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RESEARCH MEMORANDUM

PRELIMINARY INVESTIGATION OF A TECHNIQUE OF PRODUCING A HEATED CORE IN A SUPERSONIC WIND-TUNNEL STREAM

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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PRELIMINARY INVESTIGATION OF A TECHNIQUE OF PRODUCING A HEATED CORE IN A SUPERSONIC WIND-TUNNEL STREAM

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SUMMARY

An investigation at Mach numbers 1.9 and 3.0 has shown that a central core of air of high stagnation temperature can be produced in the test section of a supersonic wind tunnel. Air heated by combustion was injected into the tunnel in a streamwise direction from a sonic nozzle near the tunnel throat. The cross-sectional area of the core at the test section, which was within 90 percent of the maximum attainable stagnation-temperature rise, was about 35 percent of that predicted for isentropic, one-dimensional, nonmixing flow at Mach number 1.9. At Mach number 3.0 the core size was about 25 percent of the theoretical. Core size and shape could be controlled by core-nozzle dimensions and location with respect to the tunnel throat. Mach number profiles at the test section in the region of the core were fairly uniform and could be varied by controlling core to tunnel main air stream total-pressure ratio. In addition, core Mach number was affected by core-nozzle location and stagnation temperature of the heated air.

INTRODUCTION

During actual flight through the atmosphere, stagnation conditions are dependent upon flight Mach number and altitude. It is desirable to duplicate as many flight conditions as possible in the wind tunnels; this is especially true for propulsion system research. Some difficulties are encountered, however, when an attempt is made to match the high stagnation temperatures by heating the entire tunnel air stream. The high temperatures cause mechanical and operating problems with the tunnel and associated equipment. In addition, the cost of heating the air, especially for tunnels with high weight-flow rates, becomes very great.

One method of alleviating these problems is to heat only the central portion of the air stream. Test models could then be located at the test section within the heated core. Although various methods may be used to heat this air, one of the easiest is to burn fuel in the air before injecting it into the tunnel main air stream near the tunnel throat. The apparatus required has the advantages of small size and low initial and operating cost. Disadvantages include the change in air properties and composition resulting from the combustion process. In addition, disturbances including turbulence may result from the presence of the injection nozzle and the hot core of air in the tunnel main air stream.

The present investigation, which was conducted at the NACA Lewis laboratory, is a partial evaluation of this method of producing a heated core. The size and shape of the core and the Mach number profiles re- 3498
sulting at the test section are the main factors considered.

SYMBOLS

The following symbols are used in this report:

M	local Mach number
m	mass flow passing through diffuser
m_0	maximum-capture mass flow of diffuser
P_C	average total pressure of heated air at core nozzle
P_T	average total pressure of tunnel main air stream at tunnel throat
P_1	average total pressure at diffuser exit
T	local stagnation temperature at test section
T_C	average stagnation temperature of heated air at core nozzle
T_0	average stagnation temperature of unheated tunnel main air stream
γ	ratio of specific heats
θ	temperature-difference ratio, $\frac{T - T_0}{T_C - T_0}$
θ_l	geometric angle between diffuser axis and line joining apex of cone to cowl lip, deg

APPARATUS AND PROCEDURE

The installation of the test apparatus in two tunnels with normal operating Mach numbers of 1.9 and 3.0 is shown in figure 1. Both tunnels normally operate with approximately atmospheric inlet stagnation pressure, a stagnation temperature of 150° F, and dew points less than about -8° F. The Reynolds numbers are approximately 3.3×10^6 and 1.9×10^6 per foot for the Mach numbers of 1.9 and 3.0, respectively. The test section of both tunnels is 18 by 18 inches. The nozzle of the Mach number 1.9 tunnel is of conventional design, whereas the Mach number 3.0 tunnel utilizes an abrupt expansion on both walls in the initial expansion part of the nozzle in the manner of reference 1. Atmospheric air was heated for the core in a parallel arrangement of four jet-engine combustors using JP-4 fuel. The tunnel main air stream was dried as in normal operation but was not heated for these tests; it therefore had a stagnation temperature of about 50° F. Test Reynolds numbers were somewhat less than in normal operation because the core to main air stream total-pressure ratio was controlled by throttling the main air stream.

The exterior of the convergent sonic core nozzle was designed to conform to the walls of the subsonic portion of the tunnel nozzle in order to avoid choking upstream of the throat. All nozzles were two-dimensional. On the basis of an isentropic, one-dimensional, nonmixing expansion to the normal operating Mach number of the tunnel, the core-nozzle sizes were designed to create approximately a 9- by 9-inch core in the test section. These calculations assumed equal total pressures in the core and tunnel air streams and equal static pressures at the test section. A constant value of $\gamma = 1.4$ was used for all calculations throughout the report with negligible loss of accuracy.

The flow in the test section was surveyed with a rake extending the width of the test section, where 11 pitot tubes and 11 aspirating thermocouples were equally spaced in alternating sequence. In addition, five static-pressure orifices were located on the rake within $4\frac{1}{4}$ inches of the tunnel wall, and wall static pressures were measured at station 60.

RESULTS AND DISCUSSION

Core Studies at Mach Number 1.9

Presented in figure 2 are the results of a survey of the test section at Mach number 1.9 under conditions that generated cores of the greatest extent and uniformity. The contour lines of constant θ were obtained by interpolation of temperature profiles, such as the ones shown, taken at 1-inch increments in the plane of expansion at each axial station. For these data a 9- by 5.4-inch core nozzle was located at the tunnel throat. For ideal, inviscid flow a 9- by 8.4-inch core size at the test section was predicted. However, at station 74 the cross-sectional area of the portion of the actual core that was within 90 percent of the maximum attainable temperature rise was about 35 percent of the theoretical area. As expected, the size of the useful

portion of the core diminished downstream in the test section. Because of shock interference on the survey rake at this Mach number, measured stream static pressures could not be used and it was necessary to compute Mach number from wall static pressures at station 60 and from local pitot pressures at the various axial stations. Thus, the computed values of Mach number may not be exact, but the data indicate the approximate variation across the test section. The Mach numbers are fairly uniform in the region of the core where a uniform temperature exists. Check points in other planes at the same station give the same results. 3488
Without the core in the tunnel, Mach numbers near the center line generally did not vary by more than 0.01 across the test section and 0.03 along the test section.

Figure 3 shows the effect of varying the core-nozzle exit location from that used for figure 2. Although the core- to tunnel-total-pressure ratio for figure 3 is less than that for the previous figure, it will be shown later that the temperature data of both figures can be compared directly, although the Mach number profiles cannot be so treated. The largest core sizes and best core shapes were obtained with the core-nozzle exit located at the tunnel throat or slightly downstream.

The effect of core- to tunnel-total-pressure ratio P_C/P_T is shown in figure 4. For all core-nozzle locations, increased pressure ratios produced increased Mach numbers in the region of the core with little effect on temperature profiles and contours. For comparable core- to tunnel-total-pressure ratios, higher Mach numbers resulted with the core nozzle located upstream of the tunnel throat. Thus, in all probability the original tunnel Mach number can be reproduced in a heated-core installation.

All the data presented thus far have been obtained with a core-exit temperature of about 500° F. At Mach number 1.9 such a stagnation temperature roughly corresponds to that attained in flight at sea level. At altitude, the required stagnation temperature would be less. The effect of reducing core-exit temperature to about 300° F is indicated in figure 5. Core size and Mach numbers in the region of the core were somewhat reduced from those attained with core temperatures of 500° F. With cold flow through the core nozzle, appreciable turbulence and buffeting of the rake resulted, especially with core-exit locations near the tunnel throat. With the core flow heated, buffeting was not noticeable.

Core Studies at Mach Number 3.0

The 9- by 5.4-inch core exit used at Mach number 1.9 was also used in the Mach number 3.0 tunnel. The nozzle location (12 in. upstream of the tunnel throat) was such that by isentropic, one-dimensional, nonmixing flow a core approximately 9 by 9 inches would result at the test section. With such an extreme nozzle location, the actual core at the test section was very narrow, with the long dimension at right angles to the long dimension of the core exit. The temperature-difference ratio θ was less than 0.75. Results were so poor that data are not presented. Thus, for variable Mach number tunnel operation, a variable-size core nozzle may also be needed.

Because of the particular geometry of the nozzle used in the Mach number 3.0 tunnel, it was impractical to locate a reasonably sized core-nozzle exit at what had previously been determined as the best position, that is, at the tunnel throat. A 9- by 2-inch core nozzle located $4\frac{1}{2}$ inches upstream of the tunnel throat produced the best results attainable under the circumstances. A core- to tunnel-total-pressure ratio of 0.96 and a core-exit temperature of 500° F were the only conditions investigated at this Mach number. The data for these conditions are presented in figure 6. The core shape was approximately rectangular rather than square, a trend also observed at Mach number 1.9 with upstream core-exit locations. Core size was about 25 percent of the theoretical. Mach numbers were computed from the average of the rake static pressures in the main air stream and the local pitot pressures at each station. The wall static pressure near the beginning of the test section was about 10 percent greater than the average stream static pressure. As noted previously, the Mach number profiles are fairly uniform in the region of the core in all planes. The variation in Mach number across the test section was greater than at the lower Mach number. Computed free-stream total pressures in the core at the test section generally decreased in the downstream direction and were between 88 and 80 percent of the core-inlet stagnation pressure. Because undried atmospheric air was used for the core and water vapor was one of the products of combustion, the dew point of this air was high. Consequently, in spite of the high inlet temperature, condensation shocks could be expected (ref. 2) which would decrease total pressures in the core.

Data were also obtained with larger core nozzles located farther upstream of the tunnel throat. As expected, any dimension of the core in the test section could be increased by increasing the corresponding dimension of the core exit provided the core exit was reasonably close to the tunnel throat. Since stagnation temperatures in the core at the test section were low when the core exit was located farther upstream, the data are not presented.

Diffuser Performance in Heated Core at Mach Number 1.9

A conical shock diffuser with a cowl-inlet diameter of 2.74 inches was operated at zero angle of attack and Mach number 1.9 in the heated core near axial station 81 in order to determine resulting diffuser performance. The performance data are presented in figure 7. As described in detail in reference 3, the subcritical stability of this diffuser was very sensitive to cowl-lip position. Two cowl-lip positions that had yielded stable subcritical operation to mass-flow ratios of about 0.22 without the core were investigated within the core. With a cowl-lip position parameter θ_l of 45.8°, the conical shock was well within the cowling. Operation in the heated core somewhat diminished the subcritical stability. During such stable subcritical operation, the normal shock was observed to be shaky. A high-speed motion picture study showed that this shakiness was not true inlet buzz wherein the normal shock surges in and out of the diffuser, but only a local oscillation of the normal shock, perhaps due to varying free-stream conditions. Buzz conditions indicated in the data were of the conventional type. During operation without the core with a cowl-lip position parameter of 44.7°, the conical shock was still within the cowling but closer to the lip. Subcritical stability remained very extensive, but the inlet geometry was approaching one where shock instability would occur. During operation within the core, the conical shock was generally on the cowl lip and there was virtually no stability. Variations in conical shock angle would result from changes in Mach number and the ratio of specific heats γ. Use of the indicated core Mach numbers to calculate a core total pressure yielded the impossible situation of an irregular variation along the tunnel test section of the core total pressure between 90 and 105 percent of its upstream plenum value. Therefore, diffuser pressure recovery P_1/P_C, computed with no losses assumed from the core nozzle to the test section, may not be exactly representative of the effect of the various conditions of core operation on recovery.

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Typical schlieren photographs of this diffuser under similar operating conditions with and without the heated core are presented in figure 8. The exposure time of the photographs was 1 microsecond and 1/200 second, respectively.

SUMMARY OF RESULTS

An investigation has been conducted of a method to increase the stagnation temperature of a core of the air stream in a Mach number 1.9 and a Mach number 3.0 tunnel. A portion of the air was heated by combustion and injected in a streamwise direction from sonic nozzles into the tunnel main air streams near the tunnel throats. Temperature and pressure surveys in the test sections indicated the following results:

1. A heated core could be produced along the center line of the test sections. With the best conditions investigated, the cross-sectional area of the core that was within 90 percent of the maximum attainable stagnation-temperature rise was about 35 percent of that predicted for isentropic, one-dimensional, nonmixing flow at Mach number 1.9. At Mach number 3.0 the core size was about 25 percent of the theoretical size.

2. The best core shapes and sizes at the test sections were obtained with the core-nozzle exits located near the tunnel throats or slightly downstream. Core-nozzle dimensions directly affected core shapes and sizes.

3. Mach numbers at the test sections in the region of the core were fairly uniform and varied directly in the Mach number 1.9 tunnel with the core to tunnel main air stream total-pressure ratio at the throat. There was little effect of pressure ratio on core size and shape.

4. Increasing the stagnation temperature of the core in the Mach number 1.9 tunnel produced slight increases in Mach number in the region of the core at the test section and in core size.

5. The subcritical stability of a supersonic diffuser located within the heated core in the Mach number 1.9 tunnel was comparable to that without the core with some diffuser geometries.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, November 17, 1954

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2. Burgess, Warren C., Jr., and Seashore, Ferris L.: Criterions for Condensation-Free Flow in Supersonic Tunnels. NACA TN 2518, 1951. (Supersedes NACA RM E9E02.)

3. Beheim, Milton A.: A Preliminary Investigation at Mach Number 1.91 of a Diffuser Employing a Pivoted Cone to Improve Operation at Angle of Attack. NACA RM E53I30, 1953.

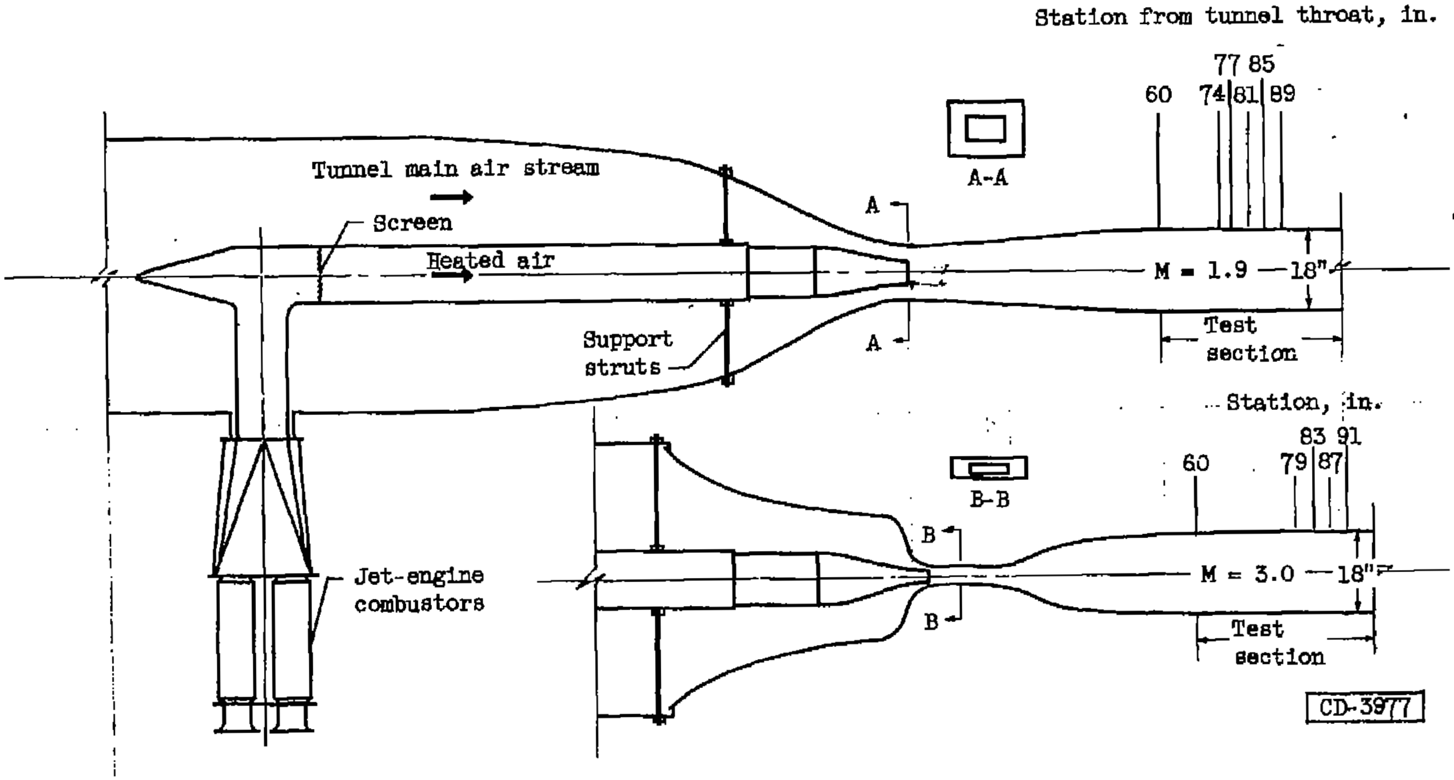

Figure 1. - Installation of heated-core test apparatus in Mach number 1.9 and 3.0 tunnels.

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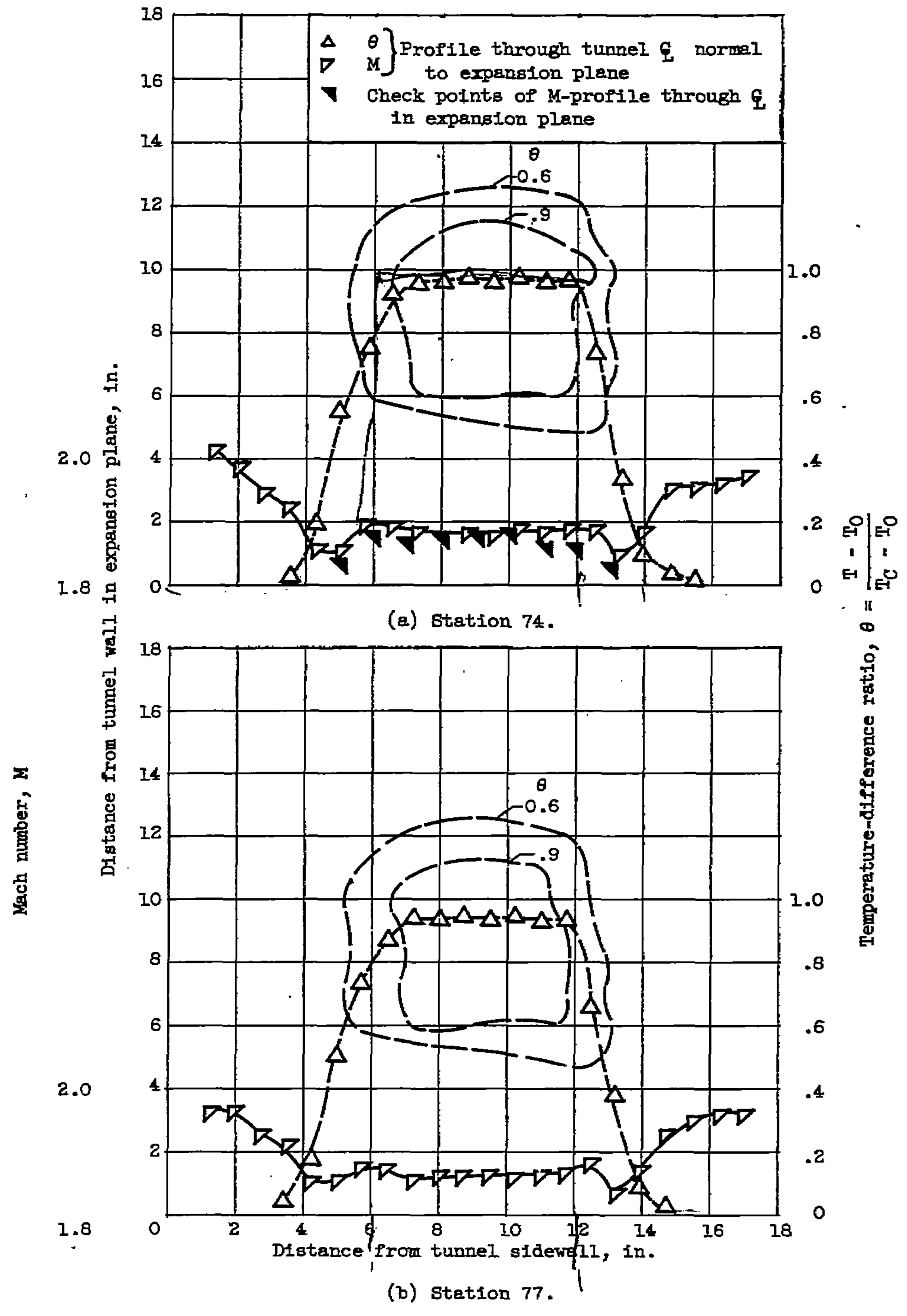

Figure 2. - Temperature and Mach number distributions in test section of Mach number 1.9 tunnel. Core-nozzle exit located at tunnel throat; $P_C/P_T = 0.93$; $T_C = 500^\circ$ F.

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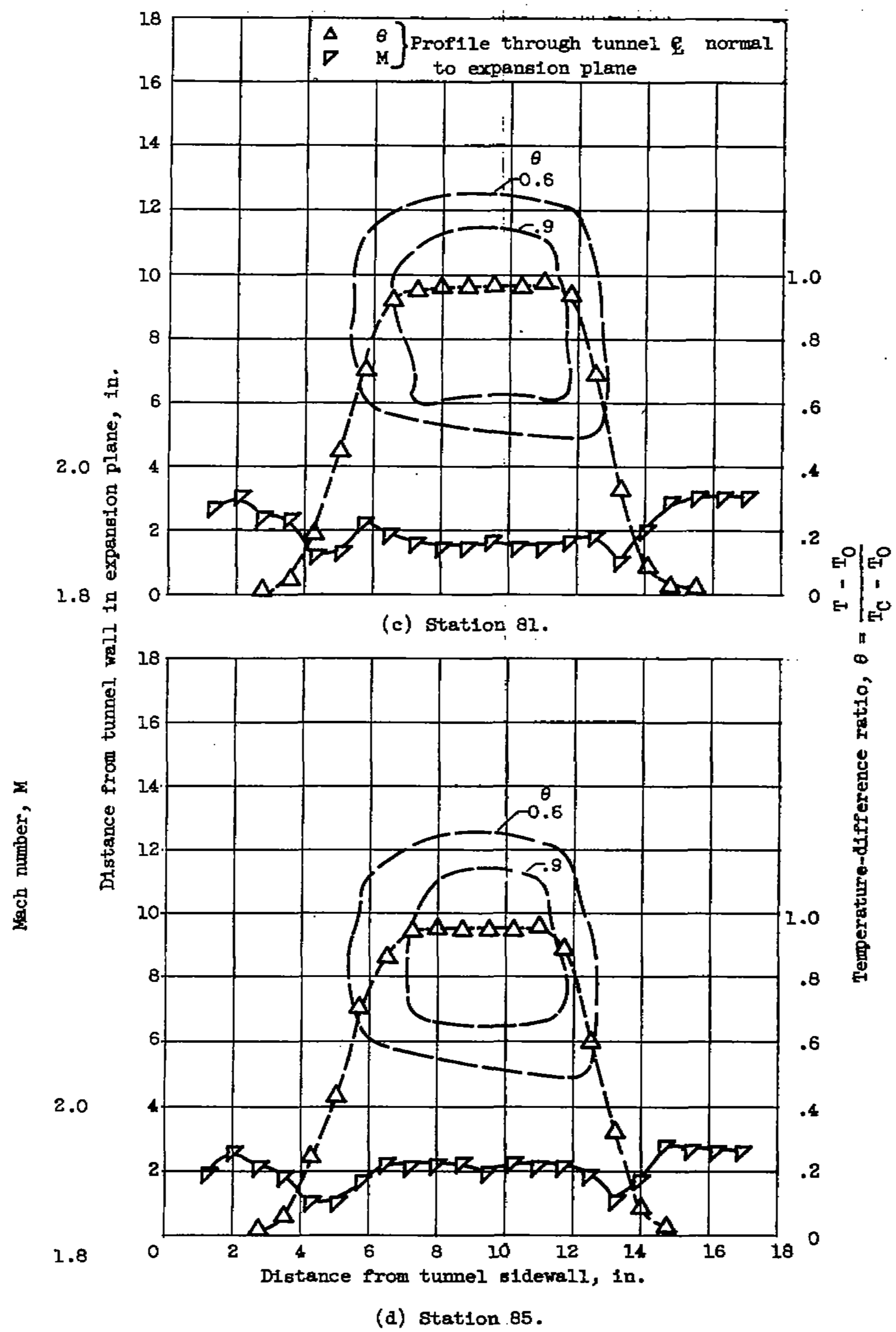
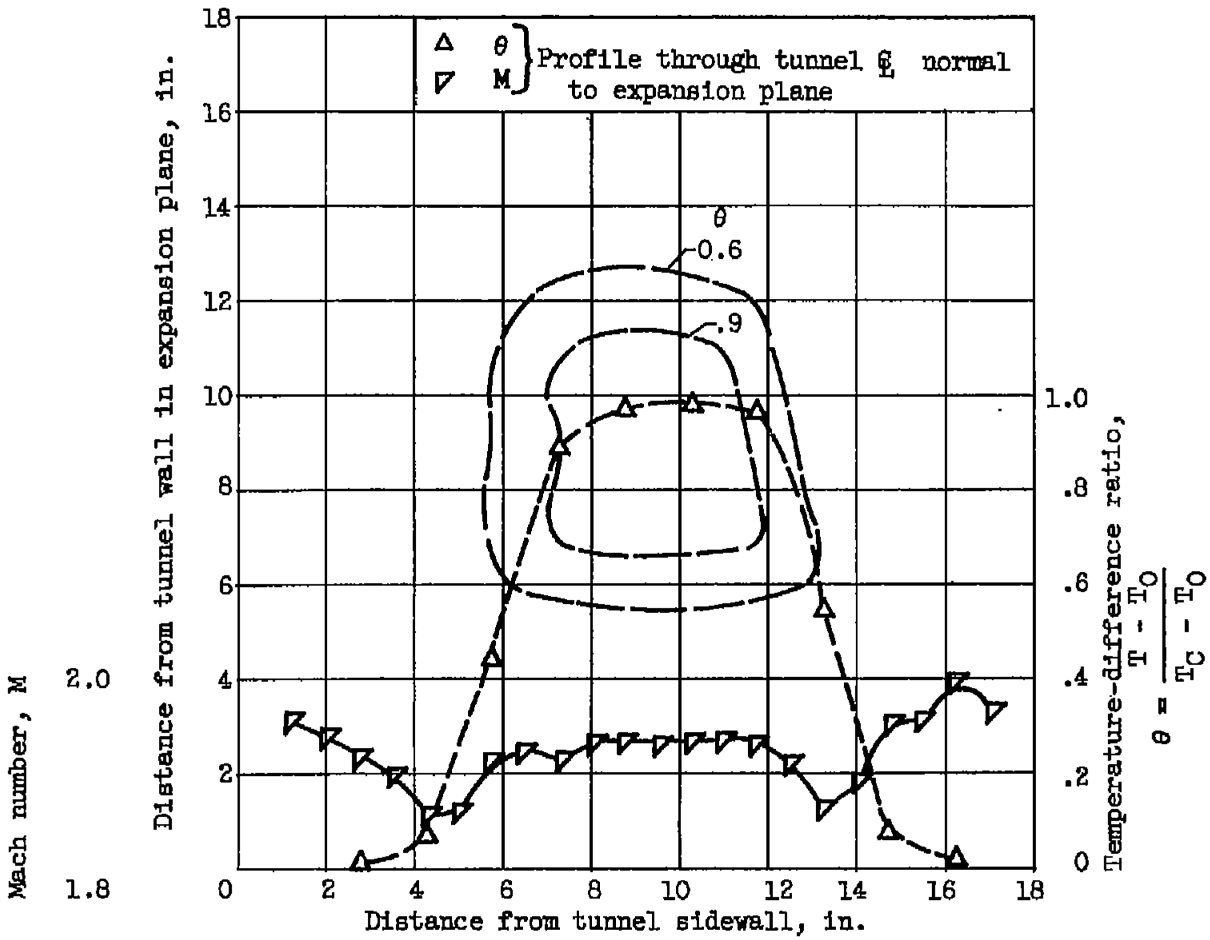


Figure 2. - Continued. Temperature and Mach number distributions in test section of Mach number 1.9 tunnel. Core-nozzle exit located at tunnel throat; P_C/P_T = 0.93; T_C = 500° F.



(e) Station 89.

Figure 2. - Concluded. Temperature and Mach number distributions in test section of Mach number 1.9 tunnel. Core-nozzle exit located at tunnel throat; $P_C/P_T = 0.93$; $T_C = 500^{\circ}$ F.

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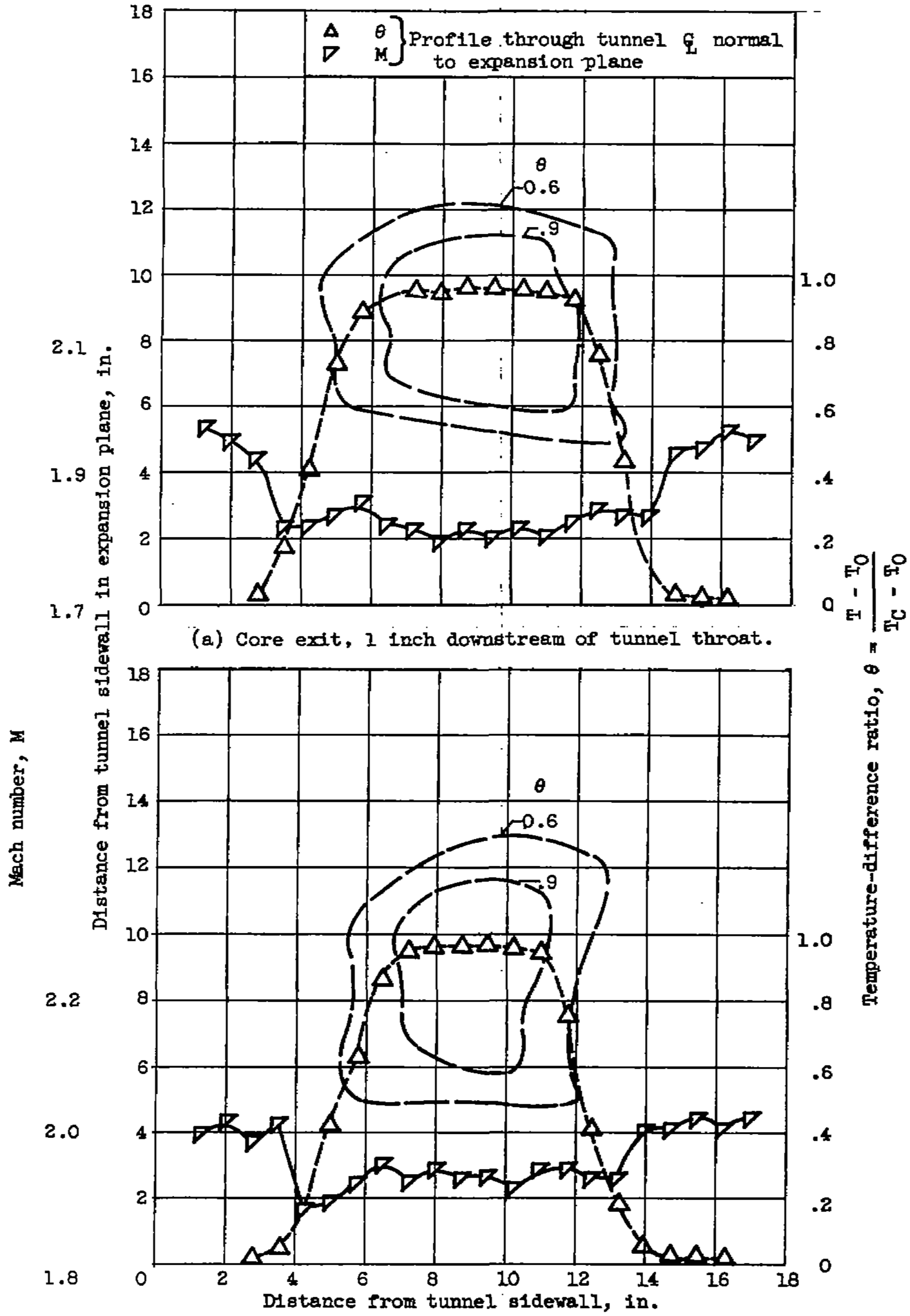

(b) Core exit, 1 inch upstream of tunnel throat.

Figure 3. - Effect of core-nozzle exit location on temperature and Mach number distributions in Mach number 1.9 tunnel. Axial station, 81; P_C/P_T = 0.88; T_C = 500° F.

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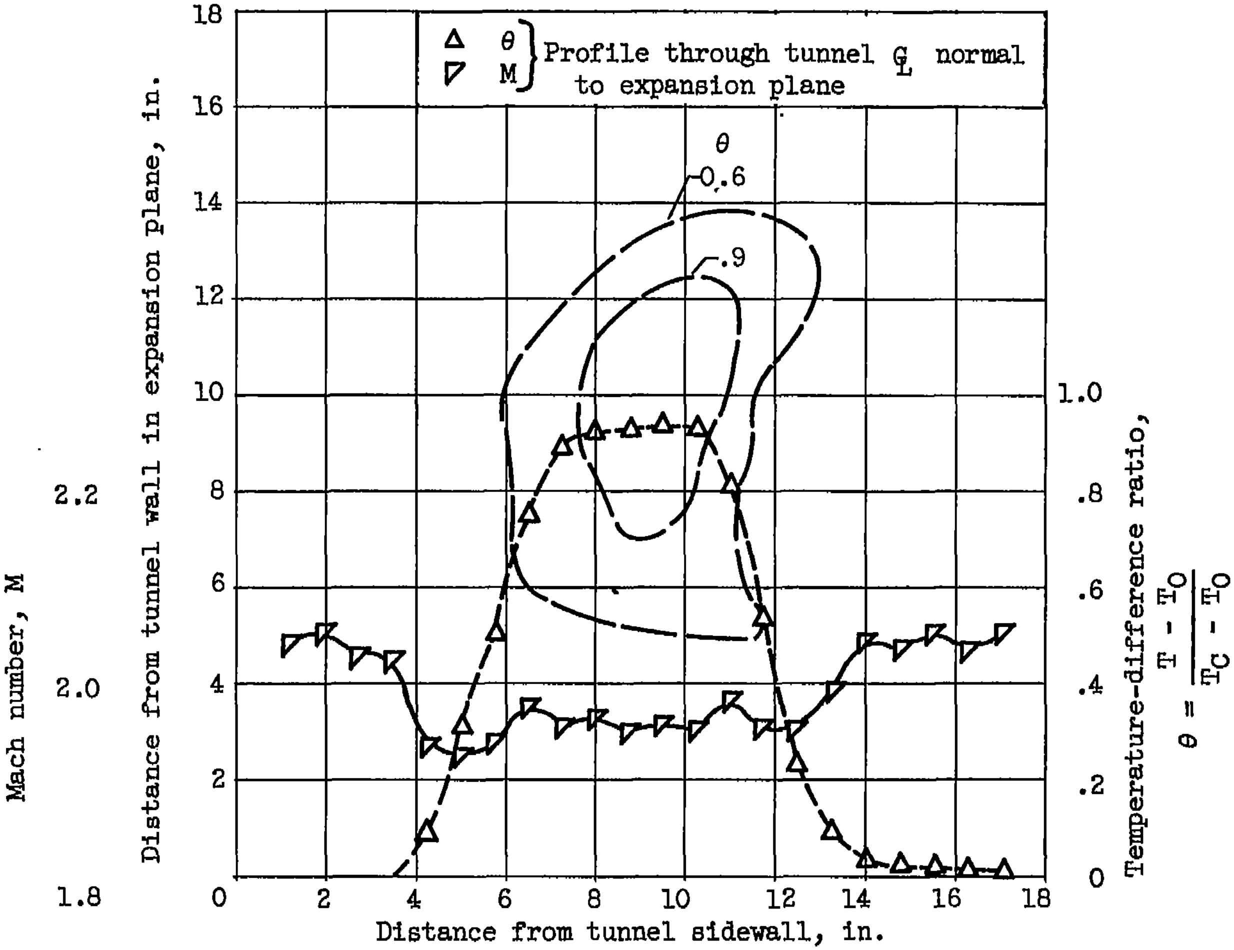
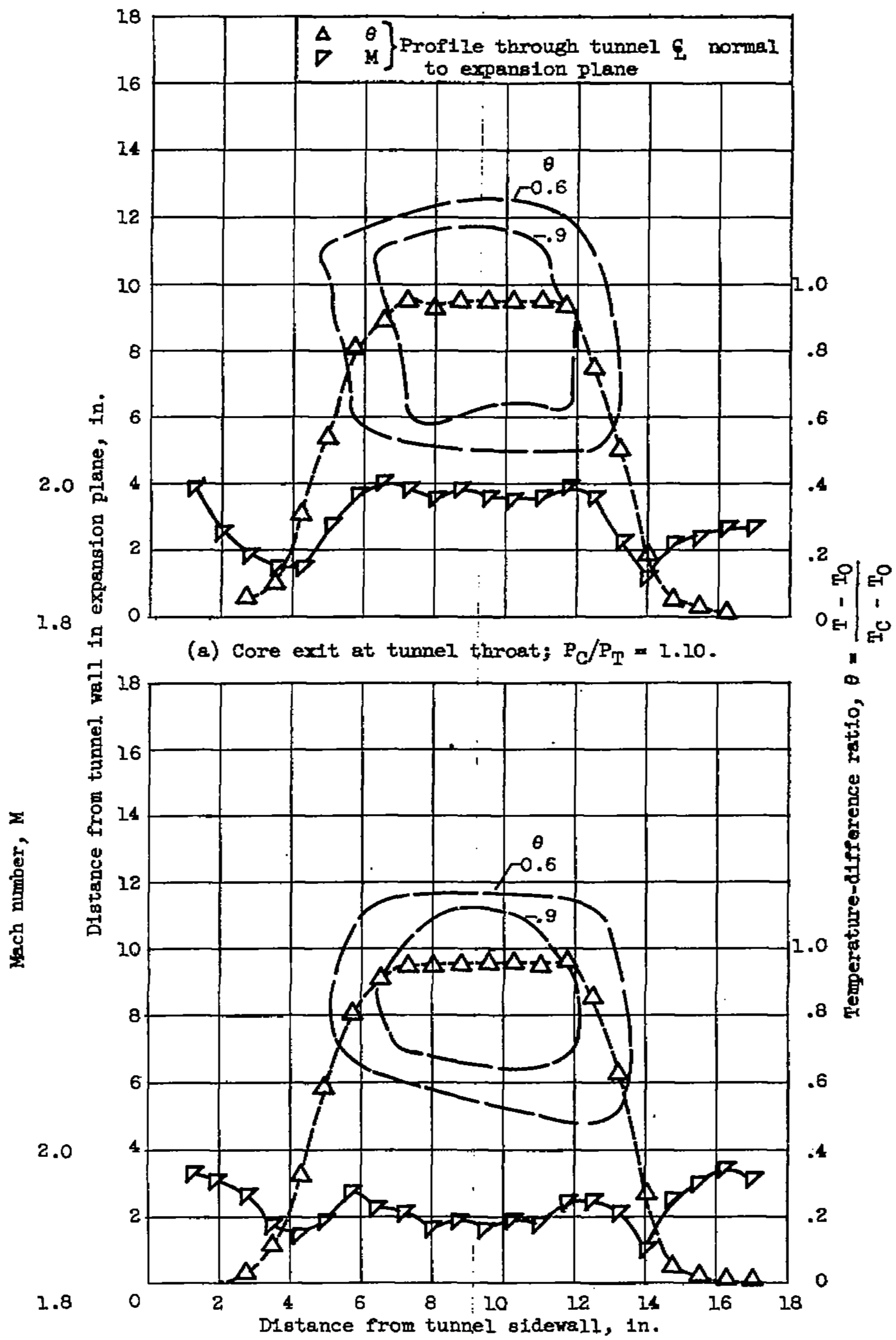


(c) Core exit, 3 inches upstream of tunnel throat.

Figure 3. - Concluded. Effect of core-nozzle exit location on temperature and Mach number distributions in Mach number 1.9 tunnel. Axial station, 81; P_C/P_T = 0.88; T_C = 500° F.



(a) Core exit at tunnel throat; $P_C/P_T = 1.10$.

(b) Core exit, 1 inch downstream of tunnel throat; $P_C/P_T = 0.99$.

Figure 4. - Effect of core- to tunnel-total-pressure ratio P_C/P_T on temperature and Mach number distributions in Mach number 1.9 tunnel. Axial station, 81; $T_C = 500^\circ$ F.

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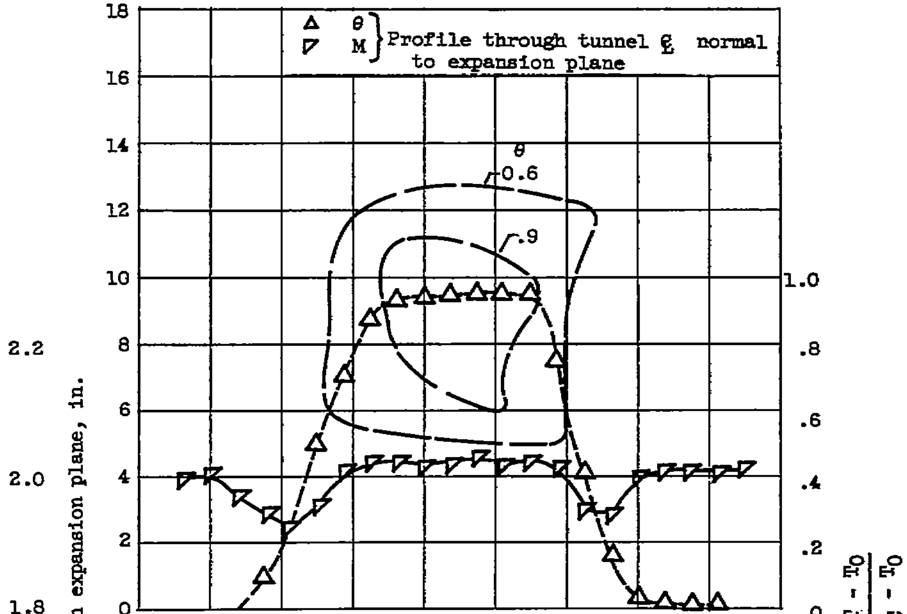
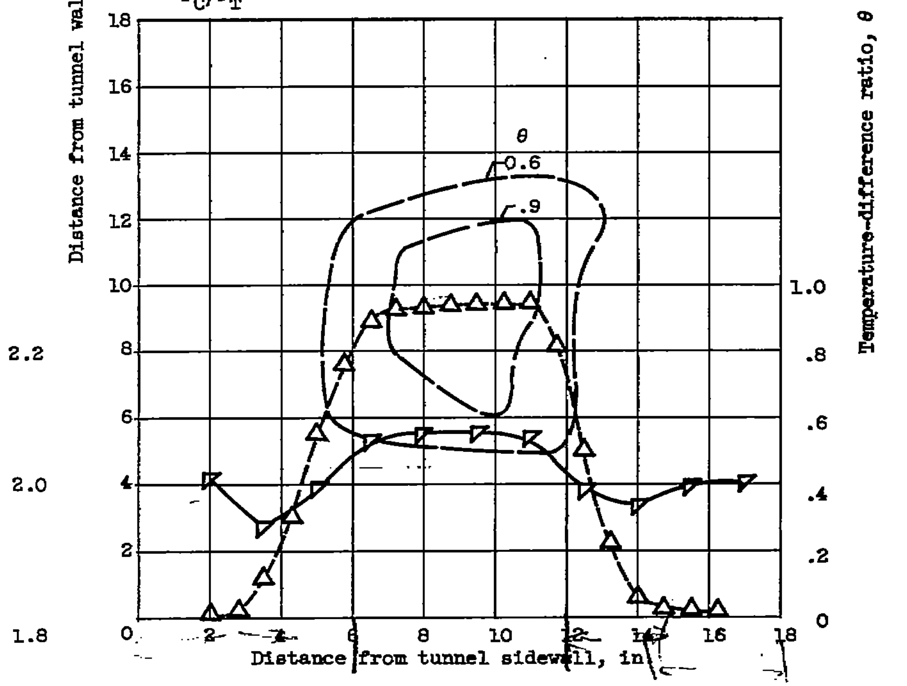


(c) Core exit, 1 inch upstream of tunnel throat; $P_C/P_T = 1.0$.



(d) Core exit, 1 inch upstream of tunnel throat; $P_C/P_T = 1.1$.

Figure 4. - Continued. Effect of core- to tunnel-total-pressure ratio P_C/P_T on temperature and Mach number distributions in Mach number 1.9 tunnel. Axial station, 81; $T_C = 500^\circ$ F.

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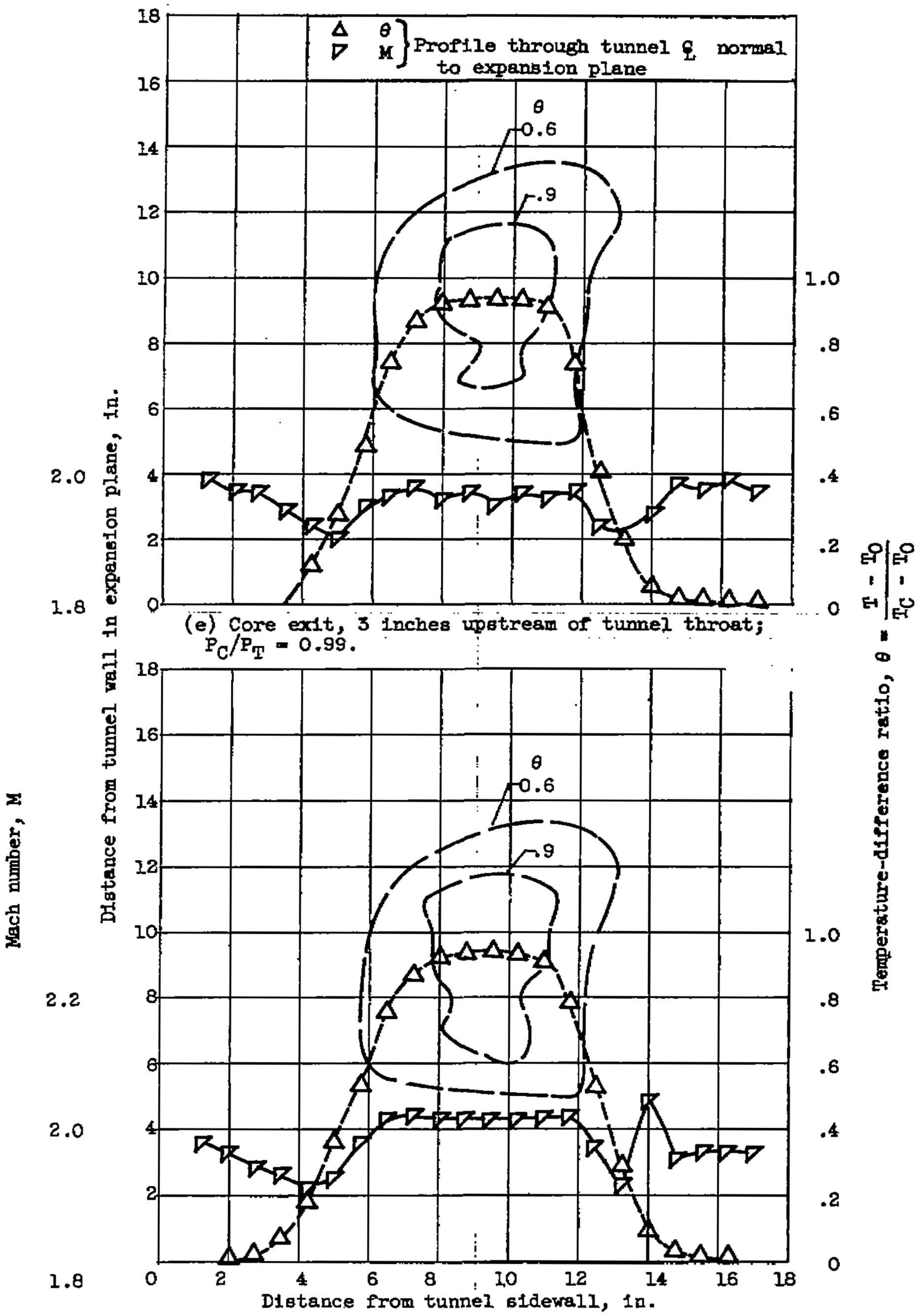

(e) Core exit, 3 inches upstream of tunnel throat; $P_C/P_T = 0.99$.

(f) Core exit, 3 inches upstream of tunnel throat; $P_C/P_T = 1.09$.

Figure 4. - Concluded. Effect of core- to tunnel-total-pressure ratio P_C/P_T on temperature and Mach number distributions in Mach number 1.9 tunnel. Axial station, 81; $T_C = 500^\circ$ F.

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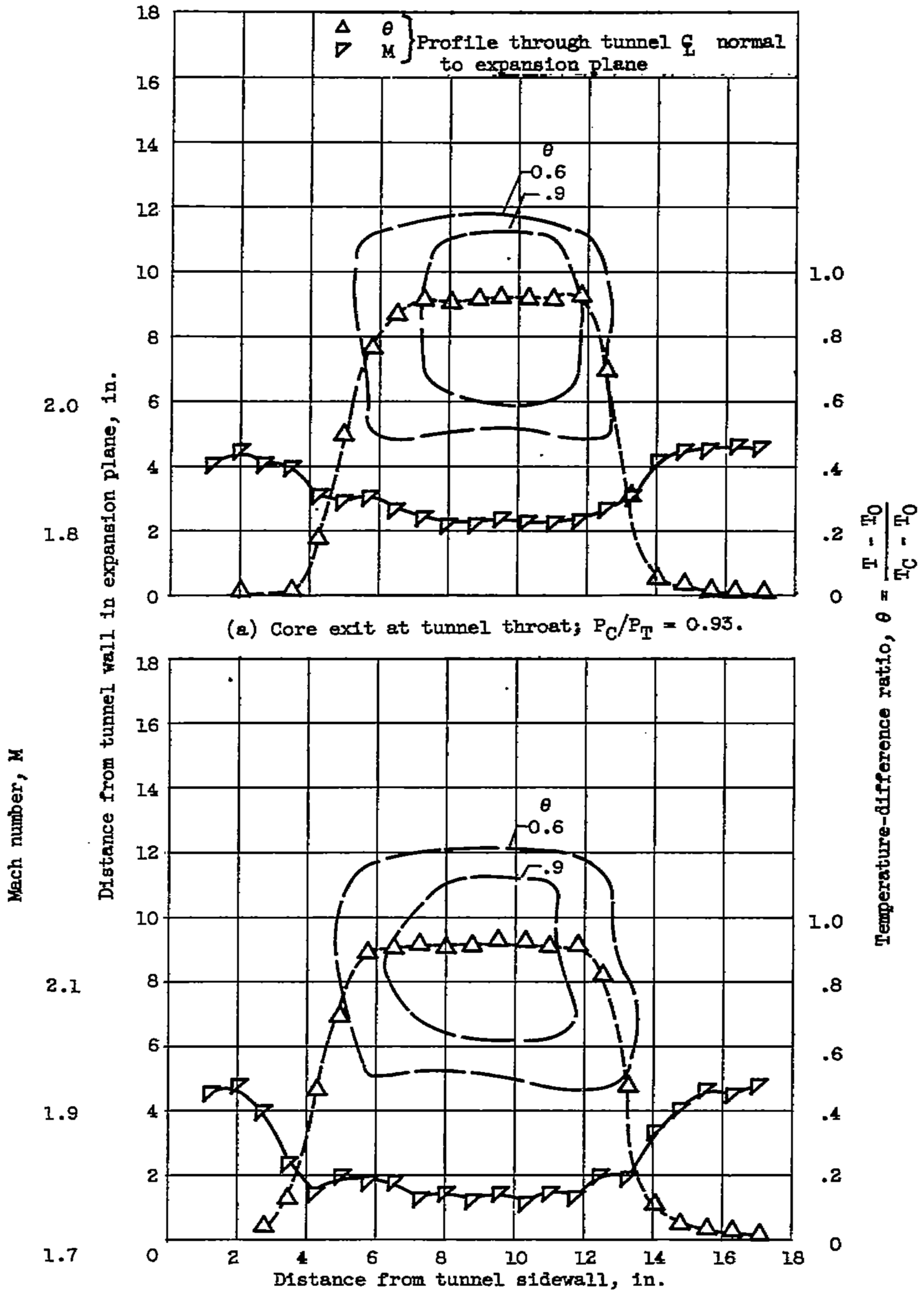

(a) Core exit at tunnel throat; $P_C/P_T = 0.93$.

(b) Core exit, 1 inch downstream of tunnel throat; $P_C/P_T = 0.88$.

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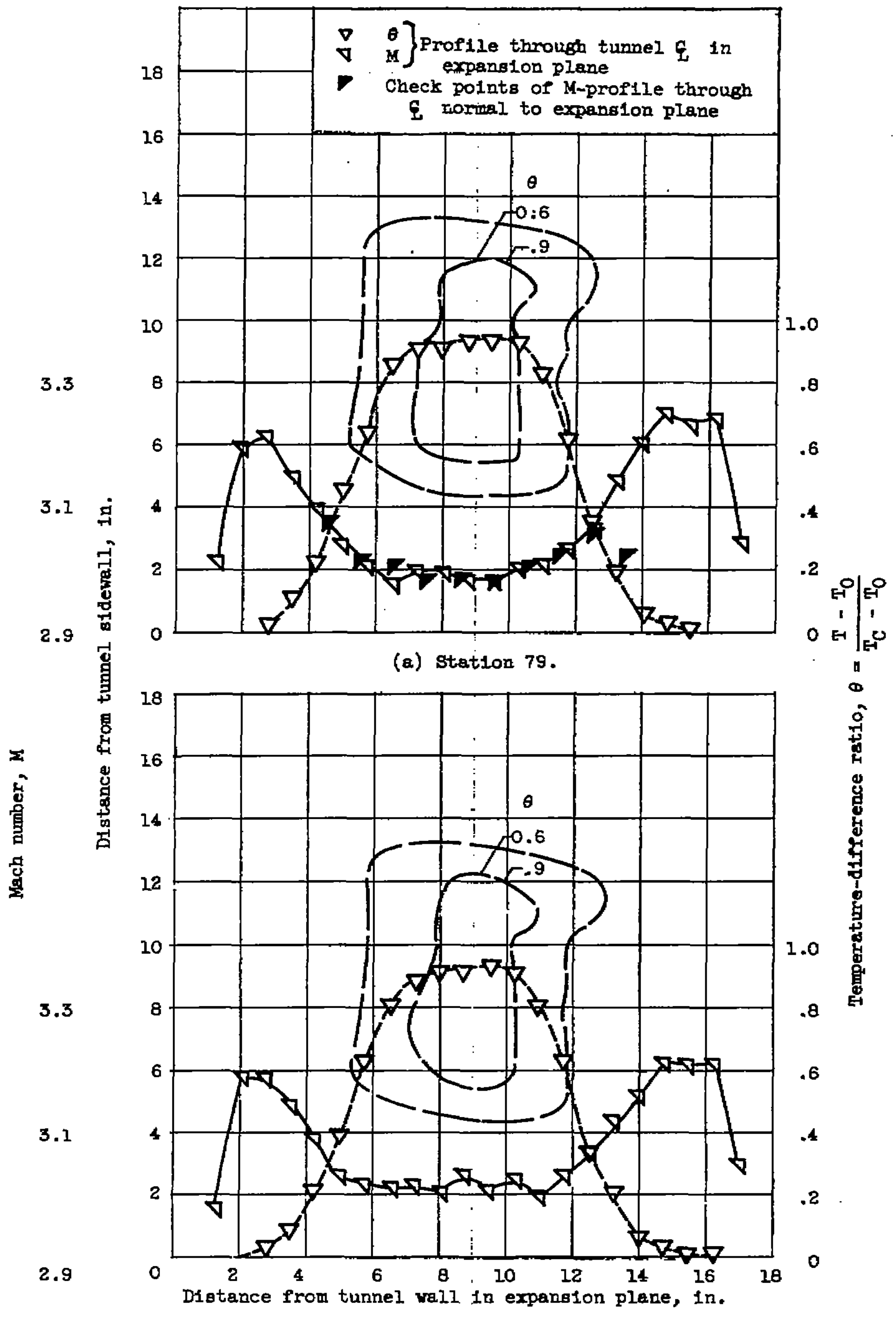
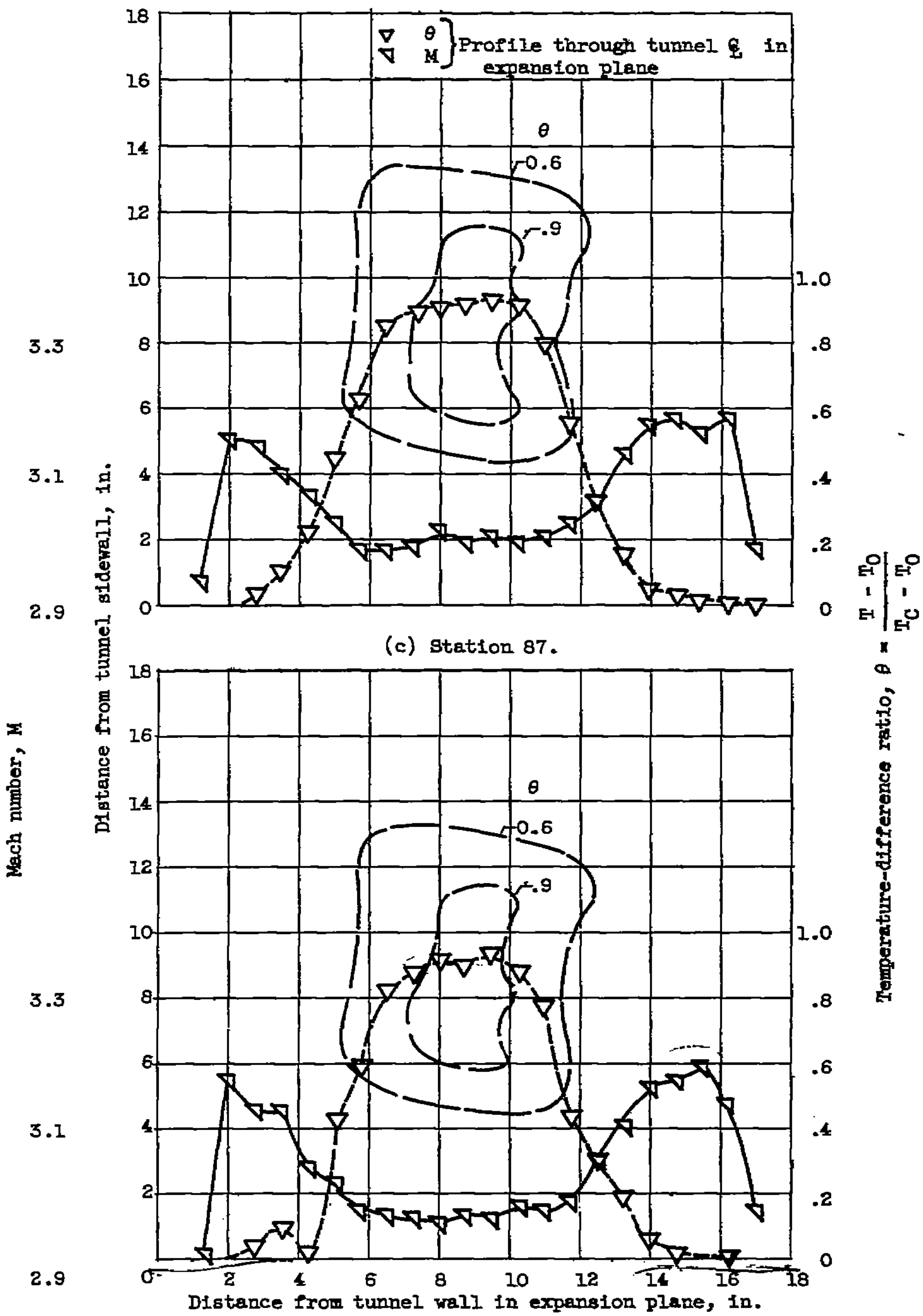
Figure 5. - Temperature and Mach number distributions with decreased core temperatures in Mach number 1.9 tunnel. Axial station, 81; $T_C = 300^\circ$ F.



(b) Station 83.

Figure 6. - Temperature and Mach number distributions in test section of Mach number 3.0 tunnel. Core-nozzle exit, $4\frac{1}{2}$ inches upstream of tunnel throat; $P_C/P_T = 0.96$; $T_C = 500^{\circ}$ F.



(c) Station 87.

(d) Station 91.

Figure 6. - Concluded. Temperature and Mach number distributions in test section of Mach number 3.0 tunnel. Core-nozzle exit, $4\frac{1}{2}$ inches upstream of tunnel throat; $P_C/P_T = 0.96$; $T_C = 500^{\circ}$ F.

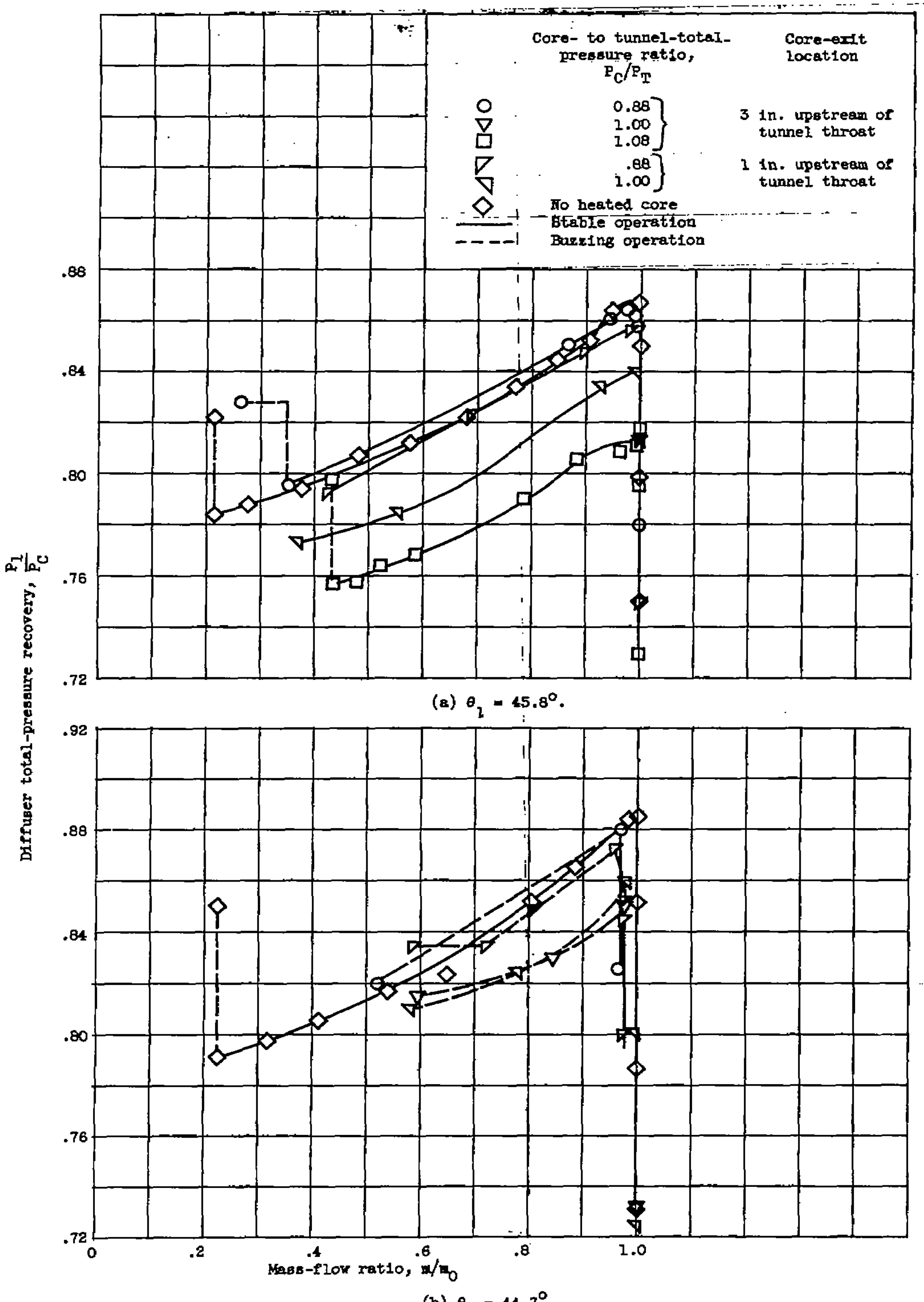
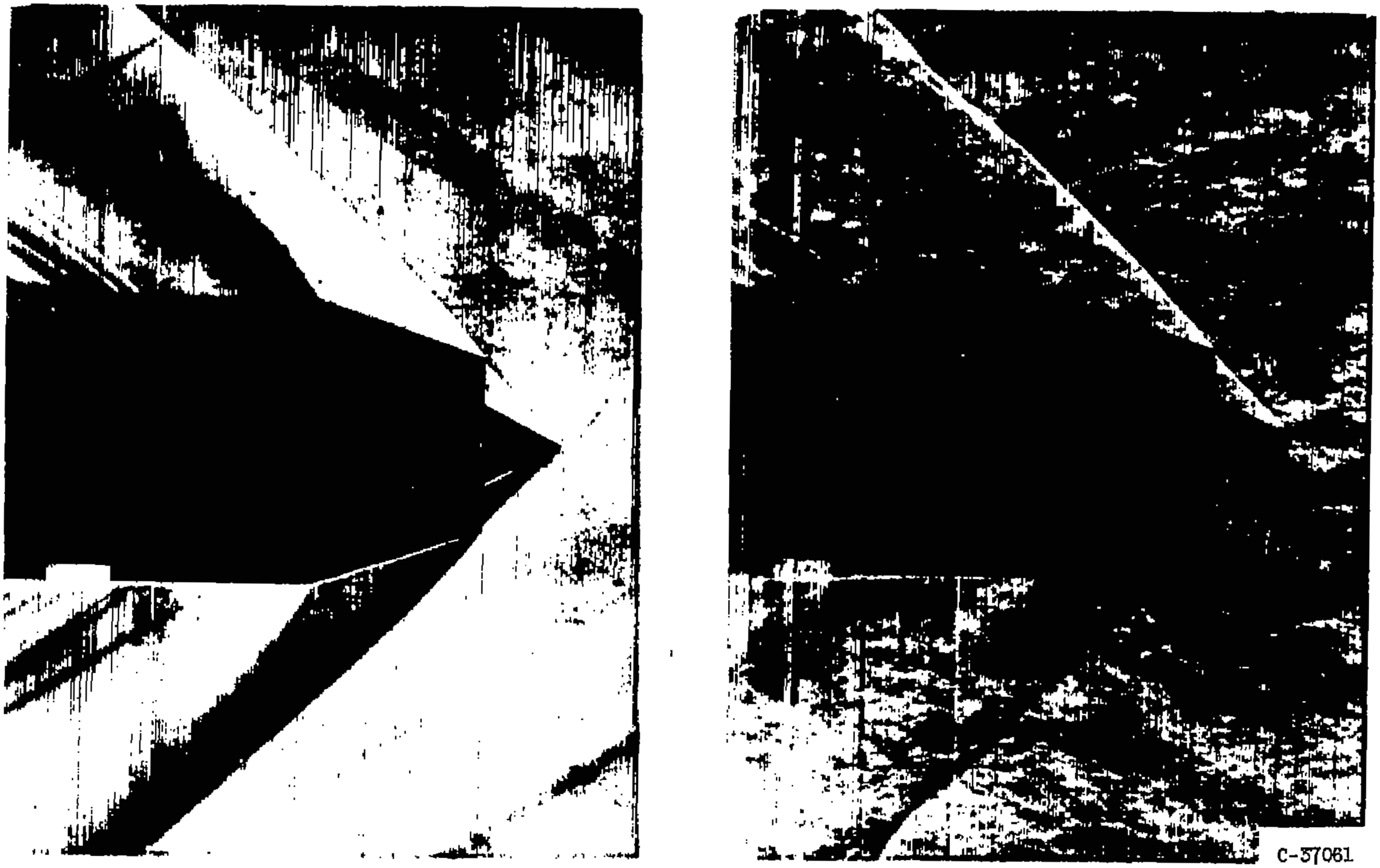


Figure 7. - Effect of heated core on diffuser stability in Mach number 1.9 tunnel. T_C = 480° F.



Without heated core.

With heated core, $T_C = 480^\circ$ F; $P_C/P_T = 1.0$; core exit, 3 inches upstream of tunnel throat.

(a) Peak pressure recovery operation.

Figure 8. - Schlieren photographs of diffuser in Mach number 1.9 tunnel. $\theta_l = 45.8^\circ$.

Without heated core.

With heated core, $T_C = 480^\circ$ F; $P_C/P_T = 1.0$; core exit, 3 inches upstream of tunnel throat.

(b) Minimum stable diffuser flow operation.

Figure 8. - Concluded. Schlieren photographs of diffuser in Mach number 1.9 tunnel. $\theta_l = 45.8^\circ$.

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