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RESEARCH MEMORANDUM

EXPERIMENTAL INVESTIGATION OF SCREECHING COMBUSTION IN FULL-SCALE AFTERBURNER

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS
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EXPERIMENTAL INVESTIGATION OF SCREECHING COMBUSTION IN FULL-SCALE AFTERBURNER

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SUMMARY

In an effort to extend the existing knowledge of screeching combustion in afterburners, a number of systematic configuration modifications were made to an afterburner installed on an engine in the altitude wind tunnel to determine their effect on the screech characteristics. These modifications included changes in the afterburner diffuser, the fuel system, and the flame holder. Screech characteristics of each modification were observed over a range of simulated altitude flight conditions corresponding to afterburner-inlet total pressures from 2200 to 4200 pounds per square foot absolute.

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The observations made during this investigation indicate that some changes in the geometry of the afterburner diffuser and flame holder have a pronounced effect on the range of conditions over which screeching combustion is encountered; in some cases screech was completely eliminated. In contrast, it was generally found that screeching combustion could not be eliminated by changes in the geometry of the fuel injection system.

INTRODUCTION

A review of the experience with afterburner and ram-jet combustion at the NACA Lewis laboratory indicates that screeching combustion was encountered in both types of combustors on a few isolated occasions several years ago. These first encounters with screeching combustion were so rare that the phenomenon was not regarded at that time as a serious combustion problem. One unpublished observation of screeching combustion was made with an afterburner as early as 1947; at about the same time, screeching combustion was observed in a ram-jet engine (ref. 1). In more recent afterburner investigations, screeching combustion has become a more frequent problem. It was generally found that screeching combustion could be eliminated by changes in internal afterburner geometry (refs. 2 and 3).

The present investigation was originally initiated in the NACA Lewis altitude wind tunnel in order to evaluate and improve the performance and stability of a specific afterburner at low burner-inlet pressures while maintaining good performance and operational characteristics at high burner-inlet pressures. During the early portion of the program, configuration changes were made to improve the afterburner performance and stability at low pressures; however, screeching combustion was encountered with several of these configurations at higher burner-inlet pressures. At the same time it was found that the variable-area exhaust nozzle was too small to permit operation over the desired range of fuel-air ratio and exhaust-gas temperature; consequently, a larger exhaust nozzle was installed. With the higher fuel-air ratios thus obtainable, screeching combustion and its attendant destructiveness became problems of such severity that the objective of the investigation was altered to that of seeking to determine those factors that influence screeching combustion. 3055

Because an adequate theory explaining the nature or origin of screeching combustion did not exist and because adequate instrumentation to explore the details of the process was not available, the investigation was carried on by altering internal afterburner components and observing the effects of such alterations on screeching combustion. These alterations included changes in diffuser innerbody design, afterburner-inlet flow distribution, flame-holder design, and fuel injector design. For about half the investigation the presence of screech was observed by the characteristic screeching sound. During the course of the investigation special instrumentation became available for the detection of screeching combustion and the recording of some screech characteristics. The observations reported herein were obtained with the aforementioned afterburner configurations over a range of afterburner fuel-air ratio and flight conditions. The flight conditions simulated correspond to afterburner-inlet total pressures from 2200 to 4200 pounds per square foot absolute.

APPARATUS AND INSTRUMENTATION

Engine

The engine used in the investigation was an axial-flow turbojet engine and afterburner combination equipped with a variable-area iris-type exhaust nozzle. With the afterburner in operation, the manufacturer's military-rated turbine-outlet temperature, as indicated by 12 parallel control thermocouples, is 1670° R.

The over-all length of the afterburner (fig. 1), including diffuser, combustion chamber, and exhaust nozzle, is $101\frac{1}{4}$ inches; the maximum diameter of the afterburner combustion chamber is 36 inches. A cooling-air passage, designed at the NACA for the present investigation, surrounded the rear portion of the afterburner (fig. 1).

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Installation

The engine with afterburner was installed in the altitude wind tunnel on a wing segment that spanned the 20-foot-diameter test section. Dry refrigerated air was supplied to the engine from the make-up air system through a duct connected to the engine inlet.

Afterburner Configurations

During the investigation, 43 afterburner configurations were used. These configurations were produced through alterations to the diffuser, the flame holder, and the fuel injection system. The combination of alterations used to make up each of the configurations is summarized in table I. Details of modifications to the various components are described in the following paragraphs.

Diffuser. - Five diffuser innerbodies were used, the details of which are shown in figure 2. These innerbodies include the original configuration (a), three modifications of the original (b, c, and d) designed to form a pilot or flame-holding surface at the downstream end of the innerbody as a possible means of improving burner stability at low burner pressures, and one modification (e) designed to eliminate (or keep to a minimum) air-flow separation from the innerbody. Antiswirl vanes attached to the skin of the innerbody were installed at the diffuser inlet on 29 of the configurations to reduce turbine-outlet swirl and thereby alter the radial mass, or velocity, distribution. Thirteen configurations had sets of 33 short antiswirl vanes (fig. 3(a)), while 16 configurations had sets of 48 full-passage vanes (fig. 3(b) and (c)). A boundary-layer tripper (fig. 4) was installed on the innerbody of configuration 43 to alter the mass and velocity distributions.

Flame holders. - The 13 flame holders used in the investigation are illustrated in figure 5. All but three of these were conventional V-gutter flame holders having projected areas that blocked from 29 to 46.8 percent of the flow area at the flame-holder position. The gutter widths of these flame holders ranged from $1\frac{1}{4}$ to $5\frac{3}{4}$ inches, and the number of annular gutter elements varied from one to four. The three exceptions to this general arrangement were flame holders (I), (K), and (L). Flame holder (I) (fig. 5(i)) had two U-shaped circular gutter elements; flame holder (K) (fig. 5(k)) comprised U- and V-shaped elements combined to form a star design; and flame holder (L) was a conventional V-gutter incorporating a long water-cooled annular splitter. The significance of these three designs will be discussed in a later section of this report. The flame holders were installed in several longitudinal positions along the afterburner, as indicated in figure 6 and table I.

Fuel-spray bars. - Fuel was injected into the afterburner normal to the direction of gas flow through conventional spray-bar fuel injectors. A total of 13 fuel-spray-bar designs was used, the details of which are shown in figure 7. The number of spray bars installed in the afterburner for each of the several designs investigated varied from 13 to 20. All but two of the 13 types of spray bars were inserted radially into the afterburner. The exceptions, spray bars (b) and (h), were installed so as to slant downstream.

The fuel-spray bars were located at several longitudinal positions in the diffuser and combustion chamber, as indicated in figure 8 and table I. For configurations 28 to 43, fuel-spray bars were located at two longitudinal positions; separate fuel manifolds and regulating systems were used for each set of spray bars. It was thus possible to operate with two separate fuel systems, either independently or combined, without shutting down the engine and facility to make the change.

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Miscellaneous. - Configuration 39 incorporated as a means of disrupting an acoustical oscillation 12 molybdenum-disilicide-coated molybdenum "antisloshing" vanes that were unequally spaced around the burner periphery 4 inches downstream of the flame-holder trailing edge. The spacing between adjacent vanes varied from $7\frac{1}{2}$ to $11\frac{1}{4}$ inches, and the vanes were placed at alternate angles of attack of $\pm 30^{\circ}$ to the direction of flow. The vanes were straight rectangular bars $4\frac{7}{16}$ inches long, 7/8 inch wide and 1/8 inch thick.

Instrumentation

Instrumentation for the measurement of pressures and temperatures was installed in various stations in the engine and afterburner, as indicated in figure 9. Total pressures and temperatures at the turbine outlet were obtained 3 inches downstream of the rear turbine flange from three rakes having seven total-pressure tubes, two wall static-pressure taps (inner and outer wall), and six thermocouples each. The 12 control thermocouples connected in parallel were equally spaced around the burner $1\frac{1}{2}$ inches from the outer wall 5 inches downstream of the rear turbine flange. Pressures at the diffuser outlet were taken from a rake containing 12 total-pressure tubes and an inner and outer wall static-pressure tap located $3\frac{1}{2}$ inches ahead of the rear diffuser flange. When the configuration permitted, flame-holder inlet pressures were measured with a rake containing 12 total-pressure tubes and inner and outer wall static taps located $9\frac{3}{8}$ inches downstream of the rear diffuser flange. At a location $1\frac{13}{16}$ inches downstream of the exhaust-nozzle inlet, pressures were measured by 20 total-pressure tubes, four stream static tubes, and two wall static-pressure taps mounted in a vertical water-cooled rake. The afterburner cooling-air passages were instrumented with total-pressure tubes, stream static tubes, wall static taps, and thermocouples located at strategic points so that cooling-air flow could be calculated.

Afterburner skin temperature was measured by six symmetrically placed thermocouples located in the plane of the nozzle segment hinge point.

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The location of special instrumentation, which included an adjustable swirl-angle probe (ref. 4) and screech-detecting devices, is shown in figure 10. The probe from which swirl angle at the turbine outlet was determined consisted of two total-pressure-indicating tubes facing $\pm 40^{\circ}$ from a true upstream direction. At each of several radial positions the probe was rotated until the two tubes indicated no difference in pressure as measured by a mercury U-tube. The angle of flow or swirl was then taken to be the angle of the probe.

A pressure pickup was employed as the main electrical means of detecting screech. This type of transducer consists of a catenary diaphragm connected to a strain generating tube wound with temperature-compensating strain gages. Specifications are: natural frequency, 45,000 cps; dynamic-pressure range, -15 to 500 pounds per square inch; accuracy, output linear with input 1 percent over full dynamic-pressure range. The transducer was either surrounded by a water jacket and mounted flush with the afterburner skin or was mounted at the end of a water-cooled exponential shaped horn. The exponential shaped horn (fig. 11) was designed to keep the pickup away from the intense heat in the afterburner, thus further protecting the strain gages, without causing any attenuation of the signal or excessive reflections.

A second type of screech pickup (fig. 12), which employed a condenser microphone tied to an adjustable water-cooled probe, is referred to as an acoustic probe. The microphone was located as near the probe sensing end as possible so as to reduce attenuation of the signal; also 50 feet of copper tubing was added after the microphone to simulate an infinite tube and thus repress any signal reflection. The unit was mounted downstream of the flame holder and was able to traverse radially across the burner for a distance of 9 inches from the burner skin.

The outputs of the two transducers were fed, generally, into a panoramic sonic analyzer that presents graphically on its viewing screen a plot of amplitude against frequency for a range of 40 to 20,000 cycles per second and is accurate to ±100 cycles per second. The transducers and analyzers were calibrated so that the approximate root mean square pressure amplitude of screech could be calculated. The viewing screen was photographed with a 3- to 5-second time exposure; and, since the point source of light swept the screen in 1 second, three to five traces appear on the film.

Screech was also recorded on a tape recorder and later viewed and photographed on the panoramic sonic analyzer. In order to check the accuracy of the screech sensors and viewer, an audio oscillator and earphones were employed to determine the fundamental screech frequency. A record of the wave form of screech was obtained by filming with an oscilloscope camera the traces produced on a modified dual-tube oscilloscope.

PROCEDURE

The screech investigation was conducted by making the previously described changes in the afterburner components and noting the effects of such changes on screech. Flight conditions corresponding to a flight Mach number of 0.5 at an altitude of 10,000 feet and flight Mach number of 1.0 at an altitude of 35,000 feet were simulated at the engine inlet and tunnel test section. Air flowing through the inlet duct was throttled and refrigerated from approximately sea-level conditions to give the desired total pressure and temperature at the engine inlet while the tunnel test-section static pressure was maintained at the desired altitude pressure. NACA standard values for the simulated flight conditions were used.

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The resulting afterburner-inlet conditions obtained at the two simulated flight conditions are shown in figures 13 and 14. Total pressures at the afterburner inlet (fig. 13) ranged from about 2200 to 2340 pounds per square foot absolute at the 35,000-foot altitude to 3850 to 4220 pounds per square foot absolute at the 10,000-foot altitude. Variations in pressure at a given altitude resulted from differences in diffuser performance when antiswirl vanes were installed. Since a total of eight engines was used during the investigation, variations in pressure and temperature could have resulted from slight differences in performance from engine to engine.

The turbine-outlet temperature was held at the manufacturer's military-rated value of 1670° R (1210° F) as indicated by 12 parallel control thermocouples. Afterburner fuel flow was varied between lean blow-out and the maximum value with wide-open nozzle operation. Manual control of the iris-type exhaust nozzle did produce some variation in the indicated values of control temperature, as shown in figure 14(a). Greater variation was encountered in the average turbine-outlet total temperatures measured by NACA instrumentation, as seen in figure 14(b). This deviation from the indicated control temperature is attributed to deterioration of the control thermocouples and variations in the temperature profiles among the engines used. The average afterburner-inlet total temperatures thus ranged from about 1640° to 1725° R.

The engine and afterburner fuel used throughout the investigation conformed to specification MIL-F-5624A, grade JP-4, having a lower heating value of 18,700 Btu per pound and a hydrogen-carbon ratio of 0.171.

Atmospheric air, throttled to give a weight flow of approximately 3 percent of the engine air flow, cooled the afterburner shell and exhaust nozzle. A water spray augmented the cooling of the exhaust-nozzle segments.

For a number of configurations, a quartz window installed in the afterburner shell between the diffuser-outlet flange and the flame holder was used for visual observation of combustion. The window was initially heated before afterburner operation to avoid thermal shock, and after ignition of the burner it was cooled by compressed air.

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Ignition of the afterburner was accomplished by means of a hot-streak system. The original system injected fuel downstream of the turbine; however, to provide more positive ignition, fuel was also injected upstream of the turbine during the present investigation.

RESULTS AND DISCUSSION

Some Characteristics of Screeching Combustion

Screeching combustion is a high-frequency pressure pulsation. As experienced in the present investigation, the predominant screech frequency was about 1000 cycles per second, and the total amplitude of the pressure oscillations observed varied up to a maximum of about 1700 pounds per square foot (root mean square) at the burner pressure level of 4200 pounds per square foot. Typical examples of frequency measurements, obtained by use of a panoramic sonic analyzer, are shown in figure 15 for operation with and without afterburner screech. The predominant amplitude can be observed on these traces at a frequency slightly above 1000 cycles per second, with progressively less predominant amplitudes at frequencies that are multiples of the basic frequency. The high-amplitude traces at frequencies up to about 300 cycles per second were present without screech as well as with screech. These low-frequency oscillations are therefore attributed to basic engine noise.

The wave shape of screeching combustion is illustrated by the trace presented in figure 16. The wave shape resembles somewhat that of a cyclic detonation or explosion, in that the rarefaction period is longer than the compression period. Wave shapes recorded are subject to some distortion caused by the instrumentation.

The range of afterburner fuel-air ratio over which screeching combustion was encountered generally increased as burner-inlet total pressure was raised. This trend is illustrated in figure 17, which also indicates the hysteresis that existed in the screech limits for most configurations. At a given burner-inlet pressure, the range of fuel-air ratio over which screech existed was narrower when approaching the screech zone than when leaving the zone after screech was encountered. (The fuel-air ratio presented in figure 17 and subsequent figures is the ratio of afterburner fuel flow to unburned air entering the afterburner.) Over the limited range of burner-inlet temperatures investigated, there was no consistent effect of inlet temperature on the screech limits. These observations confirm those of reference 3, which shows no effect of inlet temperature on screech limits.

Observations of exhaust-gas flame color and turbine-outlet temperature made during operation with screeching combustion indicate the possibilities of good mixing of the fuel and air due to the pressure oscillations and also a rise in combustion efficiency. With a fixed exhaust-nozzle area, the occurrence of screech produced a sudden increase in the indicated turbine-outlet control temperature. At the same time, the exhaust-gas flames changed in color from a reddish-blue hue to one of white as a result of the oscillations. This improved mixing in conjunction with a possible rise in heat-transfer coefficient resulted in increased afterburner shell temperatures during operation with screeching combustion, as indicated in figure 18. This figure, which shows the variation of afterburner shell temperature with afterburner fuel-air ratio, clearly illustrates the rise in shell temperature in the region of screech operation. Destructiveness to the afterburner induced by operation with screeching combustion becomes more serious and more rapid as burner-inlet pressure is raised. Damage incurred was due to the cyclic pressure oscillations in combination with the elevated metal temperatures, and the increased destructiveness at high pressures results from the proportionately increased pressure pulsations as burner-inlet pressure is raised. Typical failures produced by screeching combustion include damaged instrumentation, cracks in welds, and ruptures of the afterburner shell, an example of which is illustrated in figure 19.

Effect of Diffuser Flow Conditions

Diffuser innerbody. - Some earlier work reported in reference 3 associated screech with combustion in low-velocity regions, such as separation regions or wakes in the fuel-mixing zone. In those experiments, combustion was observed to exist on the surface of the diffuser innerbody, and evidence from other investigations indicates that it might occur on the lee-side of support struts or along the outer wall of the diffuser.

In order to determine the flow characteristics entering the burner, measurements of pressure and swirl angle were obtained at the diffuser inlet and outlet. These measurements indicated considerable swirl entering the diffuser and the burner and a large velocity gradient at the diffuser outlet. Some typical examples of the swirl angles and velocity profiles measured near the diffuser outlet are presented in figure 20(a). (Velocities were calculated from the rake total pressures with the assumption of uniform static pressure across the passage.) The velocity was very low near the innerbody and became very high in the outer half of the diffuser annulus. It should be noted that some of the configurations discussed in the subsequent paragraphs for these diffuser-outlet conditions incorporated short antiswirl vanes at the diffuser inlet, as illustrated in figure 3(a). Because these vanes had no appreciable effect on the diffuser-exit conditions, as shown in figure 20(b), data thus obtained are grouped with the other data observed with the same diffuser-outlet conditions.

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In order to determine the validity of the impression that screeching combustion was associated primarily with combustion in the low-velocity region along the diffuser innerbody, several configurations were investigated. In some of these configurations the fuel injectors were moved radially outward to remove any fuel from the low-velocity region along the innerbody and thus preclude combustion in this region. One example is configuration 24, which had spray bars (a) (fig. 7) installed in pad position (10) (fig. 8). With this arrangement, the innermost fuel injection point was about $5\frac{1}{8}$ inches from the innerbody (42 percent of the passage height), and the fuel-mixing length was $15\frac{1}{4}$ inches. This configuration encountered screeching combustion at a burner-inlet pressure of about 4000 pounds per square foot, but not at a pressure of about 2240 pounds per square foot. Visual observation through a quartz window located upstream of the flame holder verified that there was no burning along the diffuser innerbody at any time.

These observations are typical of those made with several other configurations investigated. It was therefore concluded that screeching combustion need not necessarily be associated with burning along the diffuser innerbody.

Swirl and velocity profile. - Because screeching combustion had not been eliminated by eliminating burning in the low-velocity region along the diffuser innerbody, it was considered possible that the swirl and attendant severe velocity gradient at the diffuser outlet could be factors influencing screech. As previously mentioned, the short antiswirl vanes had no effect on turbine-outlet swirl; therefore, a set of antiswirl vanes was installed across the full passage at the turbine outlet to reduce the swirl. These vanes reduced the swirl considerably, as shown in figure 20(c). In addition to reducing the swirl, these vanes produced a velocity profile without steep gradients at the diffuser outlet (fig. 20(c)).

The reduction in swirl angle and the improvement in velocity profile at the diffuser outlet with the full-passage antiswirl vanes eliminated screeching combustion for some configurations with which screech had previously been encountered. This effect can be illustrated by comparing configurations 14, 25, and 32, which were similar with the exception of the vane installations. Configuration 14 with no vanes and configuration 25 with the short vanes had the high swirl and severe velocity gradient, while configuration 32 with the long vanes had the reduced swirl and improved velocity profile. Although screeching combustion was encountered with configurations 14 and 25 at a burner-inlet total pressure of 4000 pounds per square foot, no screech was experienced at this condition with configuration 32, as illustrated in figure 22(a). A similar effect is shown by comparing configuration 26 having short vanes with configuration 28 having long vanes. Screeching combustion was encountered with configuration 26 at burner-inlet total pressures of 2250 and 4070 pounds per square foot. Configuration 28 was free of screech at pressures as high as 3850 pounds per square foot (fig. 22(a)).

In order to determine whether the change in swirl or in velocity profile was the important factor responsible for eliminating the screeching combustion, a boundary-layer tripper (fig. 4) was placed on the diffuser innerbody with the full-passage antiswirl vanes installed (configuration 43). The purpose of this tripper was to induce flow separation with the full-passage antiswirl vanes installed and thereby provide a severe velocity gradient, similar to that with no antiswirl vanes, while the swirl was maintained at a relatively low angle. In the inner 60 percent of the annulus, the diffuser-outlet velocity profile closely approximated that of the configuration without vanes, as shown in figure 21.

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The effect of velocity profile on screech is illustrated in figure 22(b), which compares configurations 14, 32, and 43, which were similar except for diffuser flow conditions. Configuration 14 had both swirl and a severe velocity gradient; configuration 32 had both reduced swirl and more uniform velocity profile; and configuration 43 had the reduced swirl with the severe velocity gradient. Both configurations 14 and 43 operated with screeching combustion at burner-inlet total pressures near 4000 pounds per square foot, but configuration 32, as previously mentioned, operated in this pressure range without screech.

On the basis of these data it is believed that the alteration in diffuser-outlet velocity profile was the primary factor responsible for eliminating screeching combustion in the configurations discussed. It should be noted that, although effective in several cases, improvement in the diffuser-outlet velocity profile is not a universal remedy for eliminating screeching combustion, inasmuch as several subsequent configurations employing the full-passage antiswirl vanes did encounter screech. In addition, it is possible that the distribution of fuel-air ratio may have been affected to some degree by installation of the vanes or the tripper, since the range of fuel-air ratio over which screeching combustion was encountered differed between configurations 14 and 43. However, this effect is considered to be only of secondary importance, as the succeeding discussion will indicate.

Effect of Fuel System and Flame Holder

Additional observations were made during the investigation to determine the effect on screeching combustion of the several fuel-system and flame-holder configurations used. These observations are summarized in the following paragraphs.

Fuel system. - The large number of fuel-spray bars used during the investigation were selected and installed so that radial fuel distribution and fuel-mixing length were varied considerably. It was found that, in general, screeching combustion could not be eliminated by changes in fuel distribution. This insensitivity of screeching combustion to fuel distribution was particularly true with a reasonably uniform diffuser-outlet velocity profile.

Exceptions to the absence of a fuel-distribution effect were encountered only with a severe diffuser-outlet velocity gradient. An example of this exception can be observed by comparing configurations 7 and 8 with configurations 9 and 10. These four configurations had severe gradients in diffuser-outlet velocity profile and were otherwise similar except for the fuel systems. Configurations 7 and 8 provided fuel injection across the entire diffuser passage, whereas configurations 9 and 10 provided no fuel in the inner portion of the annulus. Shifting the fuel concentration radially outward away from the innerbody with configurations 9 and 10 eliminated the screech previously encountered with configurations 7 and 8 at a burner-inlet total pressure of about 4200 pounds per square foot. This exception indicates that, when the diffuser-outlet velocity gradient is severe, alterations in radial fuel distribution may be effective in eliminating screeching combustion.

It was observed that variations in fuel-mixing length did not have any consistent effect on screeching combustion, although there was in some cases a trend of decreased tendency to screech as fuel-mixing length was reduced. This tendency is illustrated by a comparison of configurations 30 and 31, which both had reasonably good diffuser-outlet velocity profiles and were identical except for fuel-system changes. Configuration 30 was operated with fuel-mixing lengths of 3 and $15\frac{1}{4}$ inches, and configuration 31 was operated with fuel-mixing lengths of $15\frac{1}{4}$ and $27\frac{7}{8}$ inches. Screeching combustion was not encountered with a fuel-mixing length of 3 inches with configuration 30 or $15\frac{1}{4}$ inches with either of the two configurations. Increasing the fuel-mixing length to $27\frac{7}{8}$ inches with configuration 31 did result in screeching combustion. This observation indicates that, in some cases, reducing the fuel-mixing length will eliminate screeching combustion. When attempting to eliminate screech by reducing fuel-mixing length, caution must be exercised so that the fuel-mixing length is not shortened to the extent that burner performance is impaired. For example, reducing fuel-mixing length to as little as 3 inches would certainly reduce burner performance, particularly at high altitudes, although a mixing length of about 15 inches is generally considered adequate for good altitude performance.

Flame holder. - It was noted early in the investigation that in some cases changes in flame-holder geometry altered the limits of screeching combustion. As an example, configurations 10 and 12 were similar except for the flame-holder geometry. Both configurations included conventional circular-ring 2-V-gutter flame holders, but the flame holder of configuration 10 (flame holder (A)) had smaller gutter widths, larger ring diameters, and less stagger between the two rings than that of configuration 12 (flame holder (C)). The flame holder of configuration 12 also incorporated some small tabs or flow trippers at the trailing edge of the gutters. At a burner-inlet total pressure of 3055
about 4200 pounds per square foot absolute, screech was encountered with configuration 12 but not with configuration 10.

Another observation was that the afterburner shell and exhaust-nozzle segments overheated in many cases during operation with screeching combustion. It appeared that during such operation the flame became very turbulent and spread rapidly in much the same manner as that reported in reference 5. Based on this observation, it was believed that the distance between the outer gutter of the flame holder and the burner wall might be a factor influencing screeching combustion.

Screech occurred, for example, at a pressure level of 4220 pounds per square foot absolute in configuration 12, where the distance between flame holder (C) and the burner wall was $1\frac{1}{2}$ inches. Configuration 11, in which the distance was $2\frac{1}{2}$ inches, did not screech at this level. However, in configurations 21, 22, and 23, where the flame holders were $5\frac{3}{4}$ to 4 inches from the burner wall, only the one with the greatest distance did not screech. Because variables such as blockage were not controlled in these configurations, the degree to which the distance factor influences screeching combustion is inconclusive.

Further comparison of configurations 21, 22, and 23 led to the belief that flame-holder gutter width could have been the influencing factor instead of distance from the outer gutter to the burner wall. Figure 22(c) presents an evaluation of these three flame holders. One of these was a flame holder having a single V-gutter with a gutter width of $5\frac{3}{4}$ inches and an outer diameter of 28 inches (flame holder (G), configuration 22). Screeching combustion was encountered with this configuration over the entire operable range of fuel-air ratio at a burner-inlet total pressure of 2240 pounds per square foot absolute (fig. 22(c)); in fact, the observation of an audible sound with the afterburner inoperative suggested that this flame holder was inducing a flow instability even in the absence of combustion. The flame holder with gutter widths of $2\frac{1}{8}$ and $2\frac{1}{16}$ inches (flame holder (F), configuration 21) did not screech at burner-inlet total pressures as high as 4070 pounds per square foot absolute; while the flame holder with an outer-gutter width of $3\frac{1}{16}$ inches (flame holder (H), configuration 23) screeched at a burner-inlet total pressure of 2240 pounds per square foot absolute (fig. 22(c)). The observations made with these three flame holders strongly suggested that flame-holder gutter width was an important factor.

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A statistical summary was made of nearly all the flame-holder configurations used in this investigation. Comparison of these flame holders, which had various gutter widths as well as different fuel systems, verified the premise that flame-holder gutter width was an important factor affecting screeching combustion (fig. 23). The vertical scale on figure 23 indicates the number of different configurations in which a flame holder of a given gutter width was incorporated; and the flame holders are grouped according to gutter width, in some cases a single bar representing observations made with two flame holders having the same gutter width. From this summary, which includes gutter widths from $1\frac{1}{4}$ to $5\frac{3}{4}$ inches, it is very apparent that increasing gutter width increased the tendency for screeching combustion to occur. (Variations in blockages among the flame holders were not considered in this summary.) Although no screech was encountered in this investigation with flame holders having a gutter width of $1\frac{1}{2}$ inches or less, this particular value does not have general significance. Unpublished observations obtained with another afterburner operating at a burner-inlet pressure of about 3500 pounds per square foot absolute revealed that screeching combustion was encountered with a flame holder having a gutter width of only 3/4 inch, although the screech was less severe than that with wider-gutter flame holders.

Another factor considered of possible importance in influencing screeching combustion was the vortex systems formed by the flame-holder gutters. In an effort to alter the vortex systems, flame holders such as (D) and (H) were investigated. These flame holders had conventional 2-V-gutters, except that the inner and outer trailing edges of each gutter were in different planes. Screeching combustion was observed for both flame holders.

In a further attempt to alter the flame-holder vortex system, a large water-cooled cylindrical splitter was installed in the single-ring V-gutter flame holder having a $5\frac{3}{4}$-inch gutter width (configuration 37). The water cooling the splitter was discharged into the gas stream at the trailing edge of the splitter. This splitter extended downstream from the apex of the gutter in such a manner as to prevent interaction of the vortices formed from the inner and outer edges of the gutter (fig. 5(l)).

It is considered significant that screech was not encountered with this flame-holder configuration at burner-inlet total pressures as high as 3850 pounds per square foot absolute, although the same flame holder without the splitter plate screeched at this burner-inlet pressure as well as at pressures as low as 2240 pounds per square foot (fig. 22(d)). Similar observations were made with the same two flame holders installed in another afterburner.

The manner in which the splitter serves to eliminate screeching combustion is not definitely established. One possibility is that the splitter eliminated interaction of the vortices and thereby prevented shedding from the flame holder in a manner similar to the observations of reference 6. On the basis of recent experiments, as yet unpublished, that indicate screeching combustion is associated with acoustical phenomena, it is possible that the splitter served as a damper, disrupting acoustical oscillations set up in the burner by the flame holder. 3055

Because an annular flame holder is everywhere symmetrical with itself and the afterburner shell, it was considered pertinent to determine whether destroying this symmetry would have any effect on the screech characteristics. In order to do so, a flame holder with the gutters arranged in a star shape (flame holder (K)) was incorporated in configuration 36. As indicated by figure 22(e), this flame holder screeched badly, and the screech frequency was the same as that obtained with the more conventional flame holders.

Miscellaneous observations. - One observation that has been made is that screeching combustion is not necessarily related to good combustion performance and attendant high combustion efficiencies. For example, the flame-seat distribution of flame holders (G) and (H) is not ideal, and afterburner performance was thus poor. However, screeching combustion was encountered with configurations including these flame holders.

During operation with configuration 39, an acoustic probe, located a few inches downstream of the flame holder, was traversed radially inward from the afterburner shell during a mild screech condition. From observation of the panoramic sonic analyzer, there was no change in the frequency of screech across the burner. There was a slight variation in the amplitude of pressure pulsations, as shown in figure 24; but no particular significance has been attached to these measurements, since it has not been possible to correlate them with any acoustical oscillation that might exist in the burner. It should be noted that this configuration included a set of small antisloshing vanes inserted in an attempt to disrupt an acoustical oscillation of this type. It is now believed that these vanes were too small to have any measurable effect on screeching combustion.

Another interesting observation was made while operating configuration 36, which had both an upstream and a downstream set of fuel injectors. The fuel flow to the downstream fuel injectors was held constant; and, while the flow from the upstream set was being increased, screech was encountered at a fuel-air ratio of 0.024. As upstream fuel flow was further increased, the screech disappeared and then reappeared at a fuel-air ratio of about 0.052. As indicated in figure 25, the screech frequency was about 950 cycles per second at the lower fuel-air ratio and had increased to about 1050 cycles per second at the higher value. This trend of increased frequency with fuel-air ratio is in agreement with the observations reported in reference 5. Furthermore, if screech is an acoustical phenomenon, screech frequency would be expected to increase with fuel-air ratio and the attendant increase in gas temperature, since frequency is proportional to the speed of sound in the combustion region.

In order to determine what wave length would correspond to the nominal basic frequency observed with this afterburner, provided the screech was associated with an acoustical coupling, the combustion-gas temperature was estimated on the basis of fuel-air ratio, and the wave length was calculated. The value of wave length computed for a frequency of 1000 cycles per second corresponded very closely with the burner diameter at the flame holder. Similar computations were made for other screeching afterburners with the same results.

CONCLUDING REMARKS

Because no adequate theory existed to explain the origin or nature of screeching combustion in afterburners, and because appropriate instrumentation was not available to measure accurately the combustion and aerodynamic phenomena occurring during screech, a cut-and-try experimental program was conducted to determine whether or not simple changes in the component parts of an afterburner could be made to eliminate screech. Although the origin of the oscillations was not determined, the observations made during this investigation indicate that some changes in the geometry of the afterburner diffuser and flame holder have a pronounced effect on the range of conditions over which screeching combustion is encountered and in some cases may eliminate screech completely. In contrast, it was generally found that screeching combustion with a given afterburner geometry could not be eliminated by changes in the fuel system.

With regard to the diffuser modifications that were effective, it was found that screech was encountered even in cases where no burning existed along the diffuser innerbody, although other investigations have shown that eliminating burning in this region eliminated screech. It was also found that screeching combustion could be eliminated in some cases by modifying the diffuser so as to provide a more uniform velocity profile at the burner inlet.

The most pronounced effect of flame-holder geometry on screeching combustion was found to be that of varying gutter width. Reducing gutter width reduced the tendency of the burner to screech, the flame holders with the smallest gutters being screech-free. Screeching combustion was also eliminated by installing a long water-cooled cylindrical splitter on a large single-V-gutter flame holder. The function of this splitter was believed to be either that of preventing interaction between the vortices from opposite edges of the gutter and the resultant shedding of vortices, or damping of the acoustical oscillations believed by some experimenters to be the cause of screech.

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Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, September 3, 1953

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3. Conrad, E. William, Schulze, Frederick W., and Usow, Karl H.: Effect of Diffuser Design, Diffuser-Exit Velocity Profile, and Fuel Distribution on Altitude Performance of Several Afterburner Configurations. NACA RM E53A30, 1953.

4. Gettelman, Clarence C., and Krause, Lloyd N.: Considerations Entering into the Selection of Probes for Pressure Measurement in Jet Engines. Proc. Inst. Soc. Am., Paper No. 52-12-1, vol. 7, 1952, pp. 134-137.

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TABLE I. - SUMMARY OF CONFIGURATION DETAILS

After-burner configuration	Diffuser			Flame holder			Fuel system				Exhaust nozzle
	Designation	Innerbody	Vanes	Designation	Pad position	Blockage, percent	Designation	Number of bars	Pad position	Mixing length pad to pad, in.	
1	A	a	None	(A)	(1)	32	(a)	20	(9)	$7\frac{9}{16}$	Small
2	A	a	None	(A)	(1)	32	(a)	20	(7)	$13\frac{9}{16}$	Small
3	A	a	None	(A)	(2)	32	(b)	20	(7)	Varied	Small
4	A	a	None	(A)	(2)	32	(c)	20	(9)	$10\frac{3}{16}$	Small
5	B	b	None	(B)	(2)	33	(a)	20	(7)	$16\frac{3}{16}$	Small
6	B	b	None	(B)	(2)	33	(d)	20	(9)	$10\frac{3}{16}$	Small
7	C	c	None	(A)	(1)	32	(e)	20	(9)	$7\frac{9}{16}$	Small
8	C	c	None	(A)	(1)	32	(f)	20	(7)	$13\frac{9}{16}$	Small
9	C	c	None	(A)	(1)	32	(g)	20	(9)	$7\frac{9}{16}$	Small
10	C	c	None	(A)	(1)	32	(h)	20	(7)	Varied	Small
11	C	c	None	(A)	(3)	29	(h)	20	(7)	Varied	Small
12	C	c	None	(C)	(1)	46.8	(h)	20	(7)	Varied	Small
13	D	d	None	(D)	(5)	36.6	(i)	16	(9)	$22\frac{13}{16}$	Large
14	E	e	None	(E)	(6)	35	(a)	20	(8)	$27\frac{7}{8}$	Large
15	F	d	Short	(E)	(5)	35	(b)	13	(7)	Varied	Large
16	F	d	Short	(E)	(5)	35	(b)	20	(7)	Varied	Large
17	F	d	Short	(E)	(5)	35	(i)	16	(9)	$22\frac{13}{16}$	Large
18	F	d	Short	(D)	(5)	36.6	(i)	16	(9)	$22\frac{13}{16}$	Large
19	F	d	Short	(D)	(4)	36.6	(i)	16	(9)	$18\frac{7}{8}$	Large
20	F	d	Short	(D)	(6)	36.6	(i)	16	(10)	$15\frac{1}{4}$	Large
21	G	e	Short	(F)	(6)	24.6	(j)	16	(10)	$15\frac{1}{4}$	Large
22	G	e	Short	(G)	(6)	40	(k)	20	(10)	$15\frac{1}{4}$	Large
23	G	e	Short	(H)	(6)	32	(k)	20	(10)	$15\frac{1}{4}$	Large
24	G	e	Short	(E)	(6)	35	(a)	20	(10)	$15\frac{1}{4}$	Large
25	G	e	Short	(E)	(6)	35	(a)	20	(8)	$27\frac{7}{8}$	Large
26	G	e	Short	(E)	(6)	35	(k)	19	(10)	$15\frac{1}{4}$	Large
27	G	e	Short	(I)	(6)	38	(k)	20	(10)	$15\frac{1}{4}$	Large
28	H	e	Long	(E)	(6)	35	(k) (a)	20 19	(10) (11)	$15\frac{1}{4}$ 3	Large
29	H	e	Long	(E)	(6)	35	(l) (a)	20 19	(10) (11)	$15\frac{1}{4}$ 3	Large
30	H	e	Long	(I)	(6)	38	(l) (a)	20 19	(10) (11)	$15\frac{1}{4}$ 3	Large
31	H	e	Long	(I)	(6)	38	(k) (a)	20 20	(10) (8)	$15\frac{1}{4}$ $27\frac{7}{8}$	Large
32	H	e	Long	(E)	(6)	35	(k) (a)	20 20	(10) (8)	$15\frac{1}{4}$ $27\frac{7}{8}$	Large
33	H	e	Long	(D)	(6)	36.6	(k) (a)	20 20	(10) (8)	$15\frac{1}{4}$ $27\frac{7}{8}$	Large
34	H	e	Long	(D)	(6)	36.6	(l) (a)	20 20	(10) (8)	$15\frac{1}{4}$ $27\frac{7}{8}$	Large
35	H	e	Long	(J)	(6)	35.6	(k) (a)	20 20	(10) (8)	$15\frac{1}{4}$ $27\frac{7}{8}$	Large
36	H	e	Long	(K)	(6)	33.3	(k) (a)	20 20	(10) (8)	$15\frac{1}{4}$ $27\frac{7}{8}$	Large
37	H	e	Long	(L)	(6)	40	(k) (a)	20 20	(10) (8)	$15\frac{1}{4}$ $27\frac{7}{8}$	Large
38	H	e	Long	(G)	(6)	40	(k) (a)	20 20	(10) (8)	$15\frac{1}{4}$ $27\frac{7}{8}$	Large
[a]39	H	e	Long	(D)	(6)	36.6	(k) (a)	20 20	(10) (8)	$15\frac{1}{4}$ $27\frac{7}{8}$	Large
40	I	a	Long	(E)	(1)	39.1	(l) (a)	20 20	(9) (7)	$7\frac{9}{16}$ $13\frac{9}{16}$	Large
41	I	a	Long	(M)	(1)	39.1	(l) (a)	20 20	(9) (7)	$7\frac{9}{16}$ $13\frac{9}{16}$	Large
42	I	a	Long	(E)	(1)	39.1	(l) (m)	20 20	(9) (7)	$7\frac{9}{16}$ $13\frac{9}{16}$	Large
[b]43	J	e	Long	(E)	(6)	35	(k) (a)	20 20	(10) (8)	$15\frac{1}{4}$ $27\frac{7}{8}$	Large

[a]Antisloshing bars.
[b]Tripper on innerbody.

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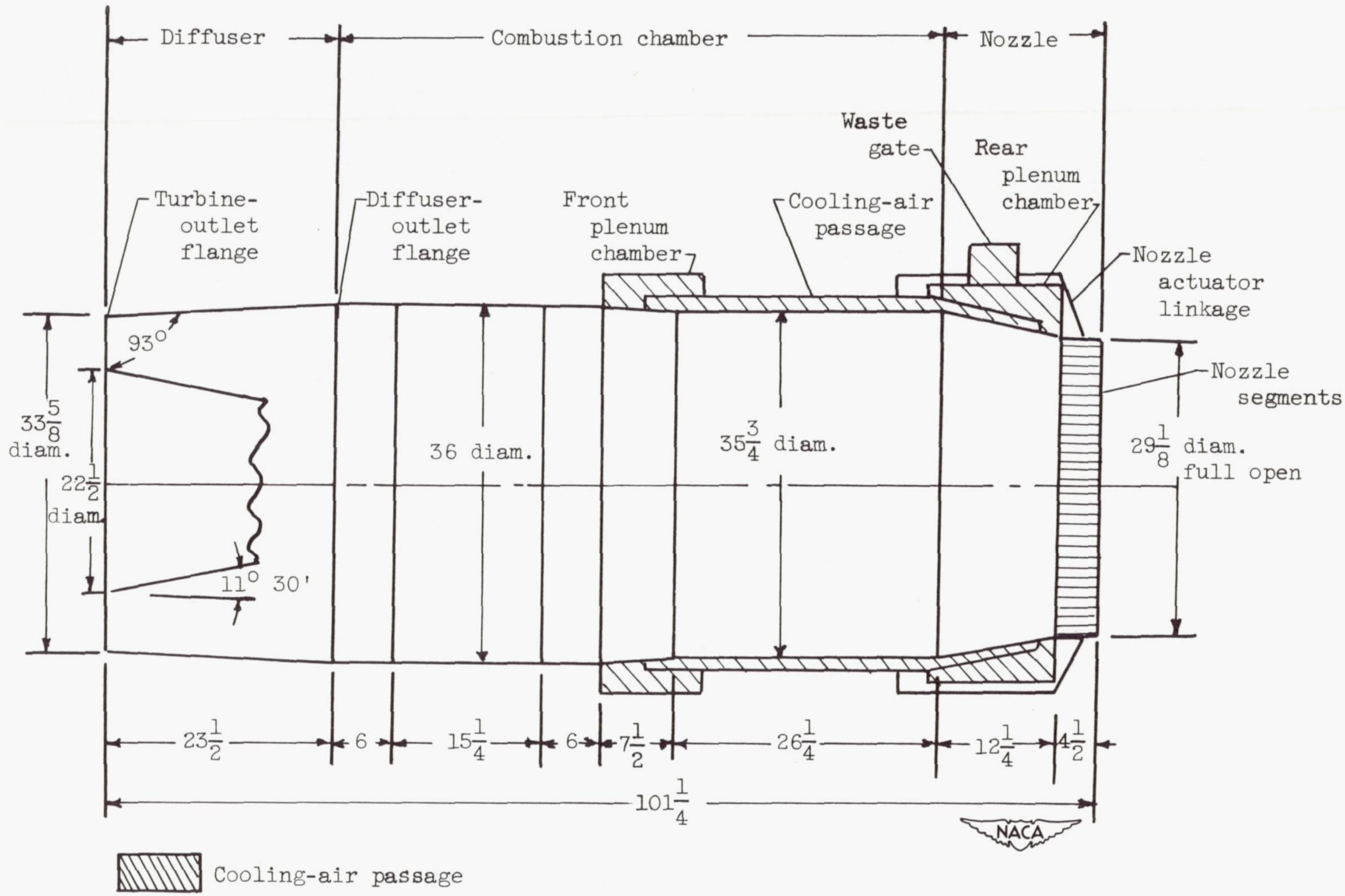

Figure 1. - Details of afterburner shell and diffuser section. (All dimensions in inches.)

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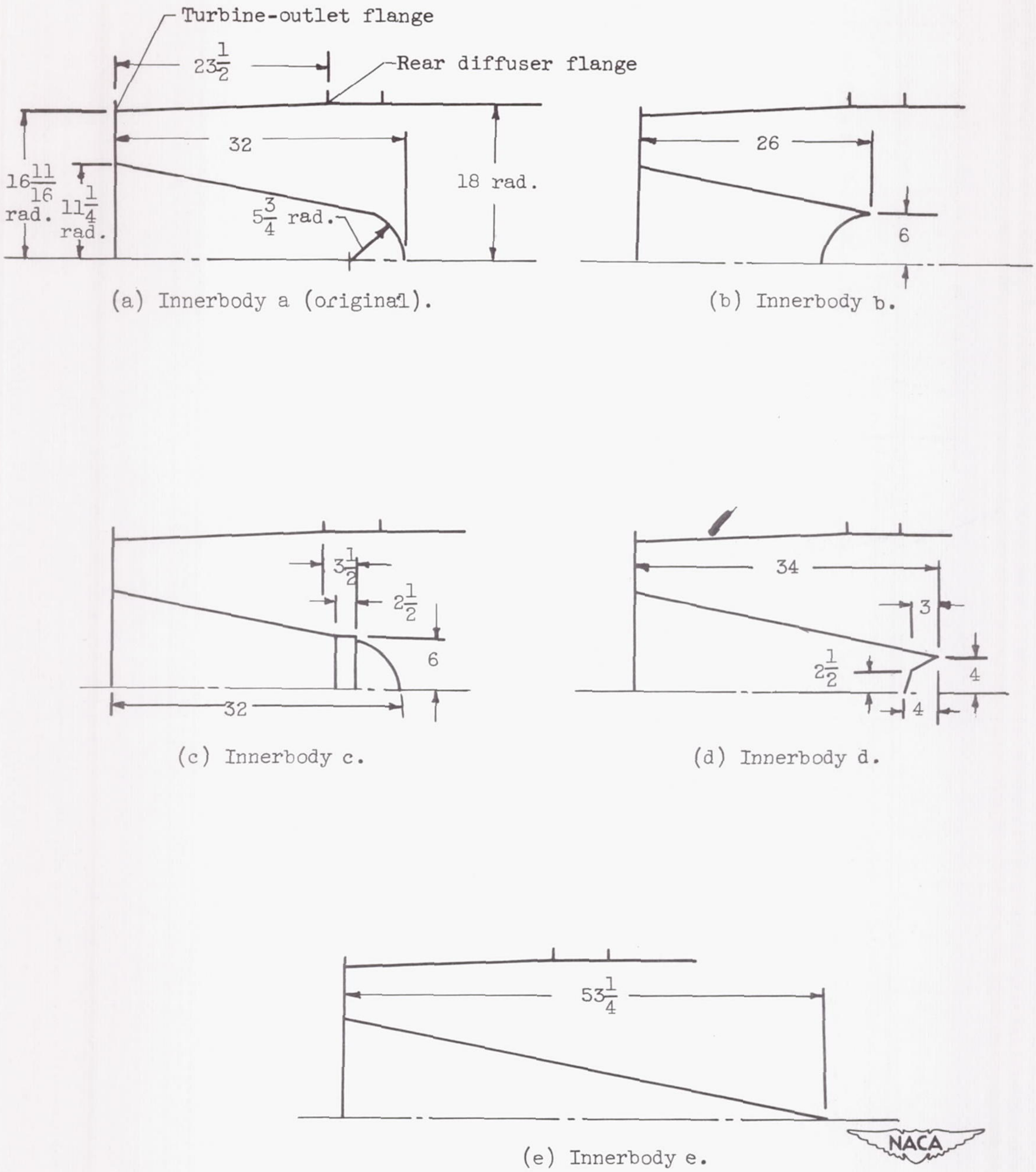

Figure 2. - Details of diffuser innerbodies investigated. (All dimensions in inches.)

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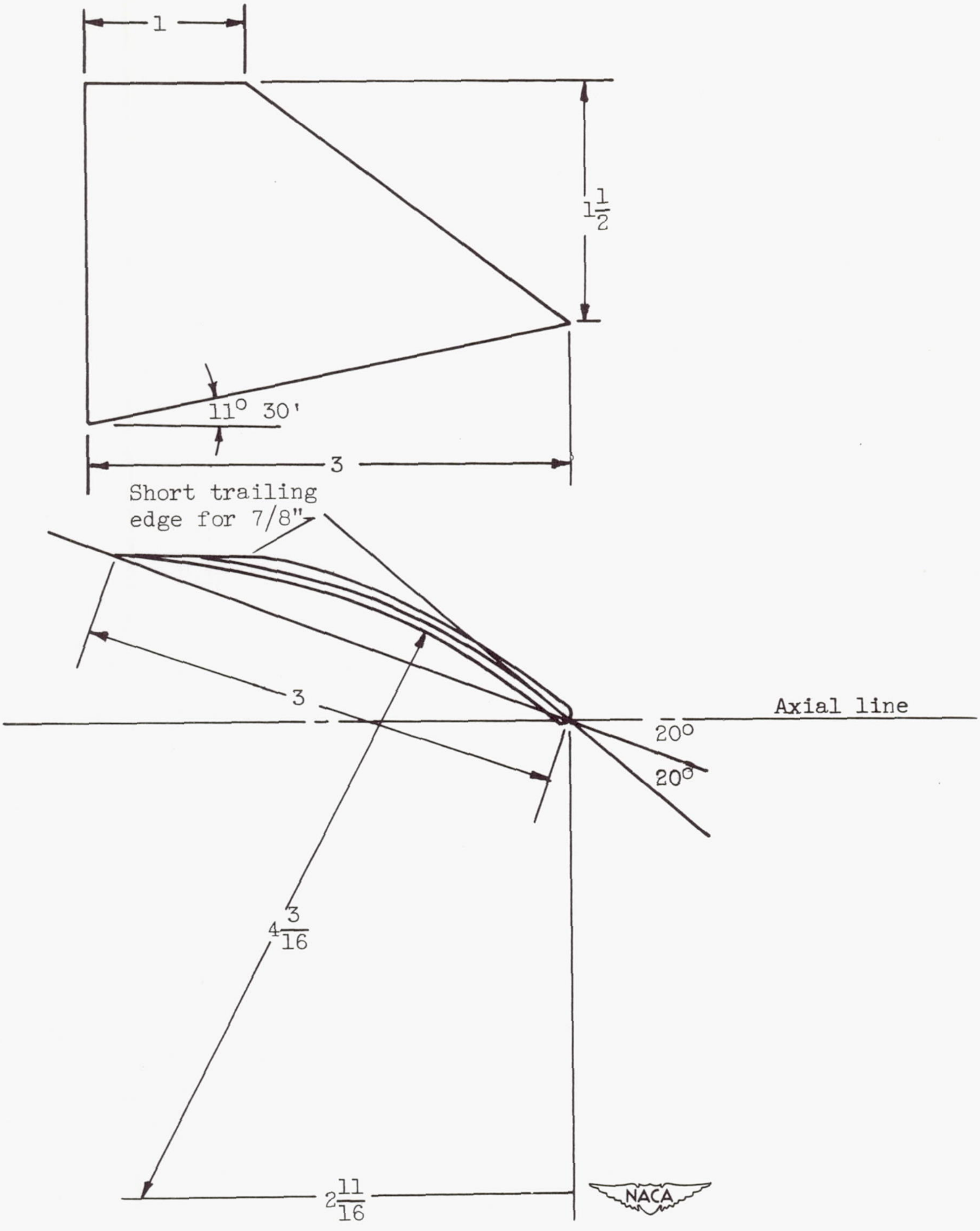
CE-3 back



(a) Details of 33 short antiswirl vanes. (All dimensions in inches.)

Figure 3. - Turbine-outlet straightening vanes.

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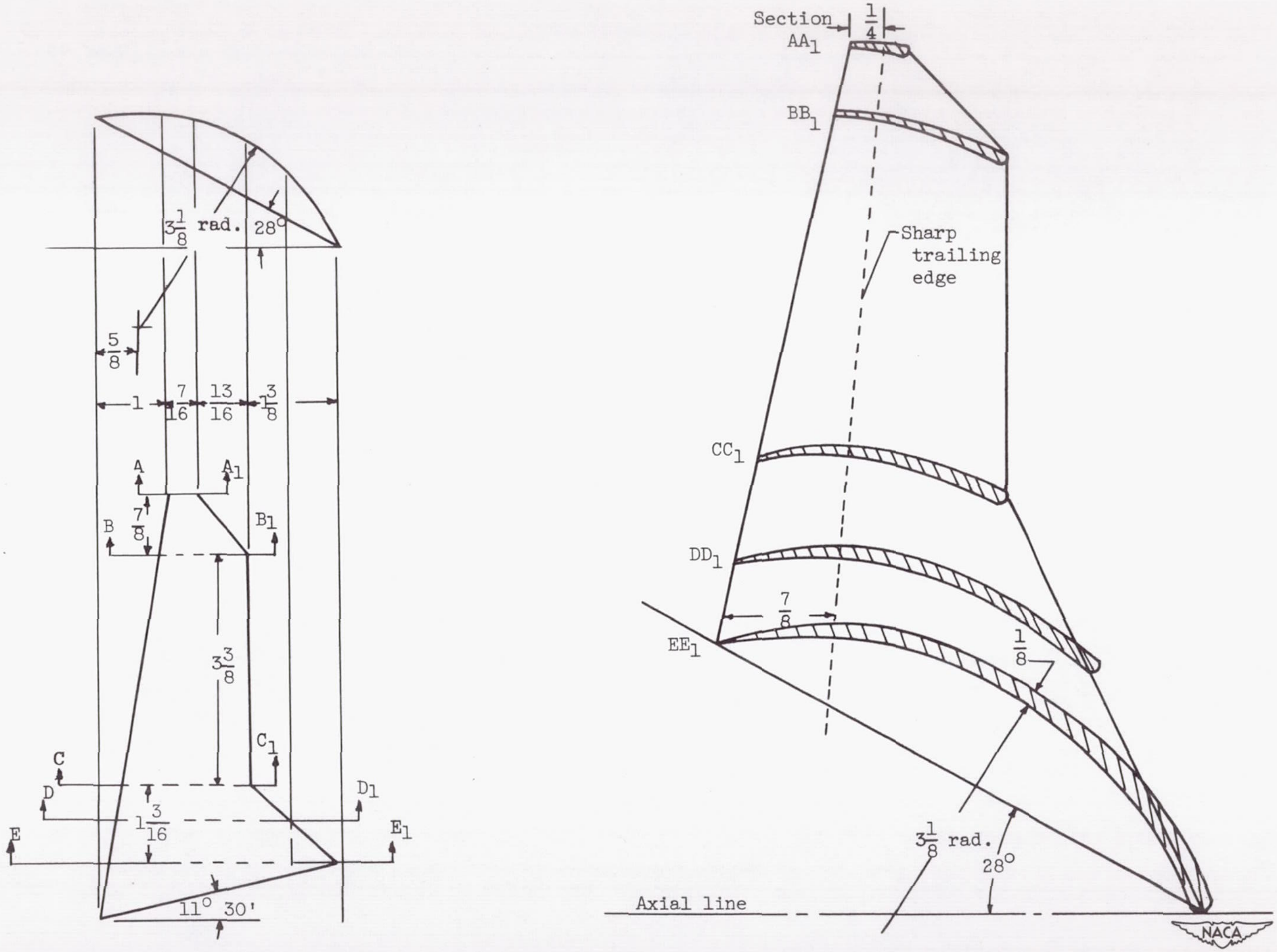

(b) Details of 48 long antiswirl vanes. (All dimensions in inches.)

Figure 3. - Continued. Turbine-outlet straightening vanes.

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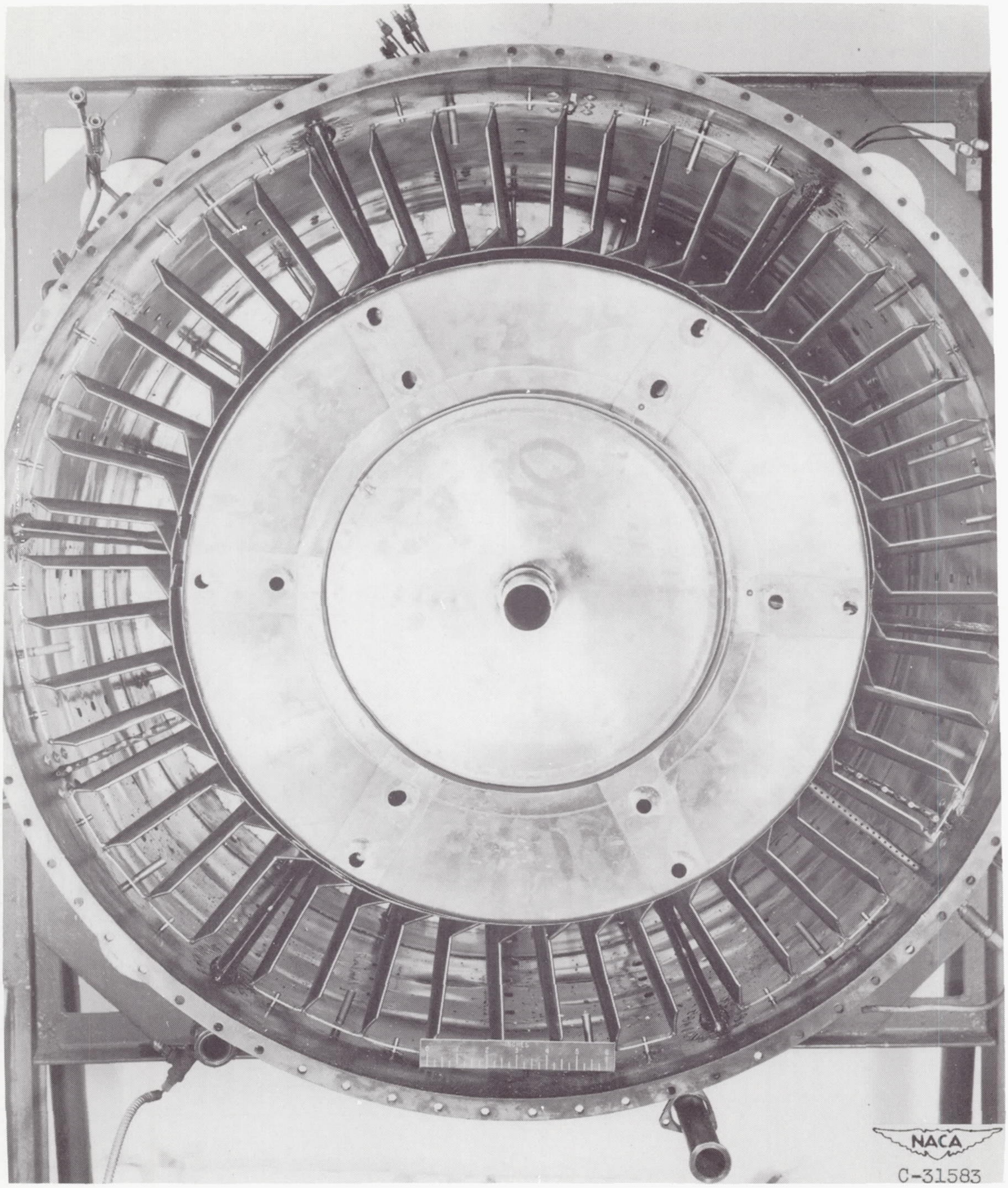


(c) View of 48 long vanes installed in diffuser section.

Figure 3 - Concluded. Turbine-outlet straightening vanes.

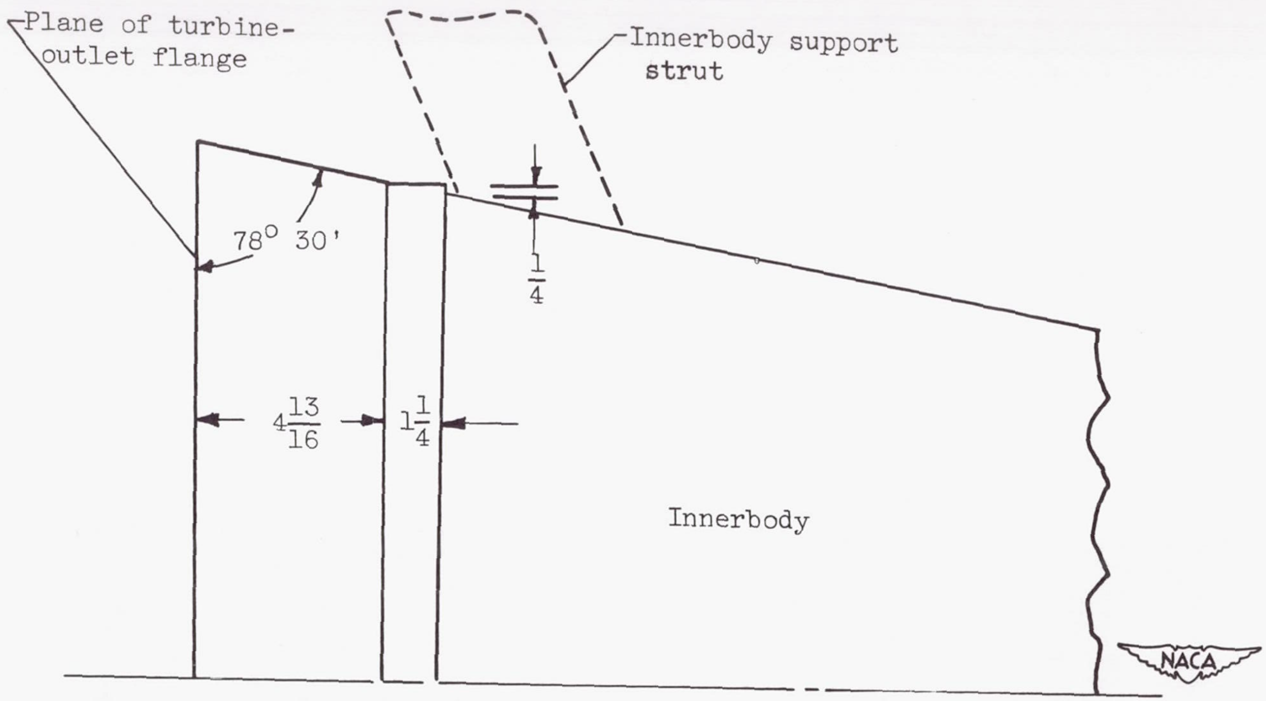
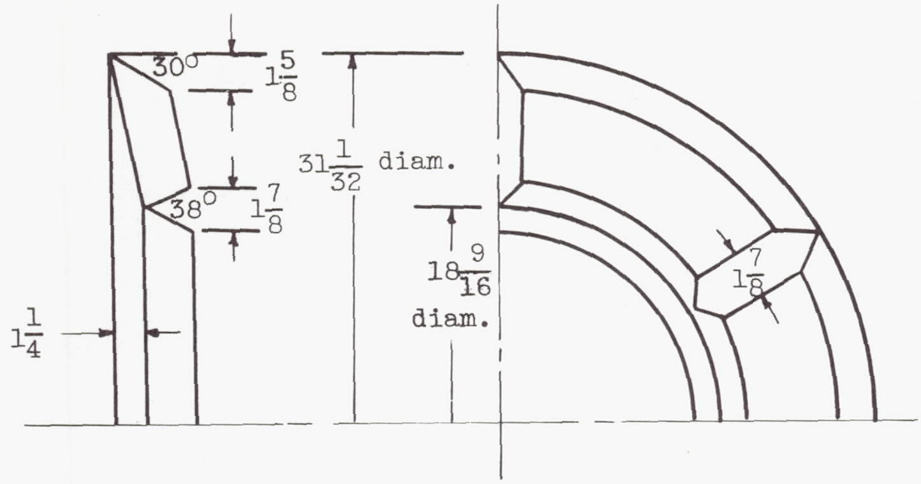
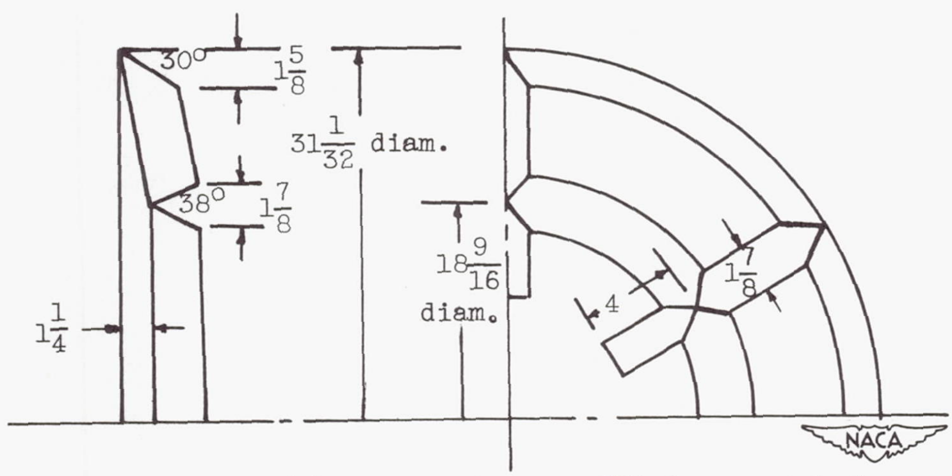


Figure 4. - Details of boundary-layer tripper incorporated with configuration 43. (All dimensions in inches.)



(a) Flame holder (A). Blocked area, 300 square inches.



(b) Flame holder (B). Blocked area, 334.2 square inches.

Figure 5. - Details of flame holders investigated. (All dimensions in inches.)

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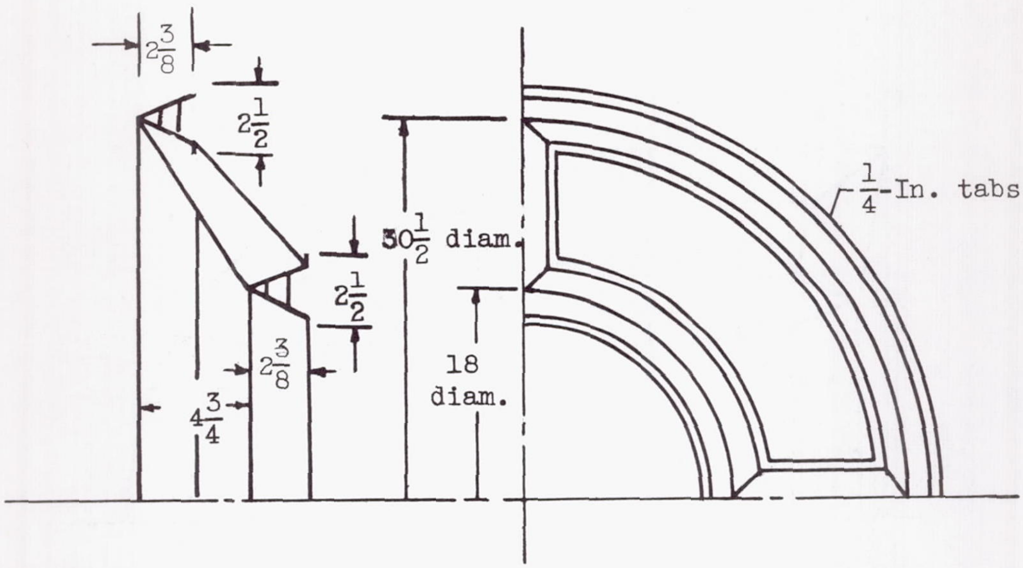

(c) Flame holder (C). Blocked area, 418.4 square inches.

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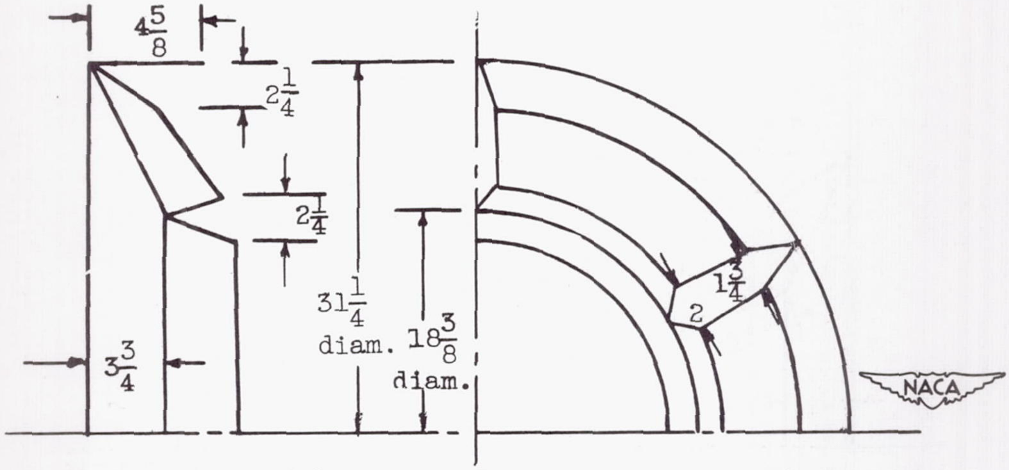

(d) Flame holder (D). Blocked area, 376 square inches.

Figure 5. - Continued. Details of flame holders investigated. (All dimensions in inches.)

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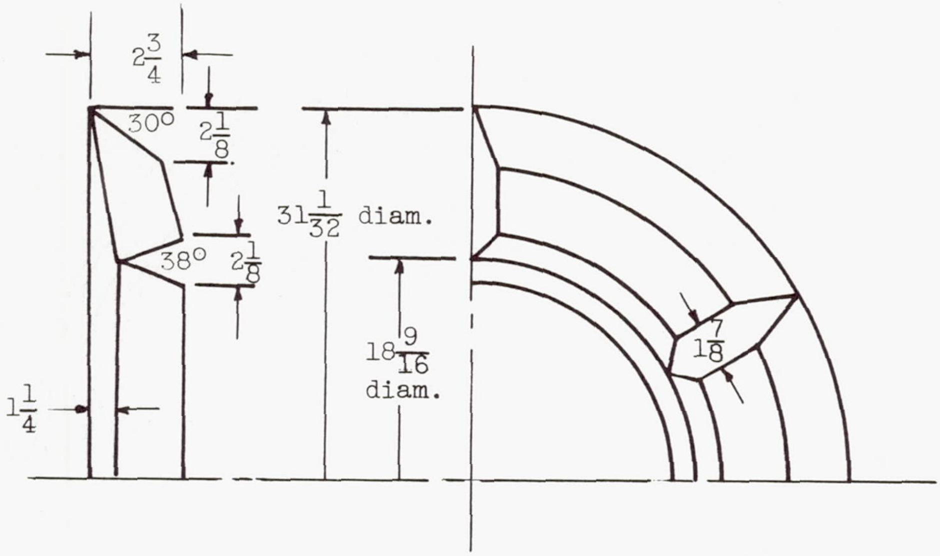
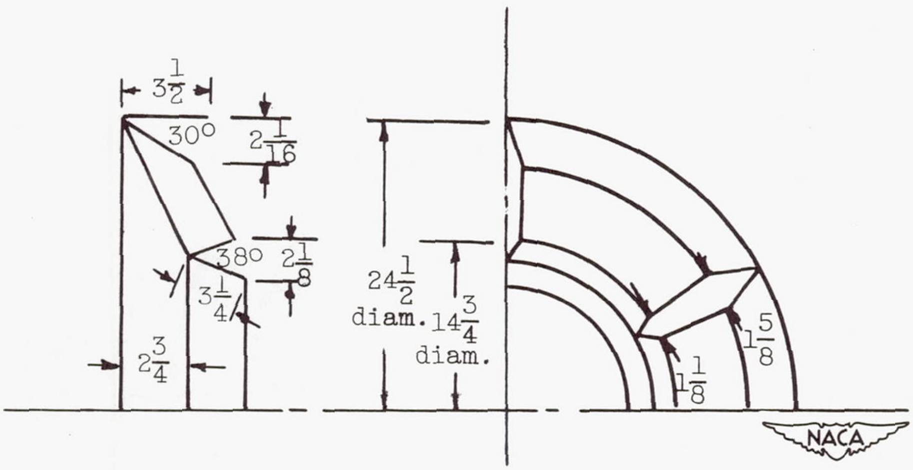
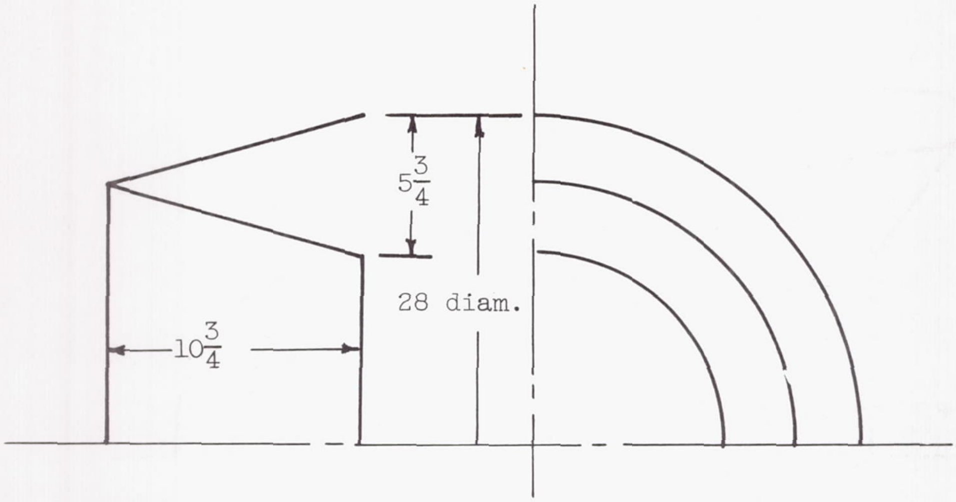


(e) Flame holder (E). Blocked area, 357.5 square inches.

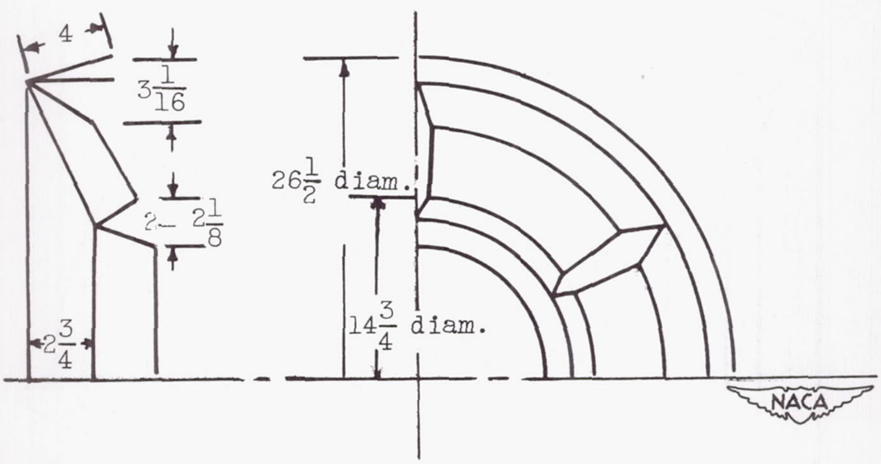


(f) Flame holder (F). Blocked area, 254.2 square inches.

Figure 5. - Continued. Details of flame holders investigated. (All dimensions in inches.)



(g) Flame holder (G). Blocked area, 402 square inches.



(h) Flame holder (H). Blocked area, 334.2 square inches.

Figure 5. - Continued. Details of flame holders investigated. (All dimensions in inches.)

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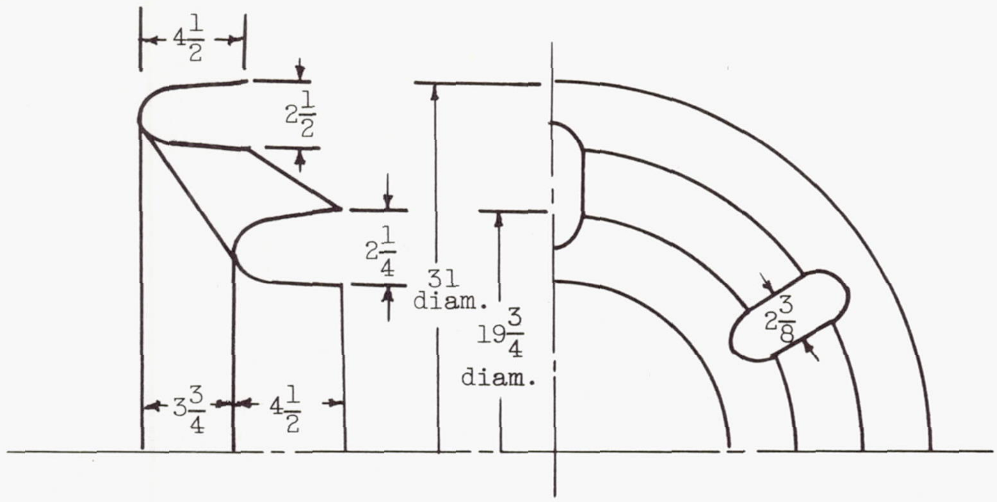
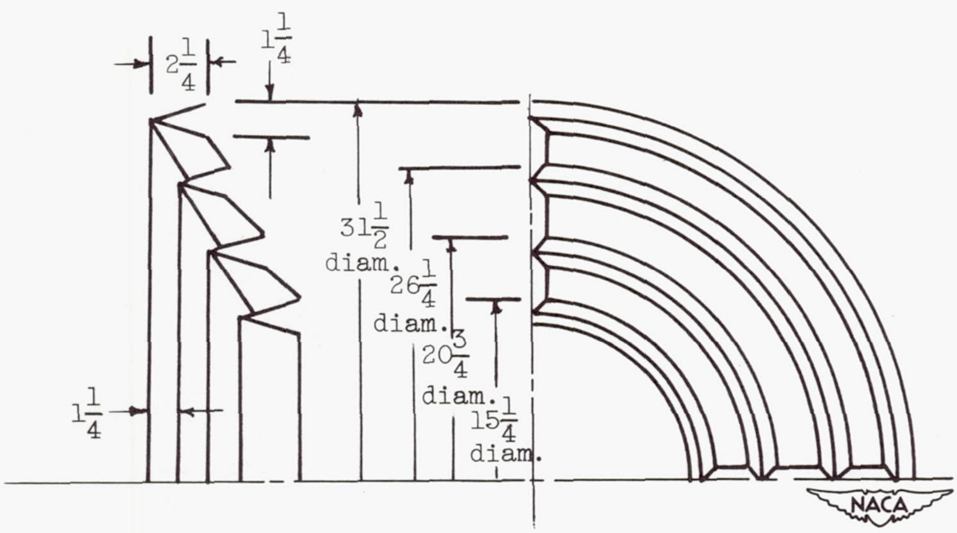


(i) Flame holder (I). Blocked area, 392 square inches.



(j) Flame holder (J). Blocked area, 366.5 square inches.

Figure 5. - Continued. Details of flame holders investigated. (All dimensions in inches.)

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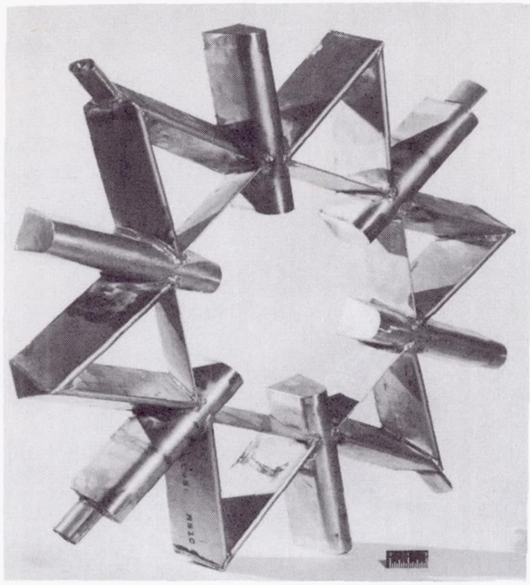

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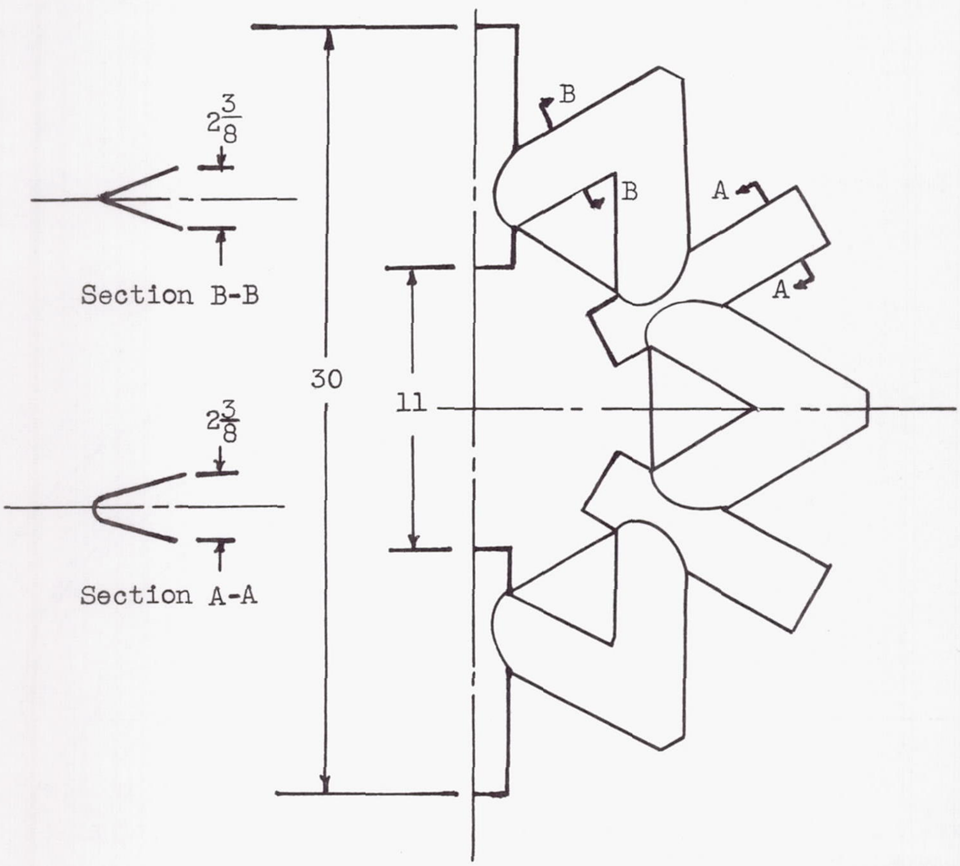

(k) Flame holder (K). Blocked area, 341 square inches.

Figure 5. - Continued. Details of flame holders investigated. (All dimensions in inches.)

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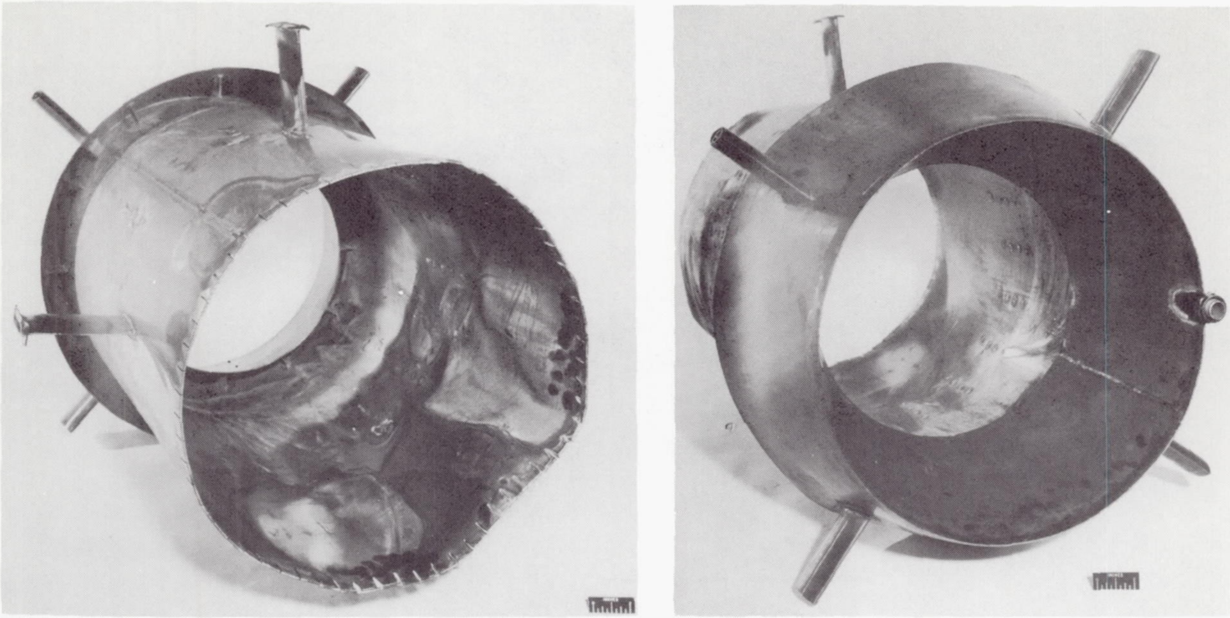

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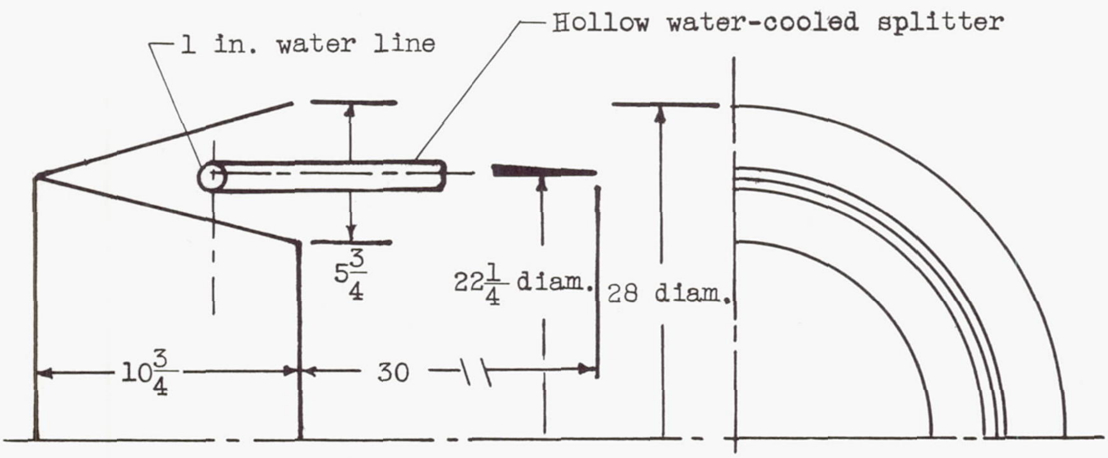
Downstream view   Upstream view



(l) Flame holder (L). Blocked area, 402 square inches.

Figure 5. - Continued. Details of flame holders investigated. (All dimensions in inches.)

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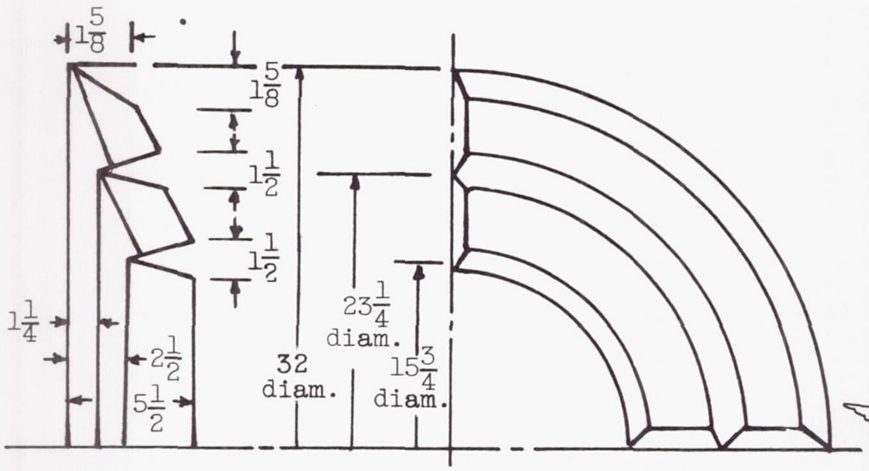

(m) Flame holder (M). Blocked area, 362 square inches.

Figure 5. - Concluded. Details of flame holders investigated. (All dimensions in inches.)

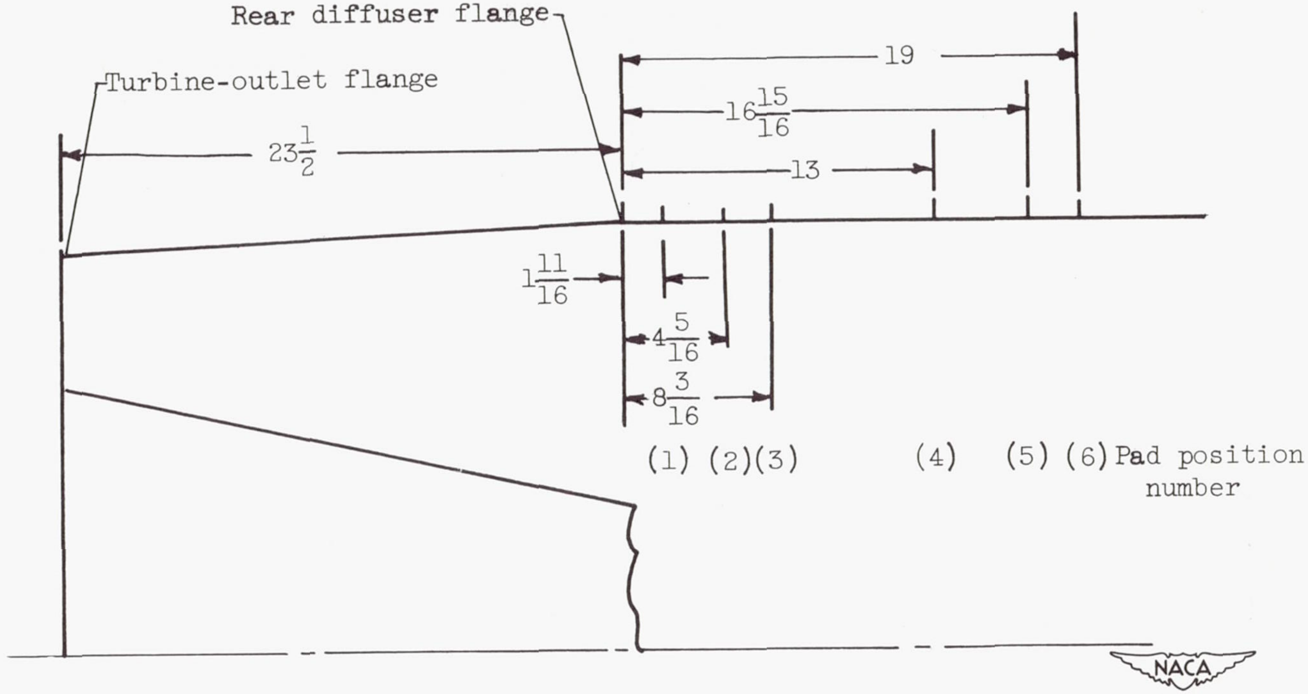

Figure 6. - Sketch of diffuser and afterburner section, indicating positions of flame holders. (All dimensions in inches.)

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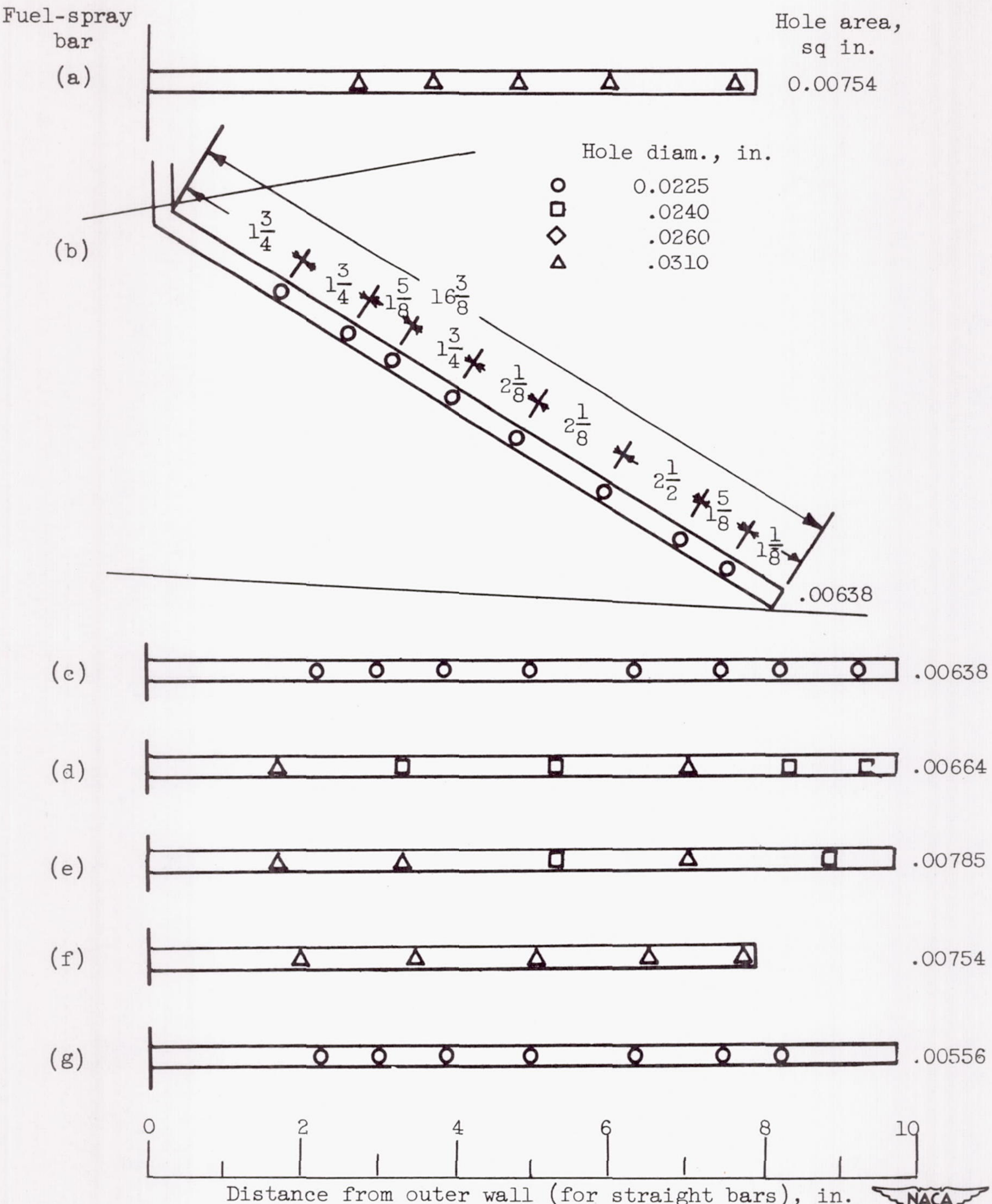

Figure 7. - Details of fuel-spray bars investigated.

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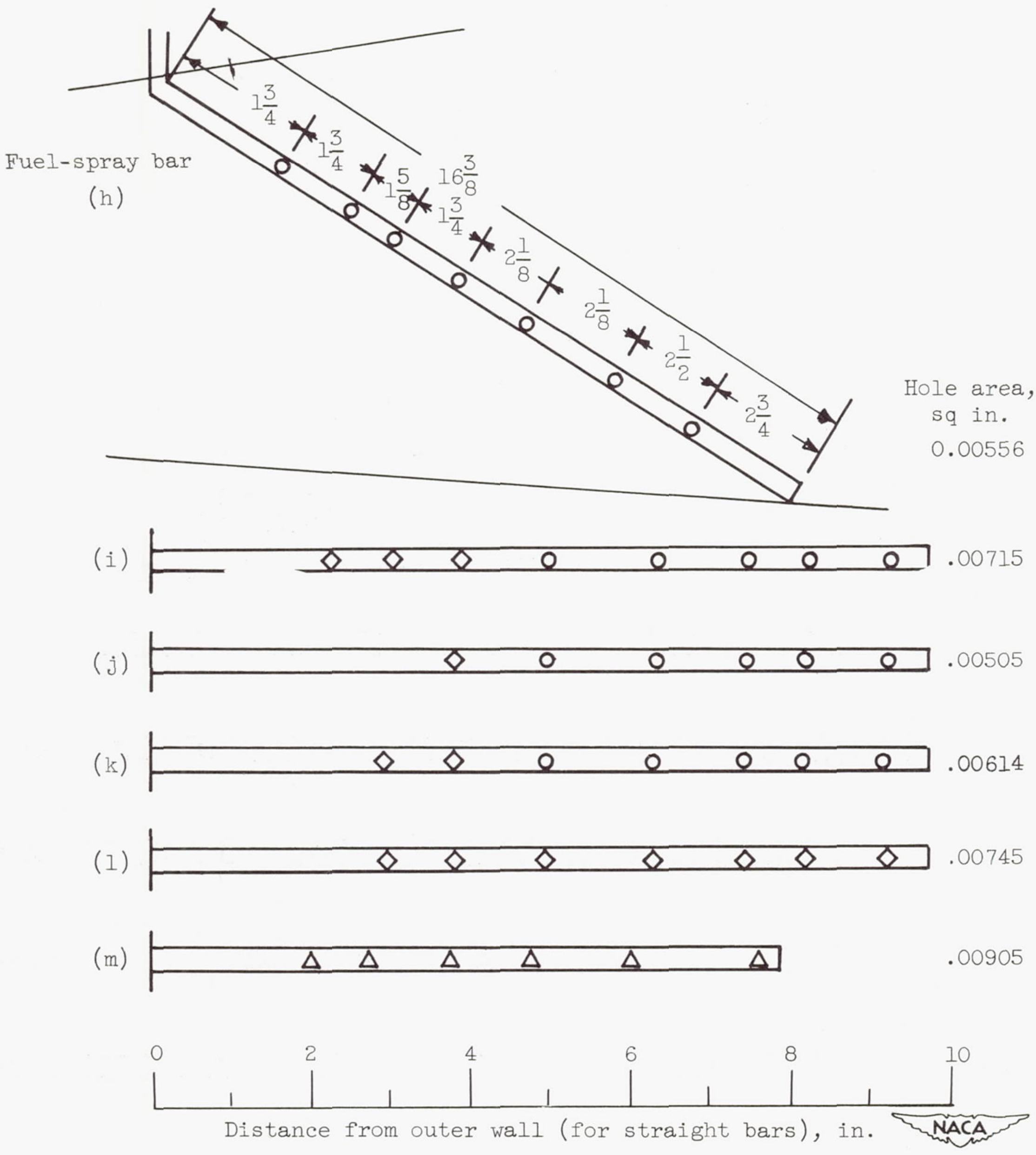

Figure 7. - Concluded. Details of fuel-spray bars investigated.

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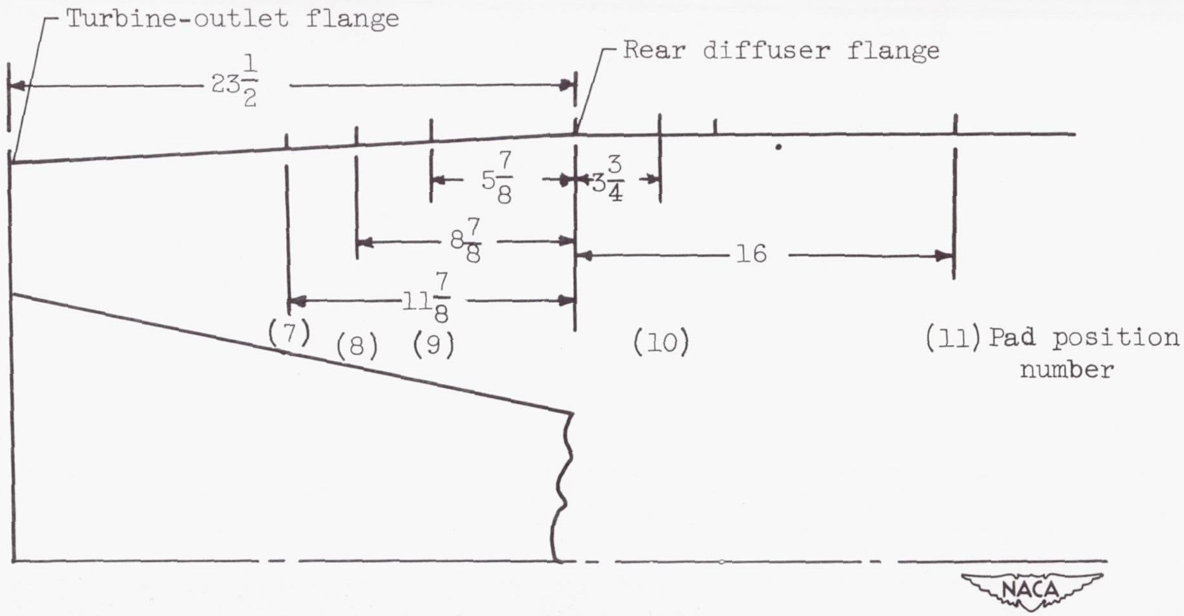

Figure 8. - Sketch of diffuser and afterburner section, indicating positions of fuel-spray bars. (All dimensions in inches.)

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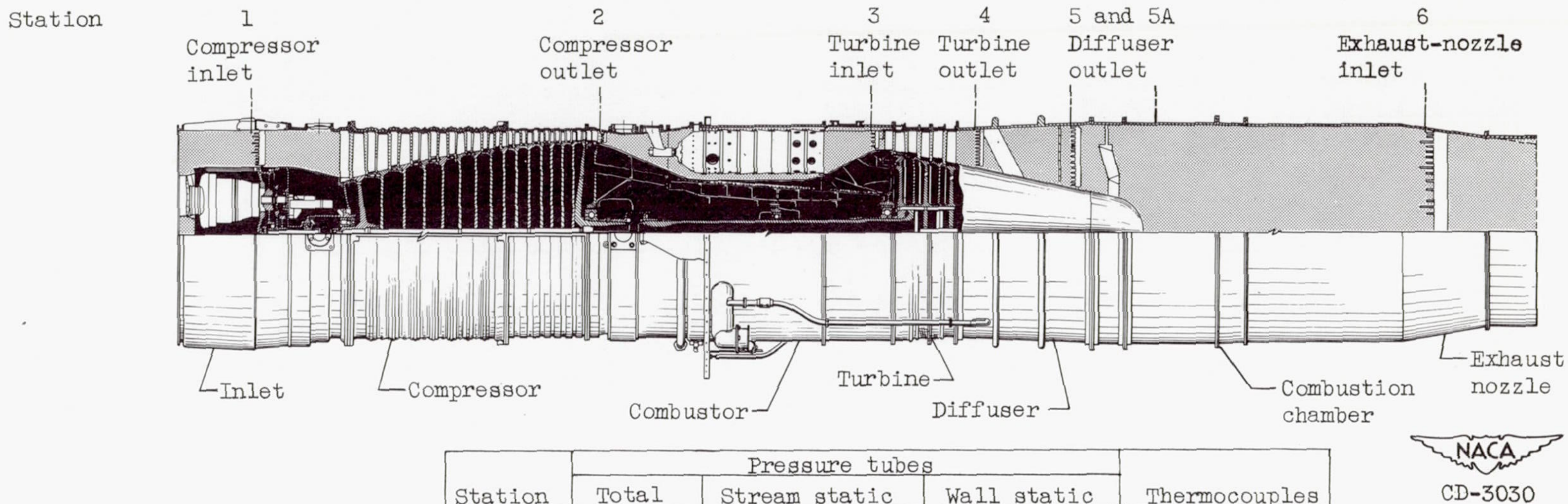

Station	Pressure tubes			Thermocouples
	Total	Stream static	Wall static	
1	28	8	4	(a)
2	8	1	0	8
3	8	0	0	4
4	21	0	6	18
5	12	0	2	0
[b]5A	12	0	2	0
6	20	4	2	0

[a]6 thermocouples located upstream of engine inlet duct
[b]Used only when flame holder was downstream of this position

Figure 9. - Cross-sectional view of engine and afterburner indicating instrumentation stations.

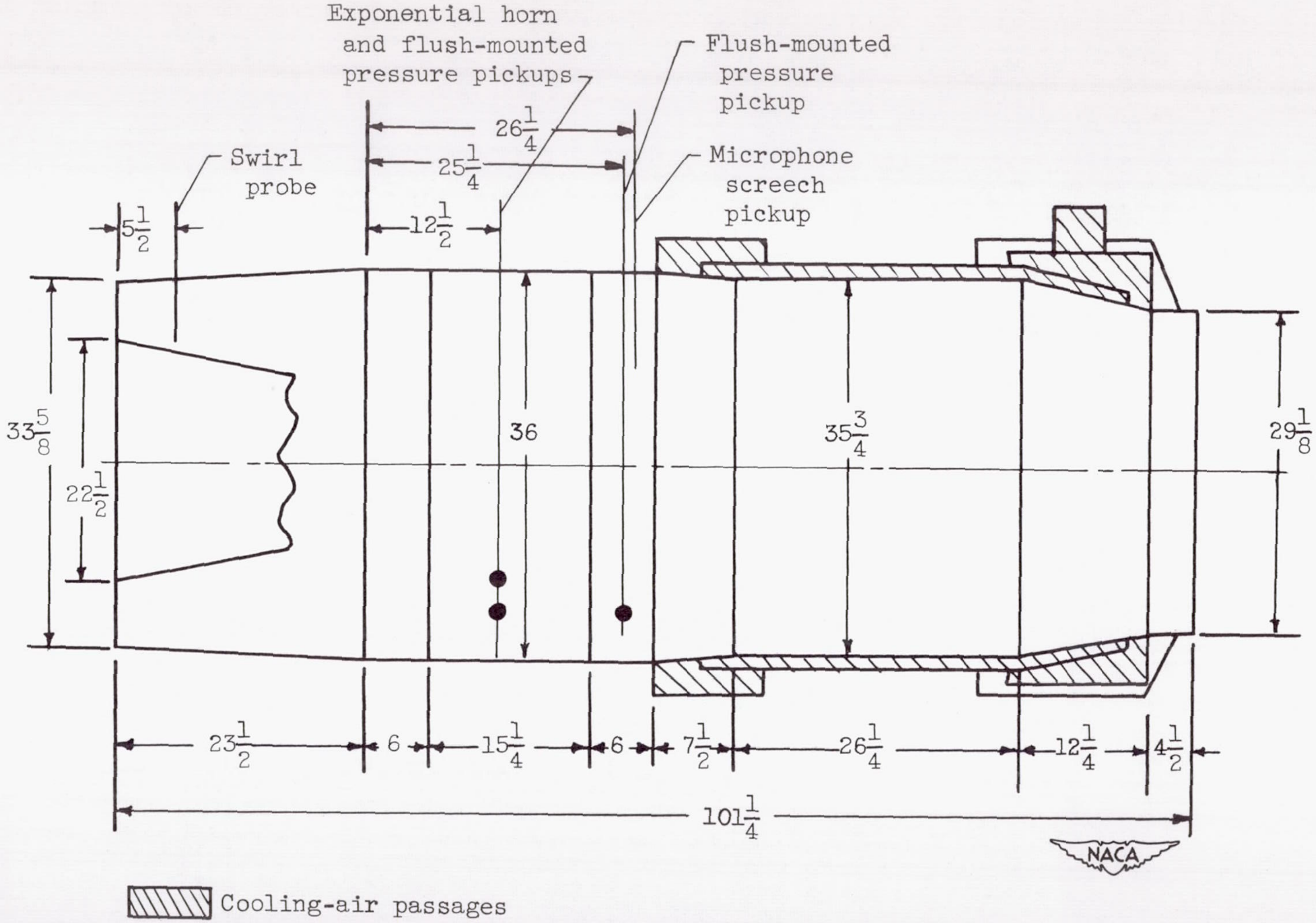

Figure 10. - Sketch of afterburner indicating positions of screech pickups and swirl surveys. (All dimensions in inches.)

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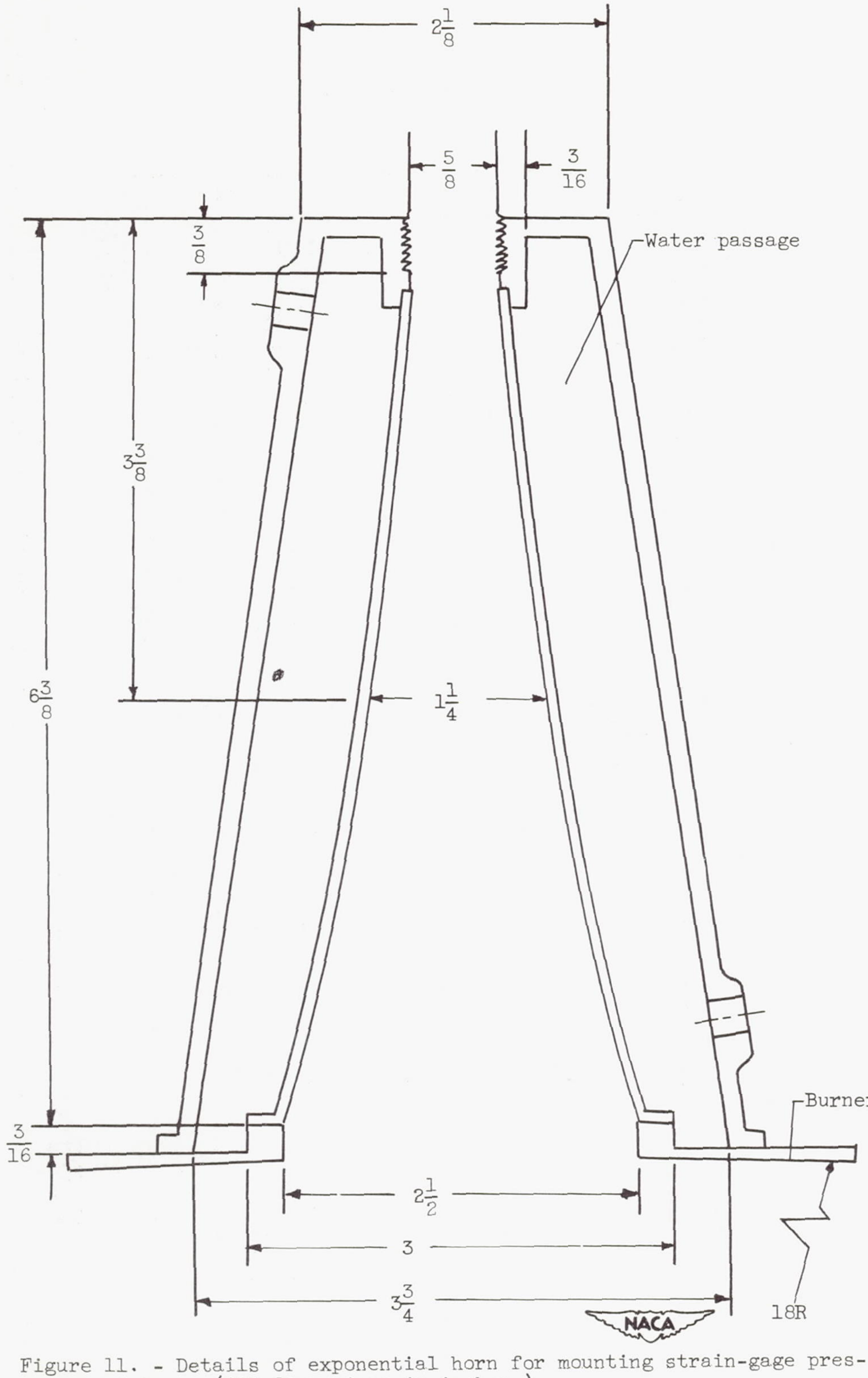

Figure 11. - Details of exponential horn for mounting strain-gage pressure pickup. (All dimensions in inches.)

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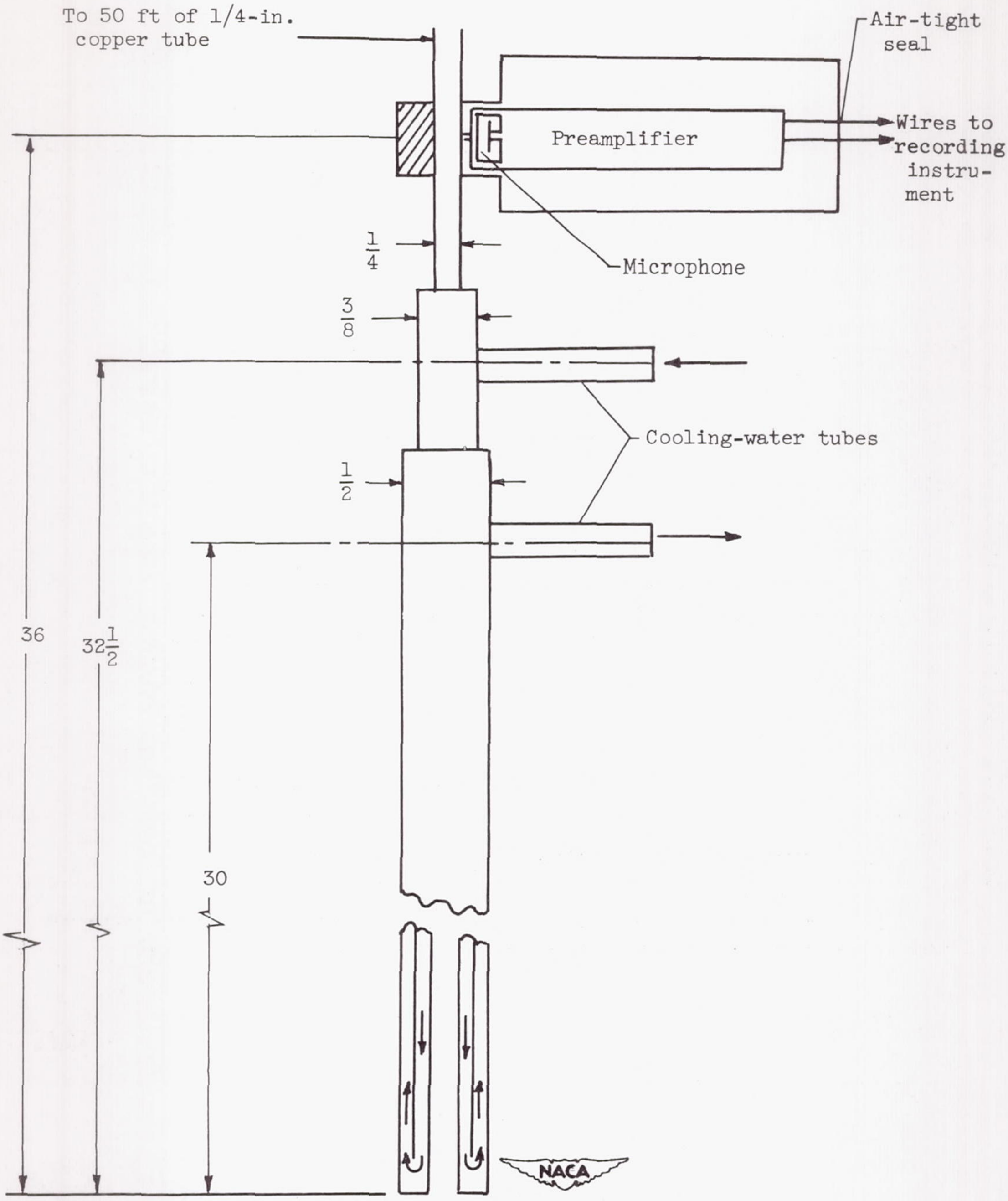

Figure 12. - Details of acoustic probe and microphone mounting. (All dimensions in inches.)

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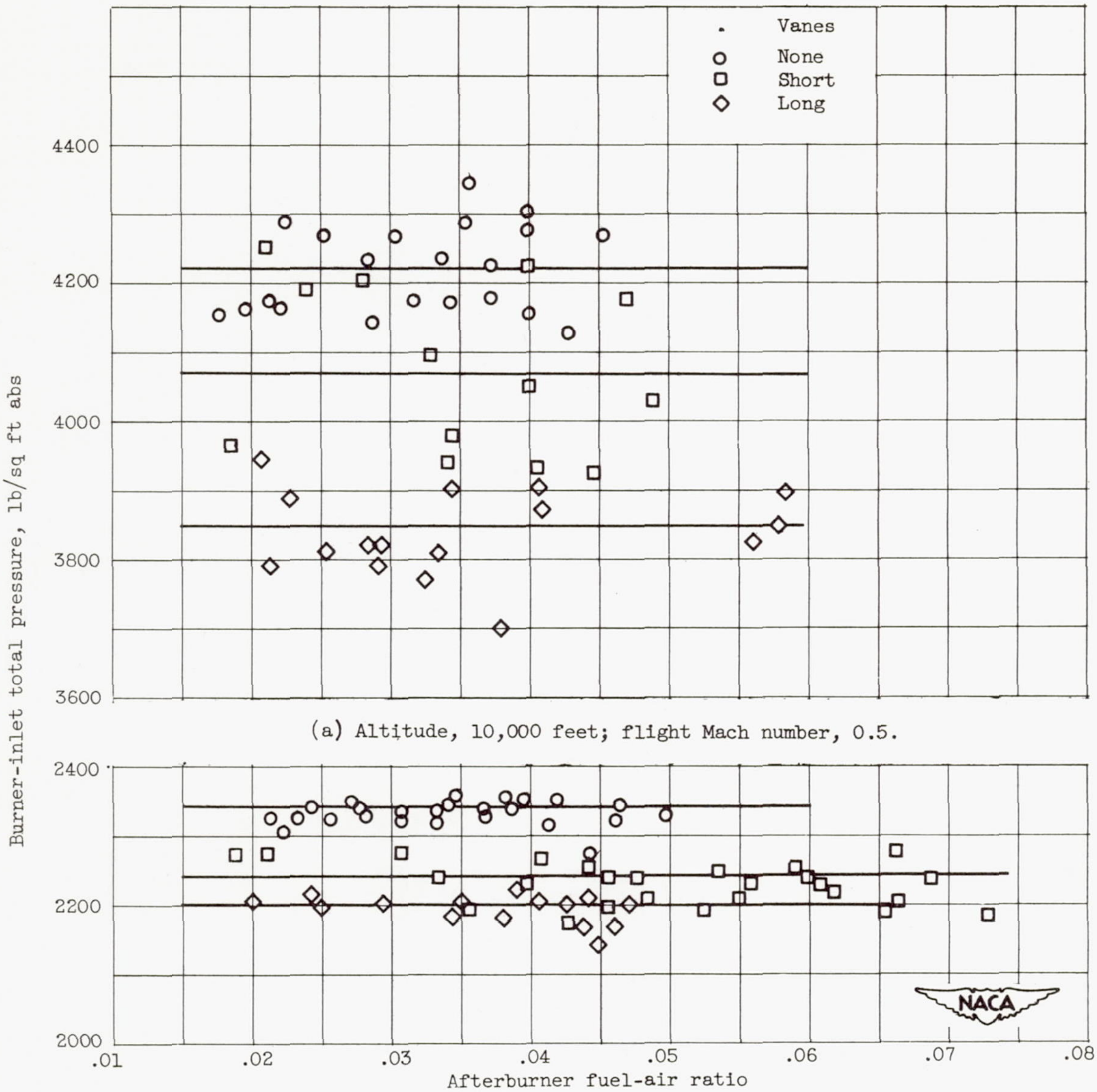

(b) Altitude, 35,000 feet; flight Mach number, 1.0.

Figure 13. - Average burner-inlet total pressures.

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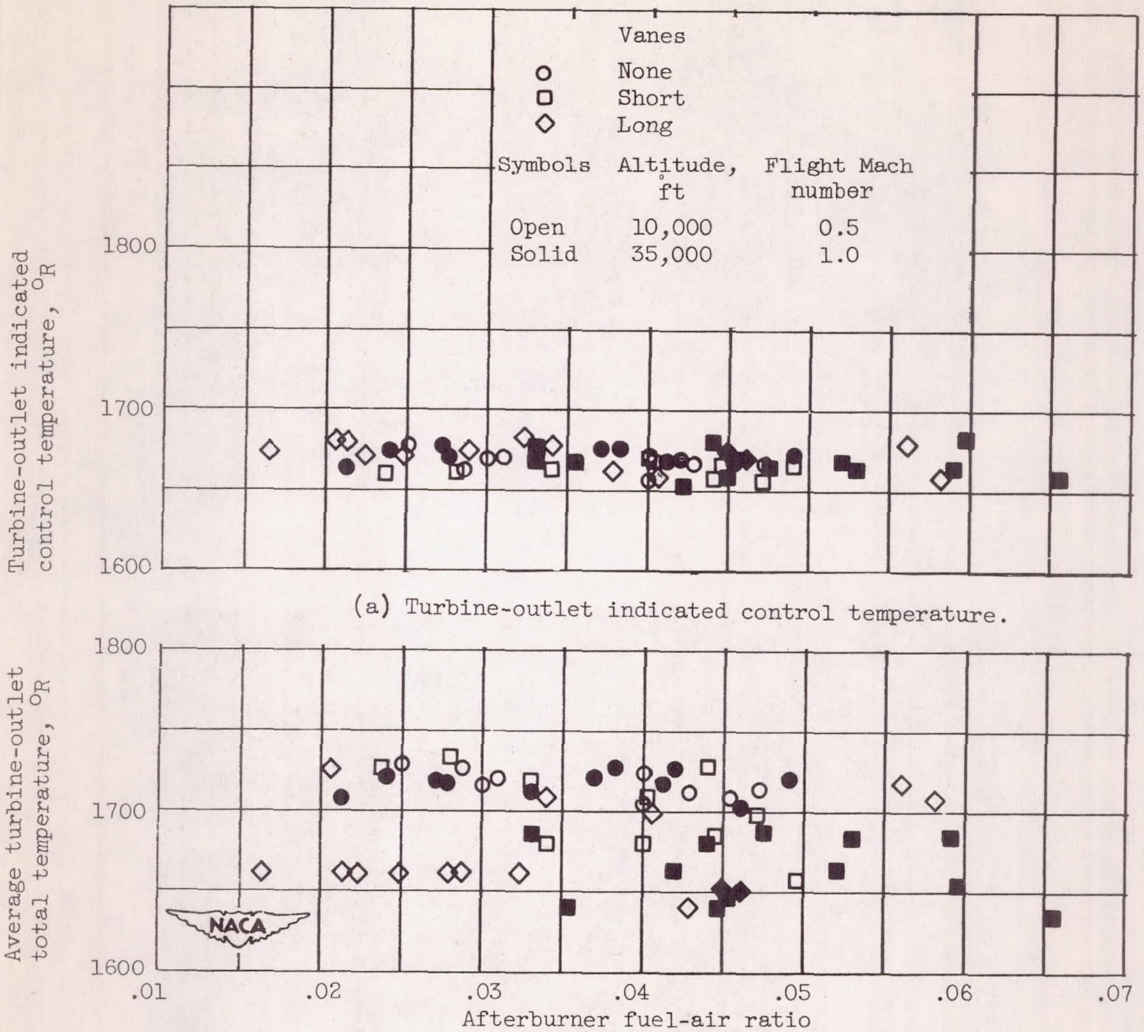

(a) Turbine-outlet indicated control temperature.

(b) Average turbine-outlet total temperature.

Figure 14. - Typical turbine-outlet temperatures.

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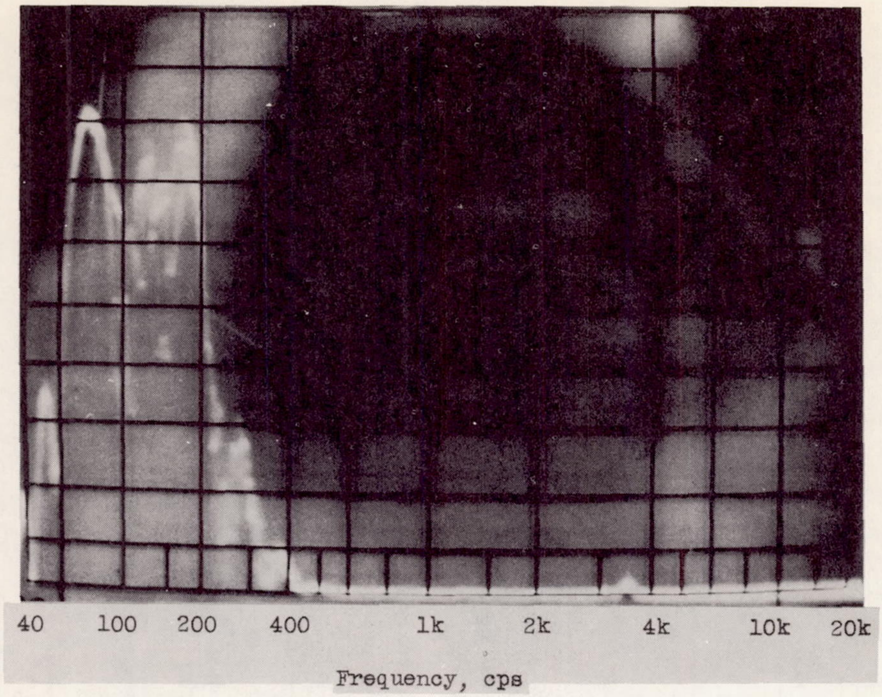
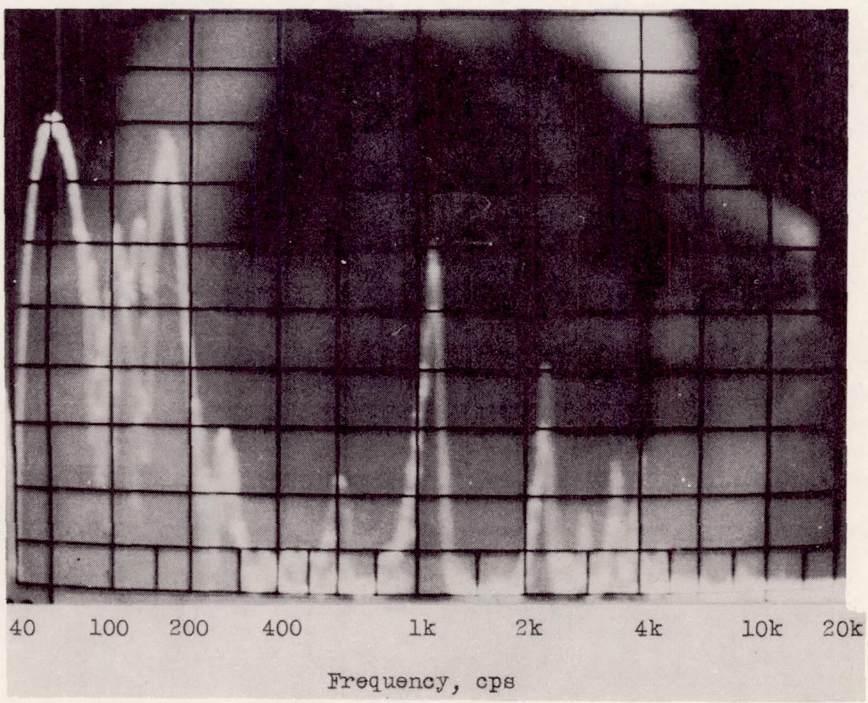


(a) Flush-mounted strain-gage pressure pickup; afterburning but no screech.



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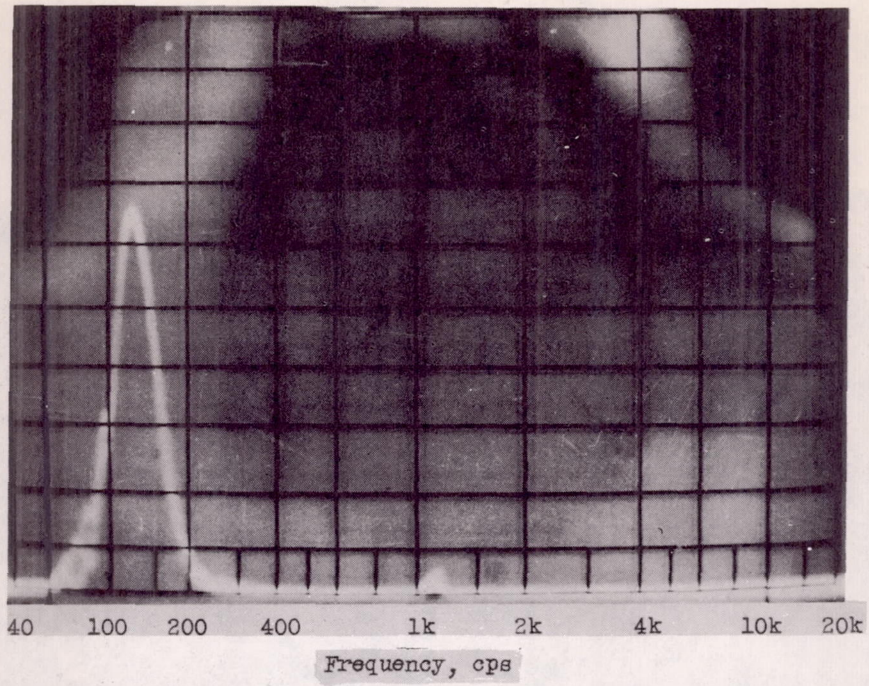
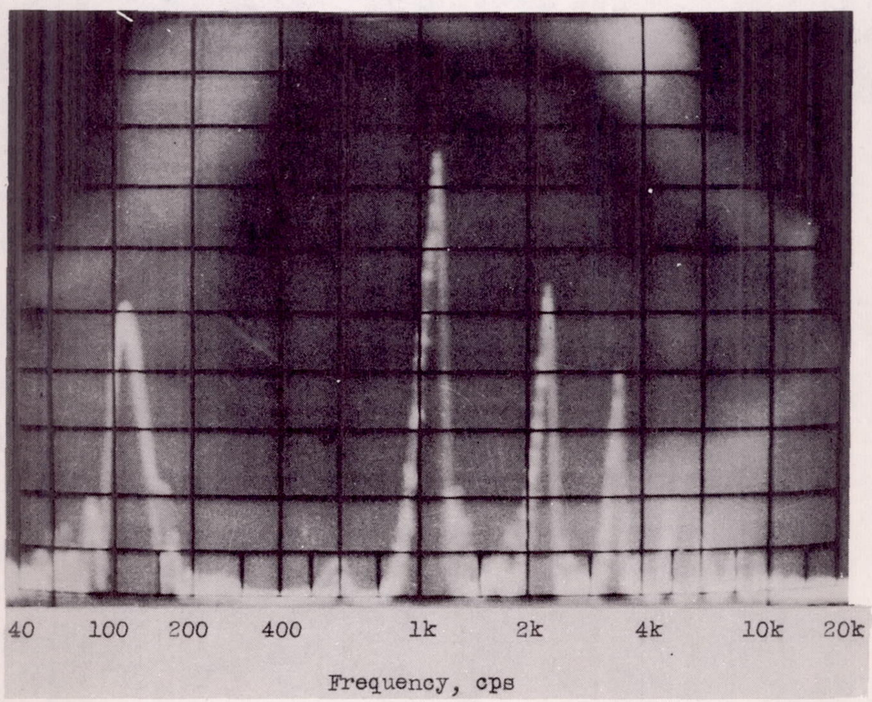
(b) Flush-mounted strain-gage pressure pickup; screeching combustion.

Figure 15. - Typical examples of panoramic traces sensed by various transducers.



(c) Exponential-horn mounted stain-gage pressure pickup; afterburning but no screech.



C-33431

(d) Exponential-horn mounted strain-gage pressure pickup; screeching combustion.

Figure 15. - Continued. Typical examples of panoramic traces sensed by various transducers.

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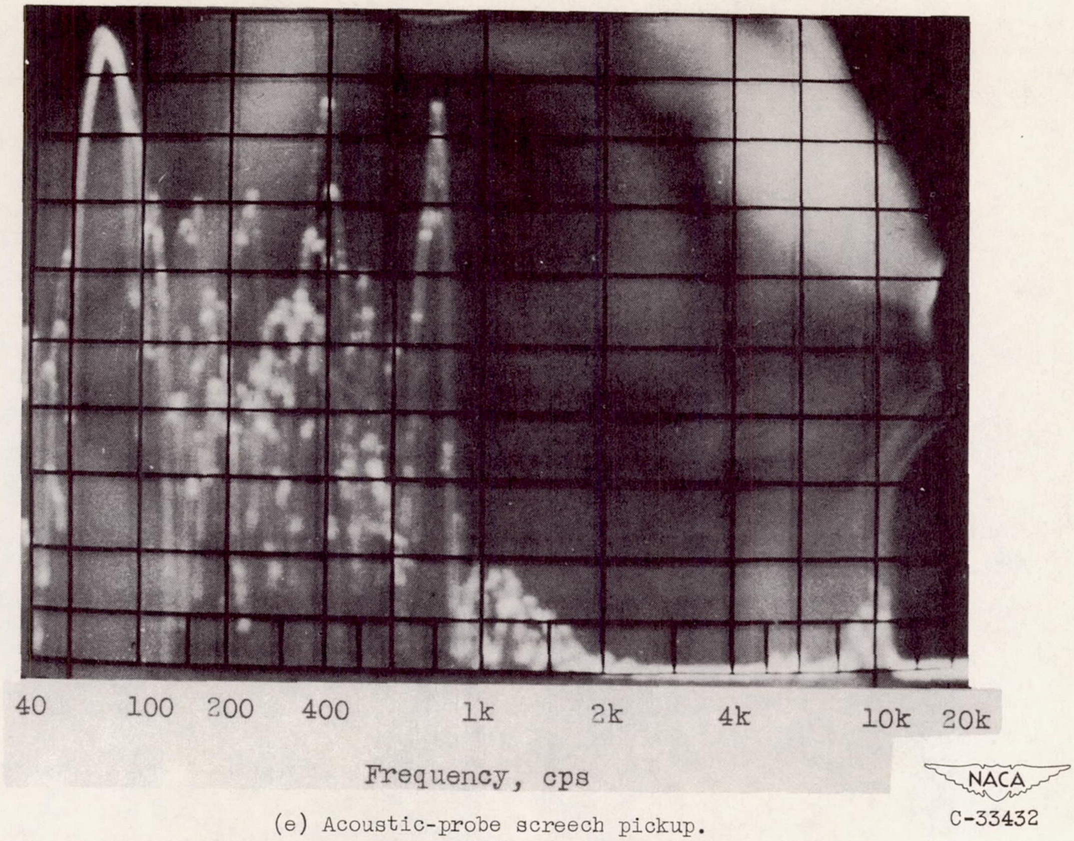

(e) Acoustic-probe screech pickup.

Figure 15. - Concluded. Typical examples of panoramic traces sensed by various transducers.

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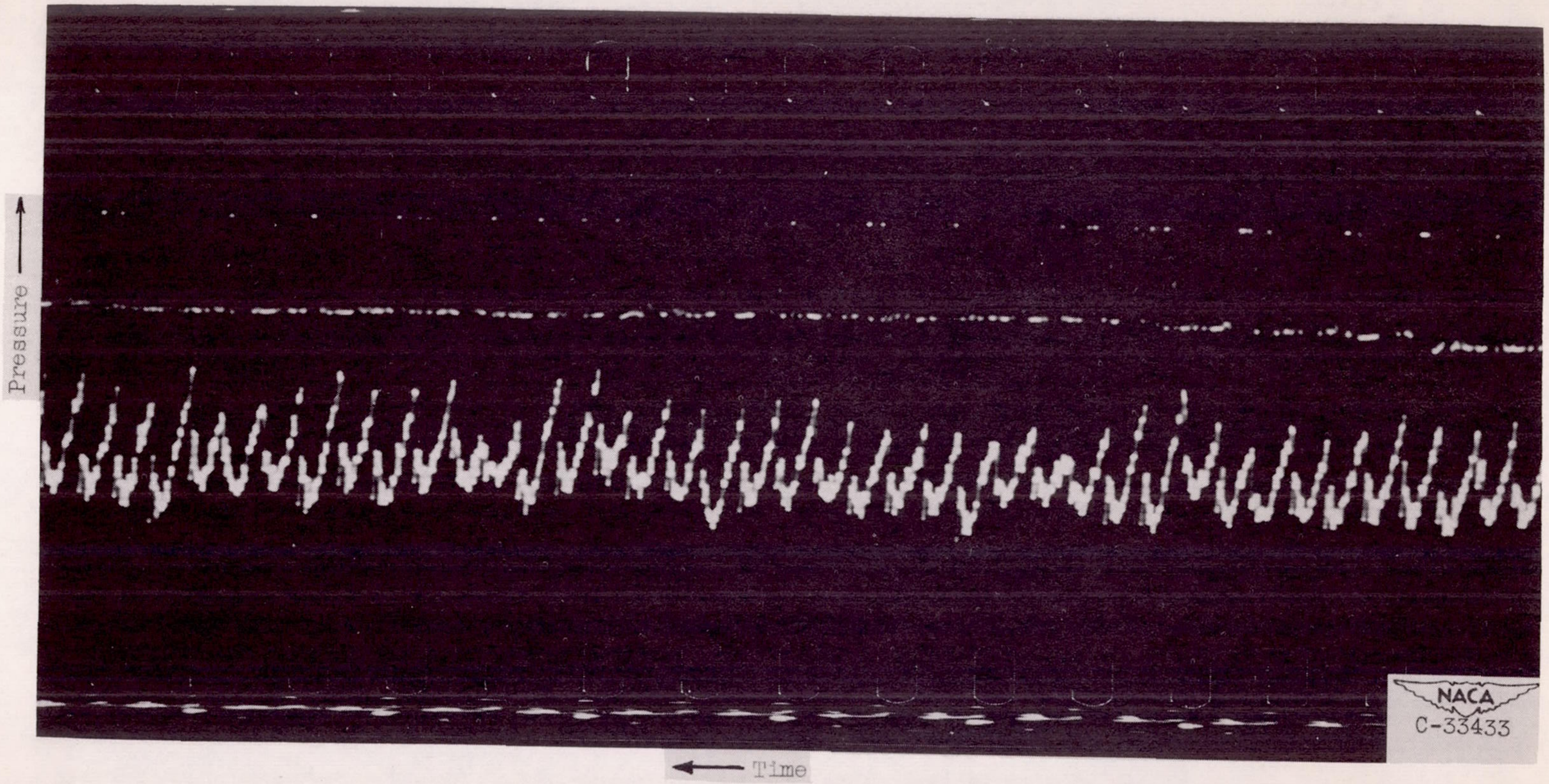

Figure 16. - Oscilloscope trace showing wave form of low-intensity screech taken with acoustic probe.

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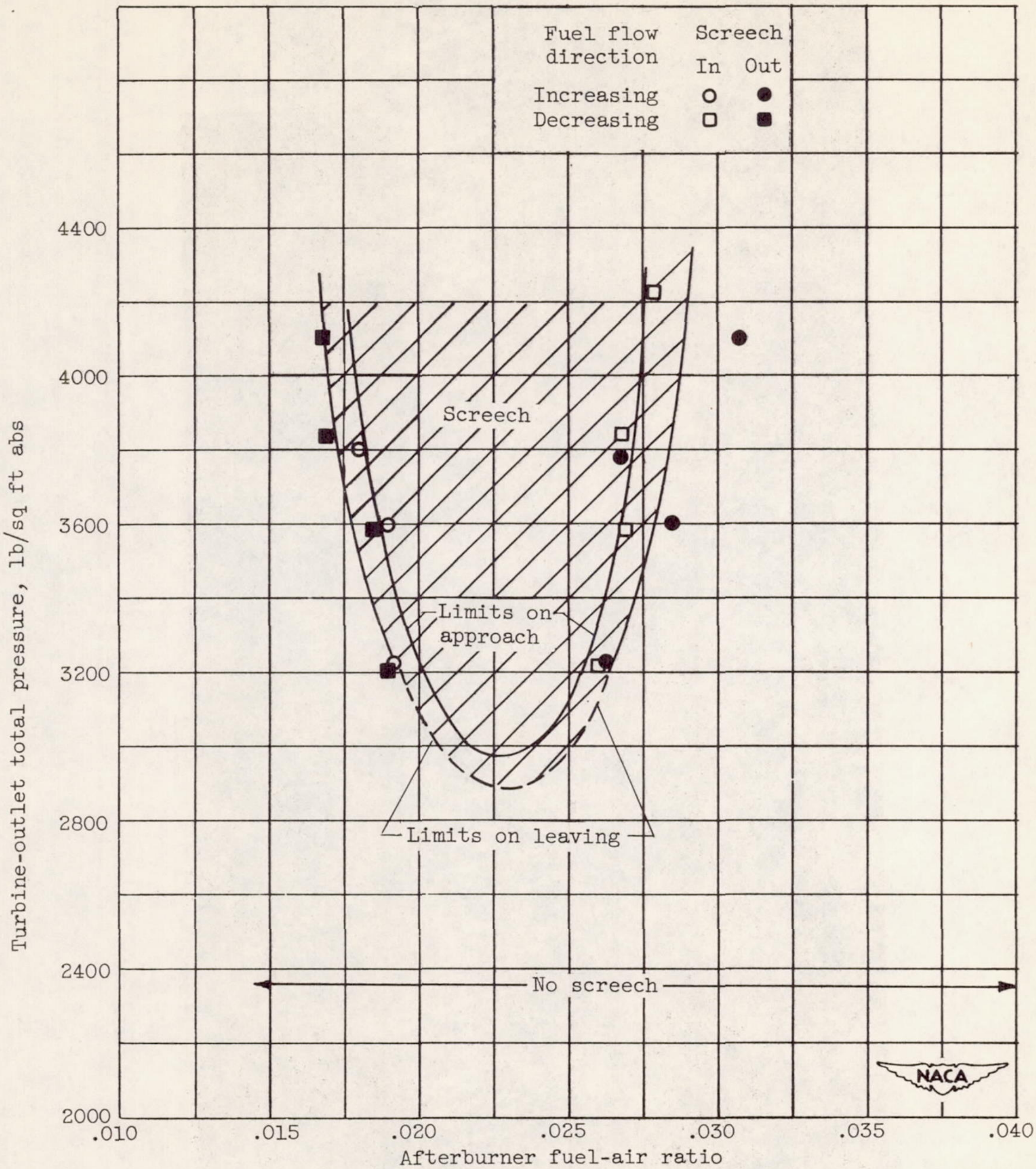

Figure 17. - Variation of screech limits with pressure level of operation for configuration 37.

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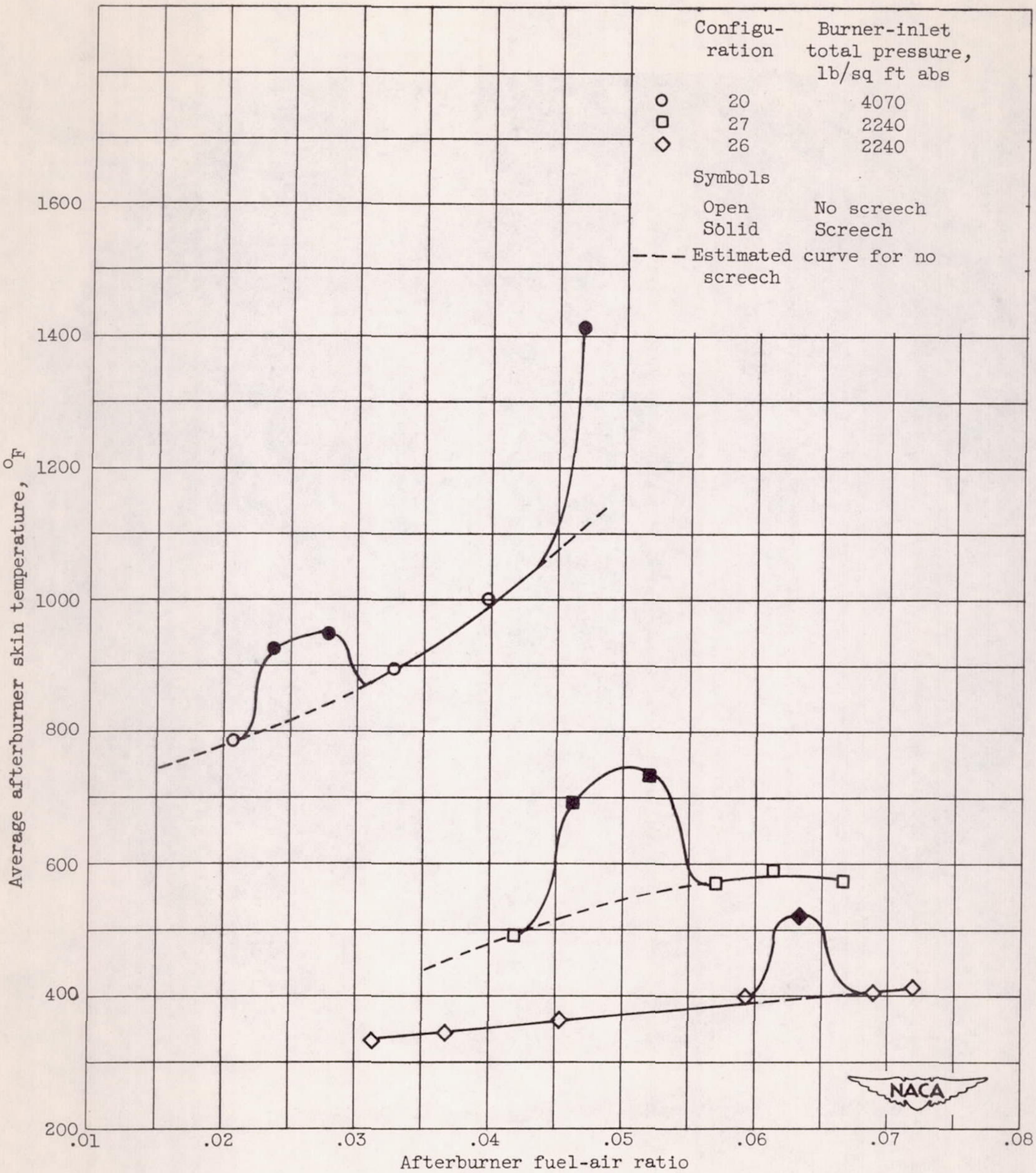

Figure 18. - Effect of screech on afterburner skin temperature.

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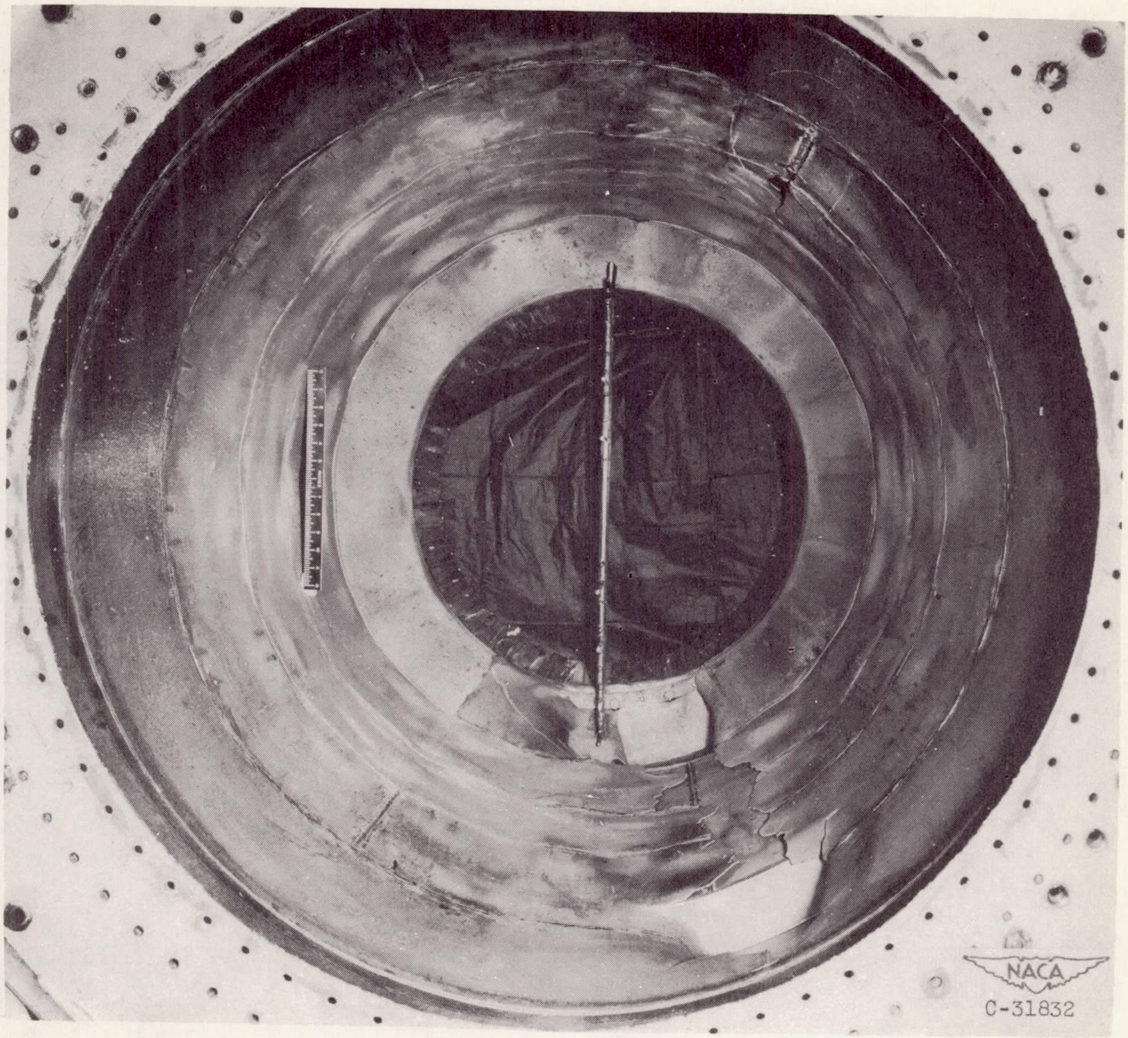

Figure 19. - Destruction of combustion chamber due to screech. Configuration 36.

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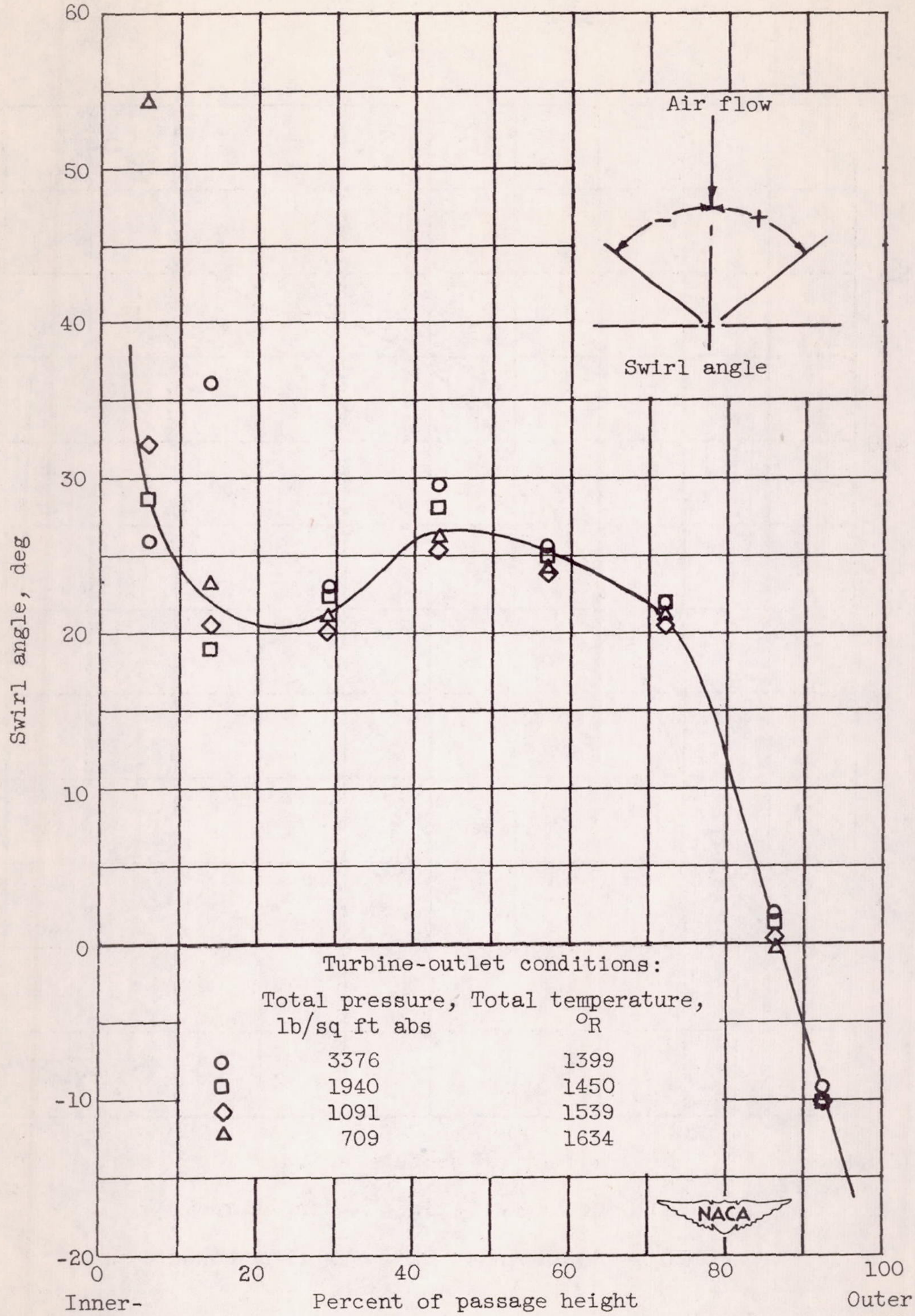
CE-7



(a) Original conditions.

Figure 20. - Diffuser flow conditions.

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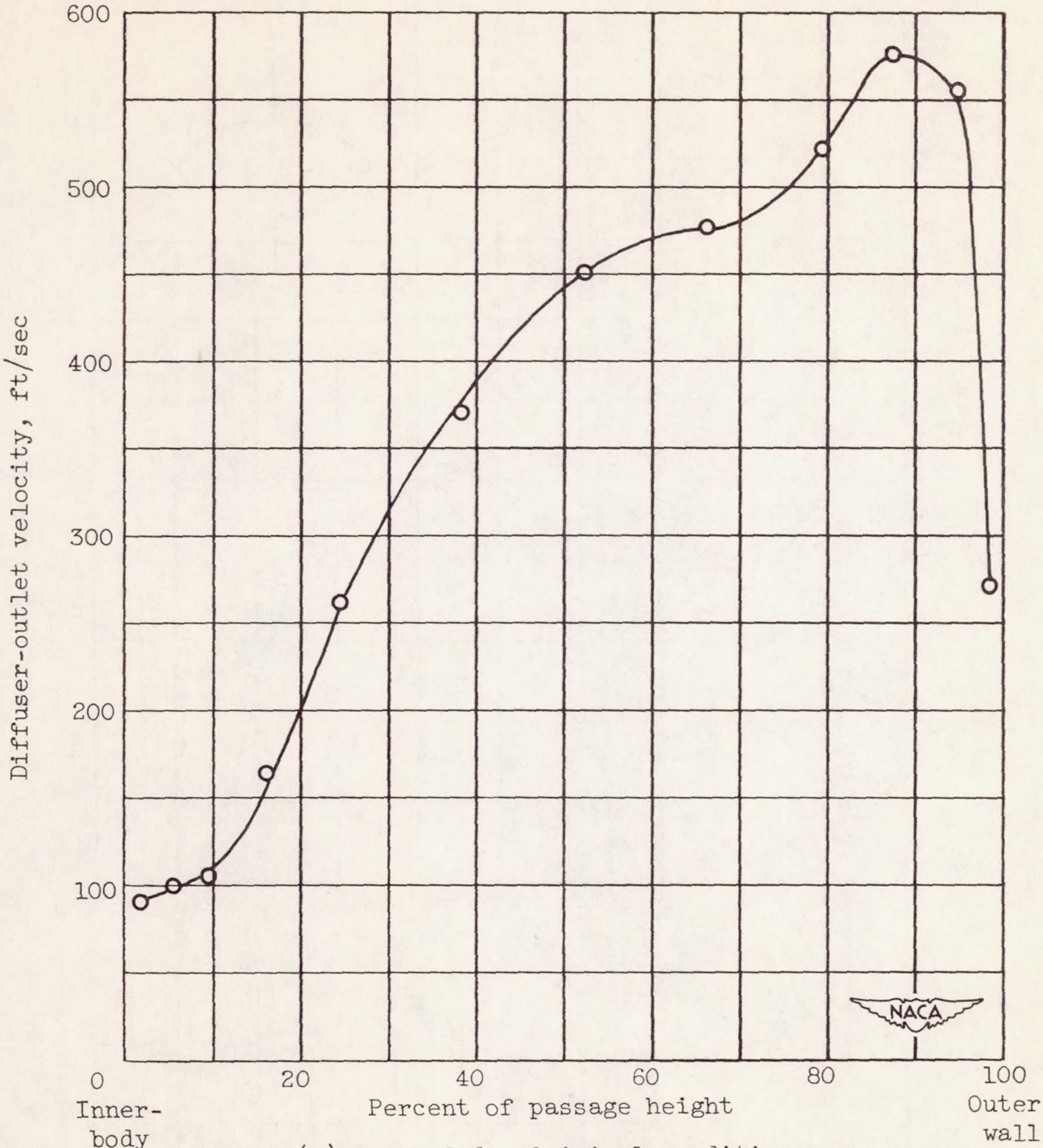

(a) Concluded. Original conditions.

Figure 20. - Continued. Diffuser flow conditions.

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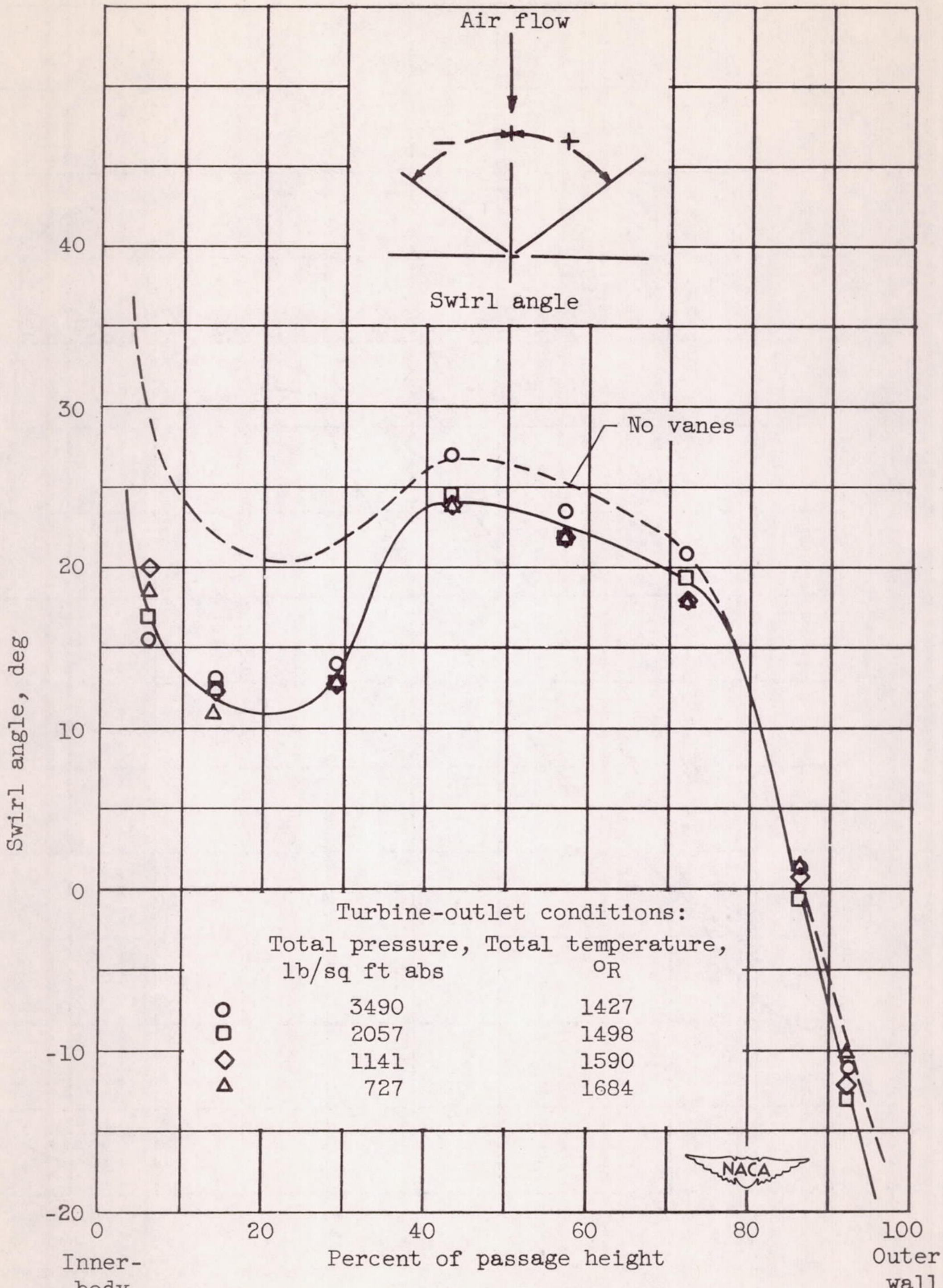
CE-7 back



(b) Conditions with 33 short antiswirl vanes.

Figure 20. - Continued. Diffuser flow conditions.

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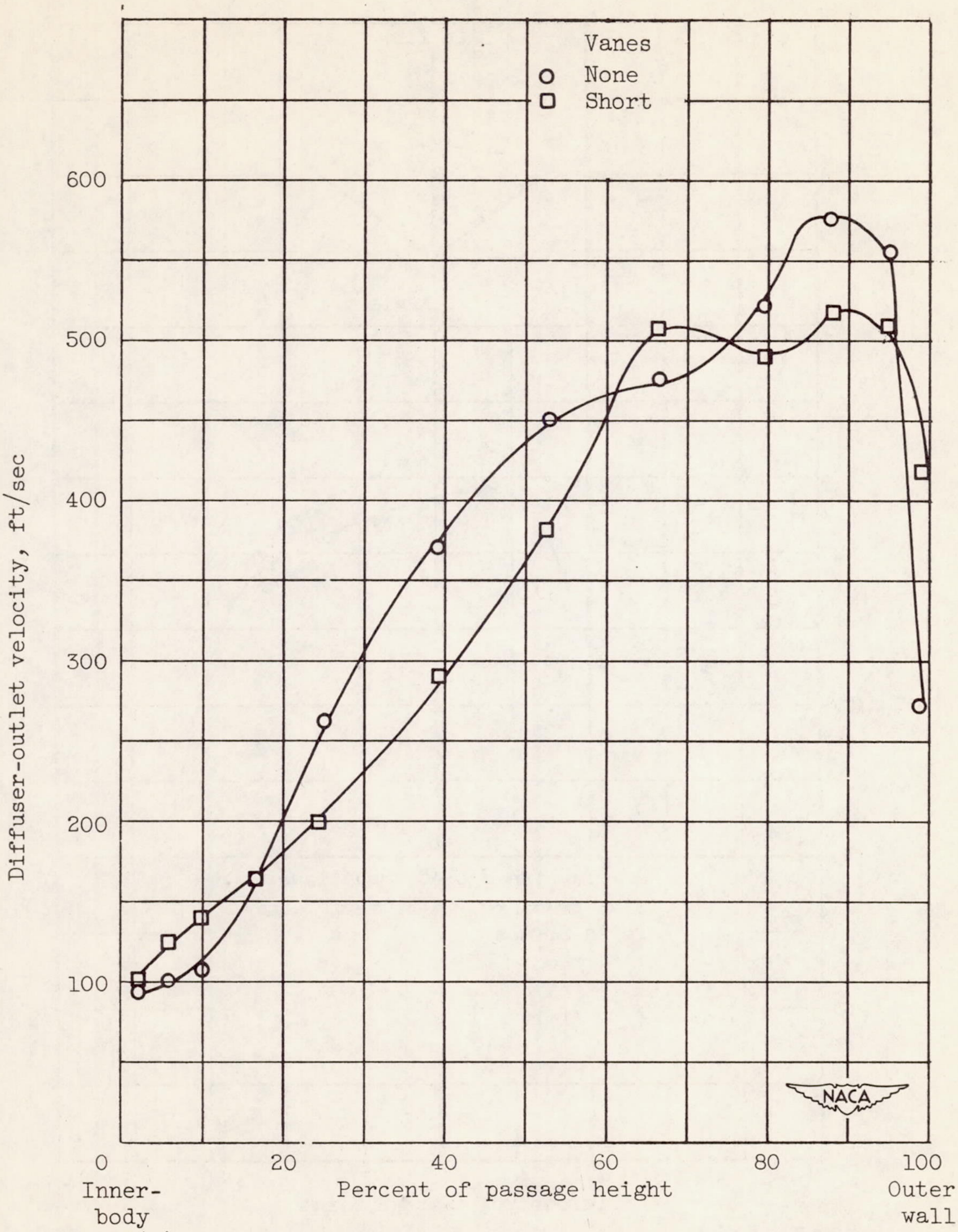
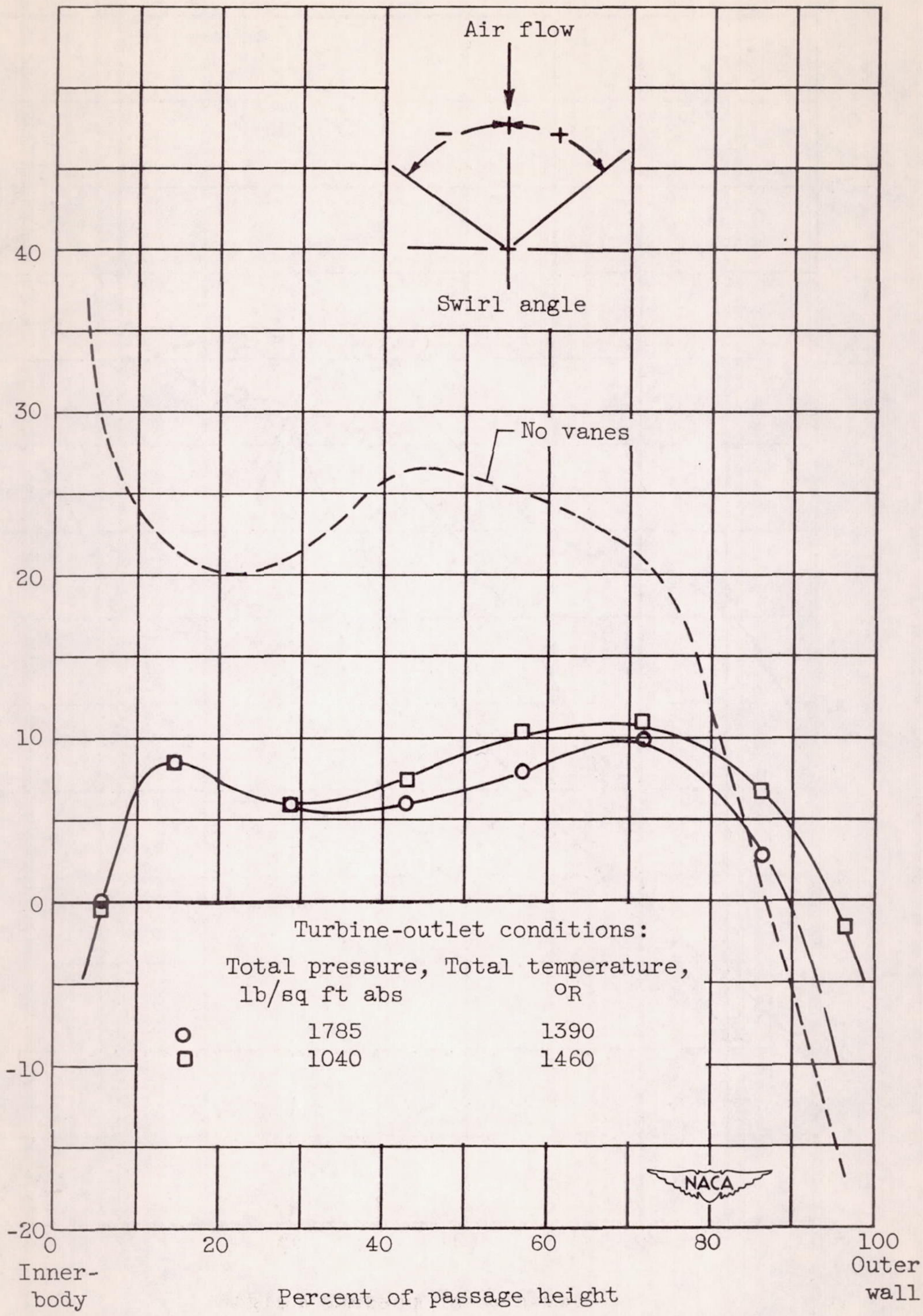


(b) Concluded. Conditions with 33 short antiswirl vanes.

Figure 20. - Continued. Diffuser flow conditions.

3055



(c) Conditions with full-passage antiswirl vanes.

Figure 20. - Continued. Diffuser flow conditions.

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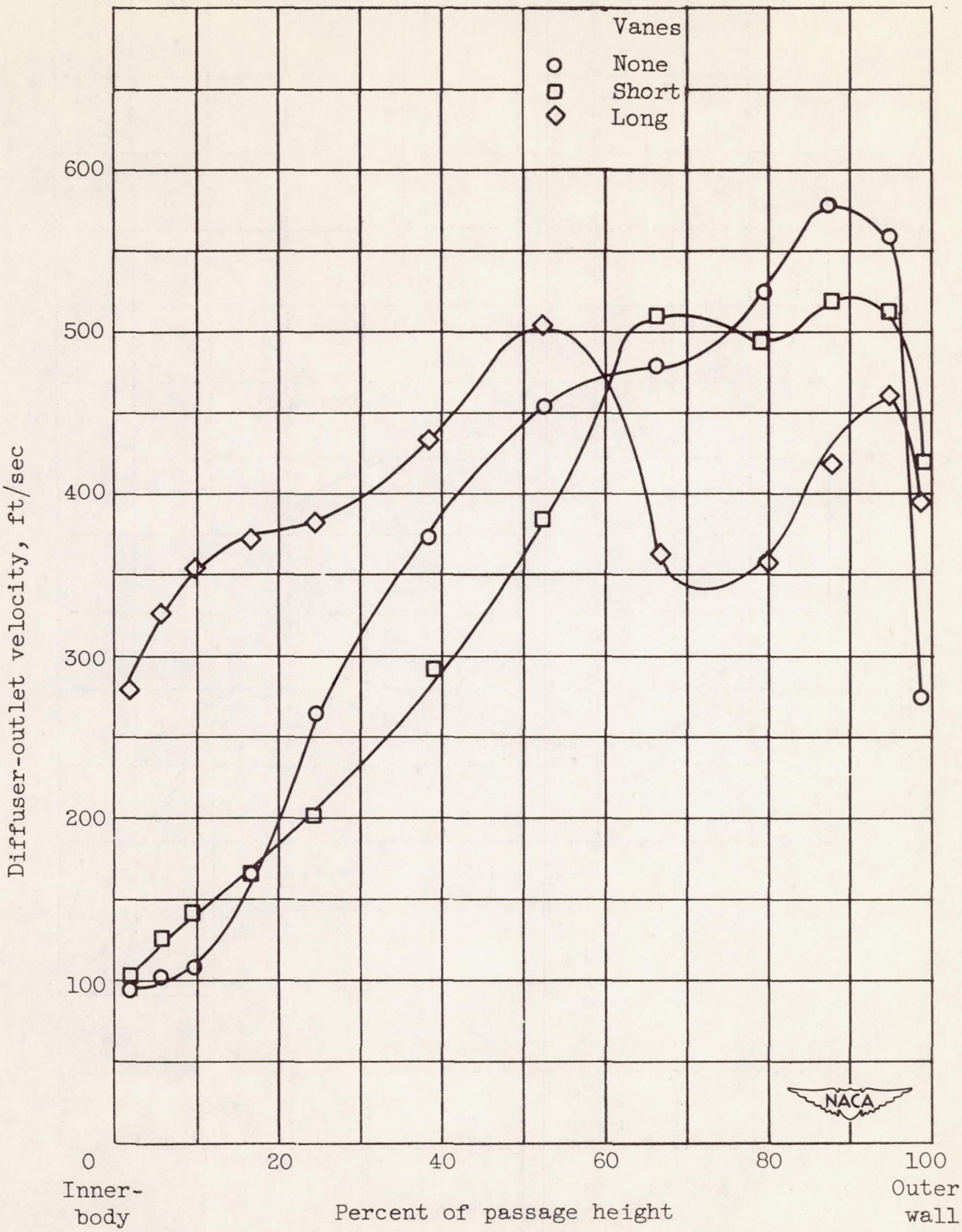

(c) Concluded. Conditions with full-passage antiswirl vanes.

Figure 20. - Concluded. Diffuser flow conditions.

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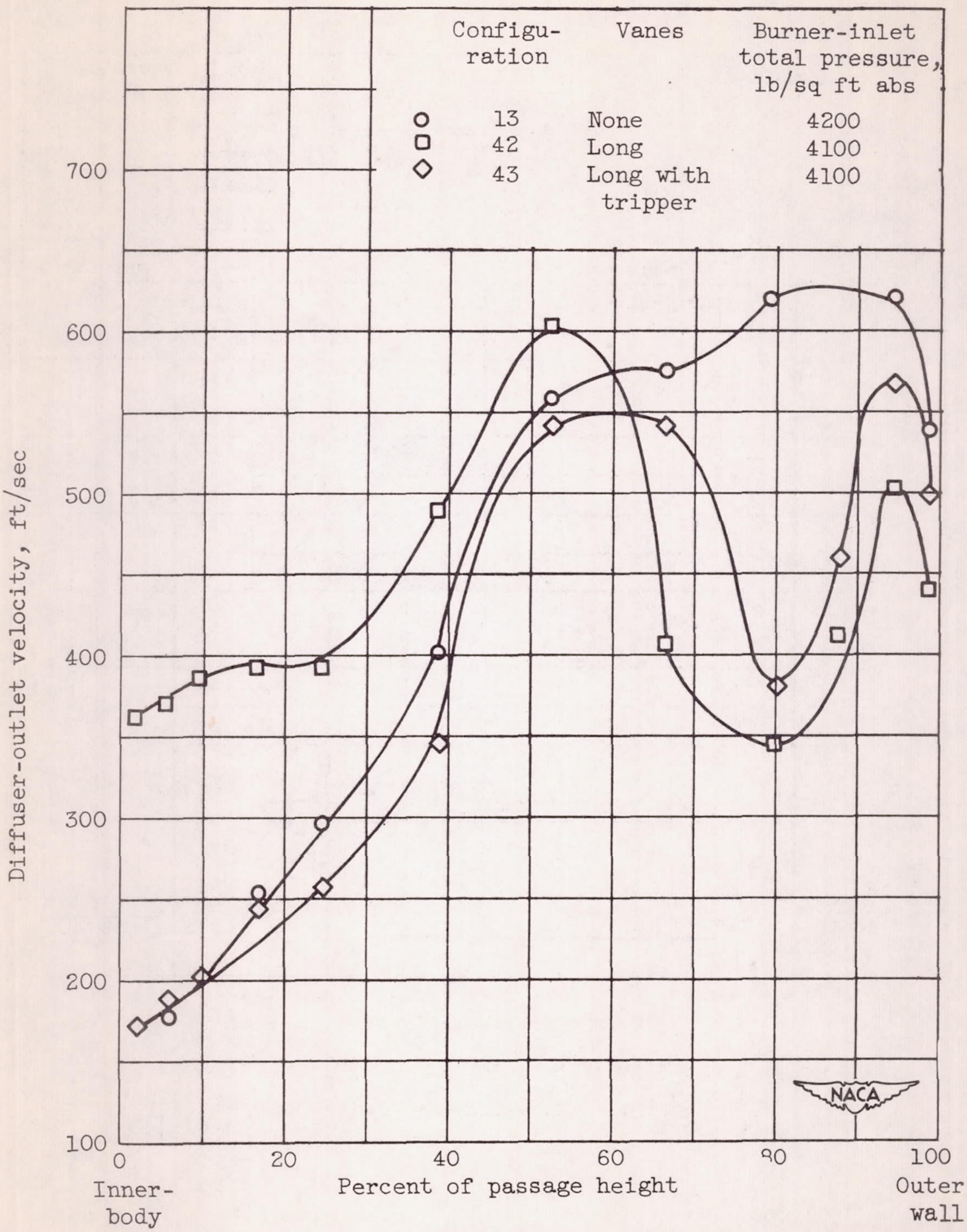

Figure 21. - Effect of boundary-layer tripper on velocity profile.

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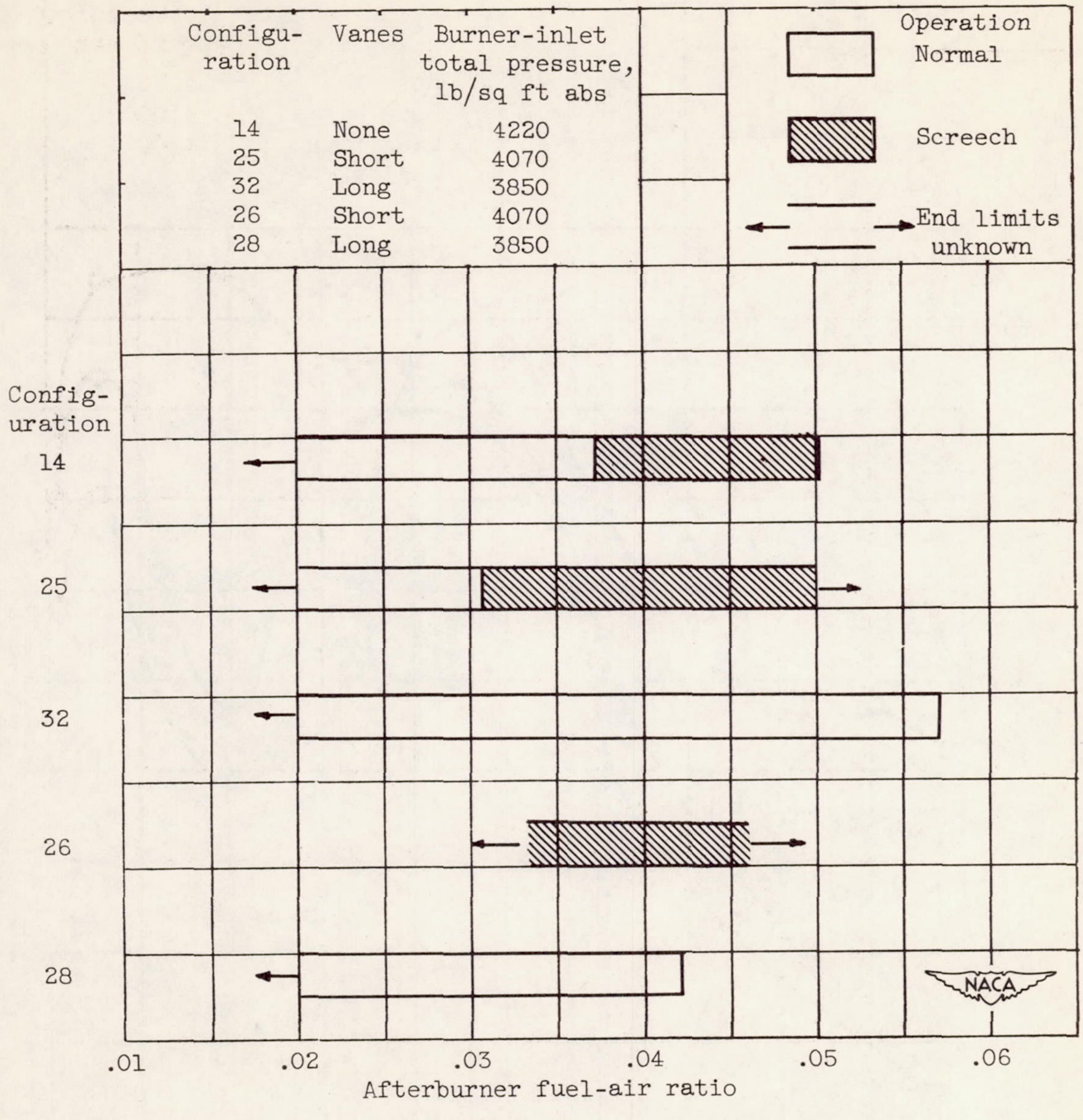

(a) Effect of antiswirl vanes.

Figure 22. - Screech limits.

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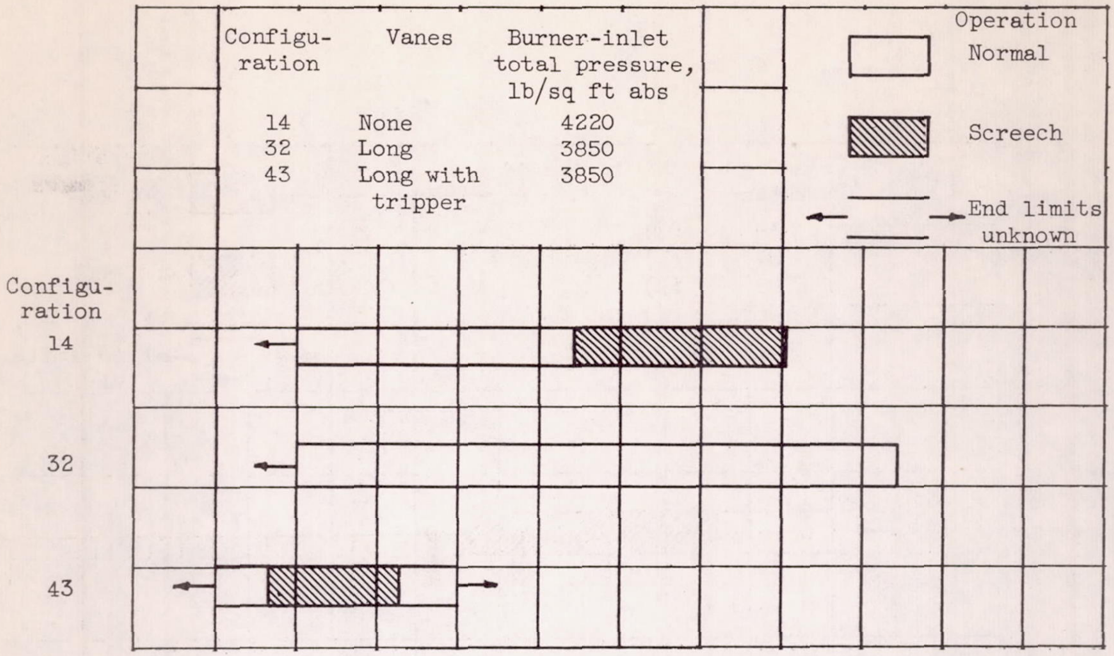
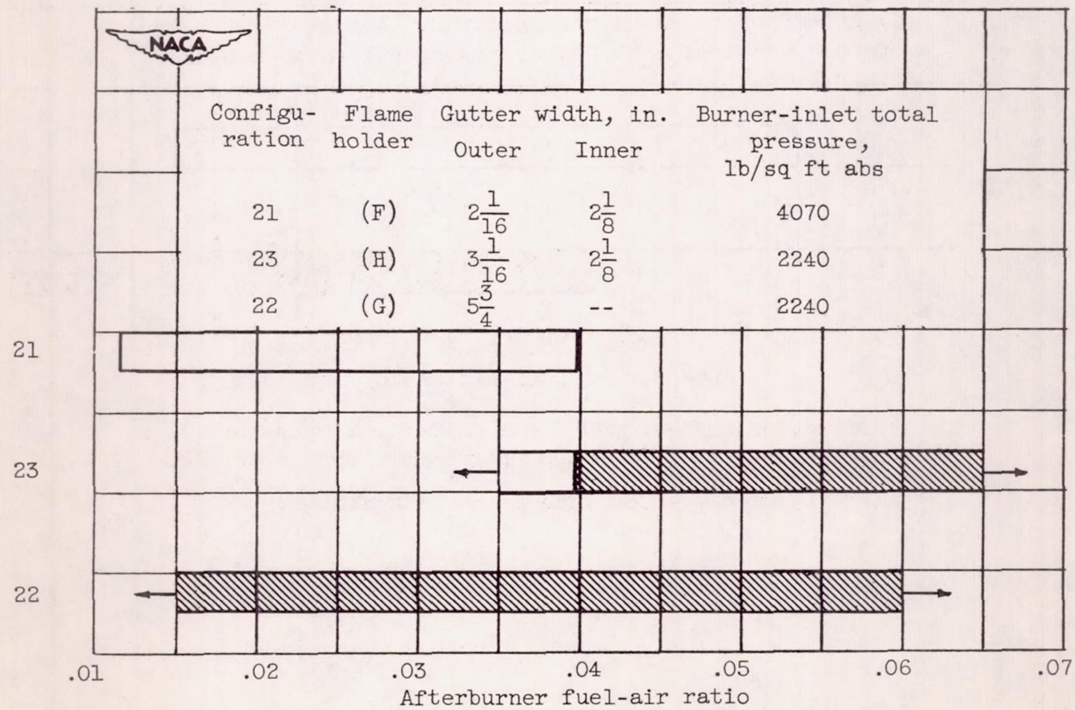
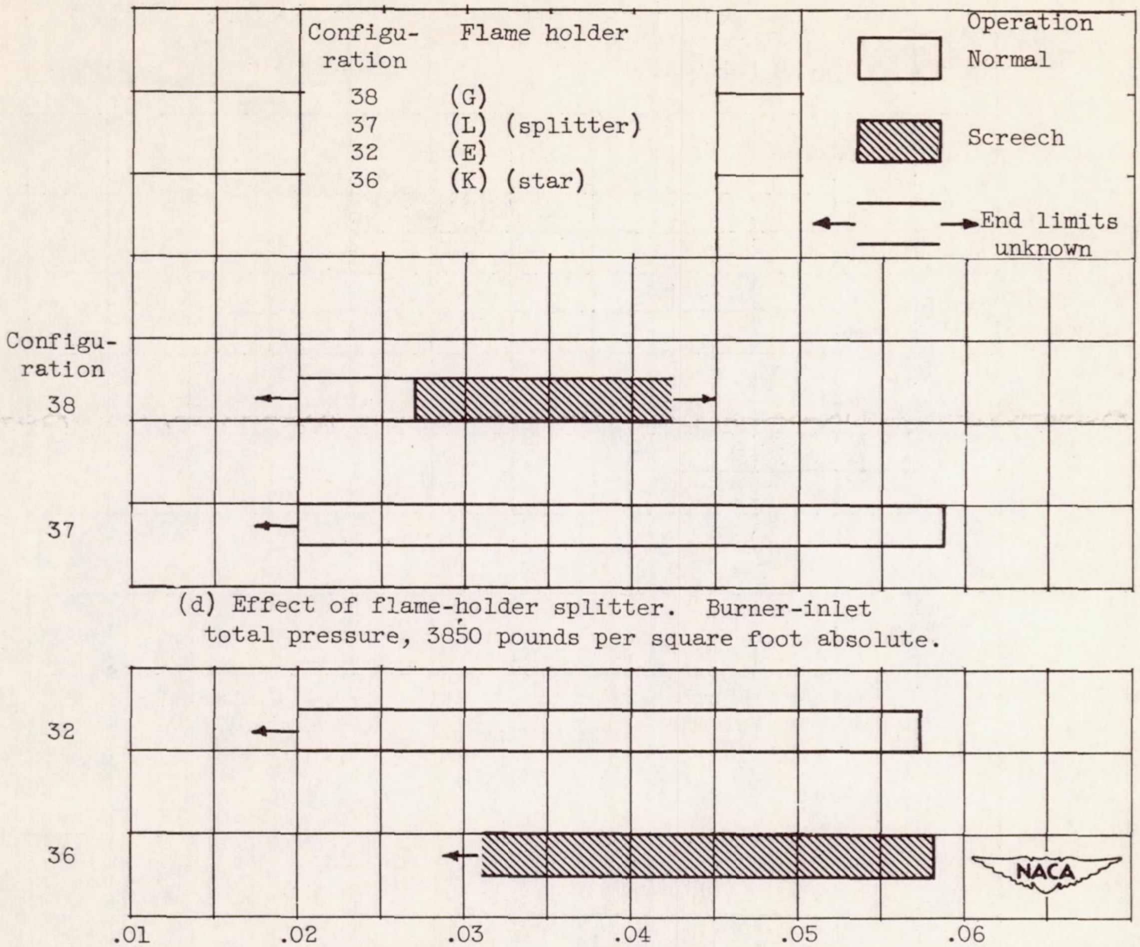


(b) Effect of velocity profile.



(c) Effect of flame-holder gutter width.

Figure 22. - Continued. Screech limits.



(d) Effect of flame-holder splitter. Burner-inlet total pressure, 3850 pounds per square foot absolute.

(e) Effect of star-shaped flame holder. Burner-inlet total pressure, 3850 pounds per square foot absolute.

Figure 22. - Concluded. Screech limits.

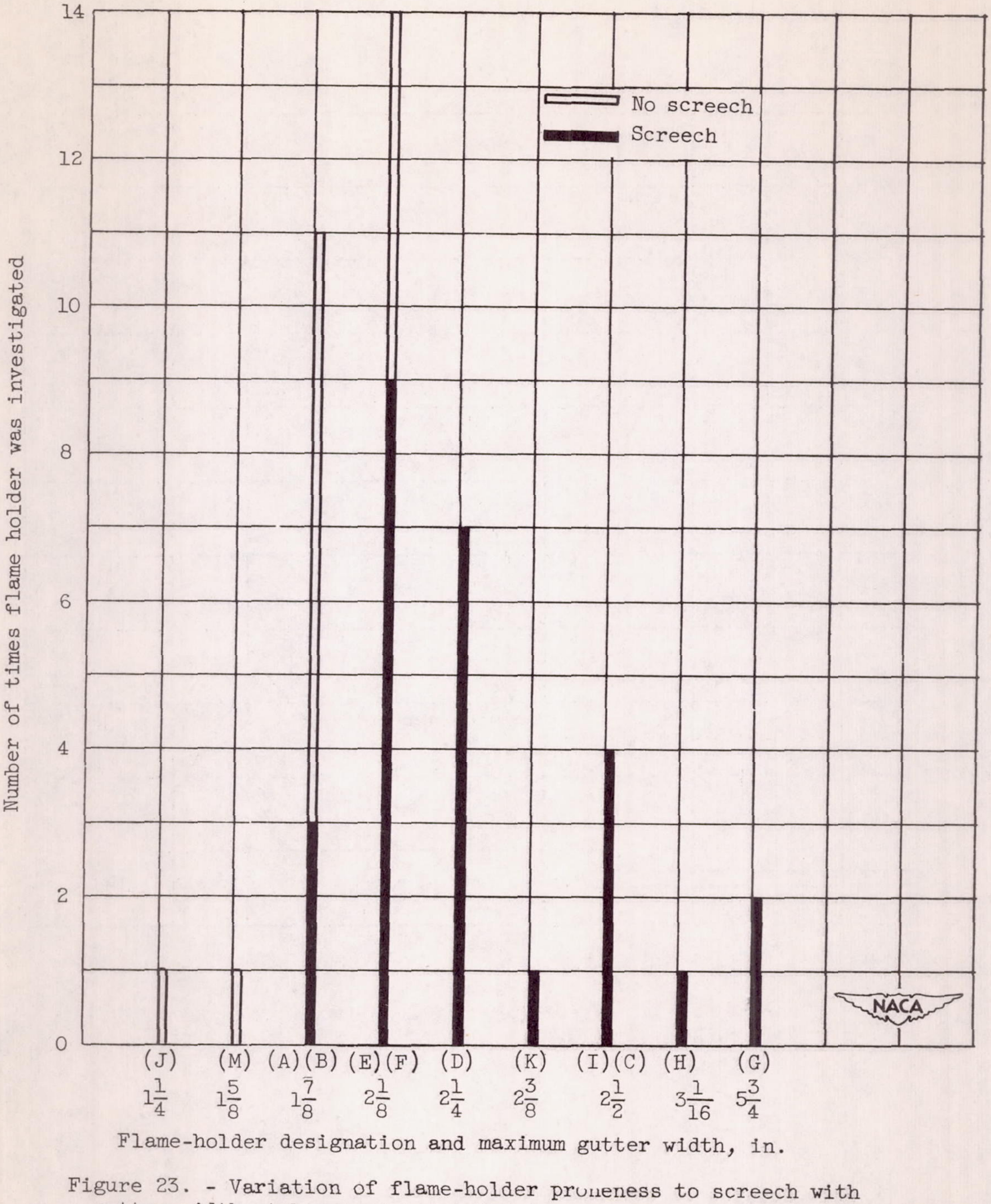


Figure 23. - Variation of flame-holder proneness to screech with gutter width at burner-inlet total pressures from 3850 to 4220 pounds per square foot absolute.

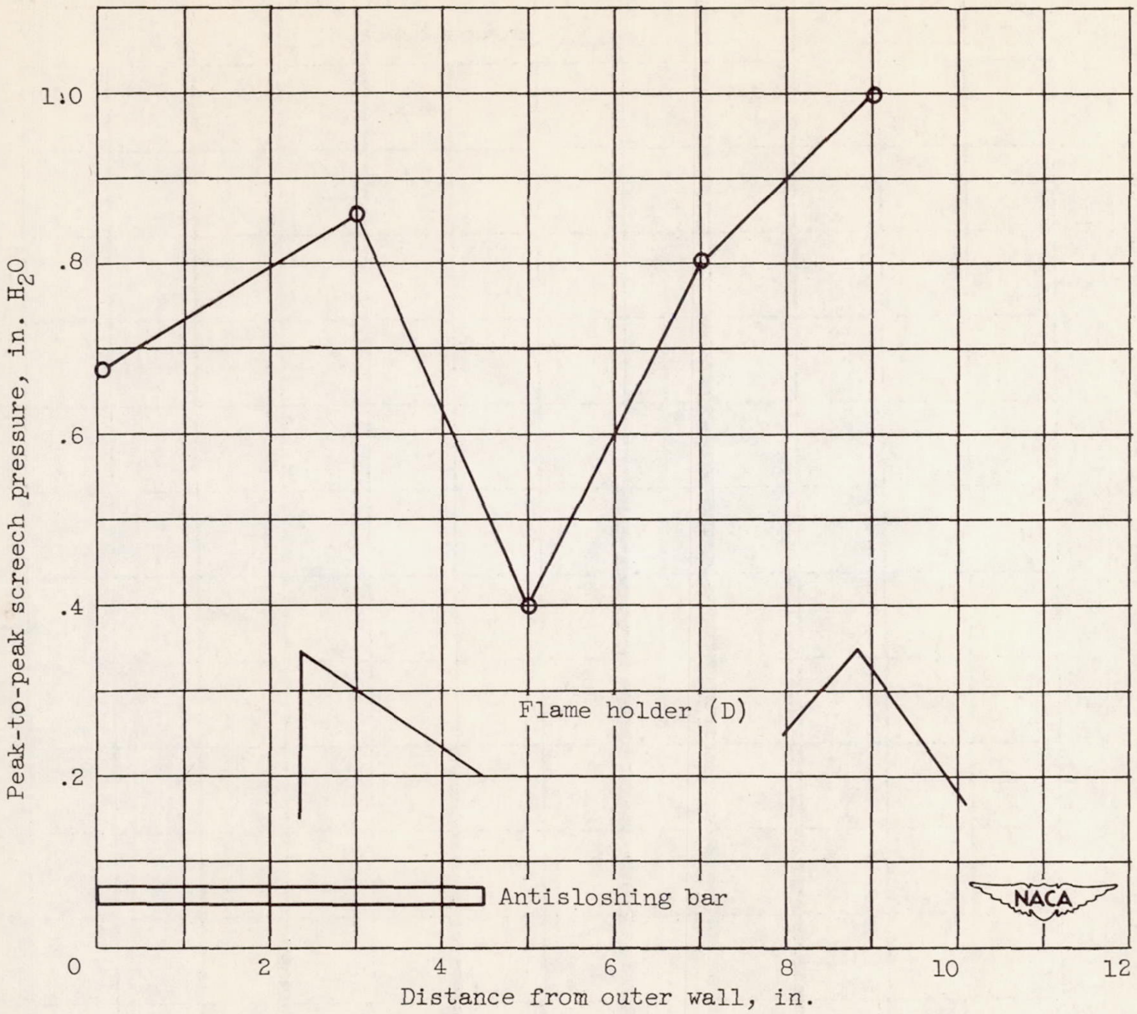


Figure 24. - Variation of screech pressure amplitude downstream of flame holder. Configuration 39.

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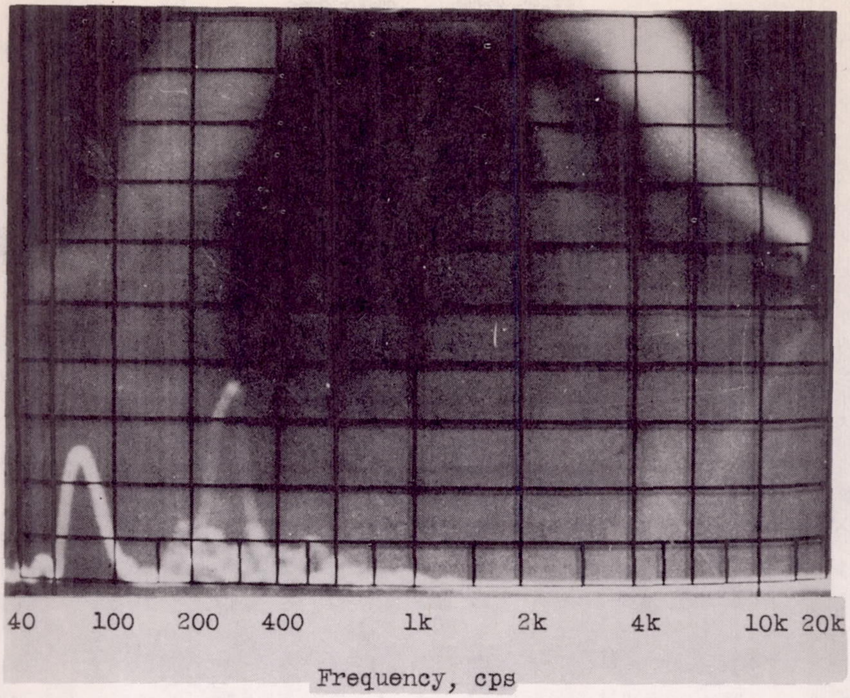
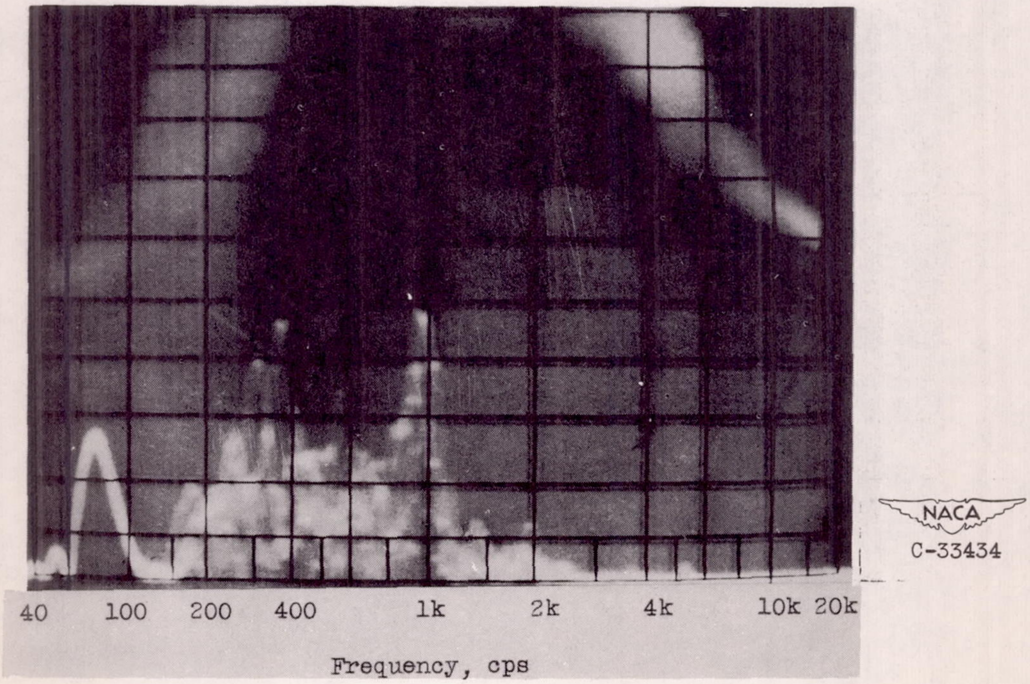
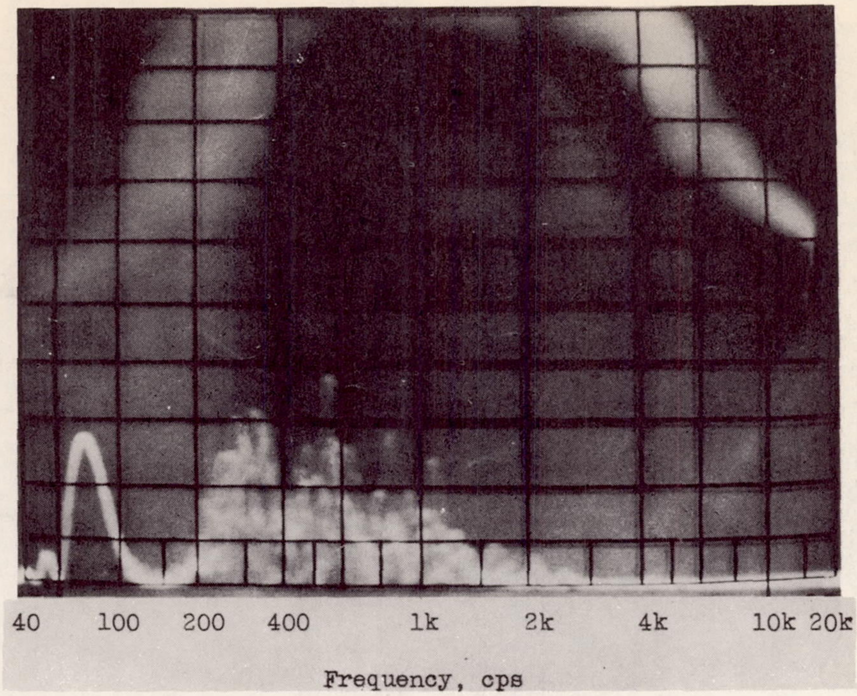


(a) Afterburning but no screech.

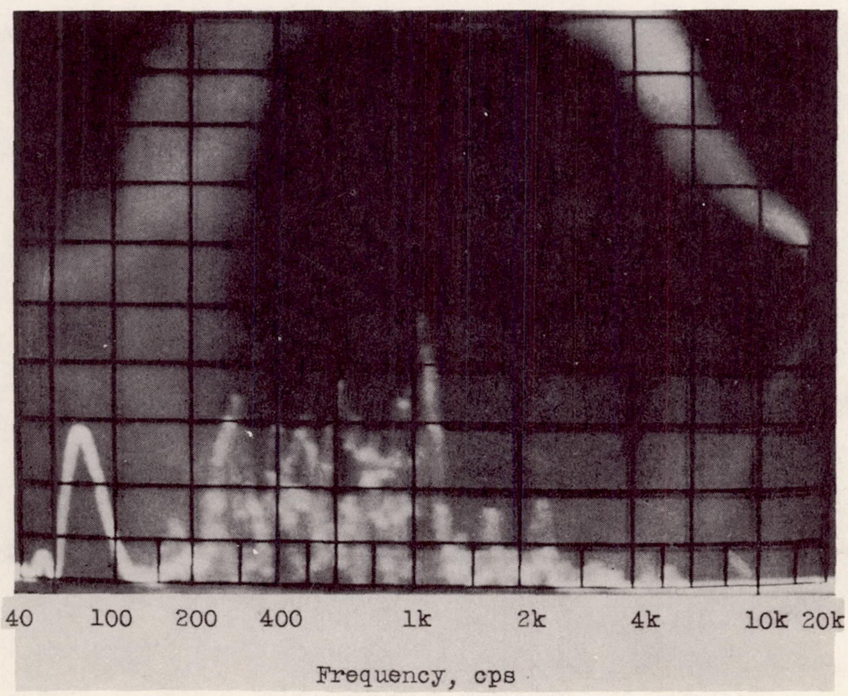


(b) Screech at low fuel-air ratio (0.024).

Figure 25. - Tape recording of frequency shift between screech at high and low fuel-air ratios.



(c) Rough burning or low-intensity screech (undiscernible to the human ear) between screech regions at high and low fuel-air ratios.



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(d) Screech at high fuel-air ratio (0.052).

Figure 25. - Concluded. Tape recording of frequency shift between screech at high and low fuel-air ratios.

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