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RESEARCH MEMORANDUM

VELOCITY AND TEMPERATURE FIELDS IN CIRCULAR JET EXPANDING FROM CHOKED NOZZLE INTO QUIESCENT AIR

By Morris D. Rousso and Fred D. Kochendorfer

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Cleveland, Ohio

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

VELOCITY AND TEMPERATURE FIELDS IN CIRCULAR JET EXPANDING FROM CHOKED NOZZLE INTO QUIESCENT AIR

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SUMMARY

A study to determine gross spreading characteristics of jets expanding from choked convergent and convergent-divergent nozzles has been made by means of total-pressure and total-temperature surveys. The surveys were made in the region from the nozzle exit to a station 6 nozzle diameters downstream for nozzle pressure ratios from 2.5 to 16.0.

A comparison of a subsonic jet with a jet issuing from a choked convergent nozzle at a nozzle pressure ratio only slightly greater than the critical showed close ageeement between corresponding Mach number and corresponding temperature profiles near the nozzle exit. Farther downstream, however, the agreement was not so good. Although the qualitative effect of further increasing the nozzle pressure ratio was to widen the jet, the pressure and temperature profiles in the subsonic mixing region were similar to those of a subsonic jet. The effects of jet expansion were eliminated by referencing all jet dimensions (jet diameter and distance downstream) to the diameter of the contour for $M/M_j = 0.5$. The results of this correlation indicated that the mixing process for jets expanding from either convergent or convergent-divergent nozzles over a range of pressure ratios was relatively independent of the jet Mach number.

In order to ascertain the utility of the results for other than the conditions investigated, the effects of jet temperature, Reynolds number, and humidity on the pressure and temperature distributions were briefly investigated. The results indicated that the downstream Mach number profiles for a heated jet are slightly narrower than those for an unheated jet whereas the downstream temperature profiles were unaffected by nozzle temperature change and that the effects of Reynolds number and humidity on jet spreading are negligible.

INTRODUCTION

Whereas subsonic jet flow has been widely studied in the past, only a limited amount of work has been done in the field of supersonic

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jet flow. An experimental investigation with an interferometer of the turbulent mixing of a free supersonic jet operated with no transverse pressure gradient is reported in reference 1. In this investigation it was found that the velocity profile characteristics in the mixing region are very similar to those of a subsonic jet. Other studies are devoted to experimental and theoretical analyses of the alternate expansions and contractions in supersonic jets issuing from underexpanded nozzles (references 2 to 4). These investigations of the periodic structure, however, neglect mixing at the jet boundary and do not permit the prediction of temperature and pressure fields in supersonic viscous jets. A more detailed study of the first period of a supersonic jet taking into account the effects of mixing was conducted by Ladenburg, VanVoorhis, and Winckler (reference 5) by means of interferometer, shadowgraph, and schlieren techniques. The interferograms were used to compute density variations, and the corresponding variations in Mach number, pressure, and temperature were computed with the assumption of isentropic flow. A comparison of these interferometer results with probe shadowgrams indicates good agreement between Mach numbers computed by means of both techniques up to 3/4 diameter downstream of the nozzle exit.

Although the first section of the jet within 1 diameter of the nozzle exit may be amenable to analysis by potential-flow theory, the remainder of the jet offers no immediate promise of analytical treatment and remains relatively unexplored. Accordingly, a simple investigation by means of total-pressure and temperature probes to determine the gross spreading characteristics of such jets was considered to be of value. Among the obvious applications of such information is the prevention of adverse heating and buffeting from jets located in close proximity to aircraft surfaces.

Investigations are consequently being conducted at the NACA Lewis laboratory to study the spreading characteristics of jets. One phase of this program was concerned with total-temperature profiles for twin jets. Another phase consisted of total-pressure surveys of twin and single jets. A third phase, the results of which are presented herein, consisted of total-temperature and total-pressure surveys of single jets expanding from convergent nozzles, and total-pressure surveys of a jet expanding from a convergent-divergent nozzle.

The parameters varied in this investigation included nozzle pressure ratio and the ratio of the nozzle-inlet temperature to the ambient temperature. A limited study was made of the effects of Reynolds number and humidity on jet spreading. Portions of the present data have been subsequently reported but are included herein for consistency and completeness.

SYMBOLS

The following symbols are used in this report:

$D_{M/M_j = 0.5}$ diameter of contour for which $M/M_j = 0.5$

$D_{\theta = 0.5}$ diameter of contour for which $\theta = 0.5$

M Mach number

M_j theoretical jet Mach number, $M_j = \left\{\frac{2}{\gamma-1}\left[\left(\frac{P_p}{p_0}\right)^{\frac{\gamma-1}{\gamma}} -1\right]\right\}^{\frac{1}{2}}$

P total pressure

p static pressure

R ratio of radial distance from jet center line to nozzle diameter

T total temperature

X ratio of vertical distance of each tube from jet center line to nozzle diameter (see fig. 1)

Y ratio of lateral distance of rake from jet center line to nozzle diameter (see fig. 1)

Z ratio of axial distance downstream of nozzle exit to nozzle diameter

γ ratio of specific heats

θ dimensionless temperature ratio, $\frac{T-T_0}{T_p-T_0}$

Subscripts:

0 ambient

p nozzle inlet

r rake

APPARATUS AND PROCEDURE

The apparatus, schematically shown in figure 1, consisted of a primary chamber with removable convergent and convergent-divergent axially symmetric nozzles that discharged into a low-pressure receiver. For the pressure surveys, a receiver having a cross section of 9 by 10 inches was used and for temperature surveys a circular receiver 2 feet in diameter was used. Nozzle dimensions are given in figure 1(b).

The inlet to the primary chamber could be opened to the atmosphere or connected to either the laboratory compressed-air or dry-air systems. The total pressure at the nozzle inlet P_p was measured by four total-pressure tubes in the primary chamber and the receiver static pressure was measured by static orifices in the receiver wall. The receiver was connected to the laboratory exhauster system, and any pressure between atmospheric and 1.8 inches of mercury absolute could be obtained by throttling, thus providing the range of pressure ratios desired with the pressure at the inlet to the primary chamber being atmospheric.

Propane was mixed with the incoming atmospheric air and burned upstream of the primary chamber for the hot-jet studies. The nozzle-inlet temperature was 950° F for the hot pressure surveys and 525° F for the temperature surveys. The values of γ for these two temperatures were 1.35 and 1.37, respectively. Pressures and temperatures in the jet were measured by traversing rakes having either 23 total-head tubes or 23 iron-constantan thermocouples. The thermocouples used in the experiments were of the shielded type (see fig. 1(c)) with aspirating holes in the walls of the shield. Previous results with this type of thermocouple have given recoveries of 0.99 in supersonic flow and it was therefore felt that the readings obtained were close to the true total temperature within the accuracy of the measuring technique.

The pitot tubes and the thermocouples were alined parallel to the nozzle axis. Lateral surveys were made for a range of nozzle pressure ratios at 1, 2, 4, and 6 exit diameters downstream of the nozzle. For the pressure data the readings obtained with multiple mercury manometers were accurate within ±0.02 inch and for the temperature data the thermocouple readings were accurate within ±2° F.

For the Reynolds number investigation, the primary chamber was connected to the laboratory compressed-air system in which air was available at pressures up to 115 pounds per square inch absolute and for the humidity investigation the primary chamber was connected to the laboratory dry-air system.

DEFINITION OF JET BOUNDARY

Because the velocity in the outer fringe of the jet approaches zero asymptotically, the jet boundary is arbitrarily defined as the locus of points for which the Mach number ratio M/M_j attains a value of 0.11, where M is the Mach number at any point in the jet fringe and M_j is the hypothetical jet Mach number corresponding to isentropic expansion from P_p to p_0.

For the subsonic boundary regions of the jet, it can be assumed that the pressure measured by the rake is the true total pressure. It can also be assumed that the static pressure in the boundary region is equal to the receiver pressure p_0. The value of the rake-pressure ratio for points near the boundary is then given by

$$\frac{p_0}{P_r} = \left\{ \frac{1}{1 + \left(\frac{M}{M_j}\right)^2 \left[\left(\frac{P_p}{p_0}\right)^{\frac{\gamma-1}{\gamma}} - 1 \right]} \right\}^{\frac{\gamma}{\gamma-1}} \tag{1}$$

The ratio p_0/P_r is plotted in figure 2 as a function of P_p/p_0 for several values of M/M_j and for $\gamma = 1.40$. The values of M/M_j given in equation (1) lose significance in regions of the jet where p_0/P_r is less than 0.53, because in these regions the static pressure is not necessarily equal to the ambient pressure and the pitot-pressure readings are subject to shock losses. For this reason, only the subsonic portion of the jet is considered for the Mach number profiles.

For each position of the rake, the location of the point for which M/M_j equals 0.11 was obtained by plotting the value of p_0/P_r for each pitot tube as a function of tube position X. As an example, in figure 3 the value of p_0/P_r is plotted as a function of tube position X for a nozzle pressure ratio of 16. Because, at this nozzle pressure ratio the value of p_0/P_r for $M/M_j = 0.11$ is 0.950 (fig. 2), the value of X corresponding to $M/M_j = 0.11$ is 1.50 nozzle-exit diameters.

The data obtained from the temperature surveys are presented in the form of the dimensionless ratio $\theta = \frac{T-T_0}{T_p-T_0}$.

RESULTS AND DISCUSSION

Pressure Surveys

The data obtained from the total-pressure surveys of a jet expanding from a convergent nozzle will be discussed in two parts; the first part is concerned with an unheated jet, and the second part considers a heated jet.

Unheated jets. - The boundaries of an unheated jet expanding from a convergent nozzle as determined from pressure surveys are given in figure 4 for an axial station 1 nozzle diameter downstream of the nozzle exit ($Z = 1$) for a range of nozzle pressure ratios. The boundaries were obtained by cross-plotting the points on the rake-survey pressure distributions for which $M/M_j = 0.11$. The boundaries so defined are adequately represented by circles that are concentric with the nozzle and, consequently, a single radius can be used to define each boundary. In the same manner, a single radius was found to define each boundary as determined from the temperature surveys.

Values for the radii of the jet pressure boundaries were determined in a similar manner for downstream stations of 2, 4, and 6 diameters and the faired results are summarized in figure 5. The boundaries are given as functions of the axial distance from the nozzle exit for several values of nozzle pressure ratio P_p/p_0. Increasing the pressure ratio results in an increased rate of expansion immediately downstream of the nozzle, as expected. Following the initial rapid expansion, the rate of growth of the jet radius decreased and appeared to vary only slightly with distance downstream. (In this discussion, all nozzle pressure ratios for which the static pressure in the nozzle-exit plane is greater than the ambient pressure are defined as overpressure ratios.)

In order to show the correspondence between the jet boundary arbitrarily defined by the Mach number ratio 0.11 and the jet visible in a schlieren photograph, points obtained from the pressure surveys at nozzle pressure ratios of 2.5 and 16.0 have been superimposed on the corresponding photographs in figure 6. The boundary, visible in the schlieren photographs, is in close agreement with the boundary determined by the pressure survey, although as the mixing region thickens the boundary becomes less clearly defined in the photographs.

Mach number profiles determined from the pressure surveys are given in figure 7 for an unheated jet at several axial stations and for a range of nozzle pressure ratios. The jet for which the data are presented in figure 7 is expanding from a convergent nozzle. In addition to the curves for jets at overpressure ratios ($P_p/p_0 > 1.89$), the velocity profiles are presented for a subsonic jet (reference 6)

having a nozzle-exit velocity of 283 feet per second ($P_p/p_0 = 1.04$). At downstream stations of 1 and 2 diameters (figs. 7(a) and 7(b)), the velocity profiles for the subsonic jet were nearly the same as those for the jet at a nozzle pressure ratio of 2.5. At 4 and 6 diameters (figs. 7(c) and 7(d)) however, the agreement is not so good.

The spreading characteristics of overpressure jets depend on both the expansion that occurs as the jet leaves the nozzle and the mixing that occurs as the jet reacts with the surrounding fluid. If mixing effects are independent of the jet velocity, it should be possible to correlate the profiles for different pressure ratios (that is, different jet velocities) if the effects of jet expansion can be eliminated. A possible method for eliminating expansion effects is to refer all lengths to some length that is known to depend on expansion effects, such as the diameter of the contour for $M/M_j = 0.5$. Such a method of correlation has been applied to the profiles of figure 7 and the results are presented in figure 8. The lack of dependence of the mixing region velocity profile upon the absolute value of the velocity, as evidenced by the correlation of the corrected data points in figure 8 and which is known to exist for a subsonic jet, appears to be also valid for supersonic jets.

(Although the limiting Mach number ratio in the subsonic region for a jet operated at a pressure ratio of 16.0 is 0.41 (see fig. 2) the profiles of figure 7 were extrapolated to a value of $M/M_j = 0.50$ in order to perform the preceding correlation.)

Schlieren photographs of a jet expanding from a convergent nozzle at several pressure ratios are presented in figure 9. A line corresponding to the Prandtl-Meyer expansion angle is drawn from the edge of the nozzle for each pressure ratio. The agreement between these constructed angles and the expansion angle of the jet visible in the schlieren photographs indicates that near the exit the jet expands according to the rules of potential-flow theory.

Heated jets. - A comparison between the Mach number profiles for unheated and heated jets over a range of nozzle-pressure ratios is given in figure 10. In general, the trends observed with the heated jet are similar to those with the unheated jet. The heated-jet profiles, though smaller than the profiles for an unheated jet near the nozzle exit approach the unheated-jet profiles farther downstream, particularly at 6 diameters (fig. 10(d)). These Mach number profiles for the heated jets were correlated by the method previously outlined (fig. 8) to eliminate the effects of expansion. The results of the correlation, given in figure 11, indicate fair agreement among the correlated contours for the heated jet over the range of pressure ratios investigated.

Reynolds number and condensation effects. - In order to extend the utility of the jet-boundary charts, a limited study was made of the effects of jet Reynolds number and humidity on jet spreading. If the flow in the jet mixing region is turbulent, the effect of Reynolds number on the Mach number profile and on the resulting jet boundary should be small. In order to determine the magnitude of this effect, the pressure at the inlet P_p was varied and the ratio P_p/p_0 was held constant. The Reynolds number of the fluid in the mixing region can also be varied by varying the nozzle-inlet temperature, the ratio of the nozzle-inlet temperature to the ambient temperature, or the nozzle pressure ratio. However, because a change in any of these variables causes a change in the jet boundary that may mask any change that might result from the corresponding change in the Reynolds number, the effect of Reynolds number alone can best be studied by varying the nozzle-inlet pressure and holding the other variables fixed. In this case, the Reynolds number can be defined by the stagnation density at the nozzle inlet, the velocity and the viscosity at the nozzle throat, and the nozzle-throat diameter. Changing the Reynolds number from 290,000 to 1,340,000 had no appreciable effect on the total-pressure distribution (fig. 12) and hence on the jet boundary. The range investigated covers the Reynolds numbers to be expected in flight.

The influence of moisture content in the air supply was investigated by varying the dew point from -20° F to +35° F. As indicated by the data of figure 12, the moisture level had a negligible influence on the total-pressure distribution.

Temperature Surveys

Temperature profiles of a heated jet expanding from a convergent nozzle are presented in figure 13 for a range of pressure ratios. The solid lines are the profiles for a jet issuing at overpressure ratios and the dashed lines are the profiles for a subsonic jet issuing at a velocity of 67.2 feet per second and a maximum temperature difference of about 24° F, as determined from the data of reference 7. The profiles for the subsonic jet are nearly the same as those for the jet operated at a pressure ratio of 2.5. The temperature profiles for the higher pressure ratios behave in the same manner as the Mach number profiles, that is, the effect of increasing pressure ratio is to widen the jet, with the profiles for all pressure ratios remaining similar in the subsonic mixing region.

The data of figure 13 were corrected to eliminate the effects of jet expansion in the same manner as in the case of the Mach number profiles (see fig. 8); that is, the 0.10, 0.20, and 0.30 temperature lines were referenced to the 0.5 temperature contour. Although the correlation shown in figure 14 was not so good as that

obtained with the pressure data, the same trend was observed insofar as the mixing process seemed to be relatively independent of the jet Mach number.

Temperature distributions are presented in figure 15 for a jet with the thermocouple rake in an arbitrary position for nozzle-inlet temperatures of 860°, 623°, and 246° F. The agreement for the various temperatures is a fair indication that nozzle-inlet temperature had little effect on the temperature profiles. It would thus appear that the temperature profiles of this report may be considered to hold for somewhat higher temperatures than the range covered.

Convergent-Divergent Nozzles

The results that have been discussed thus far concern jets issuing from convergent nozzles. For engineering purposes, it would be useful to determine, if possible, a relation between the spreading of such jets and the spreading of jets issuing from convergent-divergent nozzles. In order to determine what, if any, relation exists between jets issuing with overpressure from convergent and convergent-divergent nozzles, pressure surveys were made of a heated jet expanding from a convergent-divergent nozzle having a design exit pressure ratio of 4.60. The results of this investigation are given in figure 16 together with the results obtained with a jet expanding from a convergent nozzle and having the same degree of overpressure. (The degree of overpressure is defined as the ratio of nozzle-exit static pressure to ambient pressure.) It is seen that for the same degree of overpressure the jet issuing from the convergent-divergent nozzle is slightly larger. This is to be expected because for the same degree of overpressure, the theoretical nonviscous boundary for the jet issuing from the convergent-divergent nozzle is larger than that for the convergent nozzle. This difference in jet size is also evident in the schlieren photographs of figure 17, in which a comparison is made between jets expanding from convergent and convergent-divergent nozzles.

An elimination of the expansion effects correlated the data (fig. 18) so that the points for the corrected values of the jet issuing from the convergent-divergent nozzle fall very close to the faired curves obtained with the jet expanding from the convergent nozzle. Thus, it is evident not only that the mixing process is relatively independent of the jet Mach number but also of the type of nozzle from which the jet is discharged.

It has already been shown (fig. 9) that the boundary of a jet emerging from a choked convergent nozzle may be adequately represented near the nozzle exit by a straight line corresponding to the Prandtl-Meyer expansion angle for any given pressure ratio. In order to determine whether some theoretical prediction of the jet boundary could be

obtained to compare with the profiles and the schlieren photographs of jets expanding from a convergent-divergent nozzle, the theoretical nonviscous boundary of an axially symmetric jet was computed by the method of characteristics. This boundary, computed for a jet issuing from a nozzle designed for a pressure ratio of 4.6 and operating at a pressure ratio of 11.2, is superimposed on a schlieren photograph of the same jet in figure 17. The computed boundary falls within that visible in the schlieren, the difference between the two arising from mixing, which was not accounted for in the theoretical computation.

This difference is again evident in figure 19 where the theoretical nonviscous boundary for a jet expanding from a convergent-divergent nozzle is compared with the $M/M_j = 0.11$ contour determined by the total-pressure surveys. The dashed portion of the theoretical curve is a straight-line extension of the theoretical boundary at its maximum diameter. In an effort to predict a boundary that would agree with that observed experimentally, an estimated boundary was determined by adding the spreading of a subsonic jet to the theoretical boundary of the supersonic jet. Although the agreement between the hypothetical boundary and the boundary experimentally observed appears to be poor (fig. 19), the difference between the two boundaries never exceeds 15 percent. Thus it would appear that for engineering purposes, the method previously outlined for predicting the jet boundary is adequate inasmuch as the predicted boundary is conservative when compared with the experimental jet boundary.

SUMMARY OF RESULTS

From measurements of the total-head and temperature fields in a circular jet operated at overpressure ratios, the following results were obtained:

1. The effect of nozzle pressure ratio on jet spreading was significant. Increasing the pressure ratio resulted in increased expansion immediately downstream of the nozzle in accordance with potential theory. Following the initial rapid expansion, the rate of growth of the jet decreased and appeared to vary only slightly with axial distance.

2. For a jet issuing from a convergent nozzle at a pressure ratio slightly above critical, both Mach number and temperature profiles were nearly identical to the velocity and temperature profiles for subsonic jets issuing at any velocity. Increasing the pressure ratio beyond 2.5 resulted in a wider jet, because of the increased expansion of the jet leaving the nozzle.

3. Elimination of the expansion effects by referencing the profiles in the mixing region to the Mach number ratio $M/M_j = 0.5$

contour indicated that the mixing process for jets issuing from both convergent and convergent-divergent nozzles was relatively independent of the jet Mach number.

4. The effect of Reynolds number in the range from 290,000 to 1,340,000 on jet spreading was negligible.

5. The presence of moisture in the air had no effect on jet spreading for the range investigated.

6. The temperature distributions obtained with a jet having nozzle-inlet temperatures of 860°, 623°, and 246° F were nearly identical. The Mach number profiles for a heated jet, however, differed slightly from those for an unheated jet. The heated jet was somewhat smaller than the unheated jet, but at an axial station of 6 diameters, both heated and unheated jet profiles were nearly the same.

7. The width of a jet emerging from a convergent-divergent nozzle was greater than that for a convergent nozzle operating at a corresponding overpressure ratio because of the larger potential core existing in the jet issuing from the convergent-divergent nozzle.

8. The hypothetical boundary obtained by adding subsonic spreading to the theoretical nonviscous boundary of a jet expanding from a convergent-divergent nozzle, although not in good agreement with the boundary actually observed, never exceeds the observed boundary by more than 15 percent.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, February 27, 1951.

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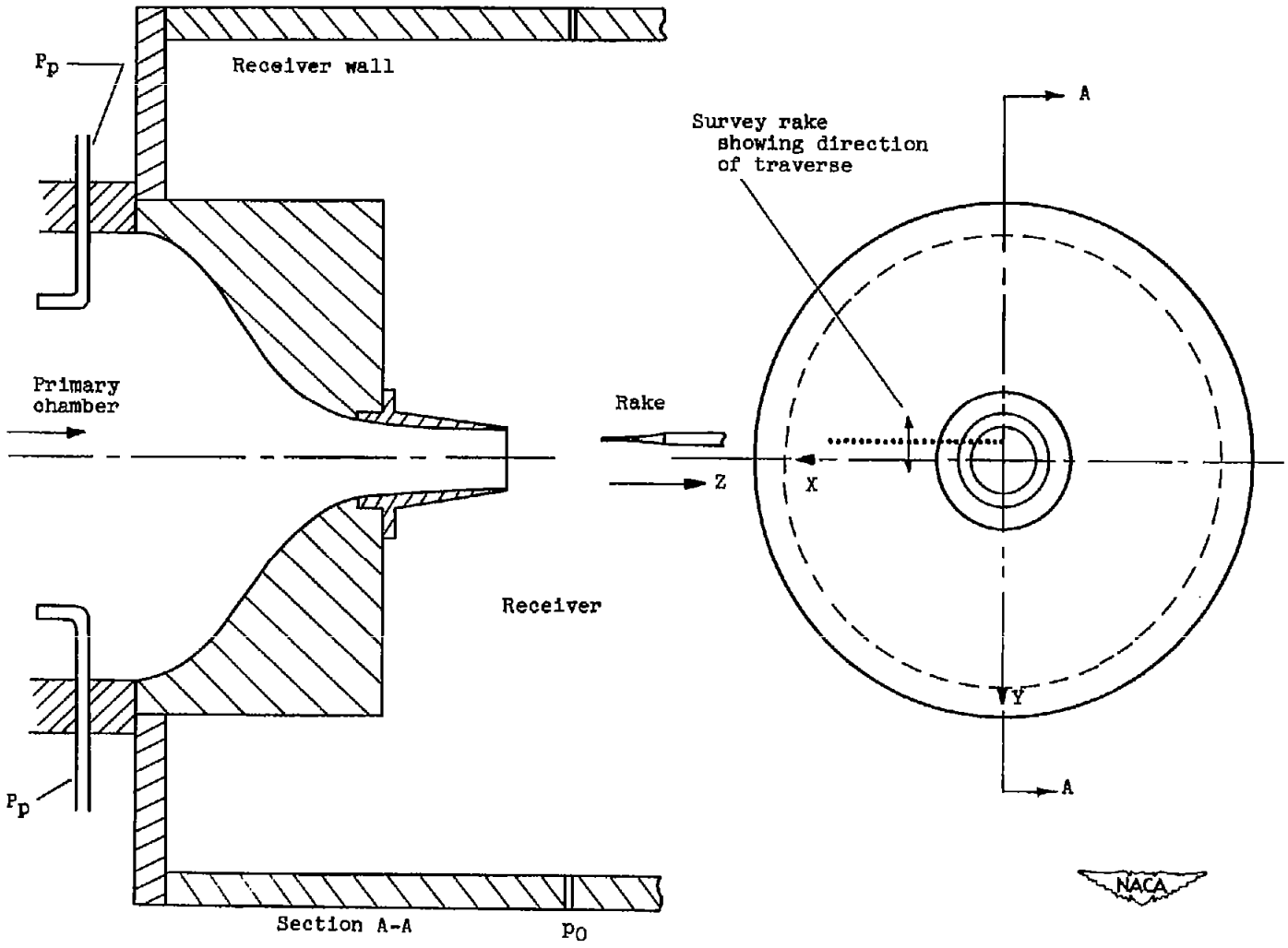

(a) Assembly of primary chamber, low-pressure receiver, convergent nozzle, and survey rake.

Figure 1. - Schematic diagram of test apparatus.

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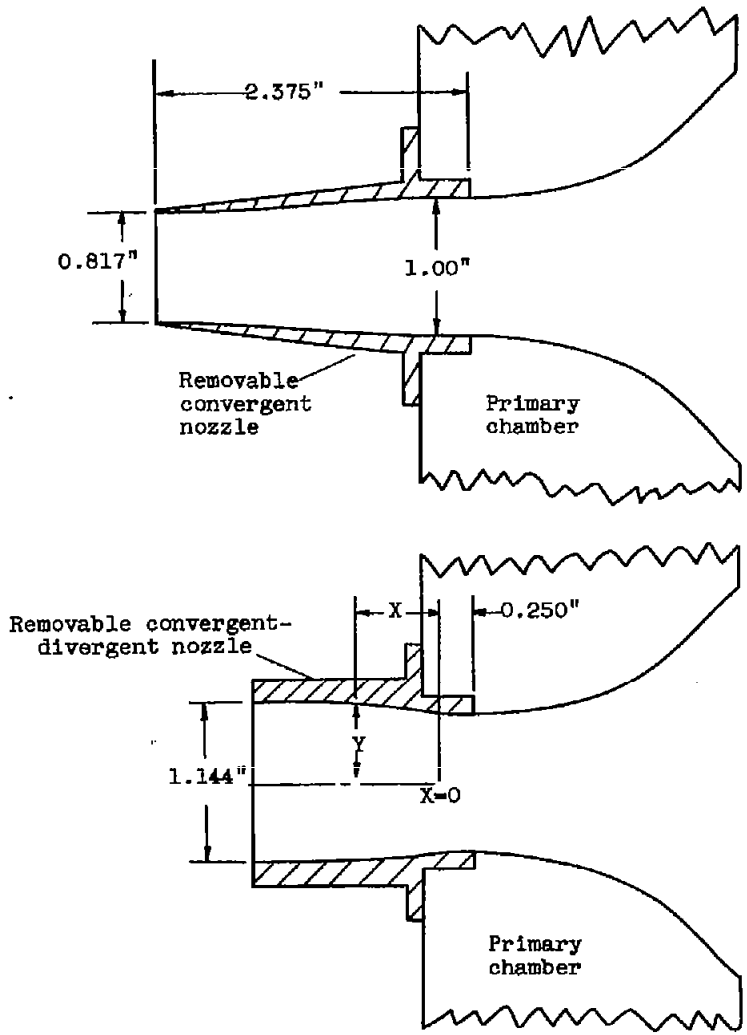
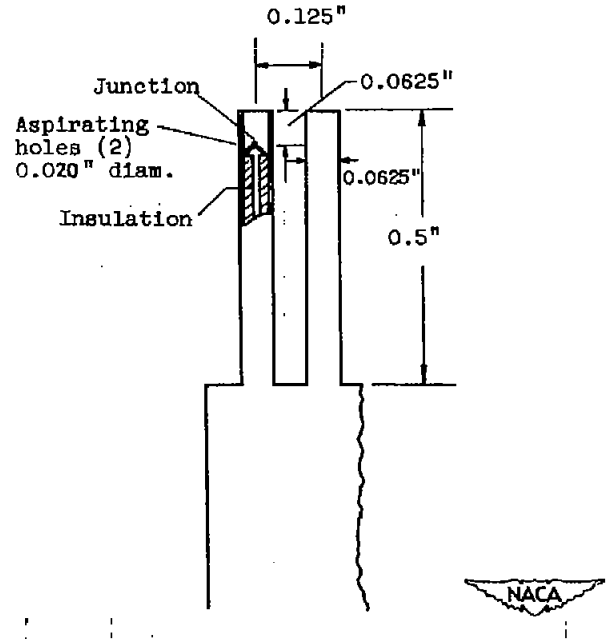


(b) Removable nozzles.



(c) Details showing two of 23-thermocouple temperature rake.

Convergent-divergent nozzle coordinates

X	Y	X	Y
0	0.500	0.8	0.563
.1	.514	.9	.565
.2	.527	1.0	.567
.3	.536	1.1	.569
.4	.544	1.2	.570
.5	.550	1.3	.571
.6	.556	1.4	.572
.7	.560		

Figure 1. - Concluded. Schematic diagram of test apparatus.

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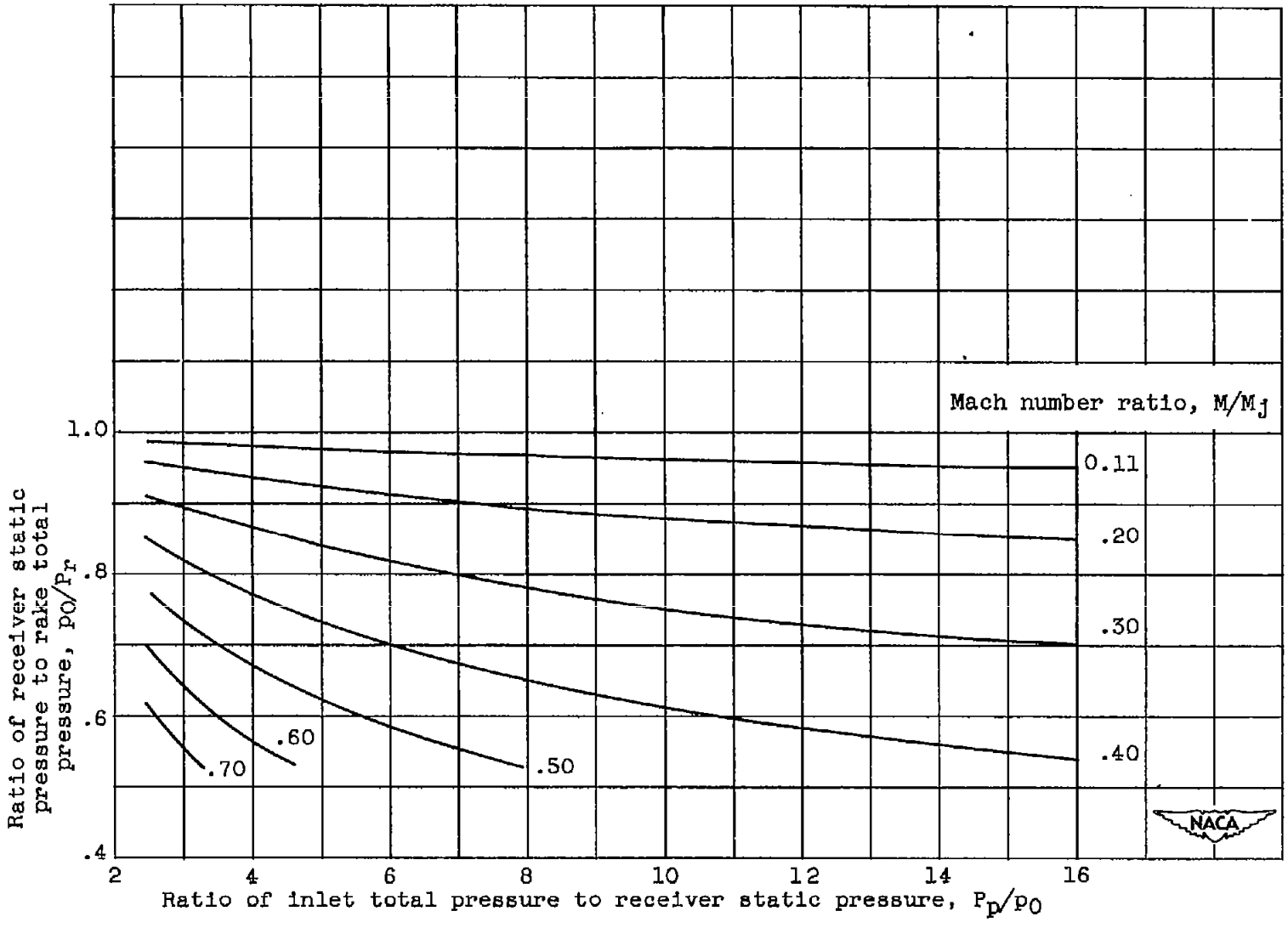

Figure 2. - Variation of rake pressure ratio with nozzle pressure ratio for several Mach number ratios. Ratio of specific heats γ, 1.40.

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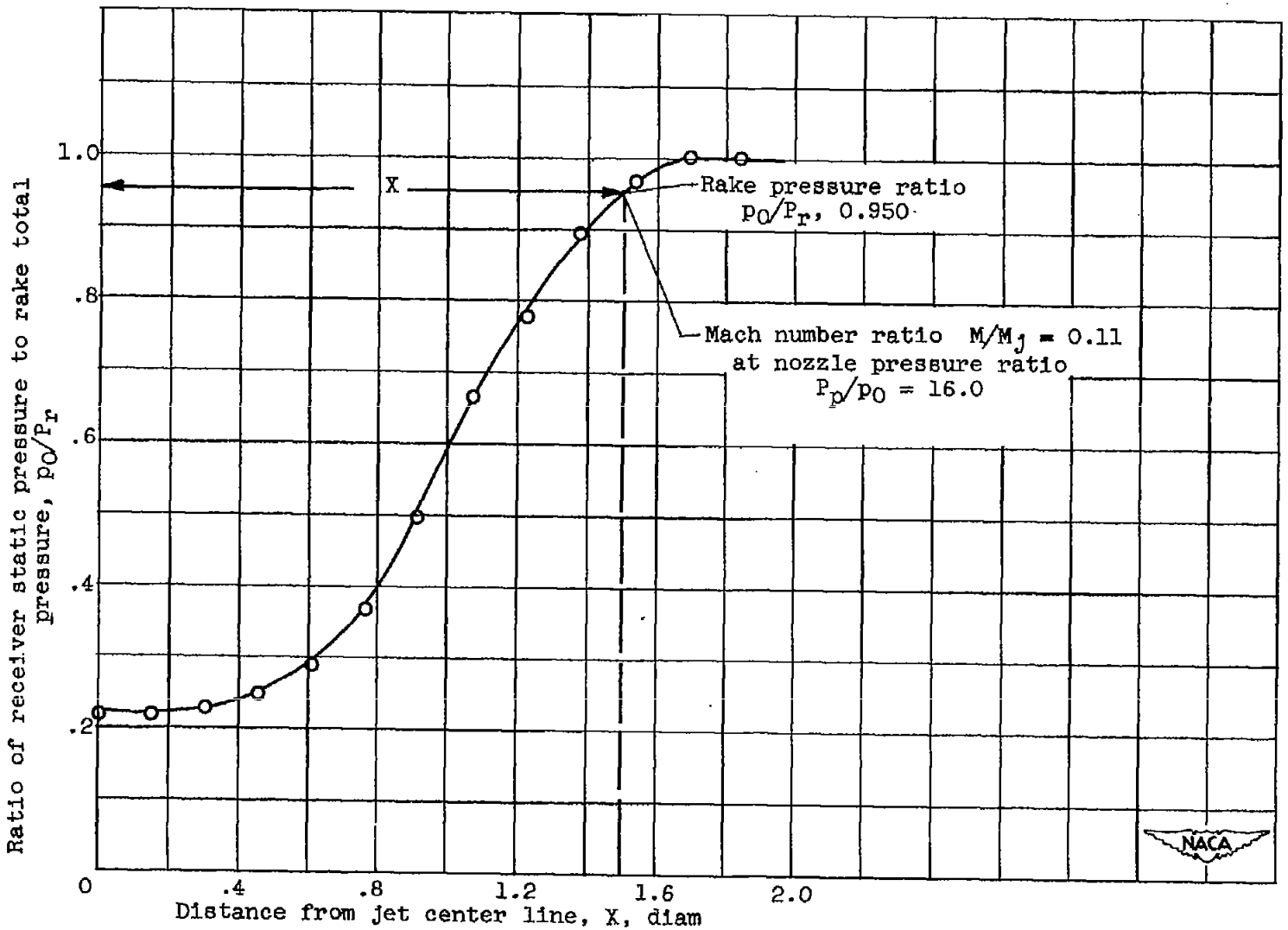

Figure 3. - Typical pressure distribution in jet wake. Nozzle pressure ratio P_p/p_0, 16.

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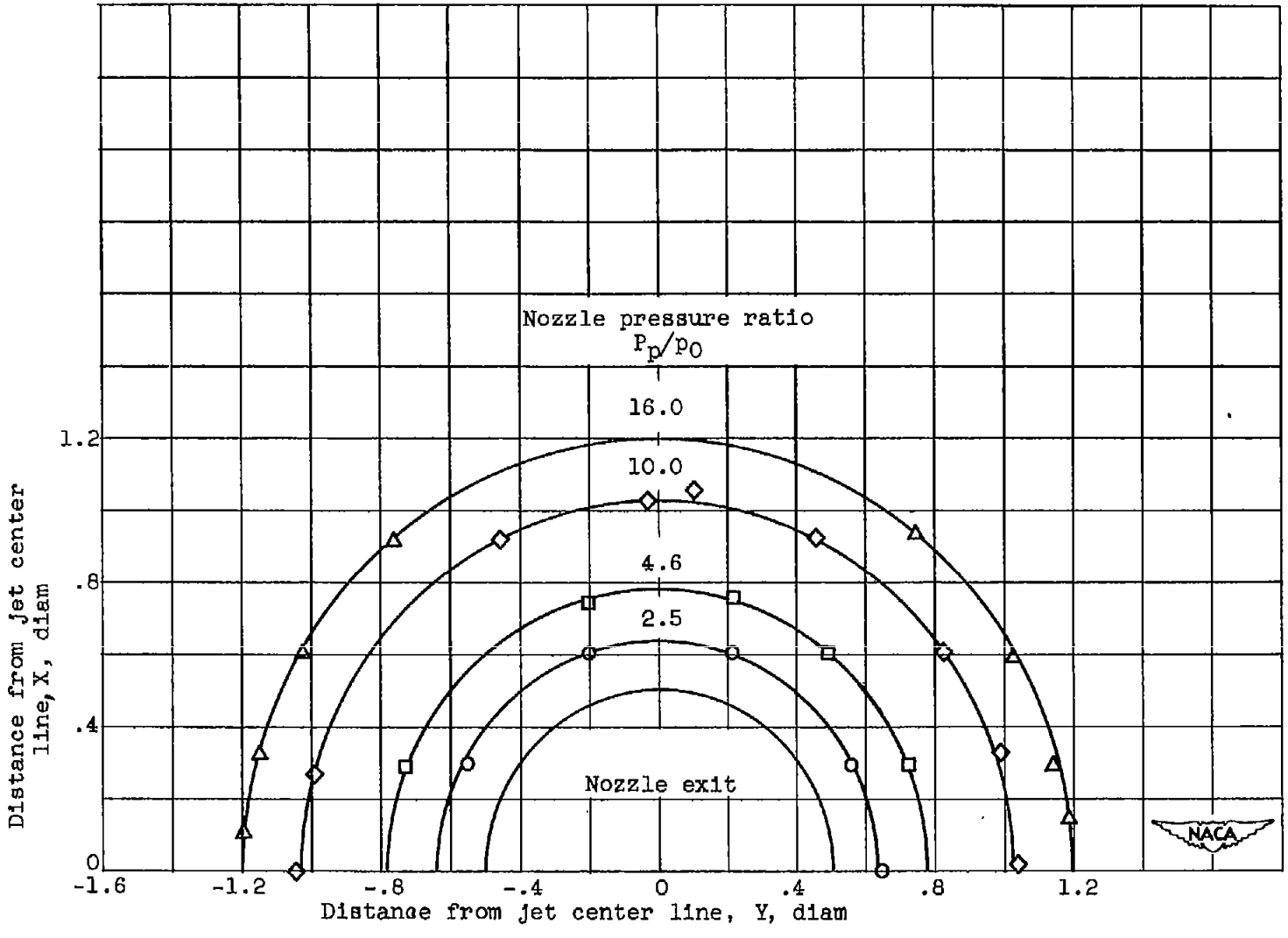

Figure 4. - Lateral boundaries for jet expanding from convergent nozzle as determined by total-pressure surveys. Mach number ratio M/M_j, 0.11; axial station Z, 1 diameter.

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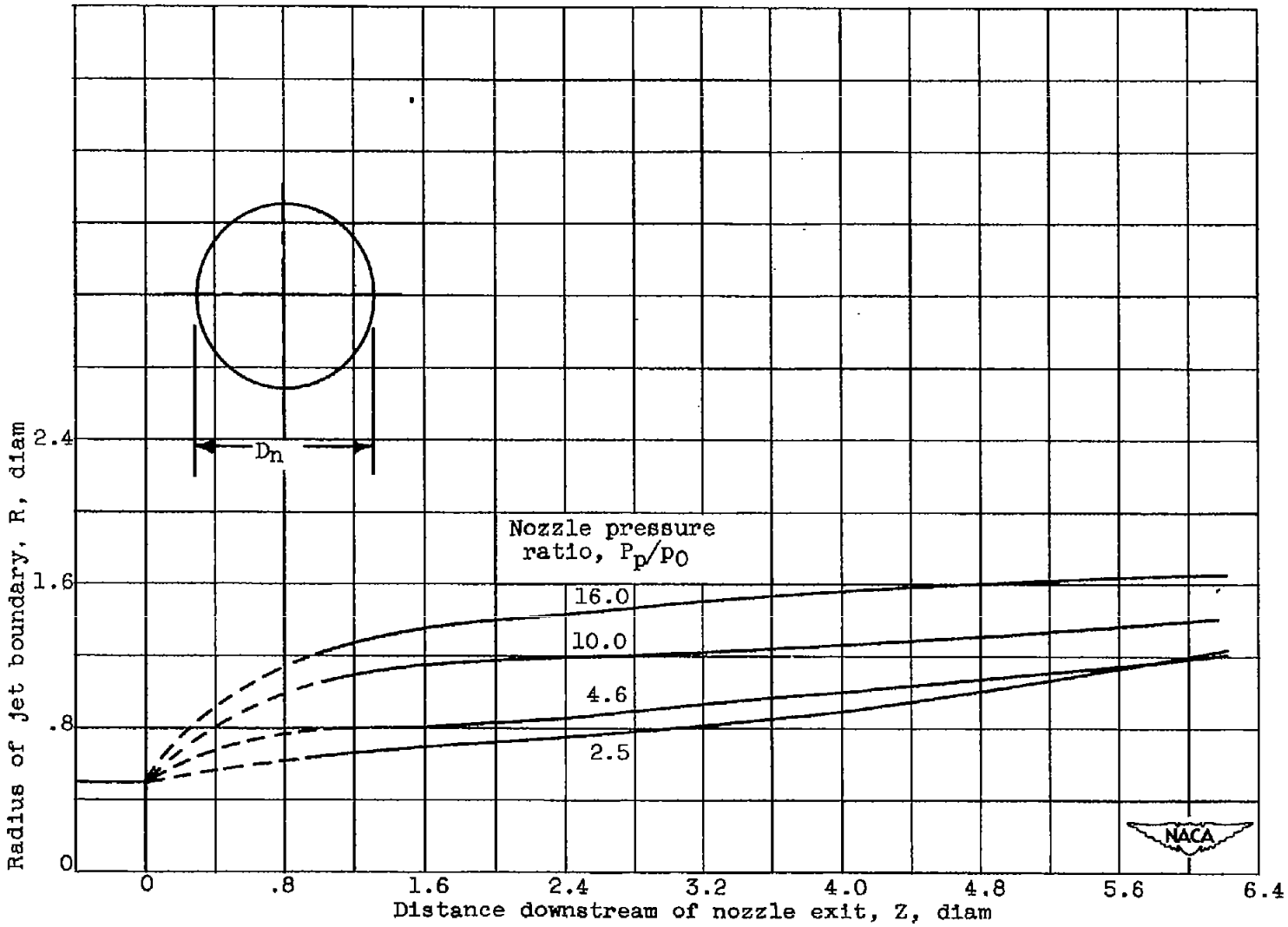

Figure 5. - Spreading of jet expanding from convergent nozzle as determined by total-pressure surveys. Mach number ratio M/M_j, 0.11.

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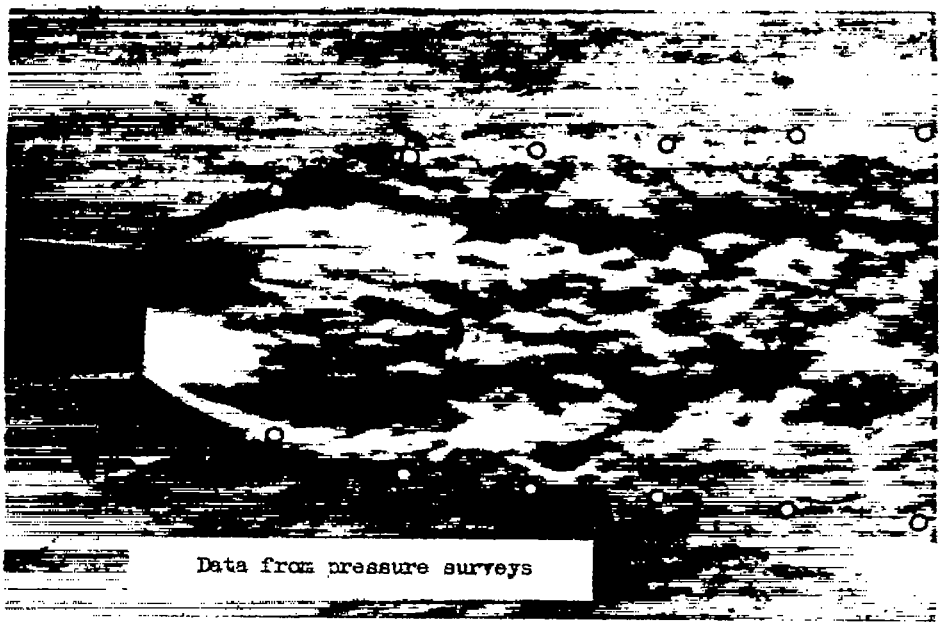
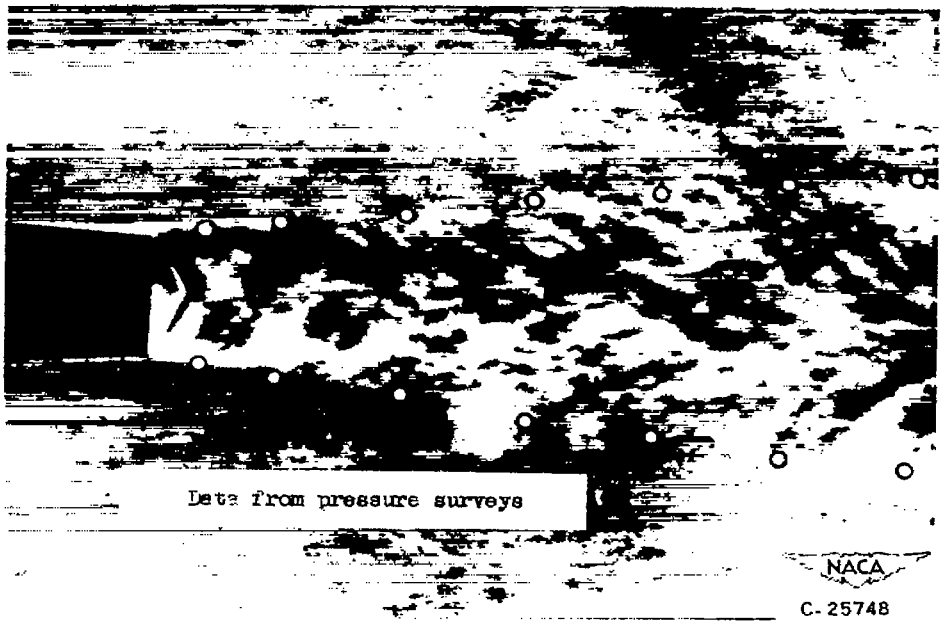
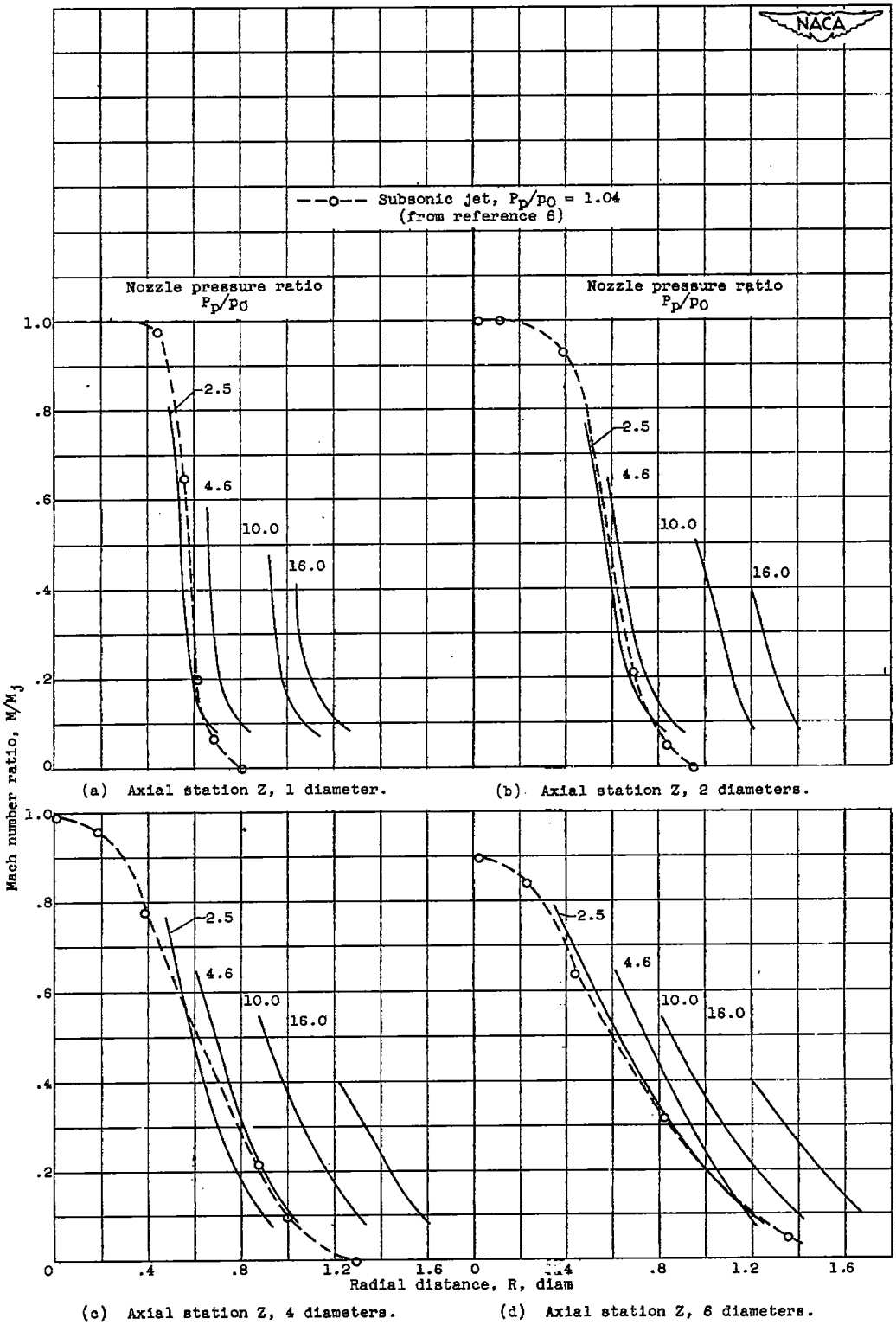


(a) Nozzle pressure ratio P_p/p_0, 16.0.



(b) Nozzle pressure ratio, P_p/p_0, 2.5.

Figure 6. - Comparison of schlieren photographs and pressure surveys of jet expanding from convergent nozzle.



(a) Axial station Z, 1 diameter. (b) Axial station Z, 2 diameters.

(c) Axial station Z, 4 diameters. (d) Axial station Z, 6 diameters.

Figure 7. - Mach number profiles in unheated jet expanding from convergent nozzle determined by total-pressure surveys.

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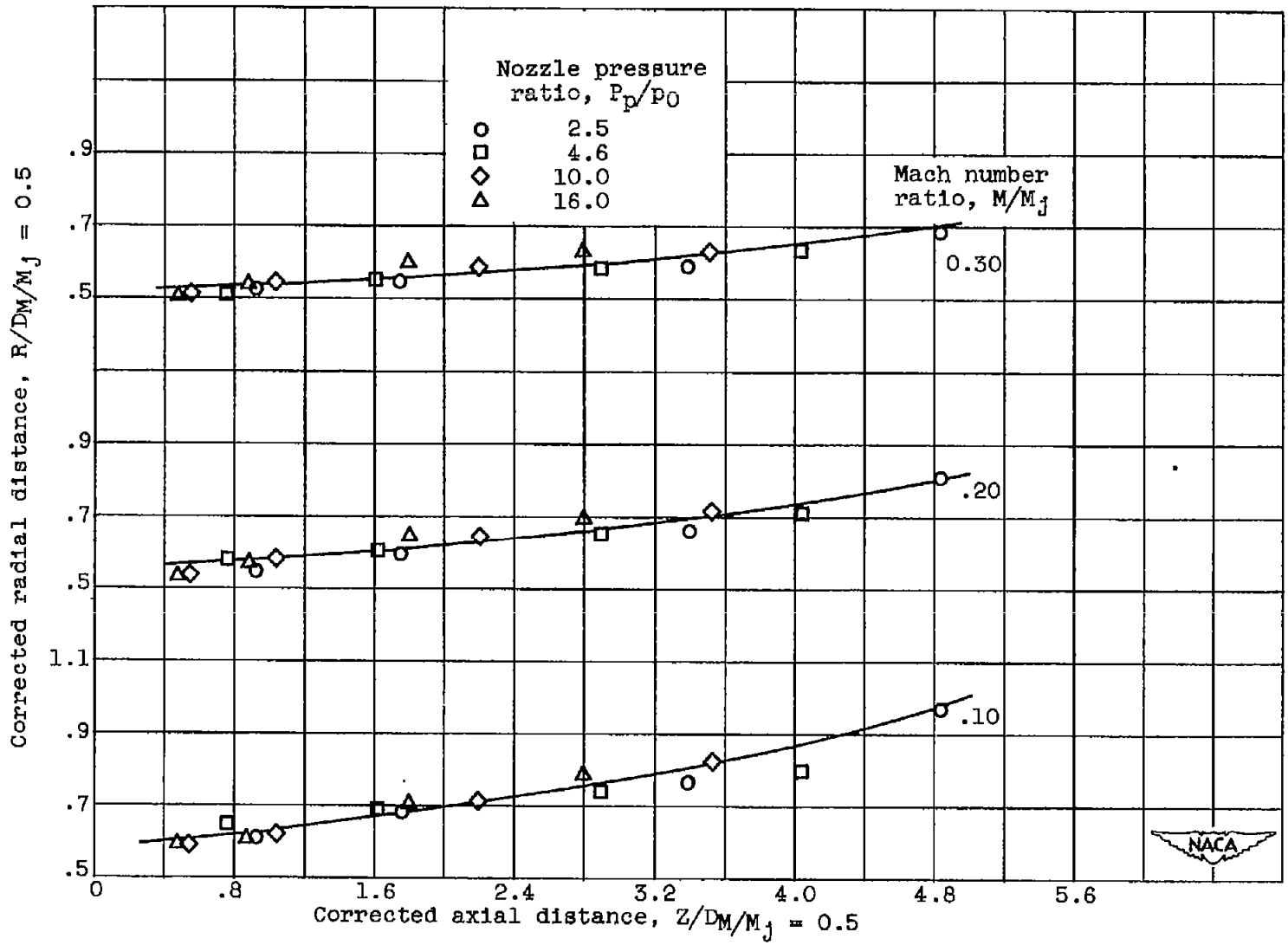

Figure 8. - Generalized Mach number contours for jet expanding from convergent nozzle. Unheated jet.

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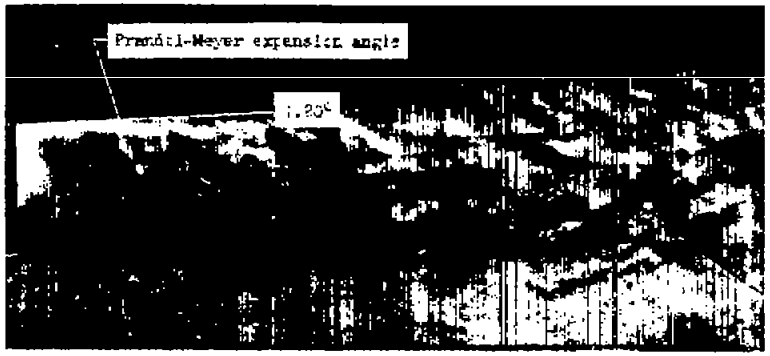
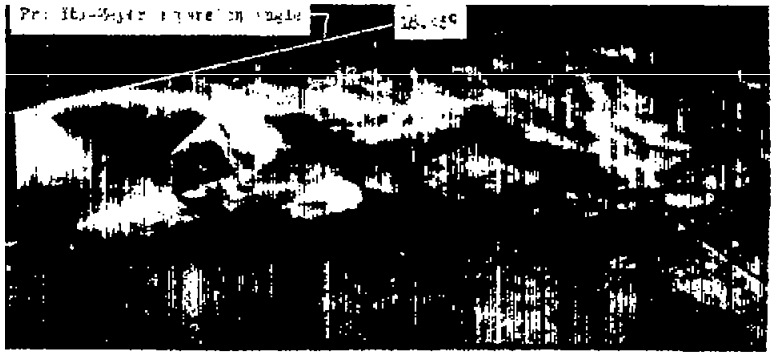
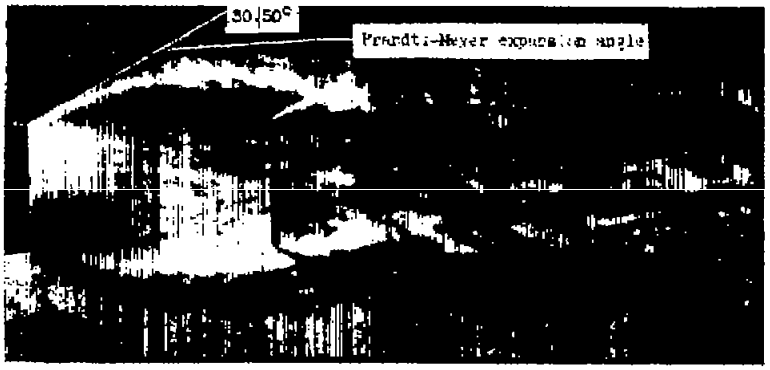


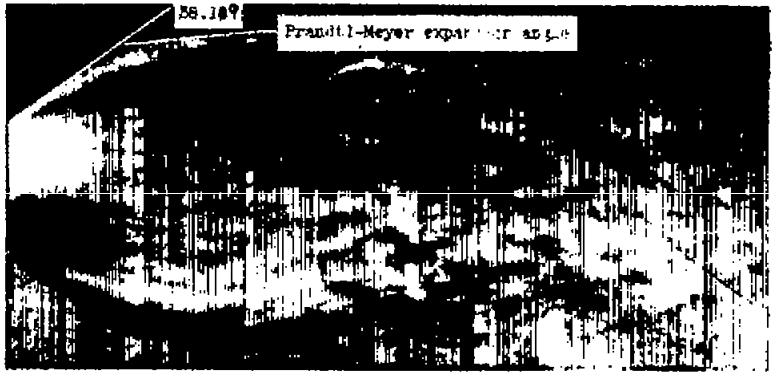
(a) Nozzle pressure ratio P_p/p_0, 2.5.



(b) Nozzle pressure ratio P_p/p_0, 4.6.



(c) Nozzle pressure ratio P_p/p_0, 10.0.



(d) Nozzle pressure ratio P_p/p_0, 16.0.

Figure 9. - Schlieren photographs of jet expanding from convergent nozzle.

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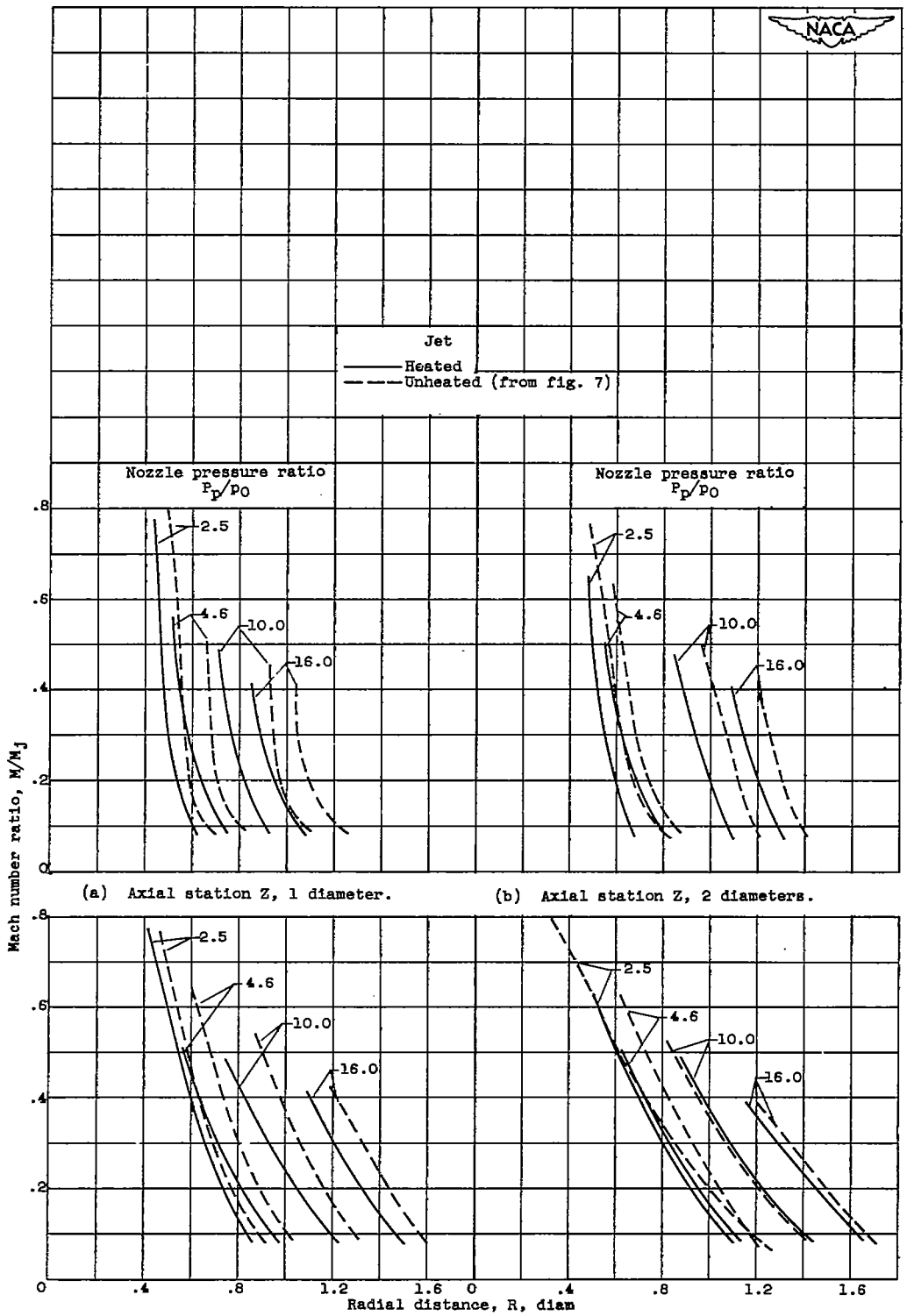

(a) Axial station Z, 1 diameter. (b) Axial station Z, 2 diameters.

(c) Axial station Z, 4 diameters. (d) Axial station Z, 6 diameters.

Figure 10. - Comparison of Mach number profiles in heated and unheated jets expanding from convergent nozzles as determined by total-pressure surveys. Nozzle-inlet temperature T_p, 950° F.

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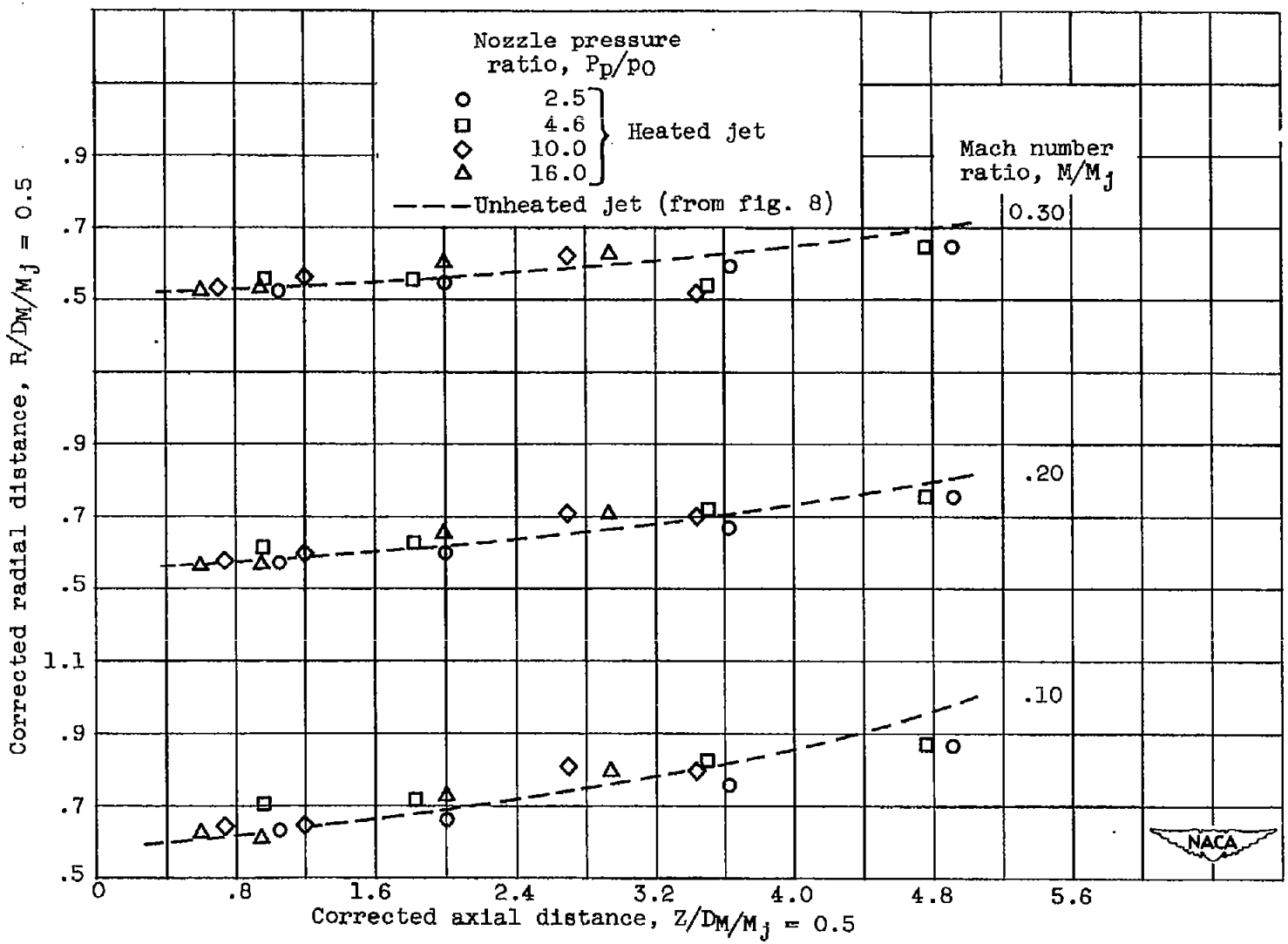

Figure 11. - Generalized Mach number contours for jet expanding from convergent nozzle. Nozzle-inlet temperature T_p, 950° F.

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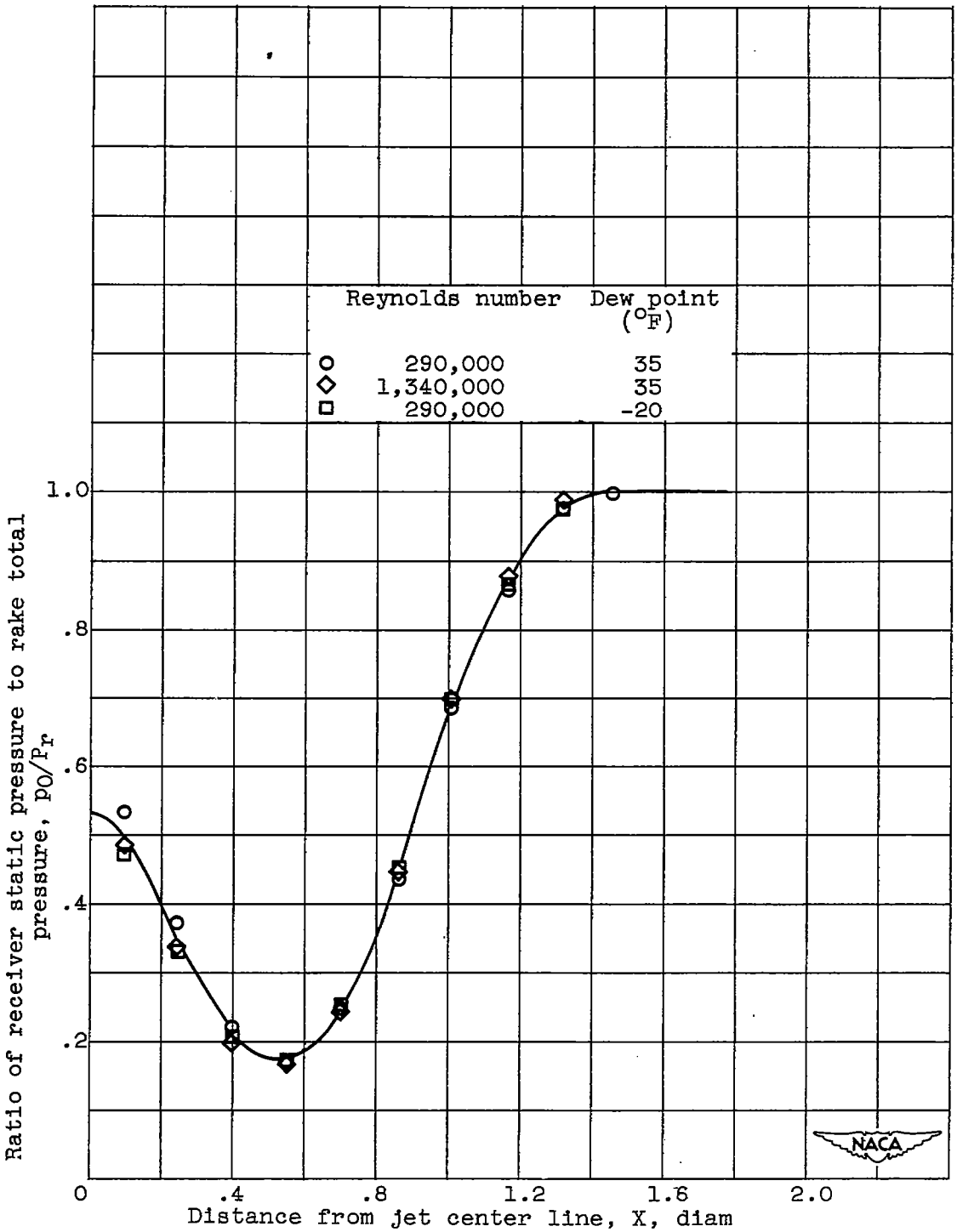

Figure 12. - Pressure distributions for single jet expanding from convergent nozzle and having (a) high Reynolds number, (b) low Reynolds number, (c) low dew point. Nozzle pressure ratio P_p/p_0, 10.0; axial station Z, 4 diameters.

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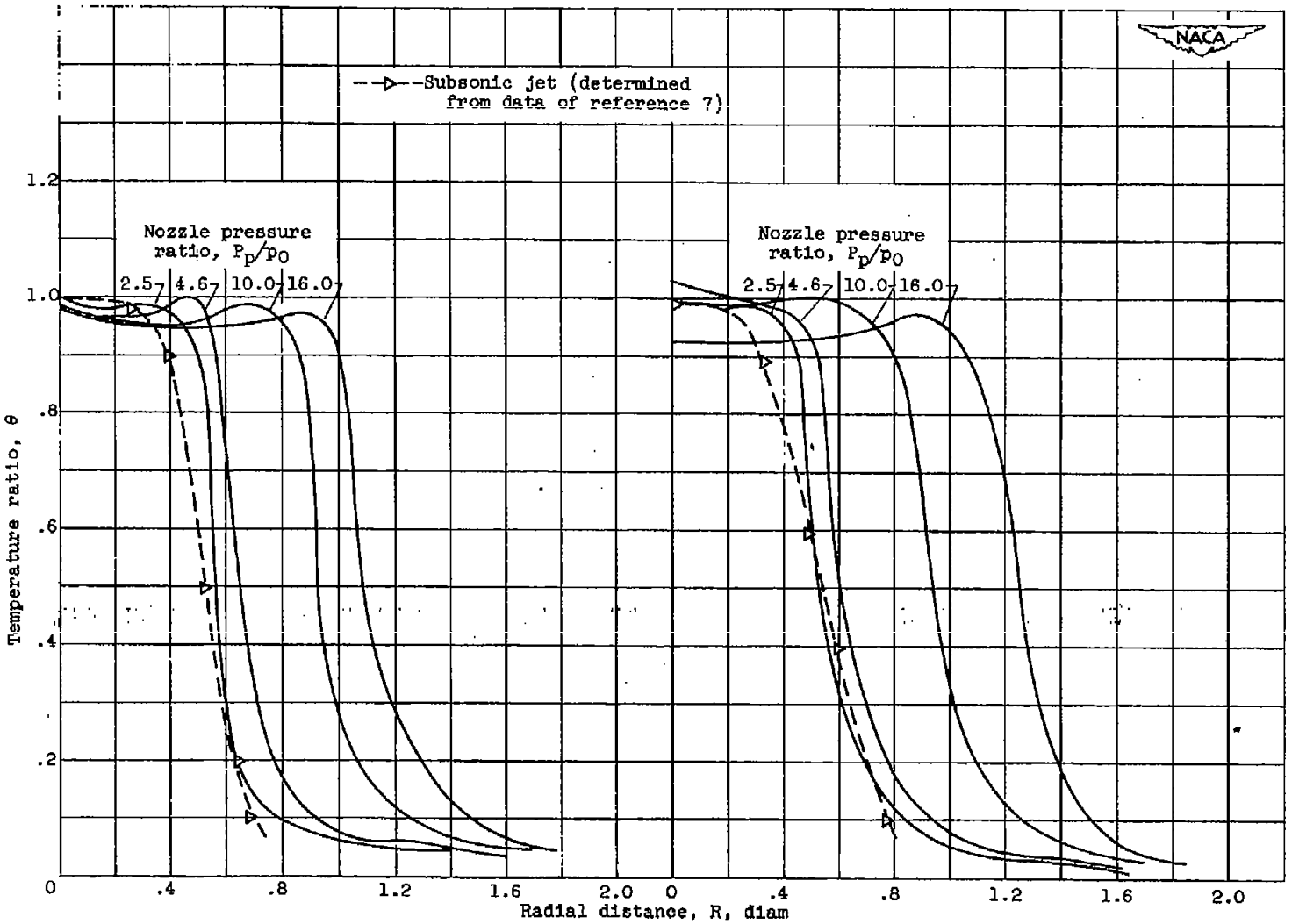

(a) Axial station Z, 1 diameter.

(b) Axial station Z, 2 diameters.

Figure 13. - Temperature profiles in heated jet expanding from convergent nozzle. Nozzle-inlet temperature T_p, 525° F.

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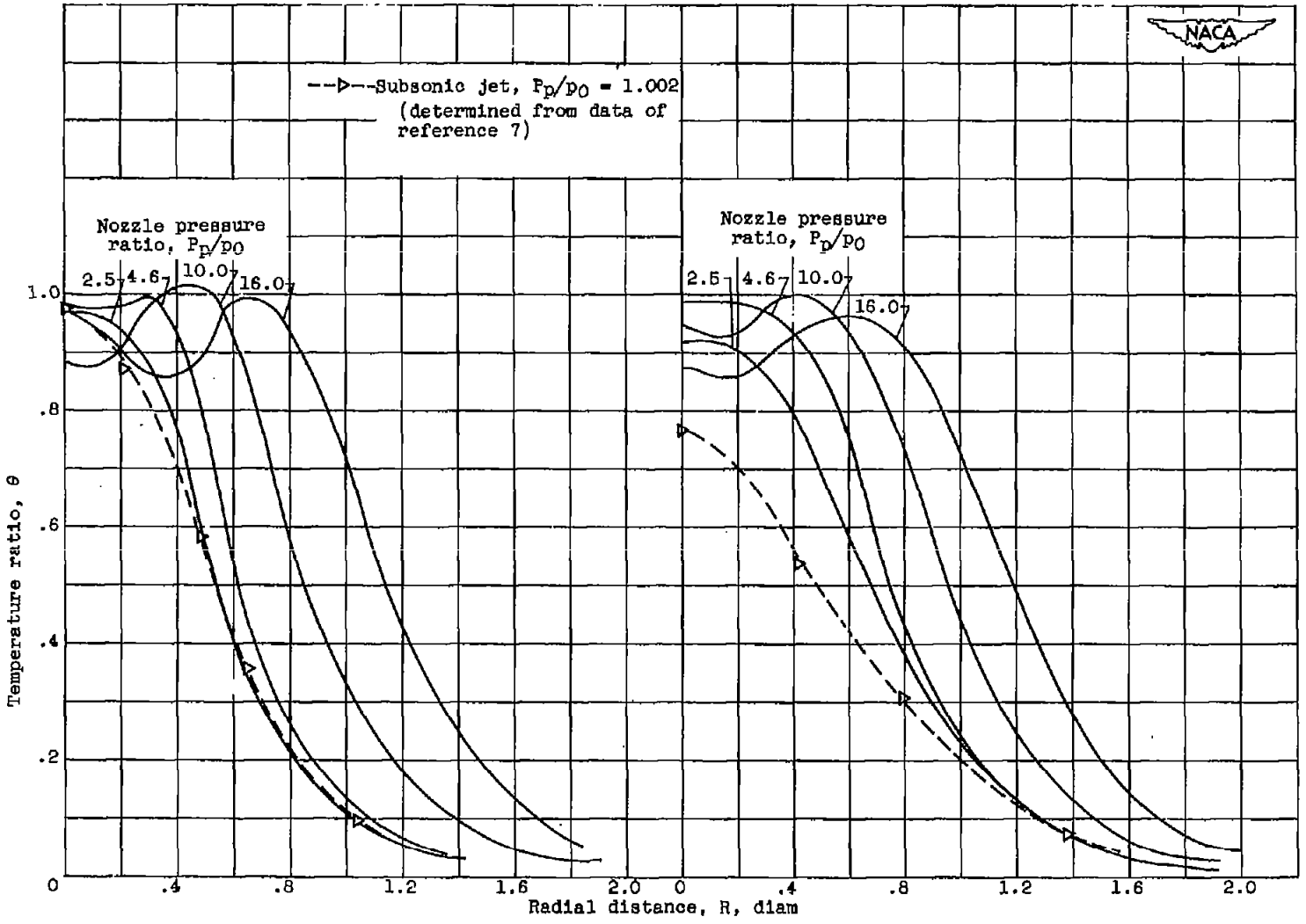

(c) Axial station Z, 4 diameters.

(d) Axial station Z, 6 diameters.

Figure 13. - Concluded. Temperature profiles in heated jet expanding from convergent nozzle. Nozzle-inlet temperature T_p, 525° F.

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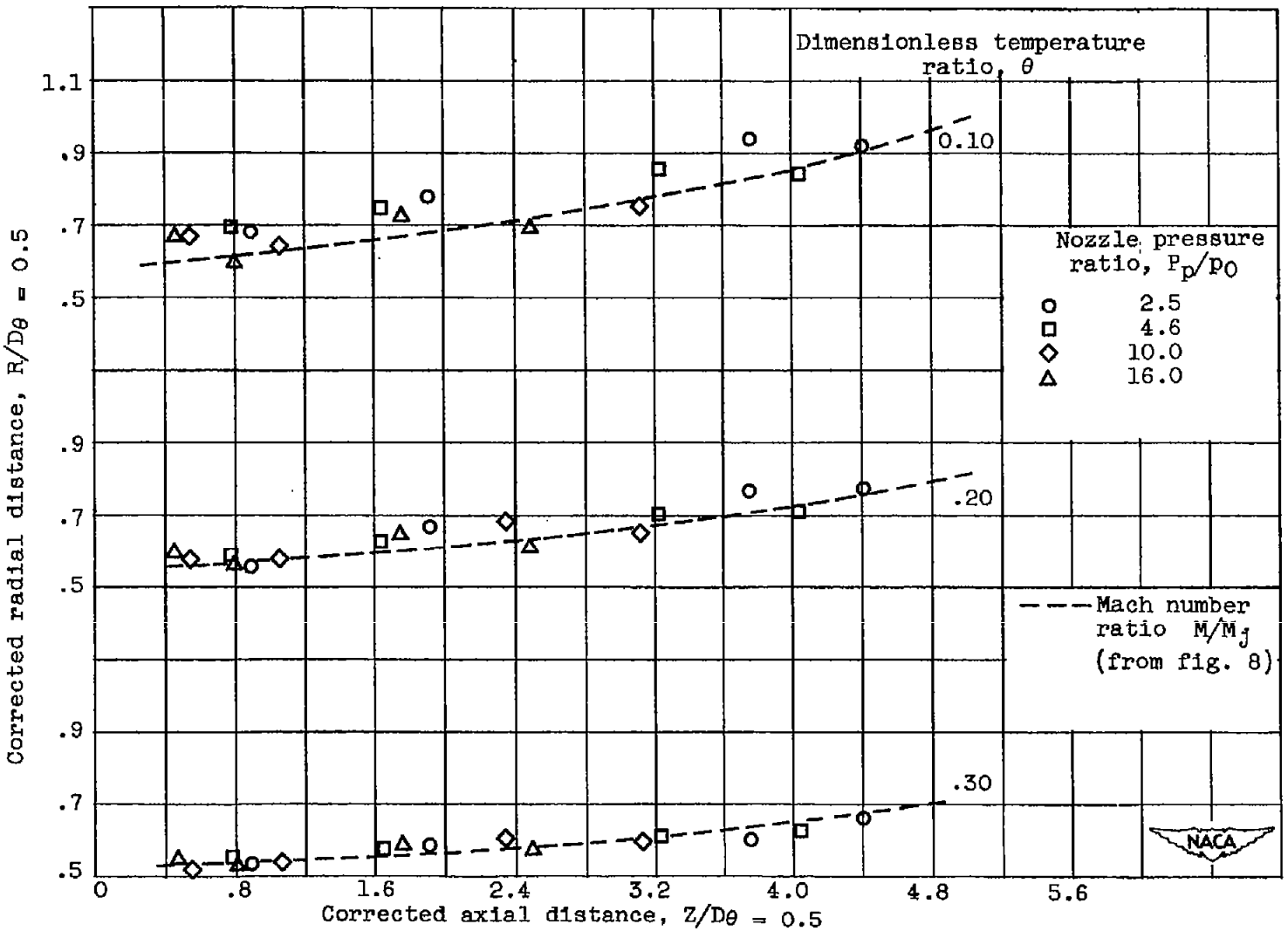

Figure 14. - Generalized temperature contours for jet expanding from convergent nozzle. Nozzle-inlet temperature T_p, 525° F.

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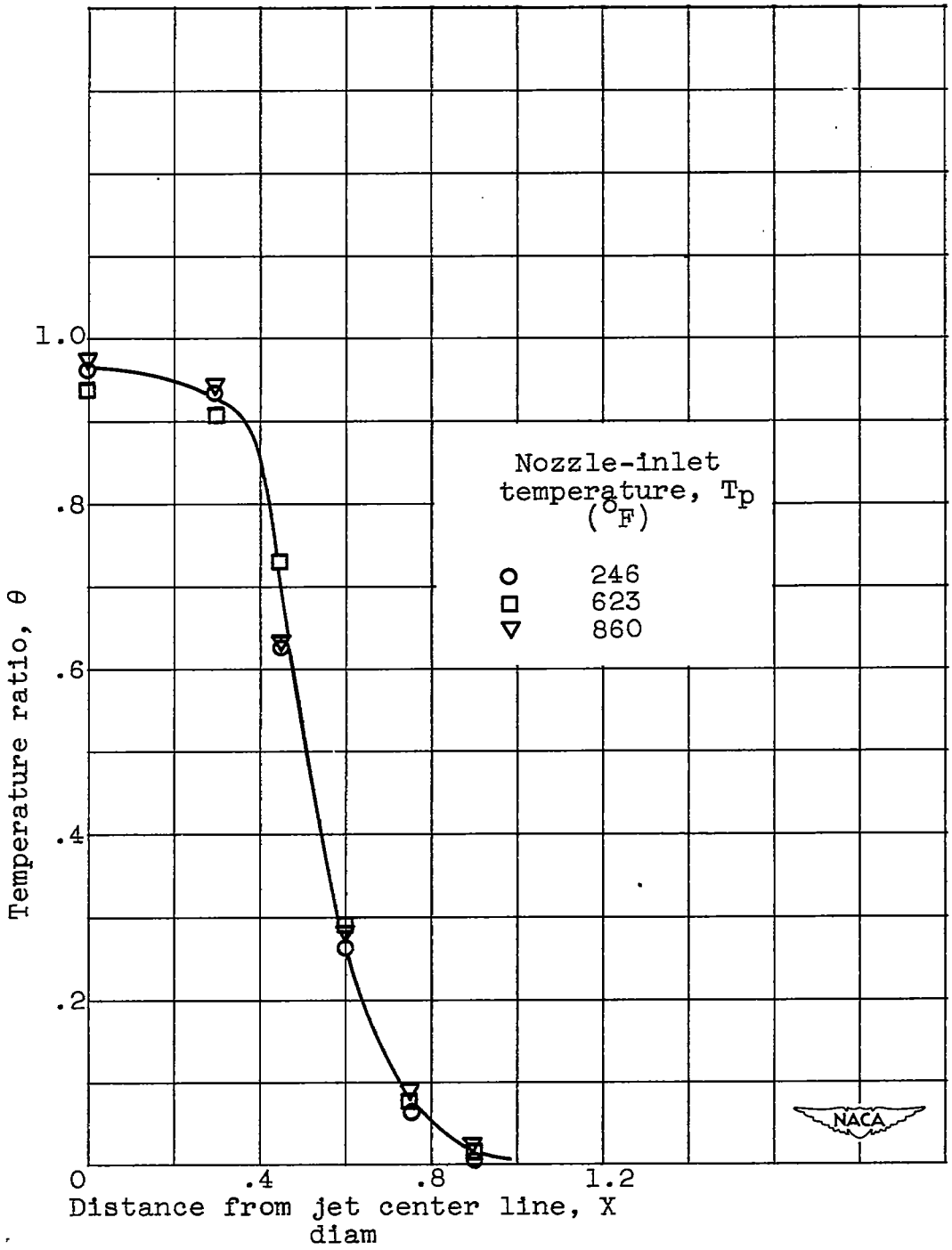
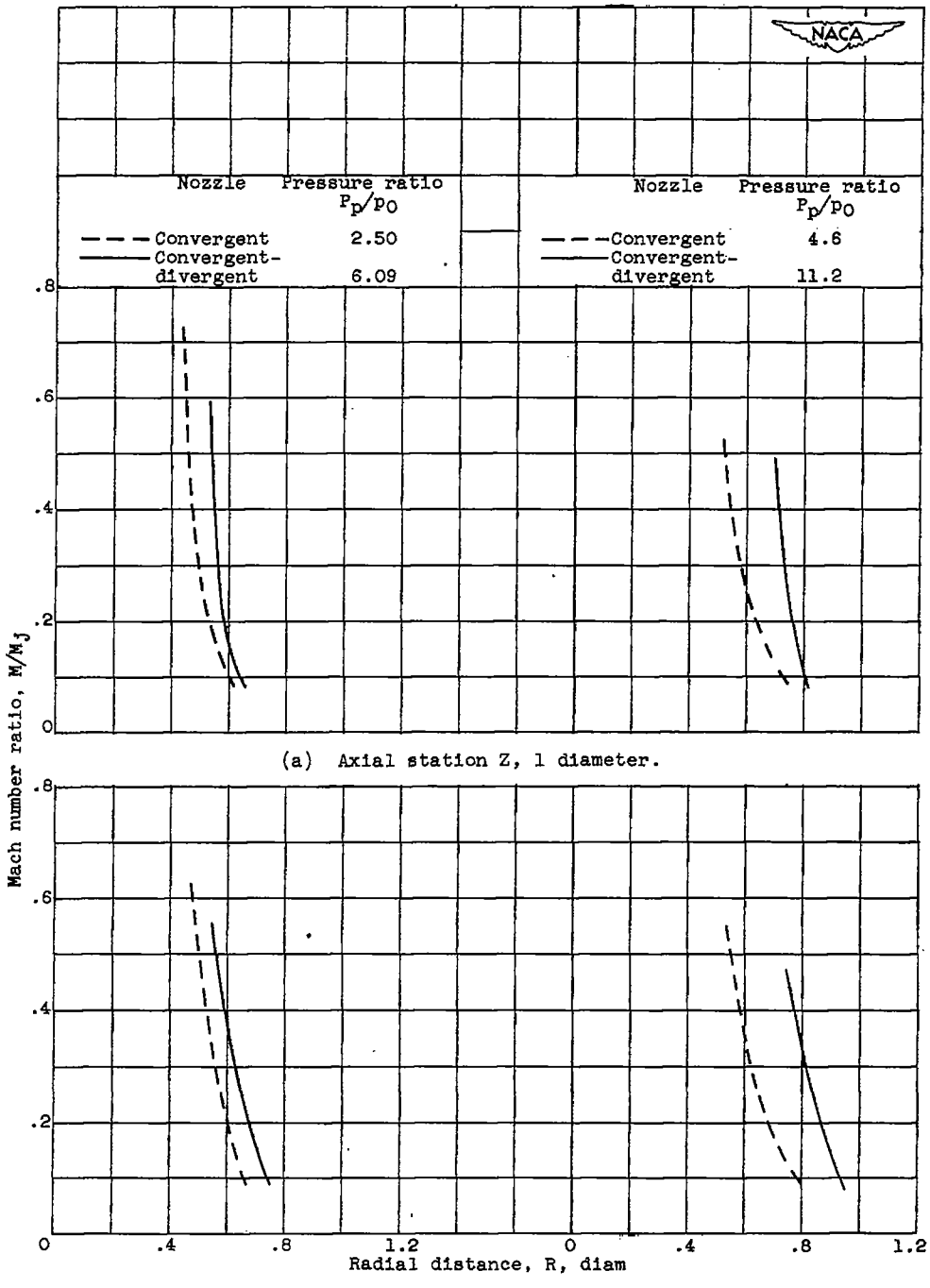


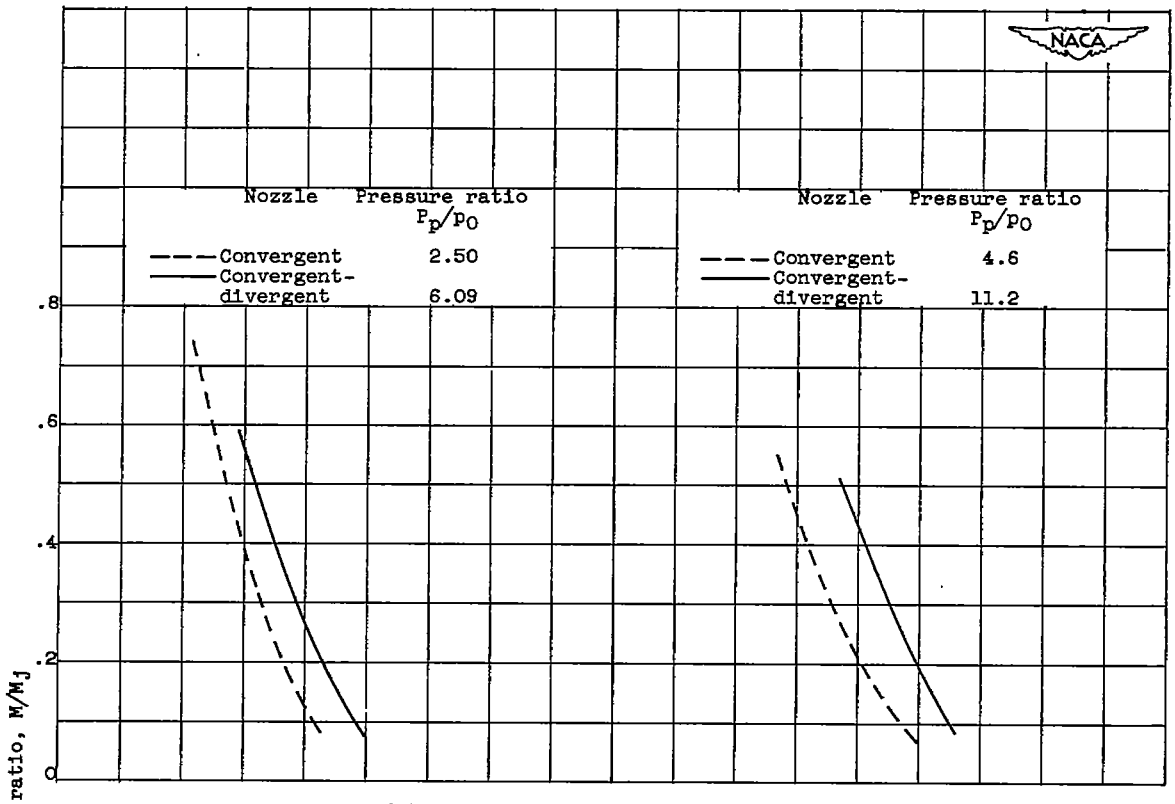
Figure 15. - Variation of temperature distribution with nozzle temperature for jet expanding from convergent nozzle. Nozzle pressure ratio P_p/p_0, 2.5; axial station Z, 1 diameter.



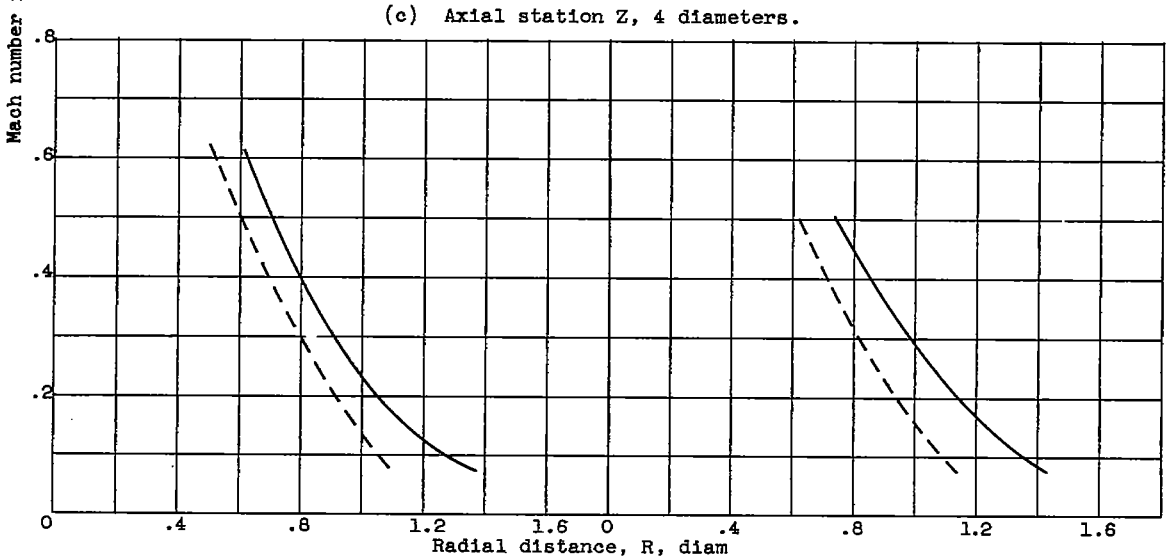
(a) Axial station Z, 1 diameter.

(b) Axial station Z, 2 diameters.

Figure 16. - Comparison of Mach number profiles for jets expanding from convergent and convergent-divergent nozzles determined by total-pressure surveys. Nozzle-inlet temperature T_p, 950° F.



(c) Axial station Z, 4 diameters.



(d) Axial station Z, 6 diameters.

Figure 16. - Concluded. Comparison of Mach number profiles for jets expanding from convergent and convergent-divergent nozzles determined by total-pressure surveys. Nozzle-inlet temperature T_p, 950° F.

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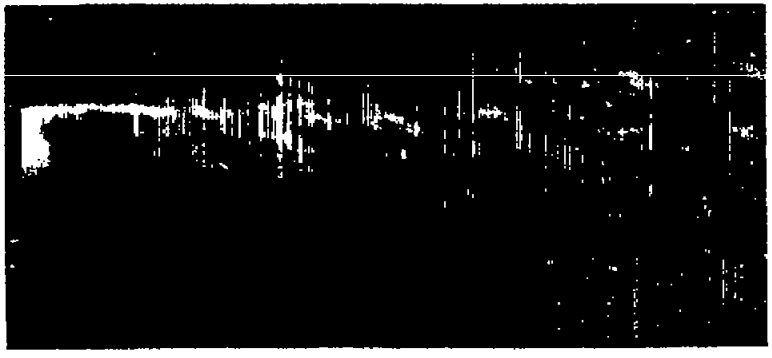
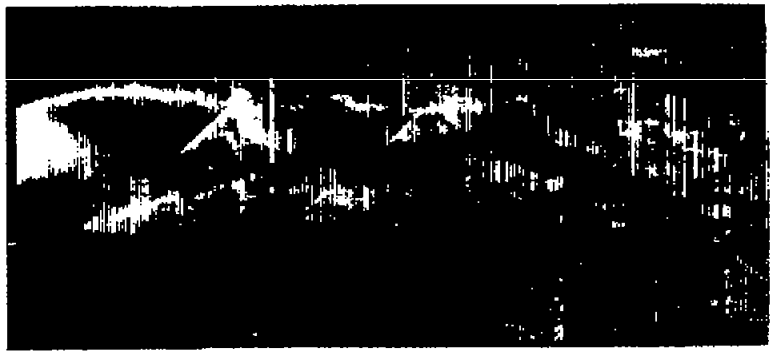
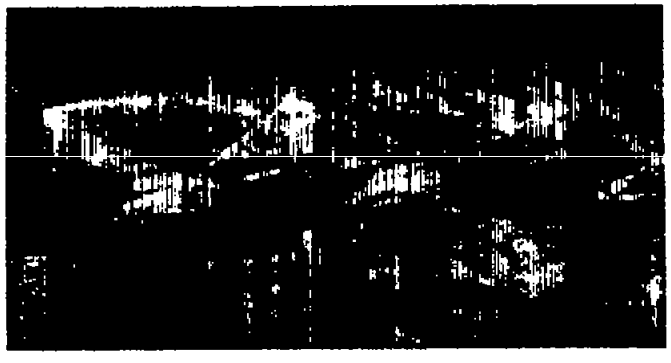


(a) Convergent nozzle; nozzle pressure ratio P_p/p_0, 2.5.



(b) Convergent nozzle; nozzle pressure ratio P_p/p_0, 4.6.



(c) Convergent-divergent nozzle; nozzle pressure ratio P_p/p_0, 6.09.

(d) Convergent-divergent nozzle; nozzle pressure ratio P_p/p_0, 11.2.

Figure 17. - Comparison of jets expanding from convergent and convergent-divergent nozzles.

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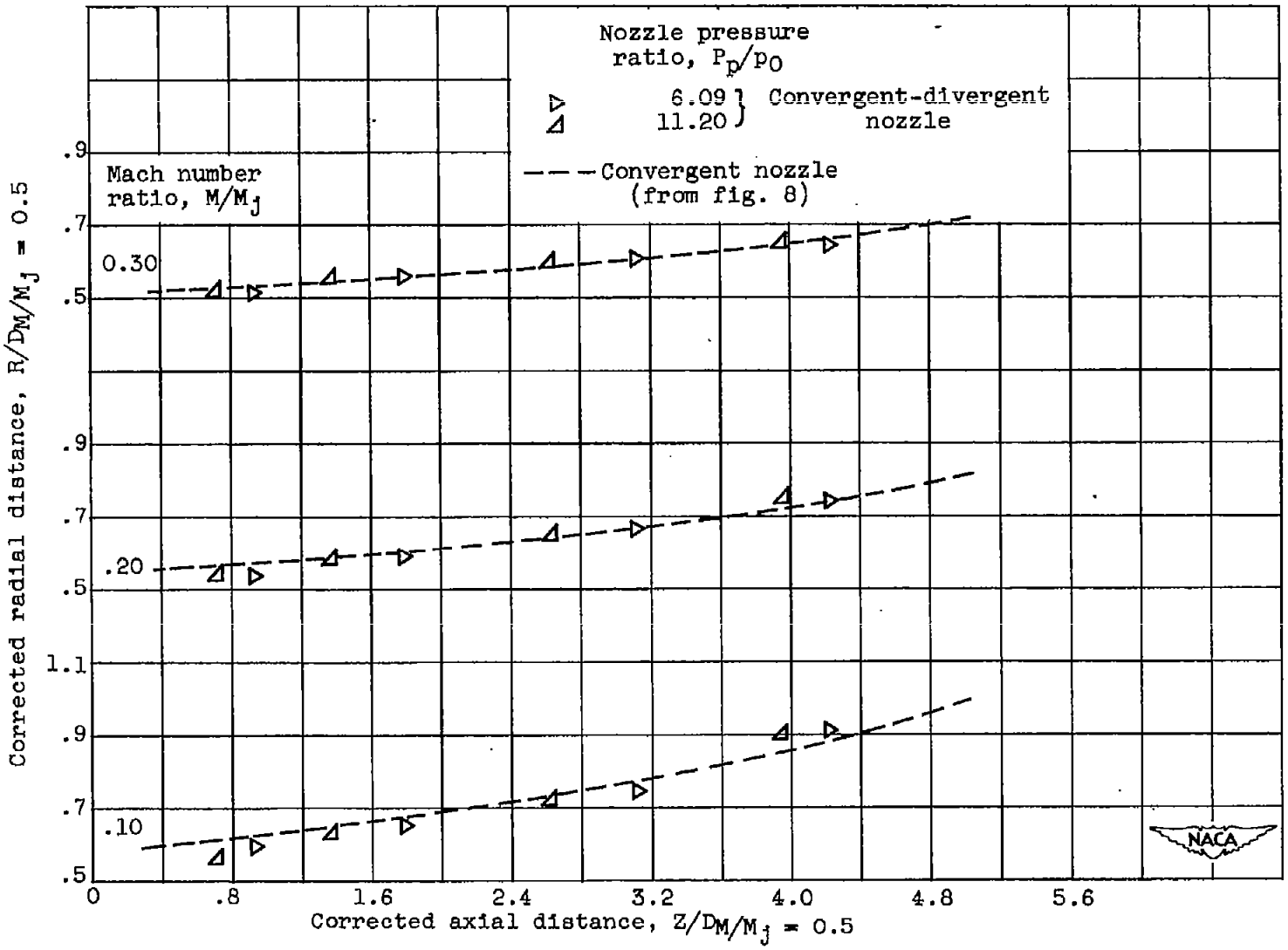

Figure 18. - Generalized Mach number contours of jet expanding from convergent-divergent nozzle. Nozzle-inlet temperature T_p, 950° F.

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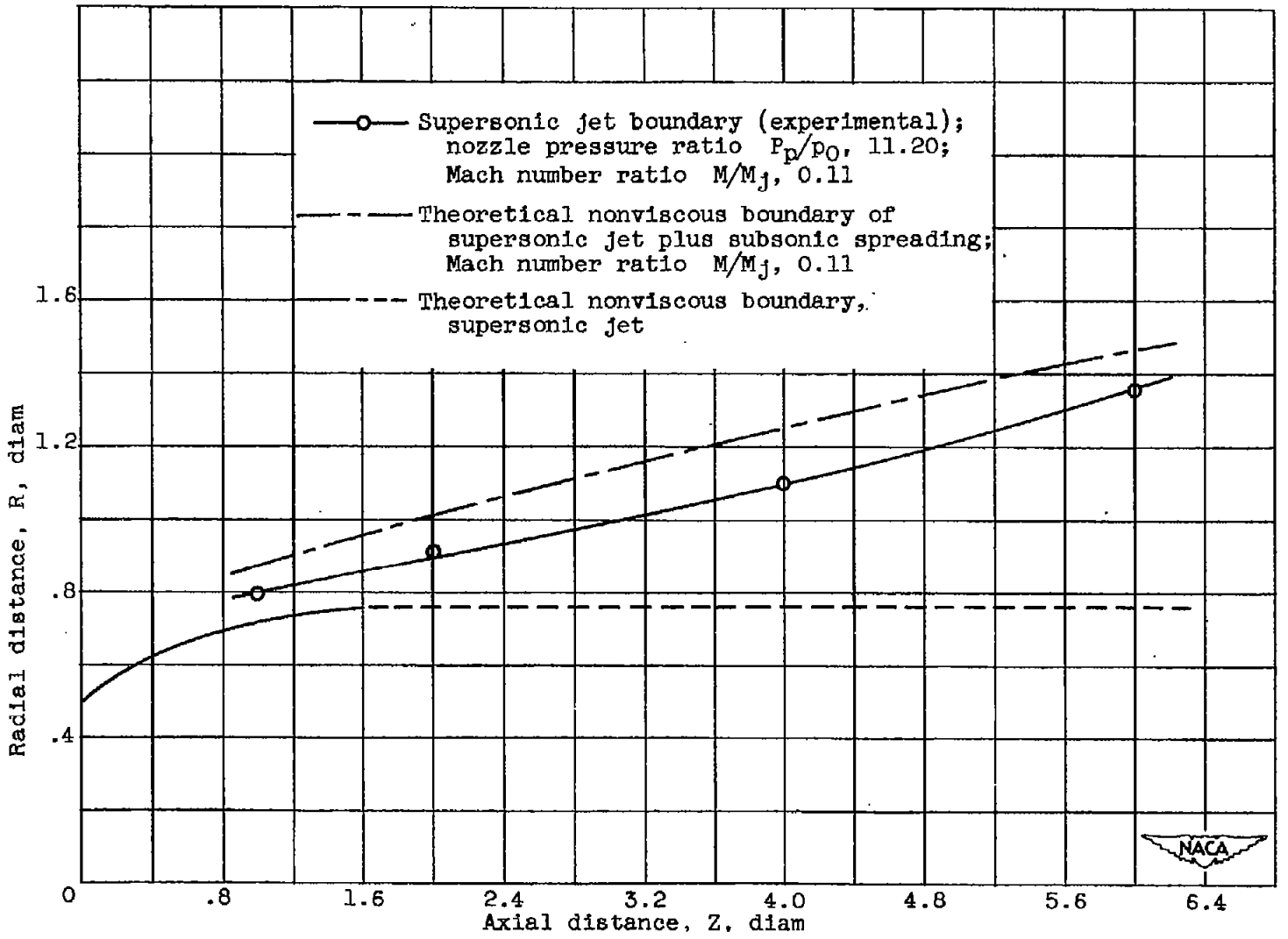

Figure 19. - Variation of jet radius with distance downstream for jet expanding from convergent-divergent nozzle.

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