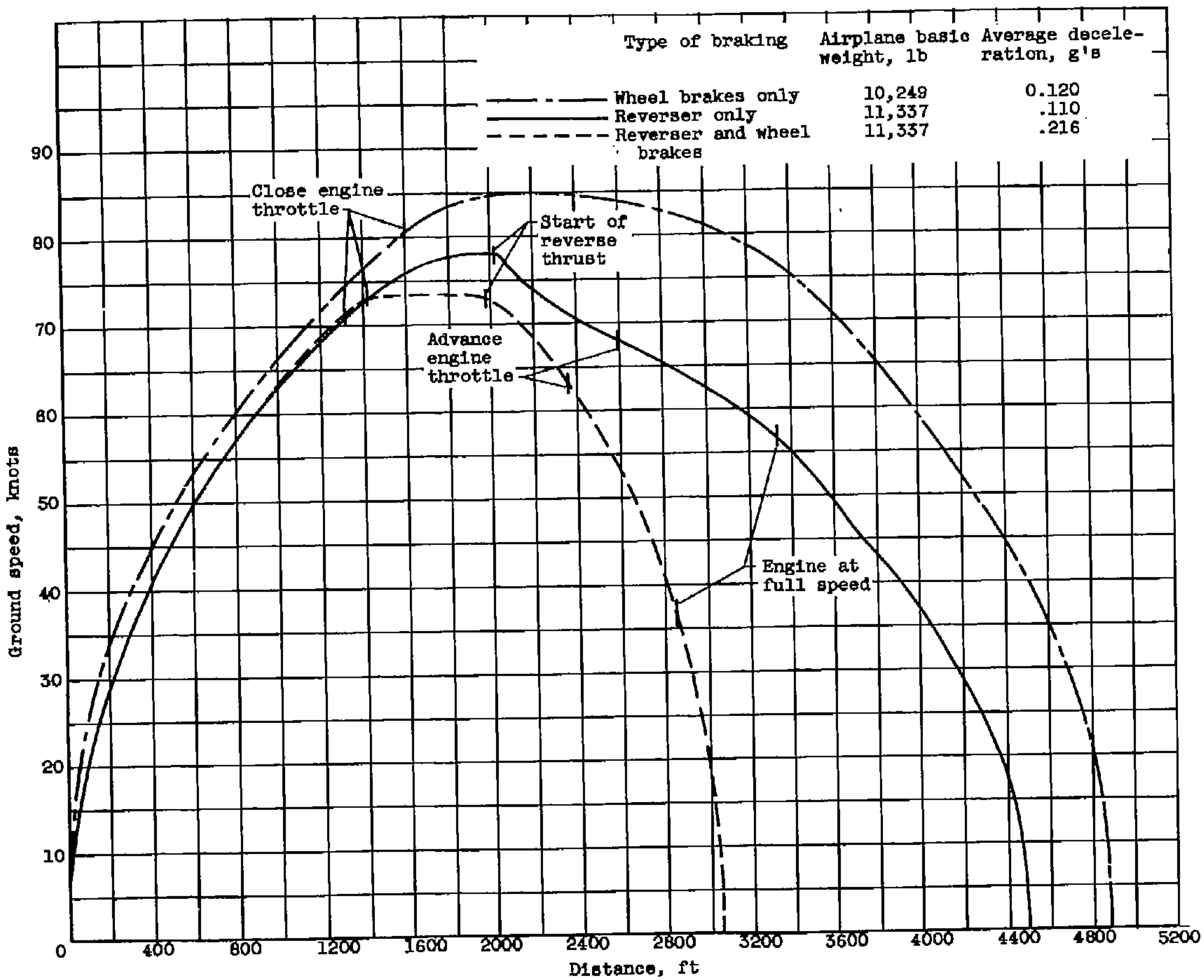

Figure 30. - Comparison of distances required to stop airplane using various braking methods.

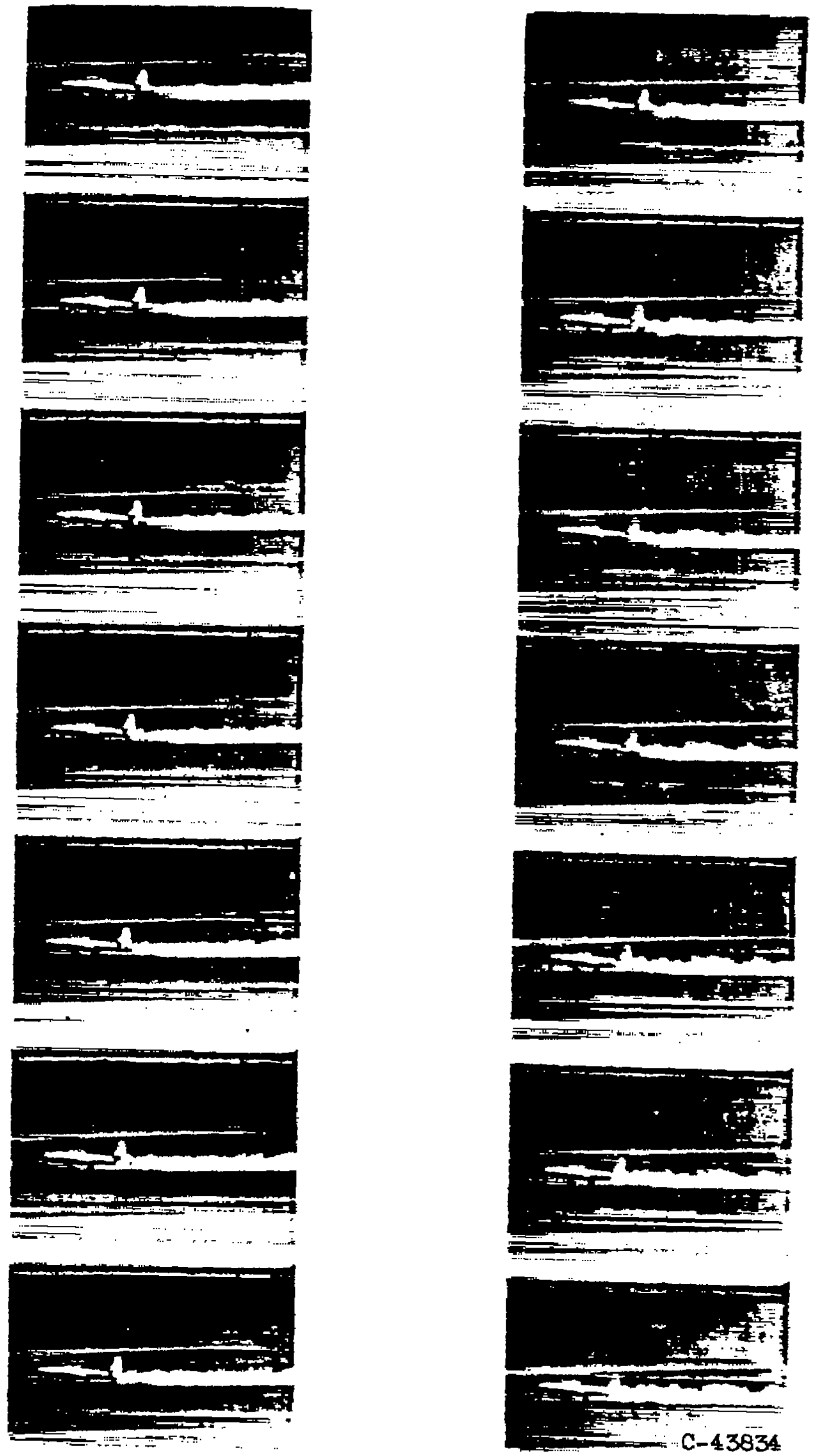

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Figure 31. - Exhaust-gas smoke-flow pattern during transition from forward to reverse thrust at average ground speed of 72 knots. Engine at 70 percent full speed.