~~SECURITY INFORMATION~~

RM L52E29a

Copy 184
RM L52E29a

~~CONFIDENTIAL~~

UNCLASSIFIED

NACA RM L52E29a

NACA

RESEARCH MEMORANDUM

PRELIMINARY INVESTIGATION OF THE EFFECTS OF HEAT TRANSFER ON BOUNDARY-LAYER TRANSITION ON A PARABOLIC BODY OF REVOLUTION (NACA RM-10) AT A MACH NUMBER OF 1.61

By K. R. Czarnecki and Archibald R. Sinclair

Langley Aeronautical Laboratory
Langley Field, Va.

CANCELLED
Classification
CHANGED TO Unclassified
By authority of Naca abstract - 1-29-54
Changed by JW Date 2-4-54

CLASSIFIED DOCUMENT

This material contains information affecting the National Defense of the United States within the meaning of the espionage laws, Title 18, U.S.C., Secs. 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON
July 29, 1952

~~CONFIDENTIAL~~

UNCLASSIFIED

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

PRELIMINARY INVESTIGATION OF THE EFFECTS OF HEAT TRANSFER ON BOUNDARY-LAYER TRANSITION ON A PARABOLIC BODY OF REVOLUTION (NACA RM-10) AT A MACH NUMBER OF 1.61

By K. R. Czarnecki and Archibald R. Sinclair

SUMMARY

A preliminary investigation has been made of the effects of heat transfer on boundary-layer transition on a body of revolution at a Mach number of 1.61 and over a Reynolds number range of 7×10^6 to 20×10^6, based on body length. The body had a parabolic-arc profile, blunt base, and a fineness ratio of 12.2 (NACA RM-10). The results indicated that, by cooling the model an average of about 50° F, the Reynolds number for which laminar boundary-layer flow could be maintained over the entire length of the body was increased from the value of 11×10^6 without cooling to over 20×10^6, the limit of the present tests. Heating the model an average of about 12° F on the other hand decreased the transition Reynolds number from 11×10^6 to about 8×10^6. These effects of heat transfer on transition were considerably larger than previously found in similar investigations in other wind tunnels. It appears that, if the boundary-layer transition Reynolds number for zero heat transfer is large, as in the present experiments, then the sensitivity of transition to heating or cooling is high; if the zero-heat-transfer transition Reynolds number is low, then transition is relatively insensitive to heat-transfer effects.

INTRODUCTION

In the design of supersonic airplanes and missiles, much dependence is placed upon experimental values of skin-friction drag. Wind-tunnel investigations of skin friction, however, are usually made under conditions of little or no heat transfer. In actual flight of high-speed aircraft, particularly during acceleration or deceleration, the temperature of the vehicle often lags behind that of the boundary layer. Under these conditions, the heat transfer to or from the boundary layer may be appreciable.

Theoretical considerations (refs. 1 to 3) have indicated that one of the most important effects of heat transfer is its influence on the stability of the laminar boundary layer. In particular, it appears possible theoretically to preserve the laminar boundary layer at high Reynolds numbers by means of heat transfer from the boundary layer into the body. Unfortunately, in its present state of development, the theory is unable to predict the magnitude of this effect with certainty, particularly at the higher supersonic speeds.

Previous wind-tunnel experiments (refs. 4 to 9) have established the existence of the expected effects of heat transfer. However, the magnitude of the stabilizing effect of heat transfer from the boundary layer to the body was not large. It should be noted, however, that in the previous tests the transition Reynolds numbers for zero heat transfer were relatively low, of the order of 1.3×10^6.

Reference 10 reported a preliminary investigation in the Langley 4- by 4-foot supersonic pressure tunnel of transition on a slender parabolic body for the case of zero heat transfer. A transition Reynolds number of about 11×10^6 was obtained in this investigation, a value considerably greater than found in the investigations of references 4 to 9. The opportunity thus presented itself to investigate the effects of heat transfer on boundary-layer stability for an experimental setup having a large initial transition Reynolds number. Accordingly, a test model which could be either heated or cooled internally was constructed, and the experimental results obtained with this model at a Mach number of 1.61, zero angle of attack, and Reynolds numbers ranging from 7×10^6 to 20×10^6 are presented in this paper.

During the preparation of this paper, a flight investigation in which large heat-transfer effects on boundary-layer stability were observed has been reported in summary form (ref. 11). The details of this investigation were not available for study at the present writing.

SYMBOLS

M	free-stream Mach number
R	Reynolds number based on body length and free-stream conditions
R_{tr}	transition Reynolds number

T_e	model effective or equilibrium temperature without heating or cooling, °F
T_w	model surface temperature with heating or cooling, °F
T_0	stagnation temperature, °F
T'_0	stagnation temperature, °F abs
ΔT	average temperature difference for entire model, $T_w - T_e$, °F
$\frac{\Delta T}{T'_0}$	average-temperature-difference ratio for entire model
T_∞	free-stream temperature, °F
u	stream-direction component of velocity fluctuations
U_∞	free-stream velocity
$\frac{u'}{U_\infty}$	root-mean-square of u velocity fluctuation level, $\sqrt{\frac{\overline{u^2}}{U_\infty^2}}$
x	distance along model
L	length of model

APPARATUS AND TESTS

Wind Tunnel

The investigation was conducted in the Langley 4- by 4-foot supersonic pressure tunnel which is a rectangular, closed-throat, single-return wind tunnel with provisions for the control of the pressure, temperature, and humidity of the enclosed air. Changes in test-section Mach number are obtained by deflecting the top and bottom walls of the supersonic nozzle against fixed interchangeable templets which have been designed to produce uniform flow in the test section. The tunnel operation range is from about $\frac{1}{8}$ to $2\frac{1}{4}$ atmospheres stagnation pressure over a nominal Mach number range from 1.2 to 2.2. For qualitative visual-flow observation, a schlieren optical system is provided.

For the tests reported herein, the nozzle walls were set for a Mach number of 1.61. At this Mach number, the test section has a width of 4.5 feet and a height of 4.4 feet. Calibrations of the flow in the test section indicate that the Mach number variation about the mean value of 1.61 is about ±0.01 in the region occupied by the model and that there are no significant irregularities in stream flow direction. The turbulence level measured on the center line of the tunnel in the entrance cone is shown in figure 1.

Model

A sketch of the NACA RM-10 model, giving pertinent dimensions and construction details, is shown in figure 2 and a photograph of the model is presented as figure 3. The body has a parabolic-arc profile with a basic fineness ratio of 15. The pointed stern has been cut off at 81.25 percent of the length, however, so that the actual body has a blunt base and a fineness ratio of 12.2. The present model has a length of 50 inches and a maximum diameter of 4.096 inches.

The model was constructed of aluminum alloy in two sections. The joint between the sections, which occurred at the 84.5-percent body station, was carefully sealed and faired until no discontinuity at the surface could be detected. Body contours were not measured but are estimated to be accurate to the same order of magnitude as those determined on a similar model in reference 10 - within 0.006 inch average deviation and a maximum possible deviation of about 0.020 inch. Surface roughness of the present model (determined by means of a Physicists Research Co. Profilometer, Model No. 11) varied between 4.5 and 6 microinches root-mean-square over most of the model and increased to about 12 microinches root-mean-square in a very small region close to the base of the body.

Heating or cooling mediums were introduced into the hollowed-out model by means of three tubes, one of which was 1/4 inch in outside diameter and the other two, wrapped around the larger, were 1/8 inch in external diameter. Small holes were drilled along the lengths of these tubes to act as spray orifices. The inside of the model was deeply grooved, wherever possible, to increase the exposed surface area and to induce turbulence in the heating or cooling gas flow so that a high rate of heat transfer is favored.

The model was mounted on a sting in the tunnel and an electrical strain-gage balance was mounted in the rear part of the model, but because of technical difficulties, no data were obtained from this balance. Fourteen iron-constantan thermocouples were installed in the surface of the model as shown in figure 2, and the leads were brought out through the base of the model on the outside of the sting. Supply lines for the spray tubes were also brought through the base of the model on the outside of the sting.

Boundary-layer profiles were determined by means of a rake of tubes shown in figure 4. The rake was constructed of 0.040-inch outside diameter (0.030-inch inside diameter) tubing, chosen to meet response-time requirements, and the ten closest to the surface were flattened to a height of about 0.025 inch per tube to give closer spacing. The rake was clamped on the sting so that boundary-layer profiles were determined about 1/64 inch ahead of the base of the model. Sheet-metal spacers were wedged between the sting and the base of the model to prevent any motion of the model relative to the rake.

Techniques and Tests

During the investigation, model equilibrium or effective temperature T_e was first recorded by using a 12-channel printing potentiometer. Boundary-layer conditions at the model base were checked by observation of the rake pressure distribution on a multitube manometer and schlieren image. These observations made it possible to determine when transition occurred at the base of the model, with the Reynolds number being varied by changes in tunnel pressure. Then liquid carbon dioxide was valved into one or more of the spray tubes as required if the model was to be cooled or steam was used if the model was to be heated. In general, the rate of cooling using carbon dioxide was much too rapid to obtain any useful data during the cooling period. Throttling of the liquid carbon dioxide to reduce the cooling rate was impractical because the lower pressure in the supply lines would result in the formation of a mixture of solid and gaseous carbon dioxide within the lines with clogging of the spray tube by the solid dry ice.

All the cooled-model data were taken during warm-up, which occurred quite slowly. On the other hand, when steam was used for the heated-model tests, the rate of heating was very slow and data were obtained both during warm-up and cooling. The rake pressure distribution and the schlieren image were observed as the model temperature changed, photographs of each were made when any significant change in the boundary-layer flow was detected. Photographs were correlated with the temperature by noting each photograph on the chart of the temperature recorder which was kept running continuously.

Tests were made with the model in the smooth condition and with circumferential roughness strips at the 4-percent, 25-percent, and 50-percent stations. The roughness strips consisted of a $\frac{1}{4}$-inch band of shellac alone and a similar shellac band cementing on carborundum grains. Grain sizes used were No. 60, No. 150, and No. 250, and the grains were fairly evenly dispersed, about 150 grains per square inch.

The tests were made with the model at zero angle of attack. The tunnel stagnation pressure was varied from 6 to 17.5 pounds per square inch, which gave a Reynolds number range based on the model length of 50 inches of about 7×10^6 to 20×10^6. Tunnel stagnation dew point was kept below about -30° F. Tunnel stagnation temperature was maintained at 109° F ± 1° F, corresponding to a static temperature within the test section of about -85° F.

RESULTS AND DISCUSSION

General Considerations

Some typical boundary-layer pressure profiles as seen on the manometer board for various degrees of cooling are shown in figure 5. The pressure profiles were identified visually during tests, photographed periodically, and correlated with the continuous model-temperature records. The boundary-layer pressure profiles were identified as laminar, transition, or turbulent on the basis of: (1) the thickness of the boundary layer, (2) the shape of the pressure profiles, (3) the rate of change of boundary-layer thickness with model temperature during heating or cooling, and (4) the correlation of the thickness of the boundary layer and shape of the pressure profiles with schlieren observations. Some typical schlieren photographs obtained during the investigation are shown in figure 6. In general, the correlation between the schlierens and boundary-layer pressure surveys was excellent.

The surface-temperature distributions over the model corresponding to the boundary-layer profiles of figure 5 are presented in figure 7. These temperature distributions are typical of the ones measured throughout the tests. The data indicate that, immediately after cooling, the temperature distribution was not uniform because of the difficulty in cooling the model in the vicinity of the balance. It was not readily feasible, however, to introduce additional coolant within the balance area. Nevertheless, as the model warmed, the temperature distribution became more uniform until at the point where transition usually first began there was very little variation in temperature over the whole model. In the case of heating the model, the temperature distribution was always fairly even because of the slow rate of heating and small final temperature difference from the equilibrium state.

Transition on Smooth Model

A plot summarizing the effects of heating and cooling on boundary-layer transition on the RM-10 with a smooth surface is presented as figure 8. Without heating or cooling, the boundary layer was laminar over the entire length of the body up to a Reynolds number of about 11.5×10^6, a value in good agreement with that determined on a nearly identical RM-10 model in reference 10. As the Reynolds number was increased above this value, the model had to be cooled in order to maintain laminar flow over the entire body. The amount of cooling required increased with Reynolds number until at $R = 20.3 \times 10^6$ a temperature differential of nearly -50° F was required to maintain a laminar boundary layer. Below $R = 11 \times 10^6$ it was necessary to heat the model in order to induce turbulent flow. A temperature difference of 12° F was sufficient to cause transition at a Reynolds number of 8.1×10^6.

An examination of figure 8 also shows an apparent discontinuity in the boundary-layer transition regions for heating and cooling in the neighborhood of the Reynolds number $\left(12 \times 10^6 \text{ to } 13 \times 10^6\right)$ for normal transition without heat transfer. The discontinuity is probably due partly to small errors (±2° F) in the effective or equilibrium surface temperature (without heat transfer) and partly to different effective surface temperatures when the boundary layer is laminar or turbulent. Temperature recovery factors for the effective surface temperature used in the preparation of figure 8 are shown in figure 9. By making allowances for the above discrepancies in effective surface temperatures, the discontinuity in transition regions is greatly reduced if not entirely eliminated, but no reduction in the scatter of test points is obtained.

It is desirable to note at this time that, as the average model temperature decreased below about -50° F $\left(\frac{\Delta T}{T_0{}'} = 0.25\right)$, a thin film of hard, translucent ice began to form on the model, with the first appearance and greatest thickness of ice usually occurring at the coldest points on the body $\left(\text{at } \frac{x}{L} \approx 0.30 \text{ to } 0.40\right)$. The longer the model was maintained at these low temperatures, the more ice accumulated. For the extreme cases, the ice covered more than three-fourths of the model surface and, in one instance, covered all of the model except for about a 2- or 3-inch length at the nose. For these cases the boundary-layer flow remained laminar over the entire length of the body. At the higher Reynolds numbers $\left(17.4 \times 10^6 \text{ to } 20.3 \times 10^6\right)$ where ice accumulations were sometimes fairly extensive, an occasional burst of turbulence appeared which almost instantaneously cleared the ice off the model in a triangular region downstream of the point where the turbulence originated. Upon disappearance of turbulence ice began to accumulate again in the cleared area. The effects of these turbulence bursts could not be picked up on either the boundary-layer pressures or schlieren observations, owing no doubt to their short duration.

Transition on Roughened Model

The results of the tests on the effects of heating and cooling on boundary-layer transition on the RM-10 with surface roughened were too scanty and of too diverse a nature to be plotted but are presented in table I. In general, it was found that, with the model surface roughened, the effectiveness of cooling in increasing the transition Reynolds number was decreased to a maximum incremental value of 1.3×10^6 even for as much as 90° F of cooling. This result was generally found to hold true regardless of the type of transition strip used, whether one of No. 60 carborundum grains, which fixed transition with no heat transfer at the strip location, or a fine shellac strip, which apparently had no effect at all on transition with no heat transfer.

Comparison with Other Available Data

A comparison of the present results of the effects of heating and cooling on boundary-layer transition with those of other experimental investigations is presented in figure 10. These data, it should be remembered, involve both two- and three-dimensional models and are also affected by differences in Mach number, pressure gradient, surface roughness, wind-tunnel turbulence levels, and other wind-tunnel flow irregularities. On the basis of the results shown, the sensitivity of boundary-layer transition to heating or cooling appears to be low when the boundary-layer transition Reynolds number for zero heat transfer is low, and high when this transition Reynolds number is high.

An attempt was made to compare the experimental results of figure 10 with available theoretical calculations, but it appears that the available calculations for supersonic Mach numbers are questionable, as has been recognized by the authors of these methods (refs. 1, 12, and 13) and by others (for example, ref. 3). As pointed out, the major inadequacies are the use of Prandtl number 1.0 in many of the calculations and the use of an insufficient number of terms in the power series used to express velocity and density distributions. No attempt was made to make any refined calculations of the effects of heat transfer on boundary-layer stability on the RM-10 in this preliminary investigation.

SUMMARY OF RESULTS

A preliminary investigation has been made of the effects of heat transfer on boundary-layer transition on a body of revolution at a Mach number of 1.61. The body had a parabolic-arc profile, blunt base, and a fineness ratio of 12.2 (NACA RM-10). The results indicate that:

1. By cooling the model an average of 50° F, the Reynolds number for which laminar boundary-layer flow could be maintained over the entire length of the body was increased from the value of 11.5×10^6 without cooling to over 20×10^6, the limit of the present tests.

2. Heating the model an average of 12° F decreased the transition Reynolds number from 11.5×10^6 to about 8×10^6.

3. With the body surface roughened by carborundum or shellac strips, the effectiveness of cooling in increasing the transition Reynolds number was decreased to a maximum incremental value of 1.3×10^6 even for as much as 90° F of cooling.

4. A comparison of the results obtained for the smooth body with previous wind-tunnel studies indicated that the effects of heat transfer on transition location are strongly dependent upon the transition Reynolds number for zero heat transfer. If the transition Reynolds number with zero heat transfer is large, as in the present experiments, then the sensitivity of transition to heating or cooling is high. However, if the Reynolds number of transition is low for the adiabatic case, then transition is relatively insensitive to heat-transfer effects.

Langley Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Field, Va.

REFERENCES

1. Lees, Lester: The Stability of the Laminar Boundary Layer in a Compressible Fluid. NACA Rep. 876, 1947. (Supersedes NACA TN 1360.)

2. Bloom, Martin: The Calculation of Boundary Layer Stability on a Flat Surface With Heat Transfer Using an Integral Solution for the Mean Flow. PIBAL Rep. No. 179 (Contract No. NAw-5809), 1951.

3. Van Dreist, E. R.: Cooling Required To Stabilize the Laminar Boundary Layer on a Flat Plate. Jour. Aero. Sci. (Readers' Forum), vol. 18, no. 10, Oct. 1951, pp. 698-699.

4. Higgins, Robert W., and Pappas, Constantine C.: An Experimental Investigation of the Effect of Surface Heating on Boundary-Layer Transition on a Flat Plate in Supersonic Flow. NACA TN 2351, 1951.

5. Scherrer, Richard, Wimbrow, William R., and Gowen, Forrest E.: Heat-Transfer and Boundary-Layer Transition on a Heated 20° Cone at a Mach Number of 1.53. NACA RM A8L28, 1949.

6. Scherrer, Richard: Boundary-Layer Transition on a Cooled 20° Cone at Mach Numbers of 1.5 and 2.0. NACA TN 2131, 1950.

7. Eber, G. R.: Recent Investigation of Temperature Recovery and Heat Transmission on Cones and Cylinders in Axial Flow in the N.O.L. Aeroballistics Wind Tunnel. Jour. Aero. Sci., vol. 19, no. 1, Jan. 1952, pp. 1-6 and 14.

8. Frick, Charles W., Jr., and McCullough, George B.: Tests of a Heated Low-Drag Airfoil. NACA ACR, Dec. 1942.

9. Liepmann, Hans W., and Fila, Gertrude H.: Investigations of Effects of Surface Temperature and Single Roughness Elements on Boundary-Layer Transition. NACA Rep. 890, 1947.

10. Czarnecki, K. R., and Marte, Jack E.: Skin-Friction Drag and Boundary-Layer Transition on a Parabolic Body of Revolution (NACA RM-10) at a Mach Number of 1.6 in the Langley 4- by 4-Foot Supersonic Pressure Tunnel. NACA RM L52C24, 1952.

11. Sears, William R.: Aerodynamics - I. A Synopsis of the Technical Sessions at the 20th Annual Meeting. Aero. Eng. Rev., vol. 11, no. 4, Apr. 1952, p. 25.

12. Lin, C. C.: On the Stability of the Boundary Layer With Respect to Disturbances of Large Wave Velocity. Jour. Aero. Sci. (Readers' Forum), vol. 19, no. 2, Feb. 1952, pp. 138-139.

13. Lees, Lester: Comments on the "Effect of Surface Cooling on Laminar Boundary-Layer Stability." Jour. Aero. Sci. (Readers' Forum), vol. 18, no. 12, Dec. 1951, p. 844.

TABLE I

EFFECTS OF COOLING ON BOUNDARY-LAYER TRANSITION ON NACA RM-10 WITH SURFACE ROUGHENED

Location of roughness strip, x/L	Type of roughness strip	Reynolds number for transition	
		Without heat transfer	With cooling
0.04	No. 60 carborundum grains No. 150 carborundum grains Shellac only	7.0×10^6 8.8 8.7	7.0×10^6 9.3 9.3
.25	No. 150 carborundum grains Shellac only	11.5×10^6 11.5	12.8×10^6 12.8
.50	No. 150 carborundum grains No. 250 carborundum grains Shellac only	11.5×10^6 11.5 11.5	12.8×10^6 [a]17.4 12.8

[a] Believed to be affected by large accumulations of ice over roughness strip.

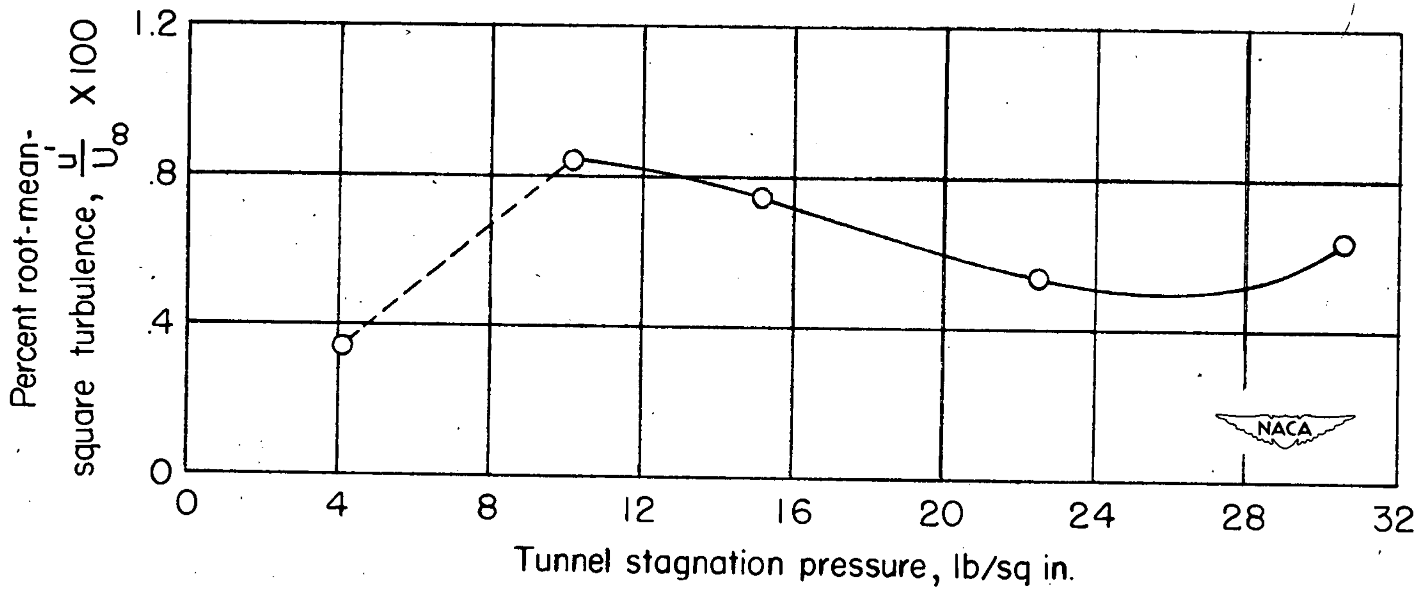
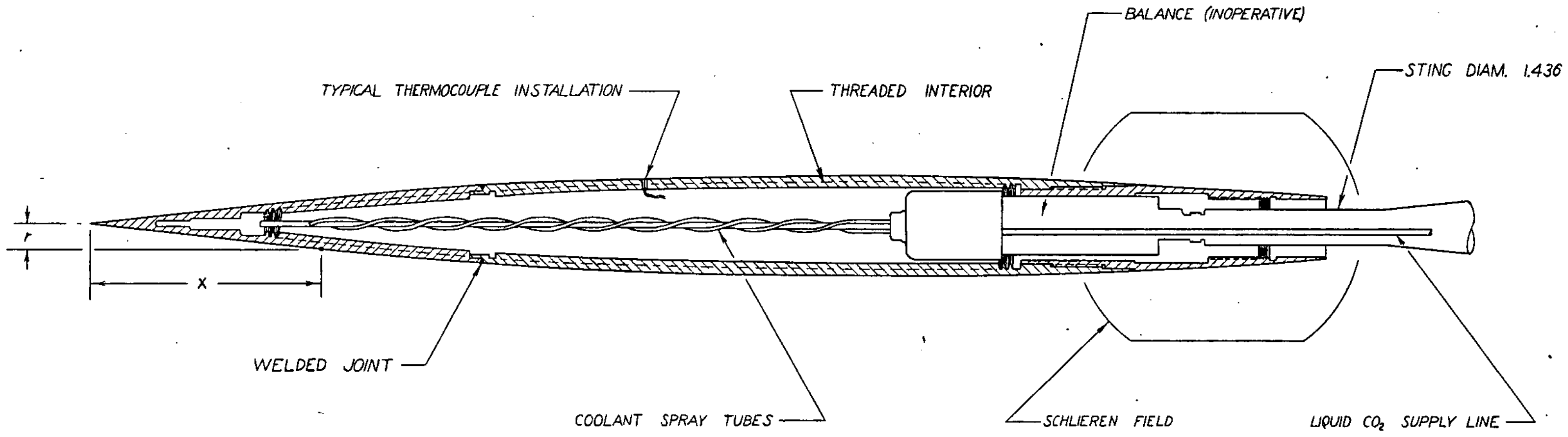


Figure 1.- Turbulence level on center line of tunnel in entrance cone. Average velocity U_∞, at point of measurement, 155 feet per second.



BODY PROFILE EQUATION: $r = 0.1333x - 0.00217x^2$

MODEL LENGTH 50.0

MAX. DIAM. 4.096

ALL DIMENSIONS IN INCHES

THERMOCOUPLE LOCATIONS		
STATION	NO.	SPACING
3.0	2	180°
12.6	2	180°
22.4	4	90°
32.0	2	180°
37.1	2	180°
46.0	2	180°

Figure 2.- Sketch of NACA RM-10 model and apparatus for heating and cooling.

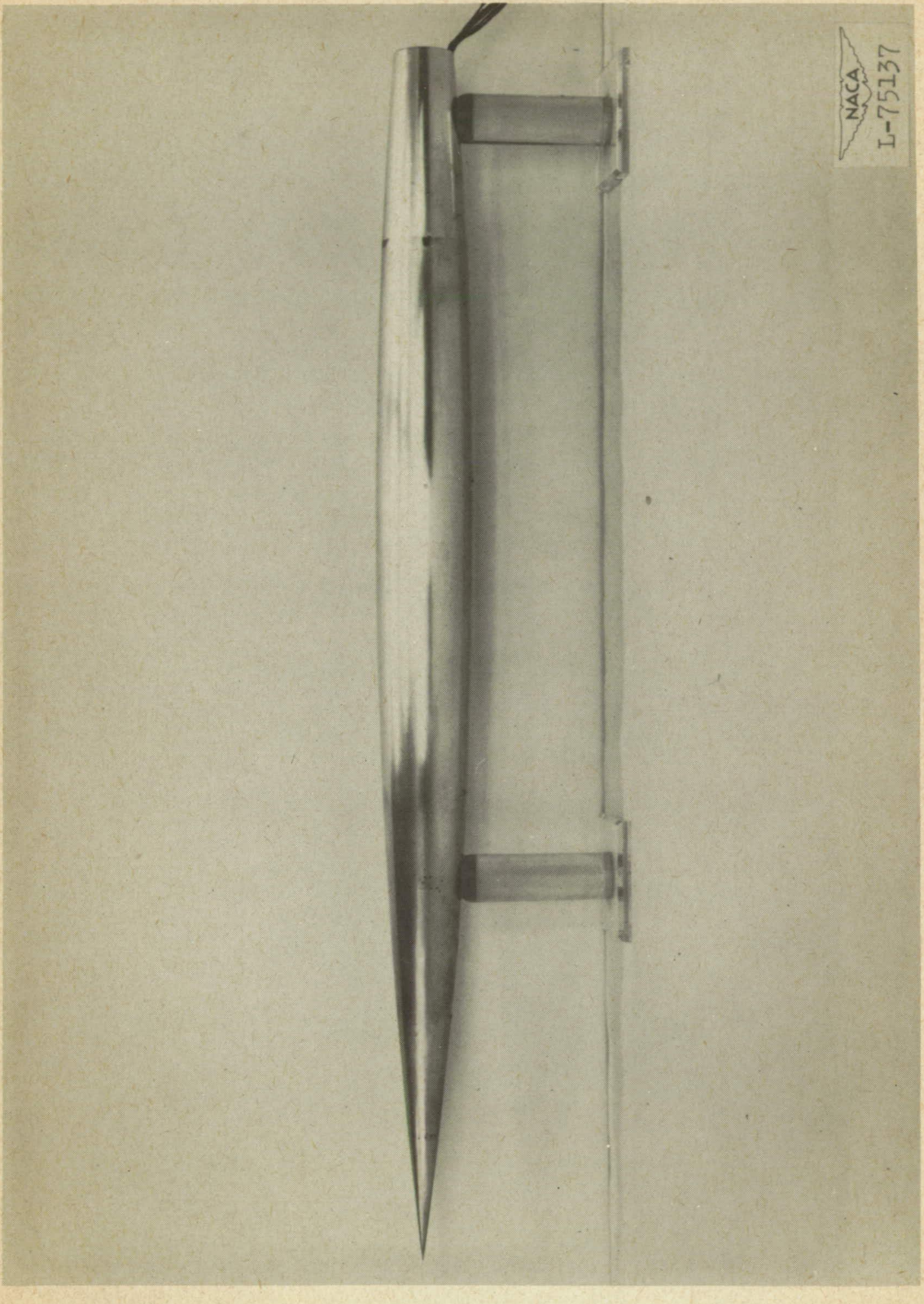
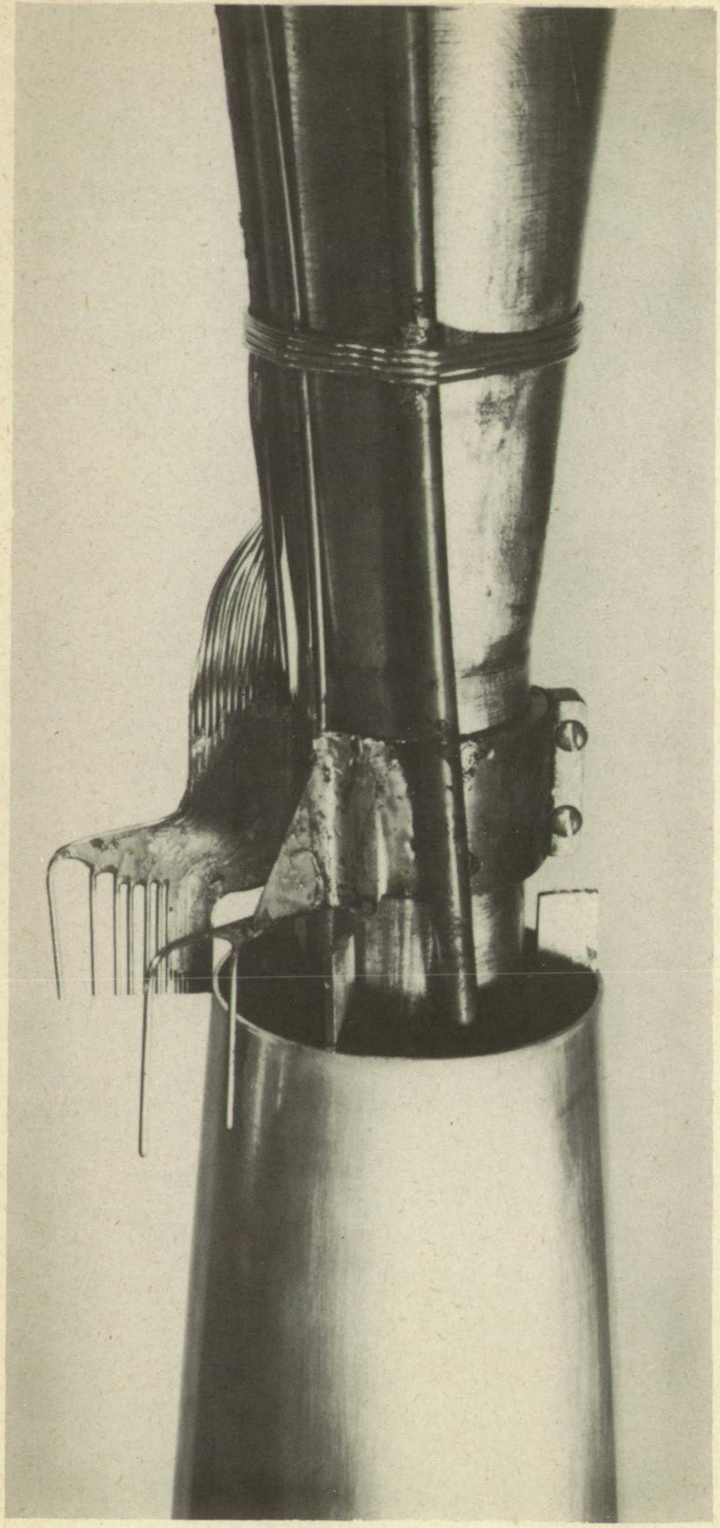


Figure 3.- NACA RM-10 model.



NACA L-75138

Figure 4.- Model base showing details of boundary-layer survey rake.

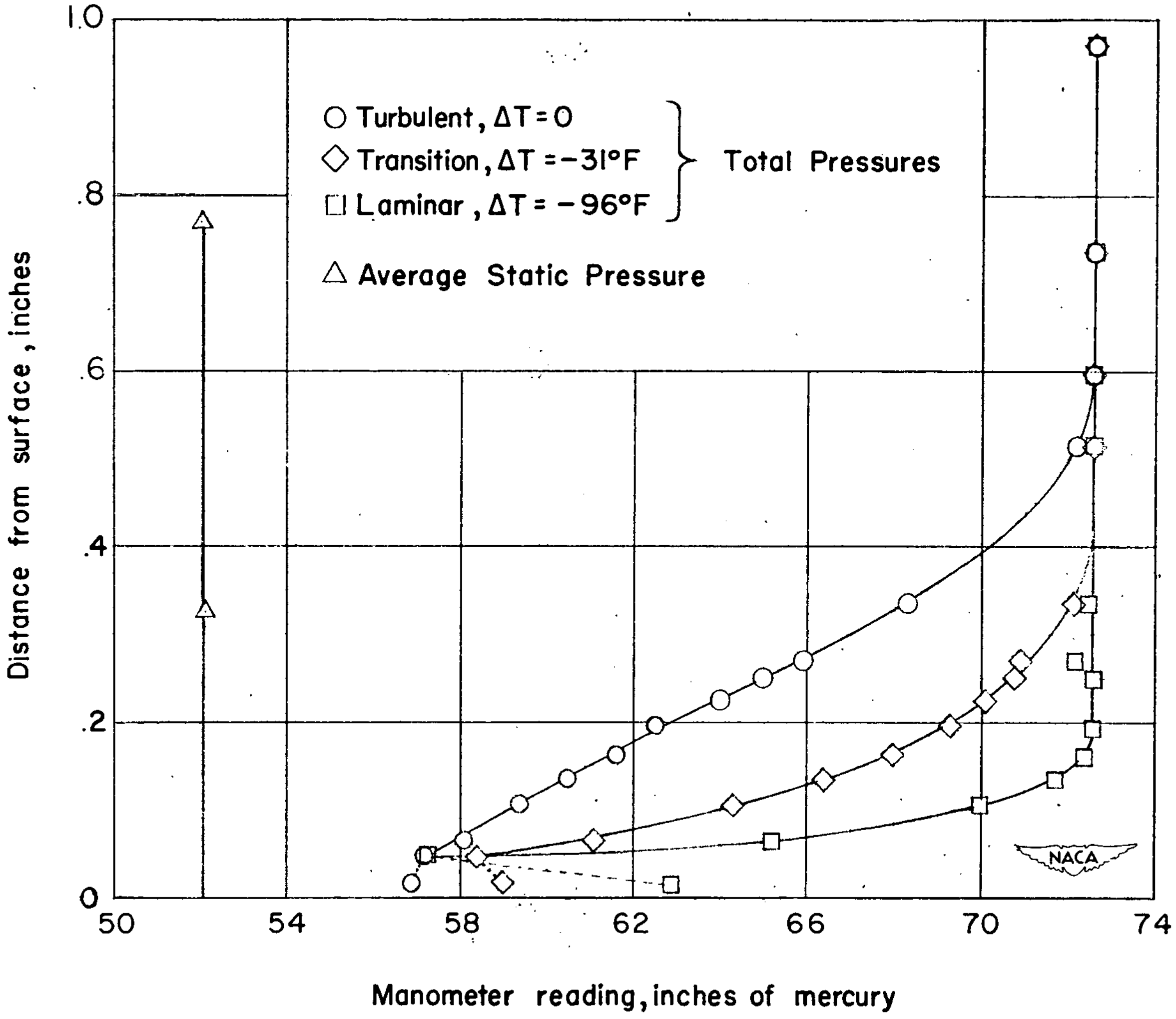
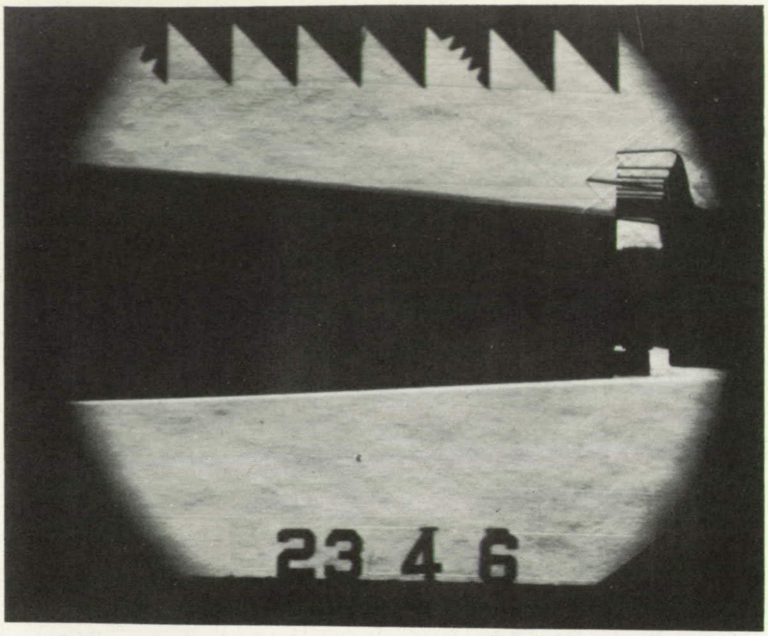
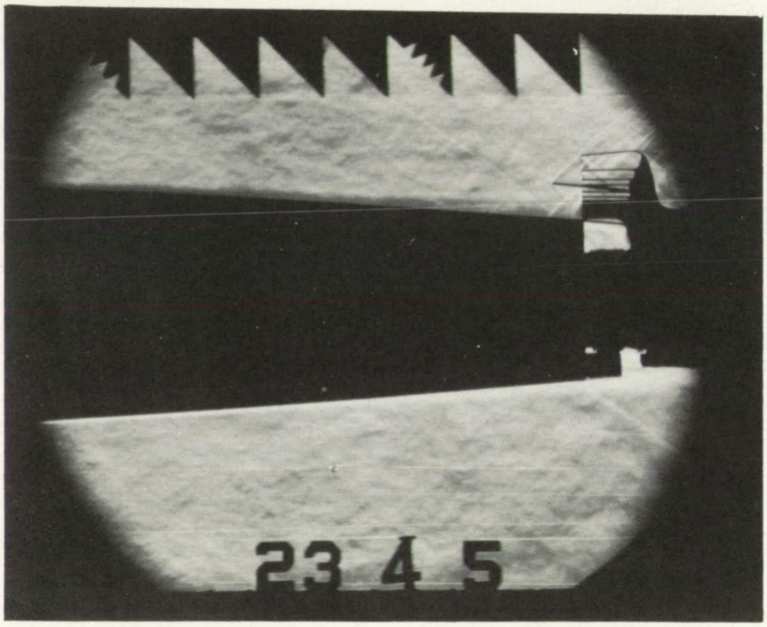


Figure 5.- Typical boundary-layer pressure profiles for different model temperature differentials at a Reynolds number of 17.4×10^6. $M = 1.61$; $T_0 = 109^\circ$ F.



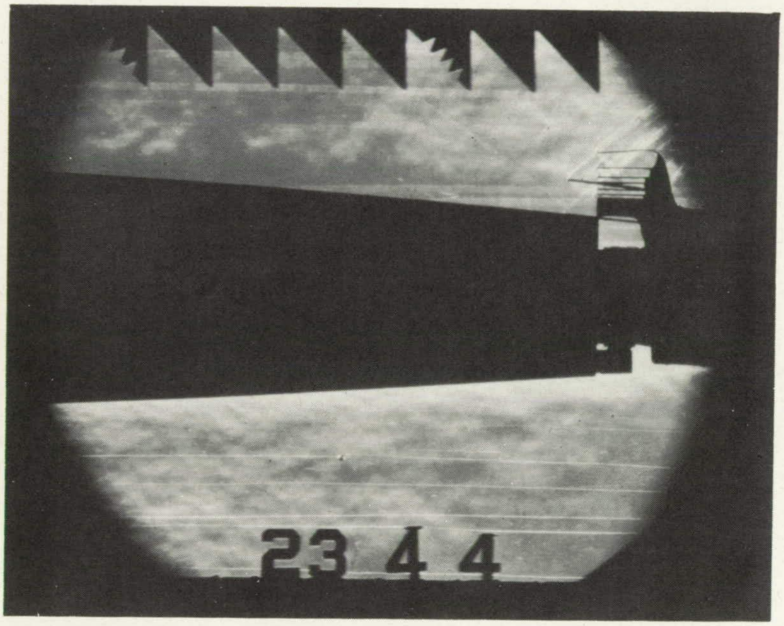
(a) Laminar; $\Delta T > -45^{\circ}$ F.



(b) Transition; $\Delta T \approx -35^{\circ}$ F.

NACA
L-75123

Figure 6.- Schlieren photographs showing the various types of boundary-layer flow at base of RM-10 at $R = 18.3 \times 10^6$ with and without cooling. $M = 1.61$; $T_0 = 109^{\circ}$ F; knife edge horizontal.



(c) Turbulent; $\Delta T = 0^\circ$ F.

Figure 6.- Concluded.

NACA
L-75124

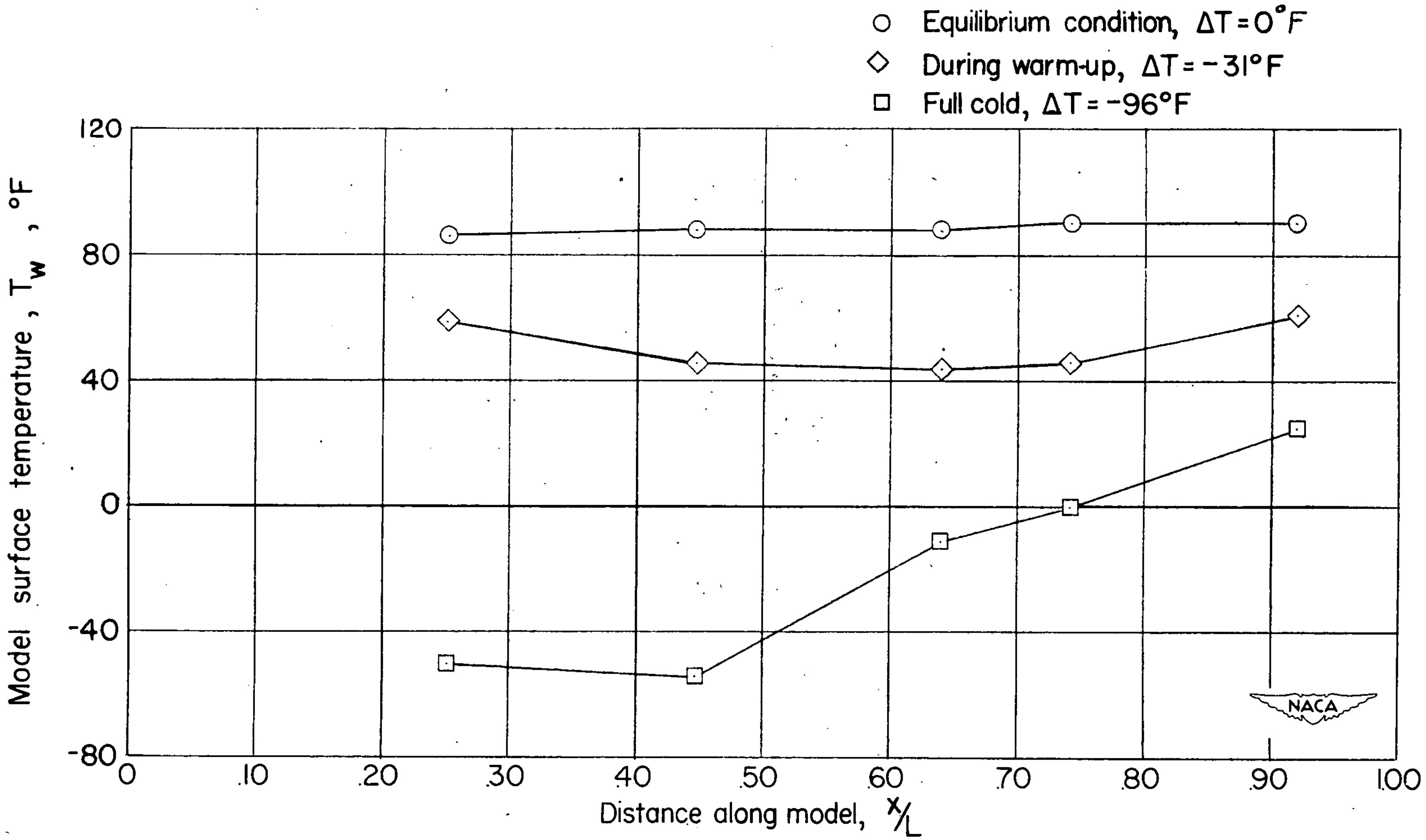


Figure 7.- Typical model temperature distributions. Reynolds number, 17.4×10^6. $M = 1.61$; $T_0 = 109^\circ$ F.

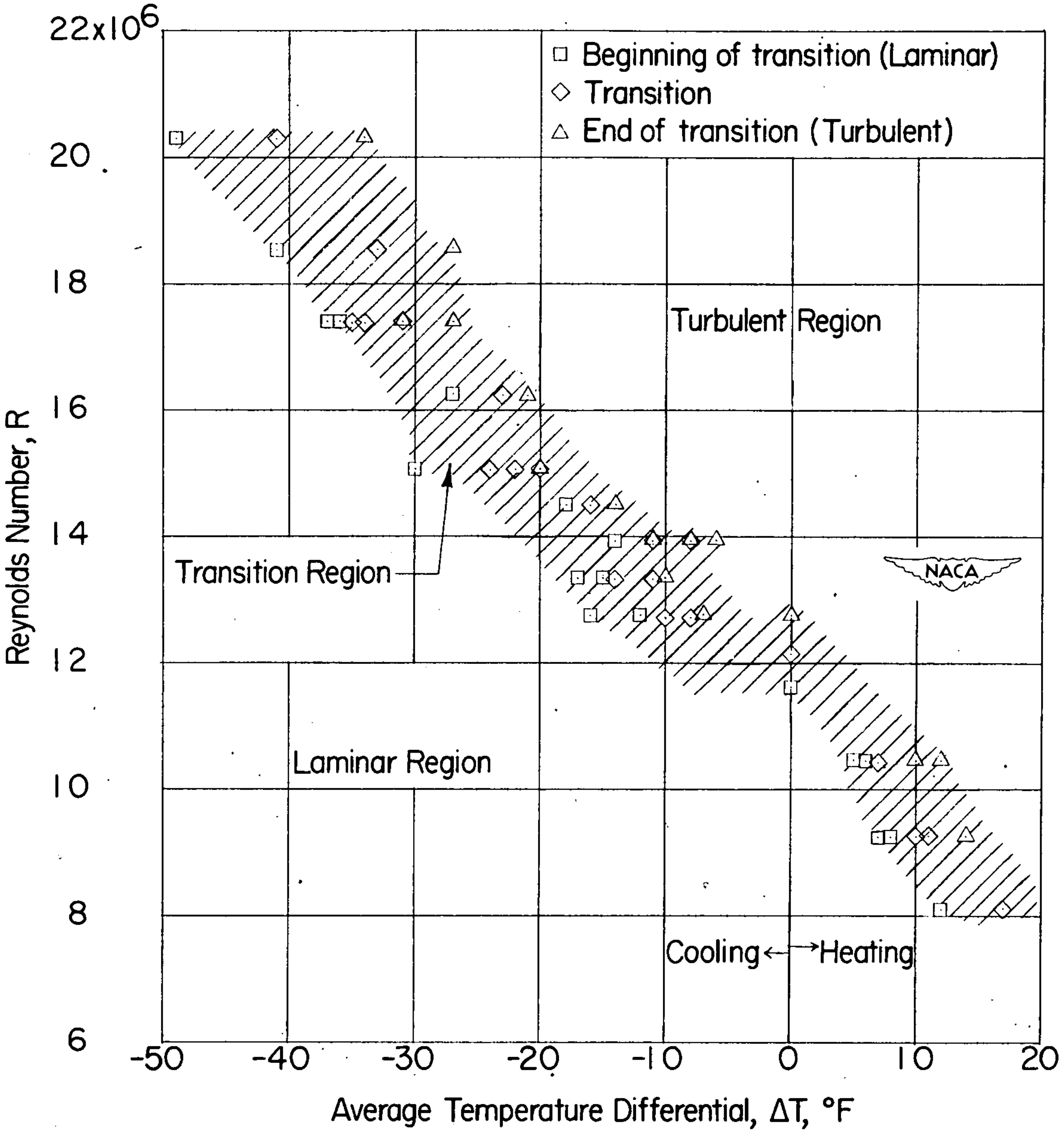


Figure 8.- Effect of heating and cooling RM-10 model upon boundary-layer transition. $M = 1.61$; $T_0 = 109^\circ$ F.

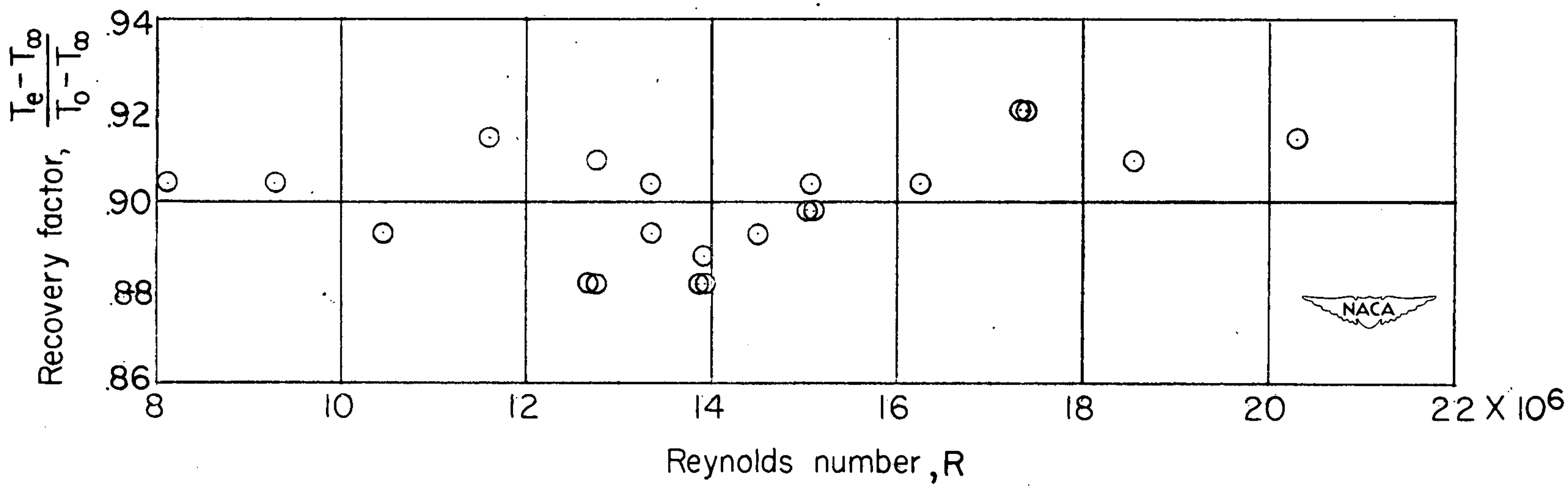


Figure 9.- Variation of average model temperature recovery factor with Reynolds number. $M = 1.61$; $T_0 = 109^\circ$ F.

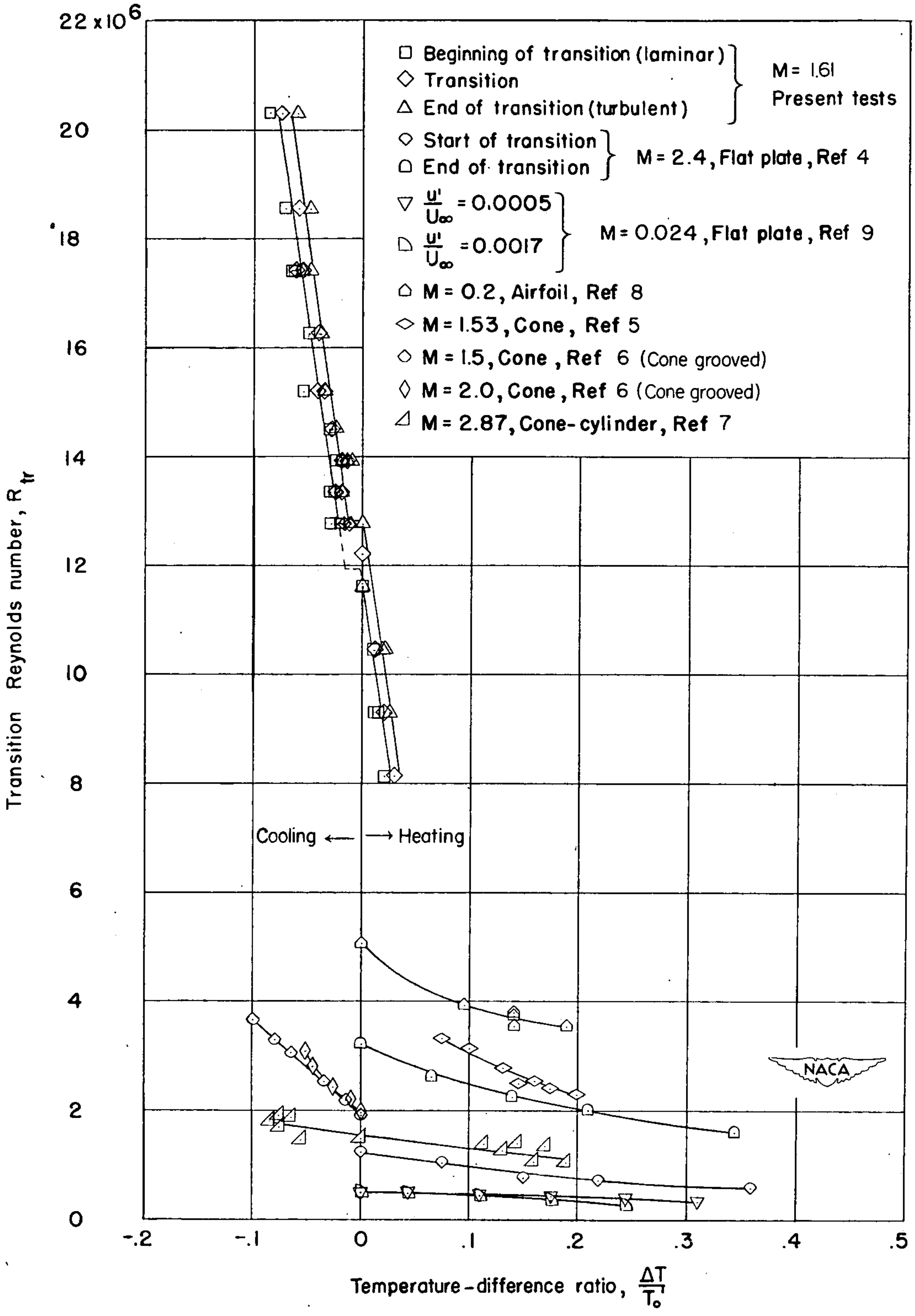


Figure 10.- Summary of available data on the effects of heating and cooling upon boundary-layer transition.

[redacted]

[redacted]

UNCLASSIFIED

UNCLASSIFIED

[redacted]