NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3020

DETERMINATION OF BOUNDARY-LAYER TRANSITION REYNOLDS NUMBERS BY SURFACE-TEMPERATURE MEASUREMENT OF A 10° CONE IN VARIOUS NACA SUPERSONIC WIND TUNNELS

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SUMMARY

An investigation was conducted in the following NACA supersonic wind tunnels to determine transition Reynolds numbers on a 10° cone at zero angle of attack: the 1- by 3-foot (Nos. 1 and 2), the 2- by 2-foot, the 6- by 6-foot, and the 10- by 14-inch at the NACA Ames laboratory; and the 8- by 6-foot, the 2- by 2-foot, the 1- by 1-foot (two), and the 18- by 18-inch at the NACA Lewis laboratory. Measurements of surface temperature at known increments along the cone were made for the case of negligible heat transfer and negligible wind-tunnel pressure gradients. The surface condition of the test body was carefully preserved throughout the program.

The trends of transition Reynolds number with stream Reynolds number and Mach number are not consistent for the various tunnels. The inconsistencies are attributed to variations in free-stream turbulence, flow irregularities introduced by the compressor systems, and other airstream disturbances such as compression- or expansion-wave boundary-layer interactions.

The results of this program show that transition Reynolds numbers can be successfully determined by measuring surface temperatures at known increments along a 10° cone, and that the transition Reynolds number is useful for relative evaluation of supersonic facilities.

INTRODUCTION

The application of wind-tunnel investigations of such aerodynamic performance characteristics as are affected by boundary-layer development is to a large extent governed by the Reynolds number at which transition from laminar to turbulent flow begins. Other parameters affecting the transition-region location in low-speed flow (listed in ref. 1) are intensity and scale of turbulence, model surface pressure gradient, location of the laminar separation point, model surface curvature, and model surface roughness. For a given model to be tested in various wind tunnels, the parameters that must be considered are simply the test-section Reynolds and Mach numbers and the intensity and scale of stream turbulence in the test section. The effect of disturbance waves in the tunnel test section must also be considered. Various tunnels operating over the same range of Reynolds and Mach number might show appreciable difference in turbulence level (scale and intensity) as a result of differences in driving compressors, entrance cone geometry, and number and mesh size of damping screens.

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In subsonic flows, the turbulence parameters are usually determined by use of hot-wire instrumentation. In supersonic flows, hot-wire probes have not yet been reduced to routine application, because of the mechanical difficulties and questions regarding interpretation of readings obtained.

During the investigations reported in reference 2 (effect of Mach number on temperature-recovery factors obtained on an instrumented cone), it was observed that the distribution of temperature-recovery factor appeared fairly sensitive to the turbulence level of the various supersonic tunnels. In order that at least a qualitative determination of the range of turbulence levels encountered in representative supersonic tunnels might be obtained, Richard Sherrer of the NACA Ames laboratory suggested that the same instrumented cone should be tested in various supersonic wind tunnels at the three NACA laboratories. This report presents the transition Reynolds numbers obtained for various facilities at the Lewis and Ames laboratories. These Reynolds numbers may be regarded as a measure of the turbulence levels and other stream disturbances that affect aerodynamic characteristics governed by the boundary layer.

WIND TUNNELS AND APPARATUS

The Ames supersonic wind tunnels for which transition data are presented are listed in the following table:

Tunnel	Type	Operation
1- by 3-foot (No. 1)	Closed circuit	Continuous
1- by 3-foot (No. 2)	Nonreturn	Intermittent
10- by 14-inch	---------	Continuous
6- by 6-foot	Closed circuit	Continuous
2- by 2-foot (Transonic)	Closed circuit	Continuous

Pressure and Mach number are variable for all the Ames tunnels.

The Lewis supersonic wind tunnels, listed in the following table, are all of the nonreturn type:

Tunnel	Mach number	Reynolds number
8- by 6-foot	Variable	Fixed (for each M_0)
1- by 1-foot[a]	Fixed	Variable
1- by 1-foot[b]	Fixed	Variable
2- by 2-foot	Fixed	Fixed
18- by 18-inch	Fixed	Fixed

[a]Variable Reynolds number jet (VRNJ); variable inlet pressure and temperature.

[b]Lewis Unitary Plan Activity (LUPA); variable inlet pressure.

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The Ames 10°-included-angle cone (selected for the test model in preference to a flat plate in order to minimize leading-edge shock effects) is made of stainless steel (18-8 alloy) and of thin-wall construction (0.032-in. thickness) in order to minimize heat transfer through and along the wall. Twenty constantan thermocouple wires were soldered into holes in the shell spaced along a ray of the cone as shown in figure 1. Four additional thermocouples were installed along the opposite ray of the cone to provide a check on the uniformity of the circumferential surface-temperature distributions. A single stainless-steel wire connected to the base of the cone completed the electric circuit. The cone surface was ground and polished until the maximum roughness was less than 15 microinches.

The surface thermocouple voltages, as well as those from the thermocouples used to measure the total temperature in the wind tunnel, were read on either indicating or recording self-balancing potentiometers accurate to $\pm0.25^\circ$ F. However, the repeatability of the temperature measurements during a test was $\pm0.5^\circ$ F because of minor variations in the stagnation temperature. Several iron constantan thermocouples were located in the section upstream of the tunnel nozzles to obtain wind-tunnel stagnation temperatures.

The local Mach number just outside the boundary layer on the 10° cone was computed from the known Mach number calibration in the wind-tunnel test section. The cone was mounted in the test section at a position of low pressure gradient.

The maximum probable error in the local recovery factor, based on the individual accuracies of the Mach numbers and temperatures, is approximately ± 1 percent for values from all the wind tunnels at all the test Mach numbers. The test-section Reynolds numbers were determined with similar accuracy.

RESULTS AND DISCUSSION

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The temperature-recovery factor is defined for a stream flowing over a thermally insulated surface as the ratio of the kinetic energy converted to heat energy at the wall through the action of friction to the kinetic energy conversion obtained in the absence of friction. The expression for the temperature-recovery factor C_r in terms of measurable quantities follows from the definition

$$C_r = \frac{\frac{T_S}{T_0}\left(1 + \frac{\gamma-1}{2} M_1^2\right) - 1}{\frac{\gamma-1}{2} M_1^2} \tag{1}$$

where

T_S adiabatic surface temperature

T_0 upstream stagnation temperature

M_1 local stream Mach number

The temperature-recovery factor is nearly constant for laminar flow, increases rapidly to a peak through the transition region, and finally decreases to the fully developed turbulent-flow value. For purposes of evaluating tunnel air stream, the transition point discussed herein is defined as the intersection of straight-line fairings of recovery-factor distributions through the laminar and transition regions as in figure 2, which shows a typical surface distribution of recovery factor.

Various tunnels operating over the same range of Mach number and Reynolds number might show appreciable difference in turbulence level (scale and intensity) as a result of differences in driving compressors, entrance cone geometry, and number and size of damping screens. However, all differences in cone transition Reynolds number cannot be attributed to wind-tunnel turbulence effects. Supersonic transition data are sensitive not only to stream turbulence but also to other disturbances in the air stream, such as compression waves from the nozzle wall intersecting the test model. In some cases these compression waves are sufficient to trigger transition and may appear, disappear, or change location in the nozzle as the Mach number or Reynolds number is changed.

Figure 3 shows some effect of tunnel disturbance on boundary-layer transition. The stream Reynolds number was held constant at 2.9×10^6. The tunnel was first operated without any known disturbances in the air stream, and the transition Reynolds number was determined to be 2.78×10^6. Then a strip of tape 0.005 inch thick and 0.75 inch wide was placed on the tunnel nozzle wall, and a shock wave was introduced that struck the test model 12.25 inches from the tip. Although the shock wave was striking the model at the transition region, no change in transition Reynolds number was observed. A piece of tape 0.0025 inch thick and 0.75 inch wide was placed on the wall so that the shock wave would strike the test model 4 inches from the tip. This shock wave striking the model upstream of transition triggered transition sooner and lowered the transition Reynolds number to 2.54×10^6.

This report presents data for several supersonic tunnels showing the Reynolds number of transition for each facility without explanation of cause of transition in the facilities.

Table I summarizes the transition-point data obtained in the supersonic tunnels. In the 8- by 6-foot tunnel tests for run 2, the cone was moved 6 inches downstream of its position in run 1. In the 1- by 1-foot LUPA tunnel and in the 1- by 1-foot variable Reynolds number jet (VRNJ), the stream Reynolds number was varied by adjusting the inlet stagnation pressure. In the VRNJ tunnel the inlet stagnation temperature could also be altered (run 2). In run 3 an inlet screen was added upstream of the nozzle entrance of the 1- by 1-foot VRNJ. This alteration increased the transition Reynolds number from approximately 0.7×10^6 to 1.3×10^6 (comparison of run 1, reading 1, with run 3, reading 2). Although the data are not yet available for publication, preliminary indications are that alterations to the surge tank of the 1- by 1-foot VRNJ and additions of four turbulence damping screens further increase the transition Reynolds number to approximately 3.0×10^6.

The temperature distributions measured along a ray of the cone have been converted to recovery-factor distributions and are plotted in figure 4. Fairings of surface temperatures rather than recovery factor were used to obtain transition Reynolds number for the low Mach numbers of the Ames 2- by 2-foot transonic tunnel (figs. 4(p) and (q)).

In the Lewis 2- by 2-foot tunnel, a slight temperature rise was observed close to the cone base as shown in figure 4(e). It is believed that this rise in temperature is due not to transition, but to the transfer of heat from the strut-support body into the cone. If the cone had been longer, a temperature rise probably would not have occurred at this same point on the cone.

The rise in surface temperature for a Mach number of 1.5 in the Ames 1- by 3-foot tunnel (No. 1) between the distances of 7 and 10 inches is the result of a compression-shock intersection with the cone (fig. 4(j)). These data are considered valid, though conservative, since the trend of transition Reynolds number with stream Reynolds number is similar to that at Mach 2.0, and the laminar runs are greater. The rise can be eliminated in the recovery-factor plots by using the local Mach number at each individual thermocouple.

Plots of the transition Reynolds number against Mach number and stream Reynolds number per foot are shown in figures 5 and 6, respectively. As may be seen from figures 5 and 6, the trend of transition Reynolds number with stream Reynolds number and with Mach number is inconsistent for the various tunnels. The 8- by 6-foot supersonic tunnel data indicate that the transition Reynolds number increases with increasing Mach number (fig. 5(b)). This trend is consistent with the results of reference 1, which indicate that the resultant turbulence level decreases with increasing supersonic Mach number. However, the 1- by 3-foot (No. 2) and the 10- by 14-inch tunnels do not substantiate this trend (fig. 5(a)). On the other hand, the 1- by 3-foot (No. 1) data indicate the opposite effect, namely, a decrease in transition Reynolds number with increase in Mach number (fig. 5(a)). 2915

The 1- by 1-foot (VRNJ) data indicate that transition Reynolds number increases with increasing stream Reynolds number (fig. 6(b)). The data from the 10- by 14-inch tunnel show the opposite trend, and the two 1- by 3-foot tunnels do not directly support either trend (fig. 6(a)). Such inconsistencies suggest the importance of evaluating free-stream turbulence levels and air-stream disturbances in supersonic tunnels. Consistent trends might be established if the turbulence components and scales of turbulence were known. In view of the difficulties attending turbulence measurements in supersonic streams, the measurements could be made in the settling chamber and the tables of reference 3 used to estimate values representative of the test section.

If caused by stream turbulence, the transition Reynolds number can often be increased by addition of damping screens upstream of the tunnel nozzle section. When compression shock waves striking the model cause low transition Reynolds number, the addition of damping screens will show no effect. In this case the source of the shock wave must be eliminated.

CONCLUDING REMARKS

An investigation utilizing a 10° cone has been conducted in the NACA Ames and Lewis laboratory supersonic wind tunnels to determine the transition-point location on the cone from the distribution of temperature-recovery factors through the transition region. The following results were obtained:

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1. A transition point may be defined as the intersection of straight-line fairings of recovery-factor distributions through the laminar and transition regions. This transition point is influenced by free-stream turbulence and other disturbances in the air stream and hence is a useful measure for comparison of supersonic facilities.

2. The trends of transition Reynolds number with stream Reynolds number and with Mach number are not consistent for the various tunnels. The inconsistencies are attributed to effects of free-stream turbulence, flow irregularities introduced by the compressor systems, and other air-stream disturbances. The transition Reynolds number can often be increased by addition of fine mesh damping screens upstream of the tunnel nozzle section.

3. The trends of transition Reynolds number might prove more consistent with stream Reynolds number and with Mach number if the turbulence intensities and the scales of turbulence were known.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, August 4, 1953

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1. Dryden, Hugh L.: Turbulence and the Boundary Layer. Jour. Aero. Soc., vol. 6, no. 3, Jan. 1939, pp. 85-100; discussion, pp. 101-105.

2. Stine, Howard A., and Scherrer, Richard: Experimental Investigation of the Turbulent-Boundary-Layer Temperature-Recovery Factor on Bodies of Revolution at Mach Numbers from 2.0 to 3.8. NACA TN 2664, 1952.

3. Tucker, Maurice: Combined Effect of Damping Screens and Stream Convergence on Turbulence. NACA TN 2878, 1953.

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TABLE I. - TRANSITION-POINT DATA

Tunnel	Run	Reading	Tunnel stagnation temperature, T_0, °R	Stream Mach number, M_0	Cone surface Mach number, M_S	Stream Reynolds number, $(Re/ft) \times 10^{-6}$	Transition Reynolds number, $(Re_t) \times 10^{-6}$
8- by 6-foot	1	1	667.5	1.985	1.905	4.755	3.22
		2	642.2	1.779	1.743	4.755	2.595
		3	621.5	1.583	1.537	4.670	2.385
		4	616.2	1.490	1.450	4.680	2.38
		5	616.5	.64	.64	3.785	1.95
	2	1	663.2	1.976	1.915	4.78	4.07
		2	638.0	1.775	1.721	4.82	3.93
		3	616.2	1.591	1.545	4.79	2.80
		4	605.0	1.490	1.460	4.80	2.76
		5	603.0	.64	.64	3.87	2.095
2- by 2-foot (Lewis)	1	1	659.0	3.93	3.75	1.03	1.19
18- by 18-inch	1	1	617.0	1.94	1.88	3.095	2.57
1- by 1-foot (LUPA)	1	1	502.0	2.92	2.815	3.41	2.885
		2	501.7	↓	↓	3.76	2.94
		3	501.2	↓	↓	4.31	2.98
		4	501.2	↓	↓	4.86	3.04
		5	501.0	↓	↓	5.39	3.03
		6	502.0	↓	↓	5.92	3.04
		7	502.2	↓	↓	6.48	3.06
		8	503.2	↓	↓	7.00	2.24
		9	503.2	↓	↓	7.61	2.60
		10	503.5	↓	↓	8.16	2.27
1- by 1-foot (VRNJ)	1	1	508.0	3.12	3.00	4.12	0.887
		2	508.0	↓	↓	3.30	.770
		3	507.0	↓	↓	2.50	.657
		4	508.0	↓	↓	1.40	.758
	2	1	556.2	3.12	3.00	1.00	0.729
		2	557.2	↓	↓	1.40	.729
		3	556.5	↓	↓	2.00	.625
		4	556.3	↓	↓	2.50	.625
		5	598.0	↓	↓	1.0	.625
		6	601.1	↓	↓	1.4	.672
		7	602.2	↓	↓	2.0	.600
		8	602.6	↓	↓	2.5	.625
	3	1	507.0	3.12	3.00	4.95	1.485
		2	506.0	↓	↓	4.02	1.205
		3	506.0	↓	↓	3.02	1.210
		4	506.0	↓	↓	2.0	1.05
		5	506.0	↓	↓	1.5	.913
1- by 3-foot (No. 1)	1	1	522.7	1.97	1.91	1.92	-----
		2	537.6	↓	↓	3.73	3.51
		3	553.1	↓	↓	5.44	3.26
		4	565.9	↓	↓	6.94	3.59
		5	524.2	1.50	1.46	1.81	-----
		6	542.9	↓	↓	3.75	3.85
		7	558.0	↓	↓	5.33	3.77
		8	572.0	↓	↓	6.90	3.99
1- by 3-foot (No. 2)	1	1	Variable	1.50	1.46	8.50	0.354
		2	↓	1.97	1.91	8.42	1.12
		3	↓	3.00	2.89	8.42	1.12
		4	↓	3.77	3.60	9.12	.76
10- by 14-inch	1	1	517.3	4.48	4.23	6.43	1.82
		2	516.4	↓	↓	5.50	1.92
		3	513.2	↓	↓	4.83	1.93
		4	523.8	4.67	4.44	5.71	4.71
6- by 6-foot	1	1	576.0	1.90	1.842	2.75	2.04
		2	555.0	↓	↓	2.24	2.15
		3	542.0	↓	↓	1.62	----
		4	519.0	↓	↓	1.07	----
		5	576.0	1.80	1.745	2.85	2.37
		6	580.0	1.73	1.68	2.89	----
		7	582.0	1.63	1.582	2.96	2.34
		8	576.0	1.53	1.486	3.085	----
		9	576.0	1.18	------	3.205	----
2- by 2-foot (Ames)	1	1	560.7	1.304	1.272	3.77	2.62
		2	557.9	↓	↓	4.77	2.62
		3	537.9	↓	↓	2.39	2.58
		4	559.3	1.207	1.18	3.84	2.87
		5	561.5	↓	↓	4.77	2.93
		6	546.3	↓	↓	2.85	2.80
		7	537.7	↓	↓	2.38	----
		8	555.4	1.100	-----	3.85	2.76
		9	561.8	↓	-----	4.79	2.93
		10	542.0	↓	-----	2.84	2.20
		11	536.4	↓	-----	2.51	----
		12	553.1	1.05	-----	3.87	2.69
		13	560.7	↓	-----	4.77	2.54
		14	539.9	↓	-----	2.83	2.36
		15	535.5	↓	-----	2.80	----
		16	550.4	1.001	-----	3.83	2.52
		17	558.1	↓	-----	4.78	2.59
		18	537.6	↓	-----	2.83	2.59
		19	534.4	↓	-----	2.52	2.31
		20	547.1	0.95	-----	3.88	2.38
		21	553.8	↓	-----	4.80	2.57
		22	535.9	↓	-----	2.86	2.72
		23	532.5	↓	-----	2.54	2.28
		24	544.1	0.90	-----	3.88	2.50
		25	553.1	↓	-----	4.86	2.17
		26	534.7	↓	-----	2.84	2.36
		27	531.9	↓	-----	2.58	----

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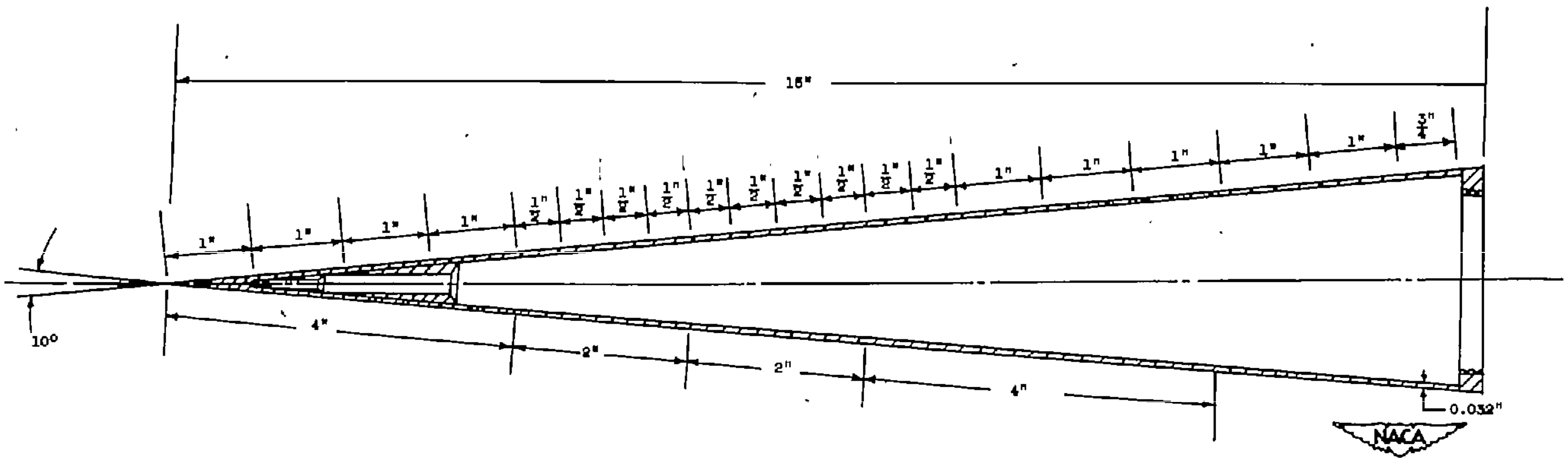

Figure 1. - Thermocouple location on stainless-steel 10° cone.

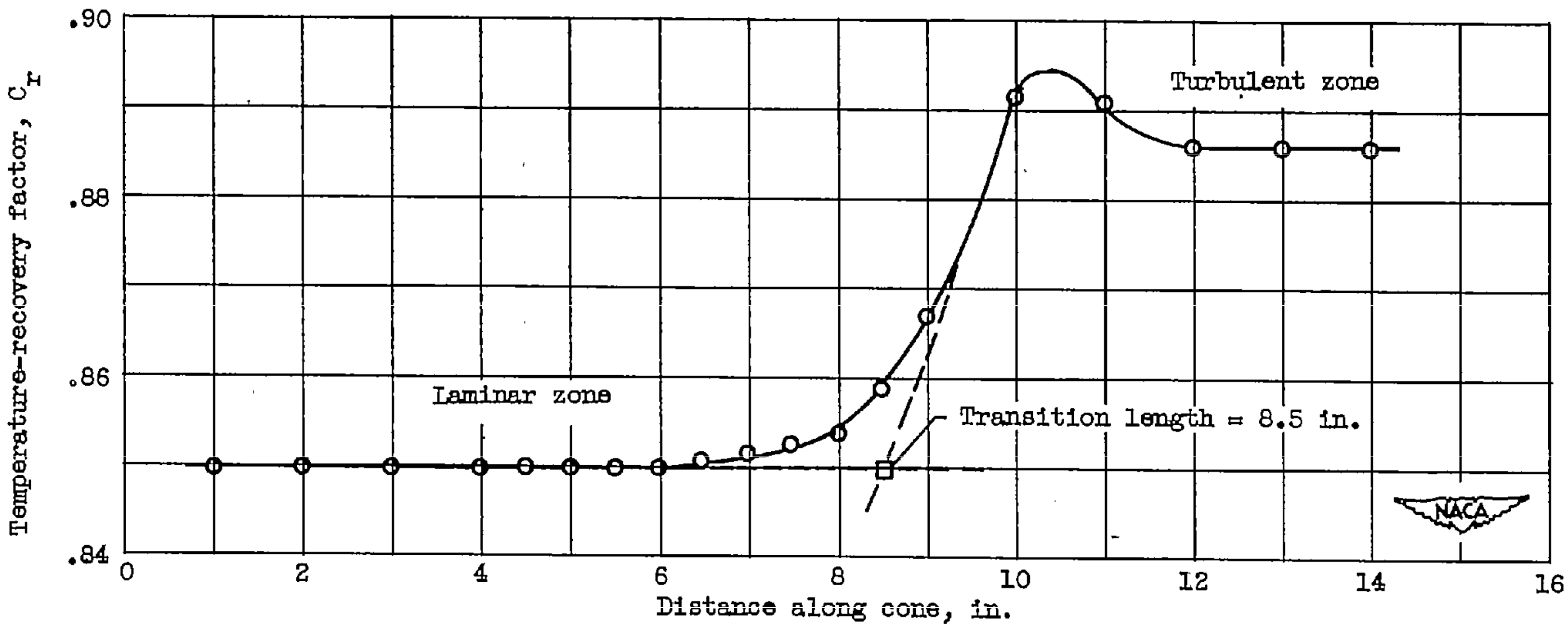

Figure 2. - Typical determination of transition Reynolds number. Free-stream Reynolds number per foot, 4.31×10^6; transition Reynolds number, $(4.31 \times 10^6)\ 8.5/12 = 3.055 \times 10^6$.

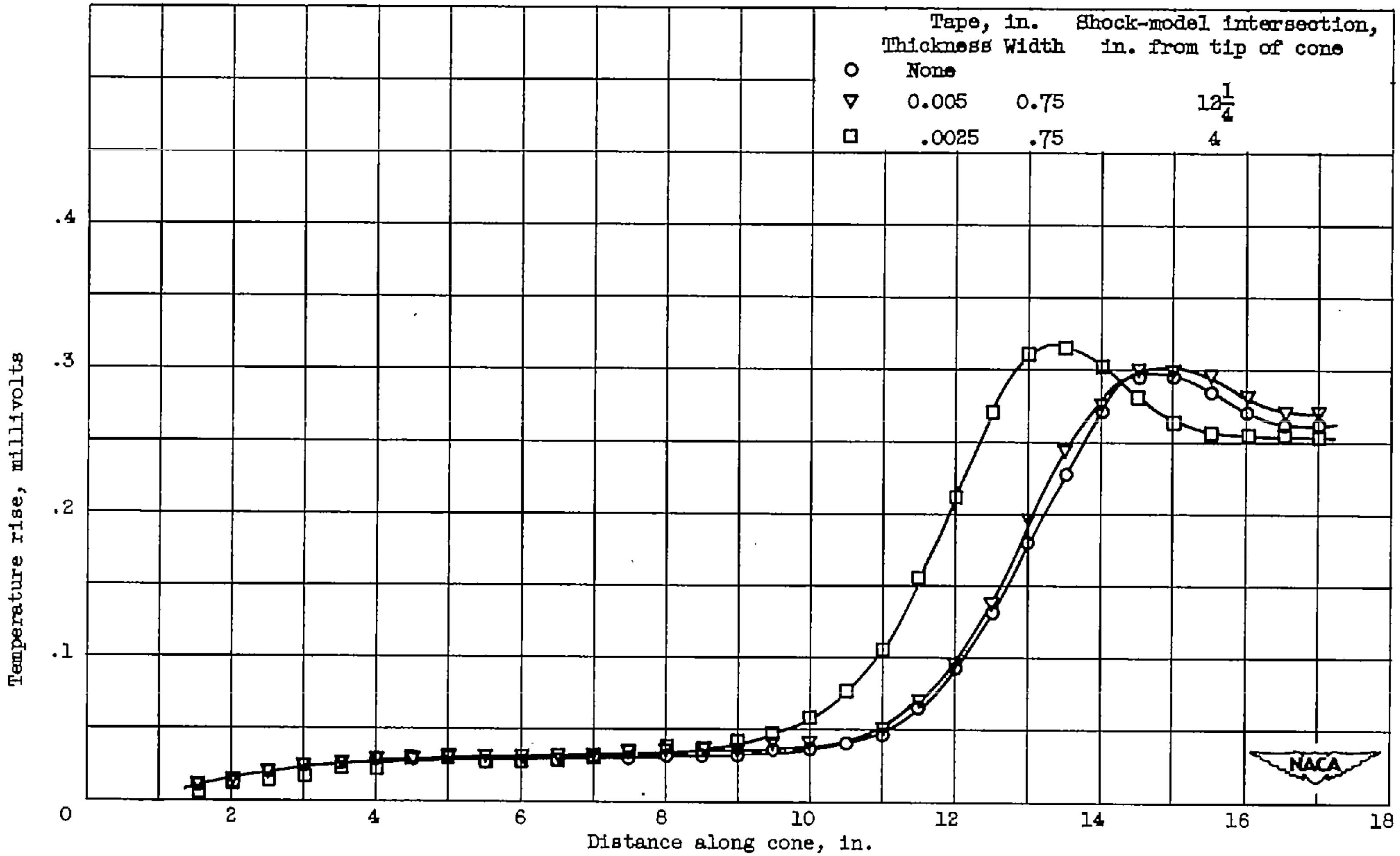

Figure 3. - Effect of tunnel disturbance on boundary-layer transition. Stream Reynolds number, 2.9×10^6; Mach number, 3.1.

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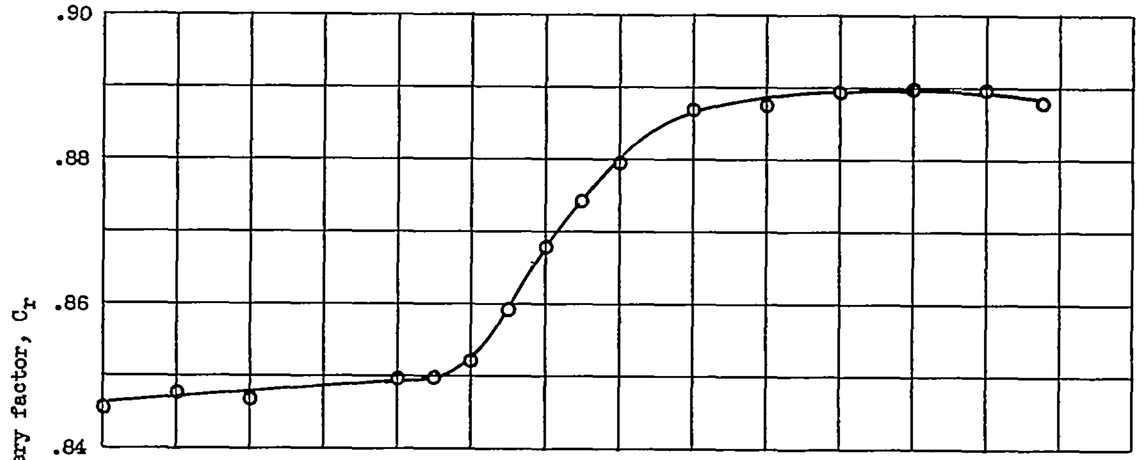
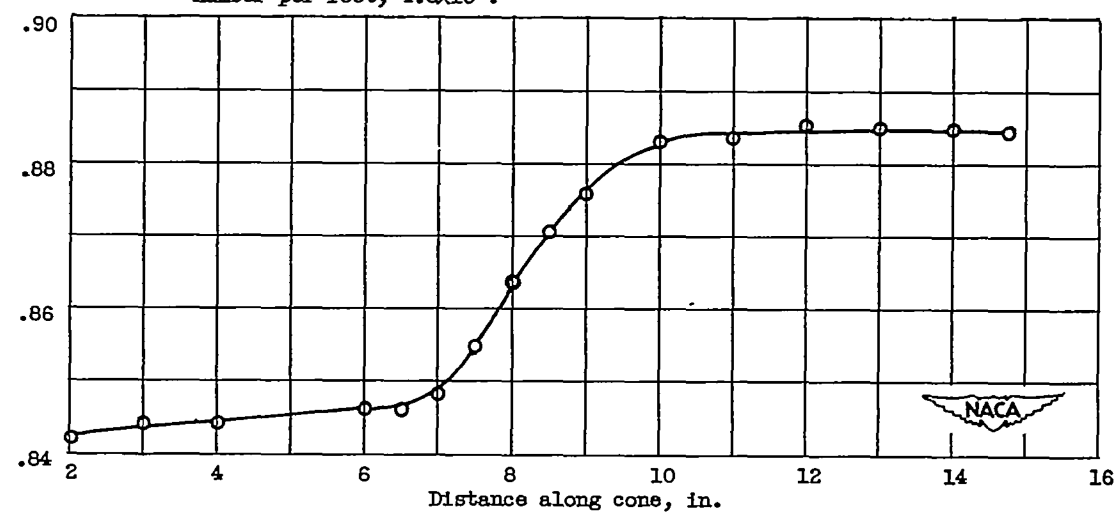


(a) Tunnel, 8- by 6-foot; stream Mach number, 1.49; stream Reynolds number per foot, 4.8×10^6.



(b) Tunnel, 8- by 6-foot; stream Mach number, 1.591; stream Reynolds number per foot, 4.79×10^6.

Figure 4. - Variation of temperature-recovery factor along 10° cone.

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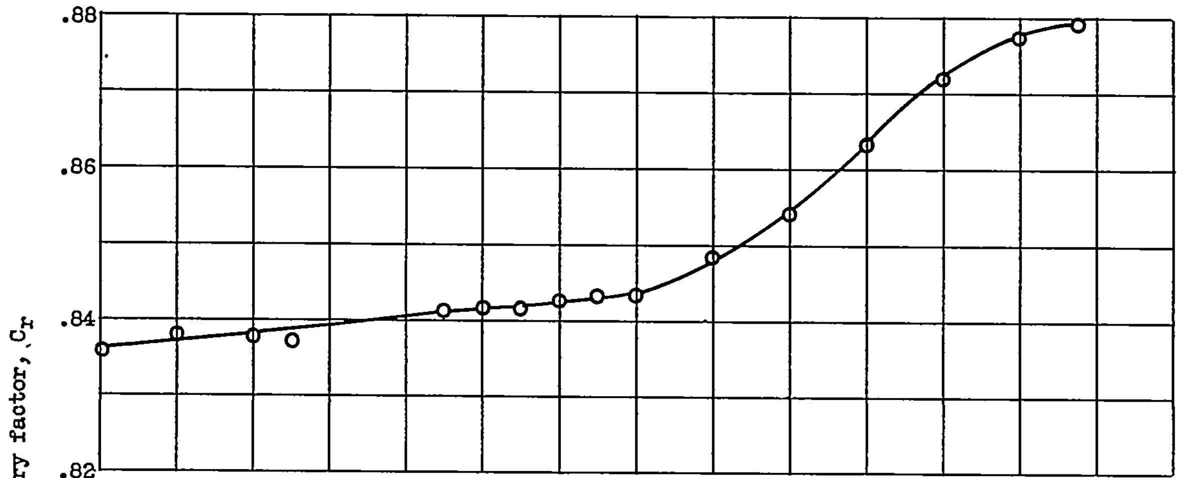
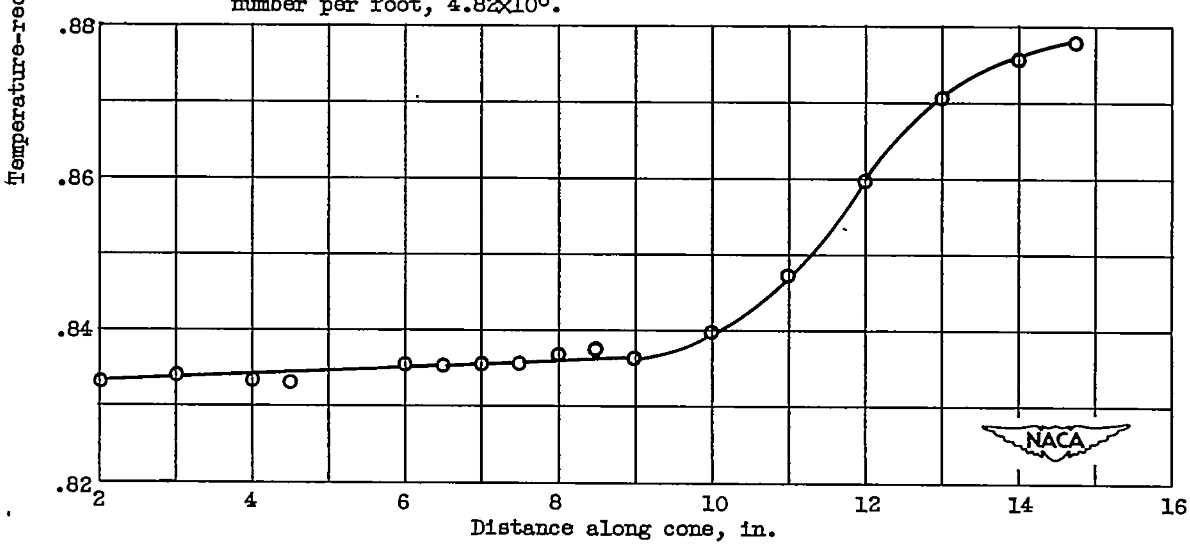
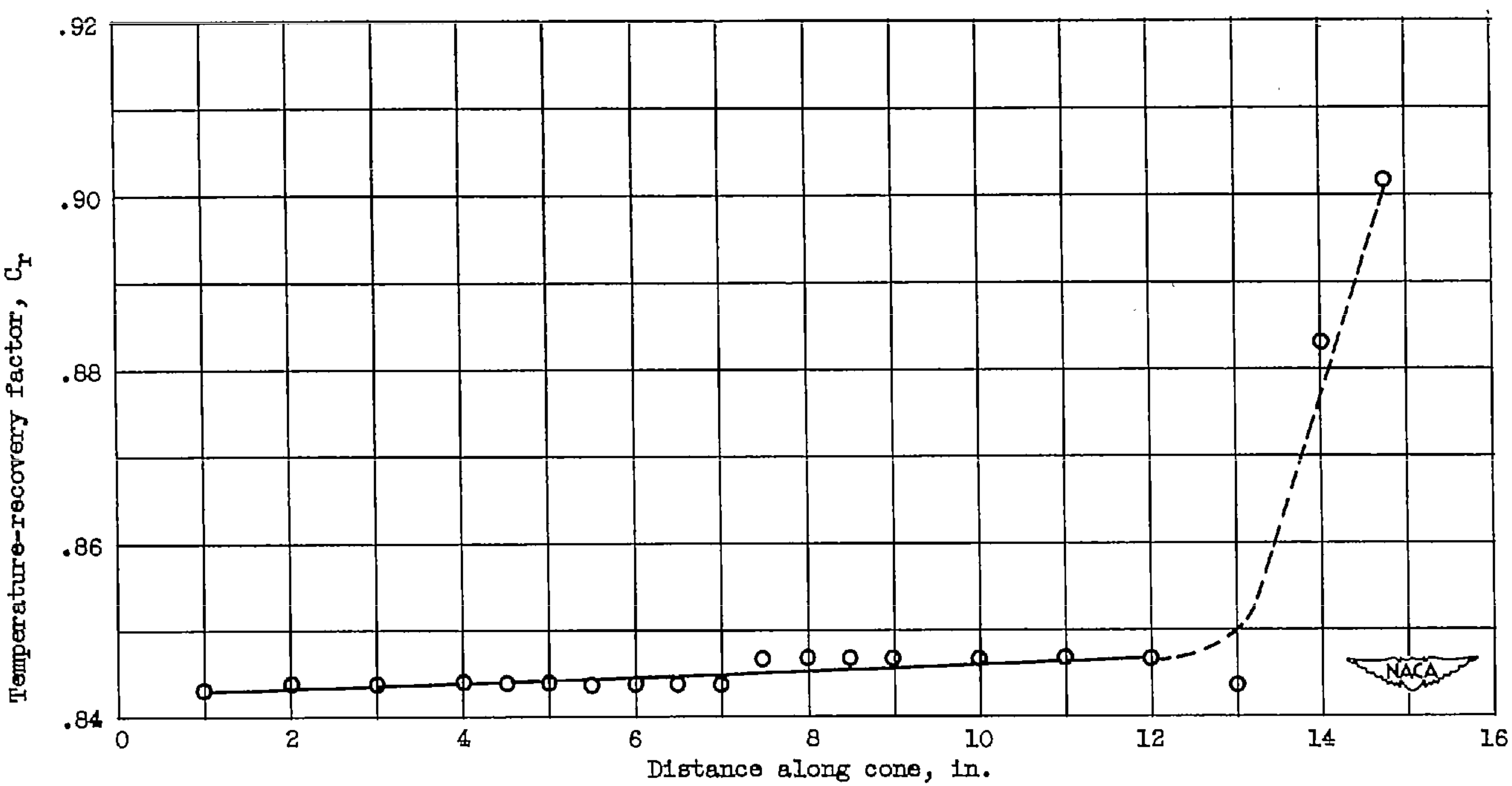


(c) Tunnel, 8- by 6-foot; stream Mach number, 1.775; stream Reynolds number per foot, 4.82×10^6.



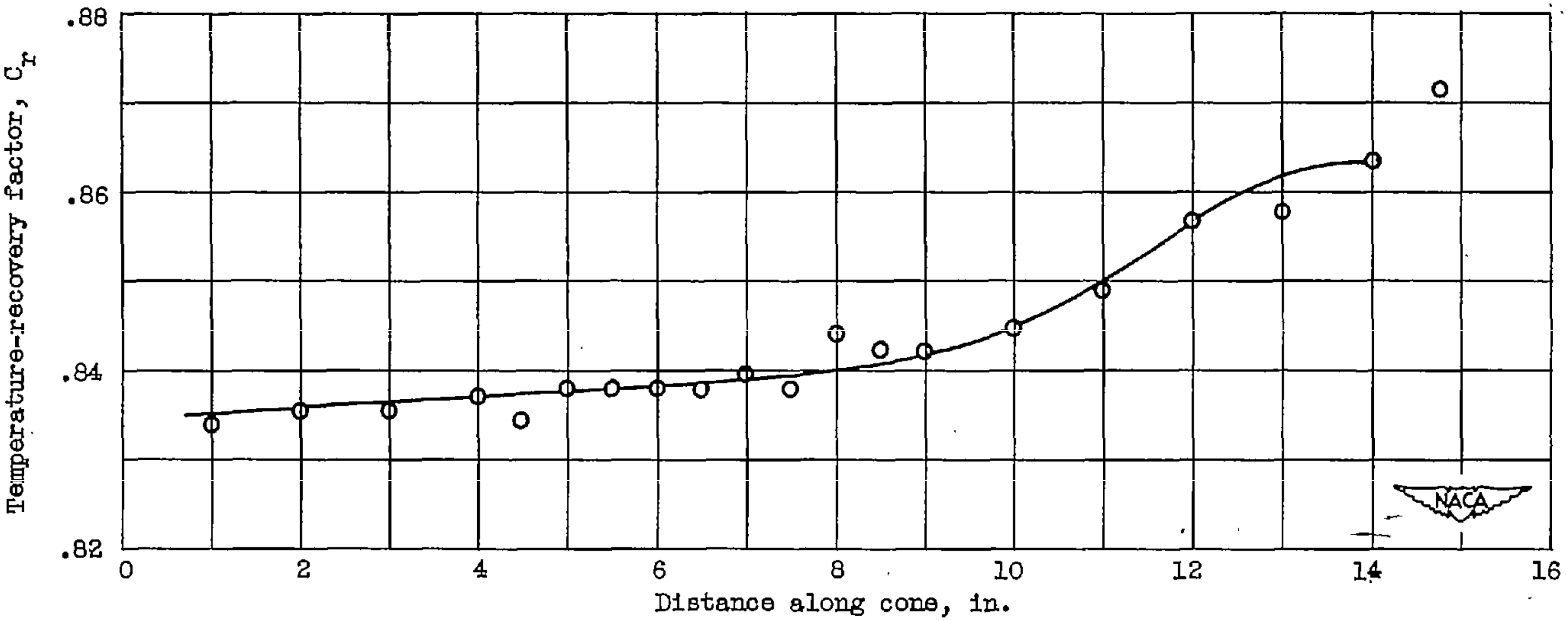
(d) Tunnel, 8- by 6-foot; stream Mach number, 1.976; stream Reynolds number per foot, 4.78×10^6.

Figure 4. - Continued. Variation of temperature-recovery factor along 10° cone.



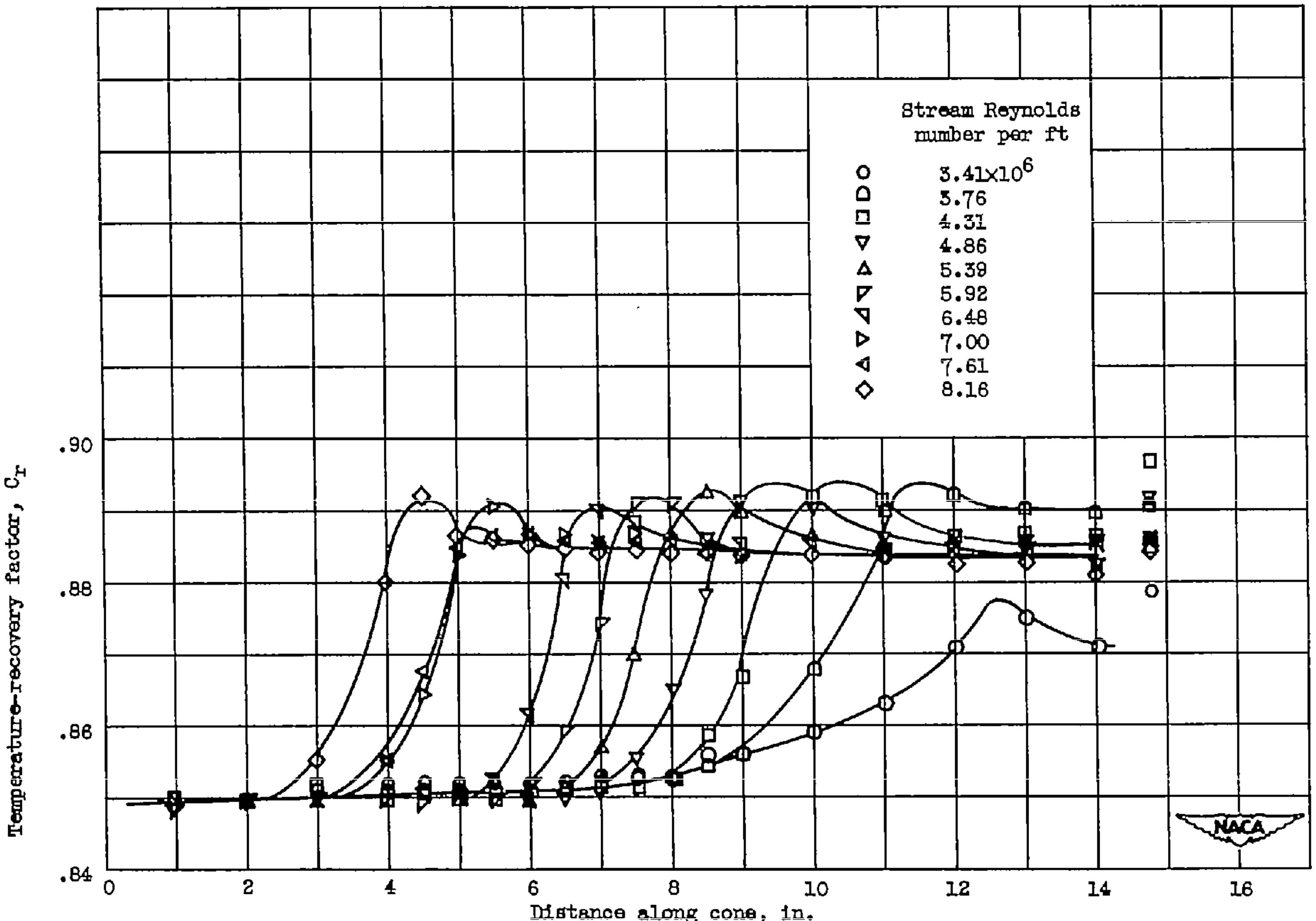
(e) Tunnel, 2- by 2-foot (Lewis); stream Mach number, 3.93; stream Reynolds number per foot, 1.03×10^6.

Figure 4. - Continued. Variation of temperature-recovery factor along 10° cone.



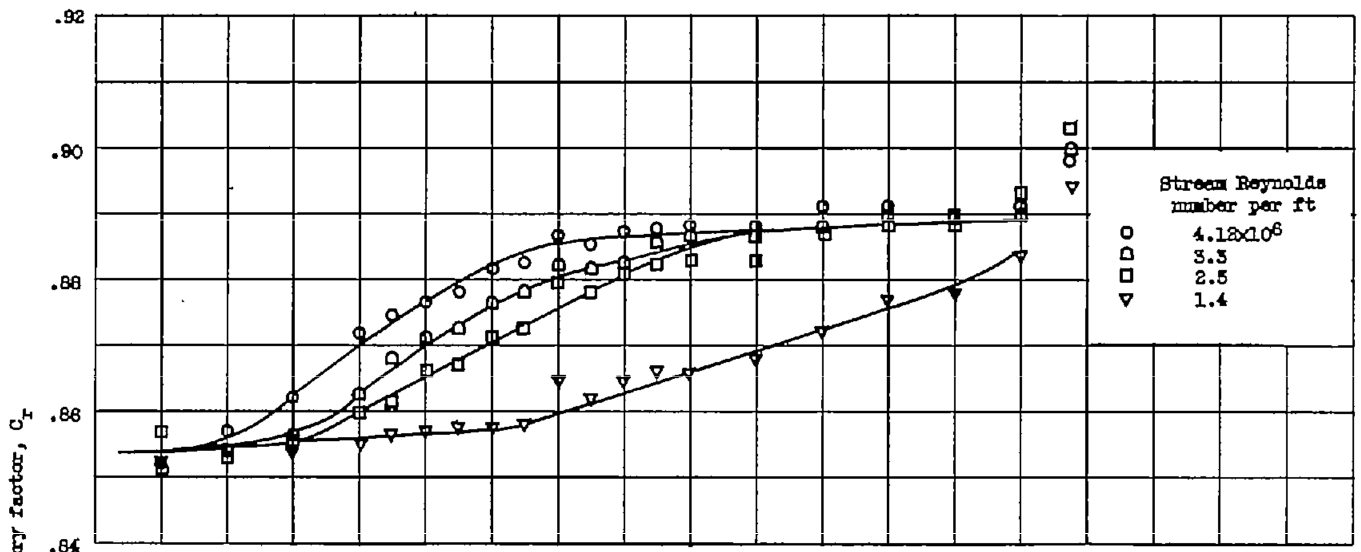
(f) Tunnel, 18- by 18-inch; stream Mach number, 1.935; stream Reynolds number per foot, 3.095×10^6.

Figure 4. - Continued. Variation of temperature-recovery factor along 10° cone.

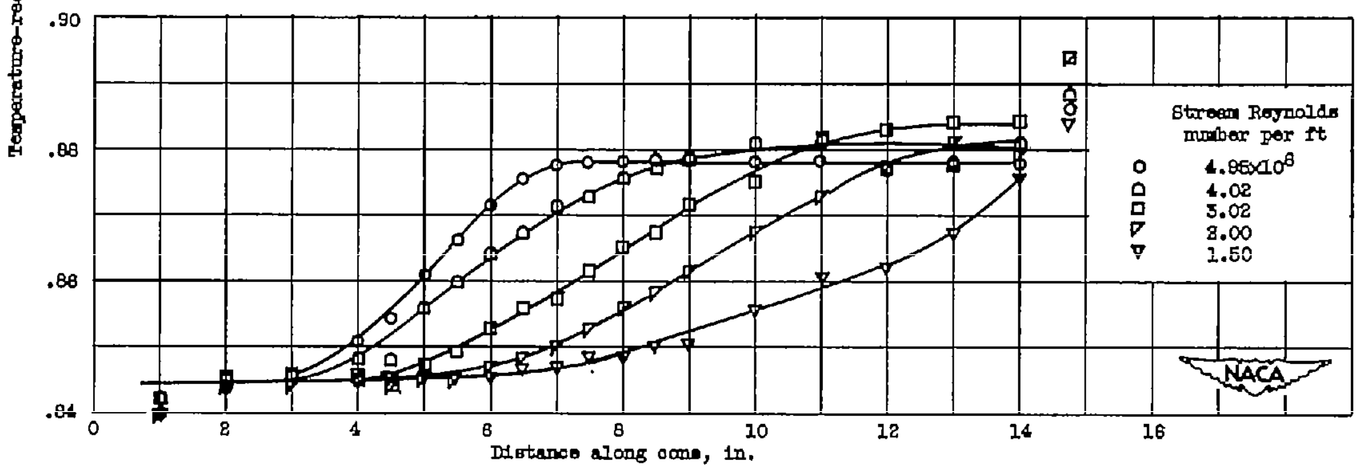


(g) Tunnel, 1- by 1-foot (LUPA); stream Mach number, 2.92.

Figure 4. - Continued. Variation of temperature-recovery factor along 10° cone.

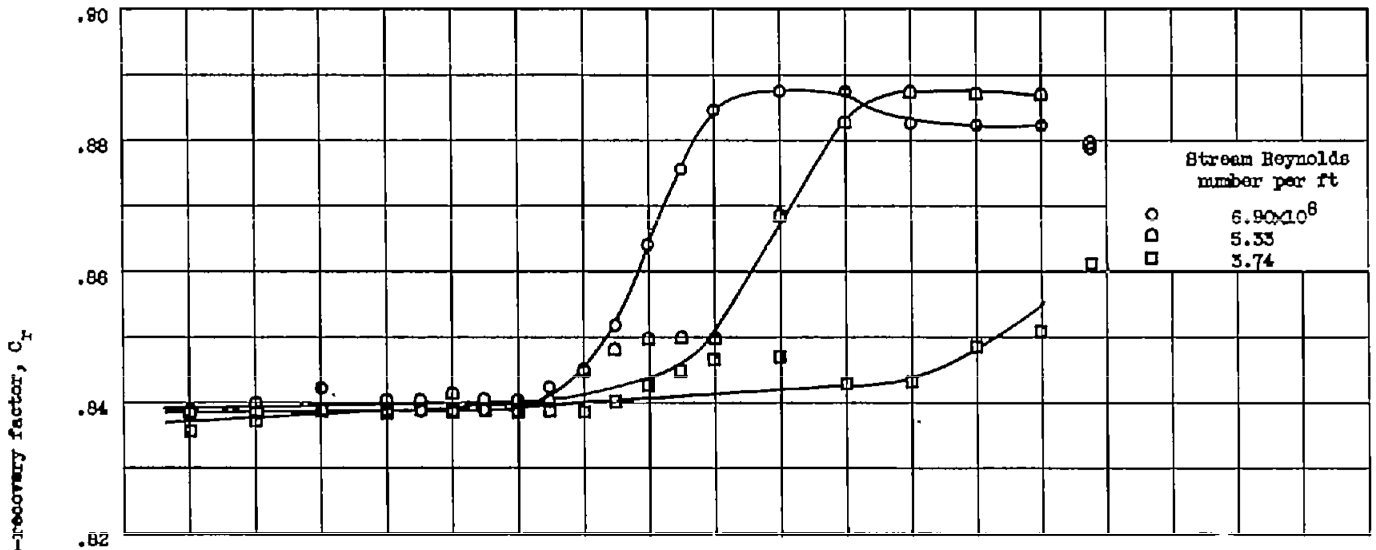


(h) Tunnel, 1- by 1-foot (VRNJ); stream Mach number, 3.12; run 1.

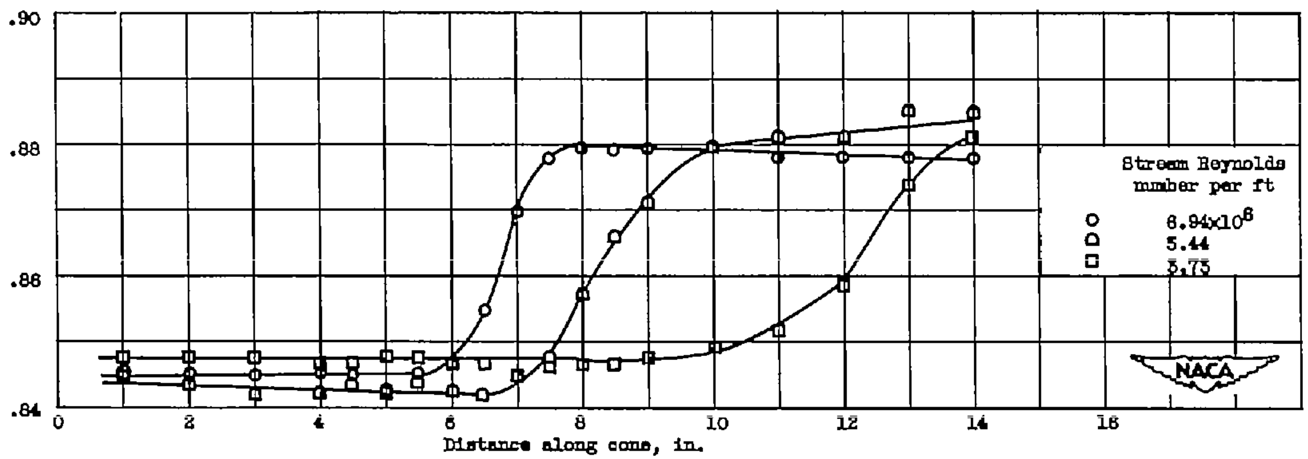


(i) Tunnel, 1- by 1-foot (VRNJ); stream Mach number, 3.12; run 3.

Figure 4. - Continued. Variation of temperature-recovery factor along 10° cone.

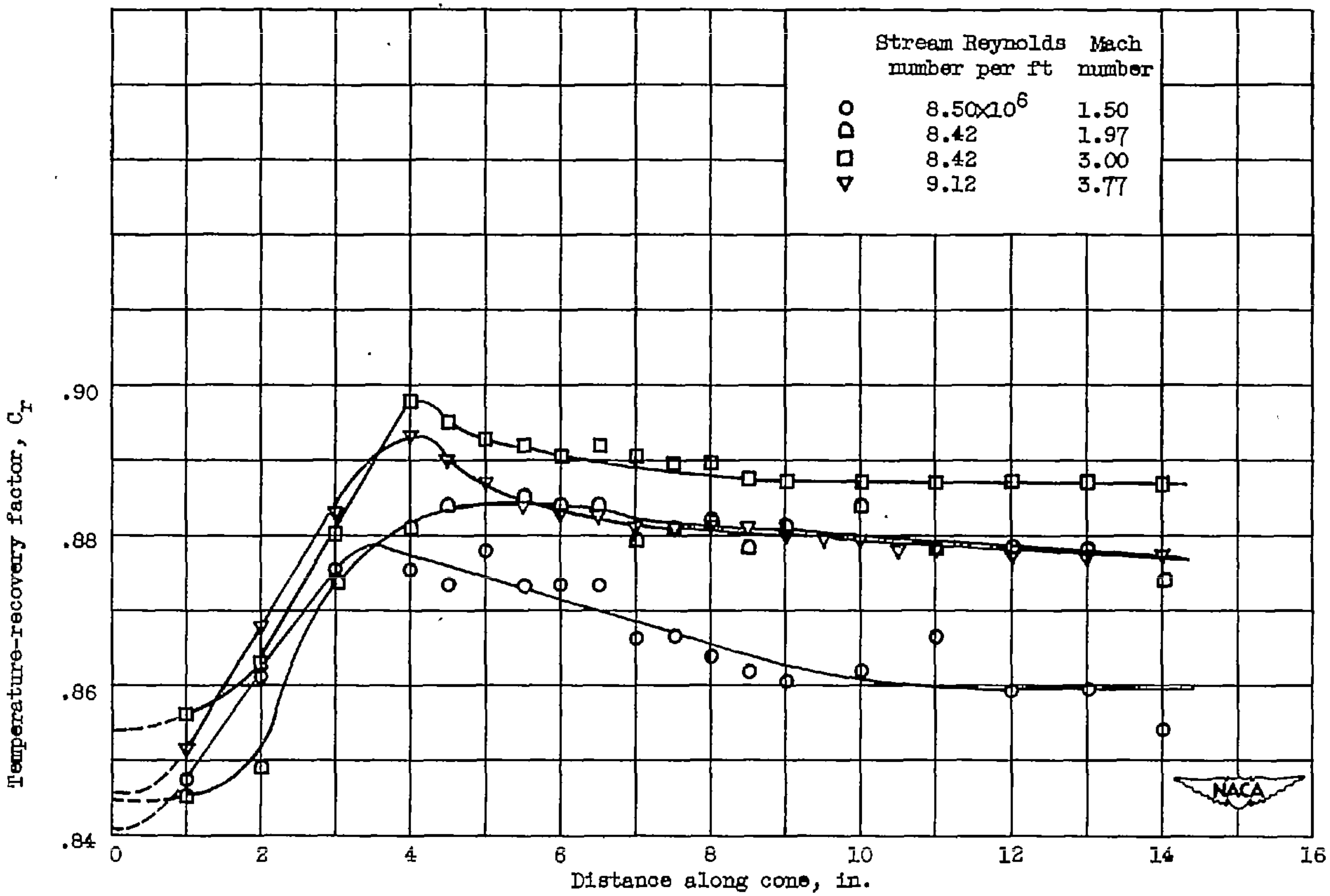


(j) Tunnel, 1- by 3-foot (No. 1); stream Mach number, 1.5.



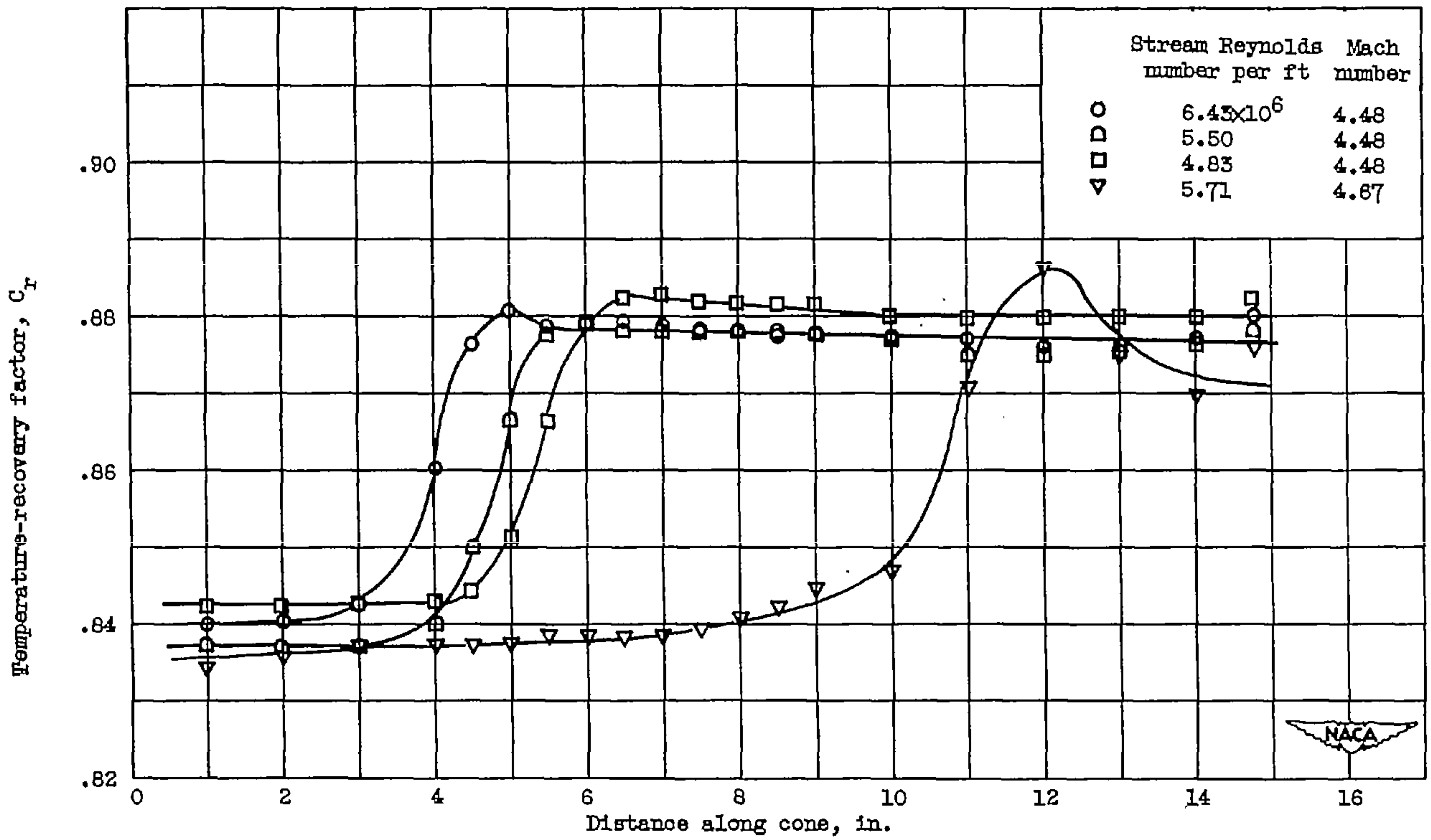
(k) Tunnel, 1- by 3-foot (No. 1); stream Mach number, 1.97.

Figure 4. - Continued. Variation of temperature-recovery factor along 10° cone.



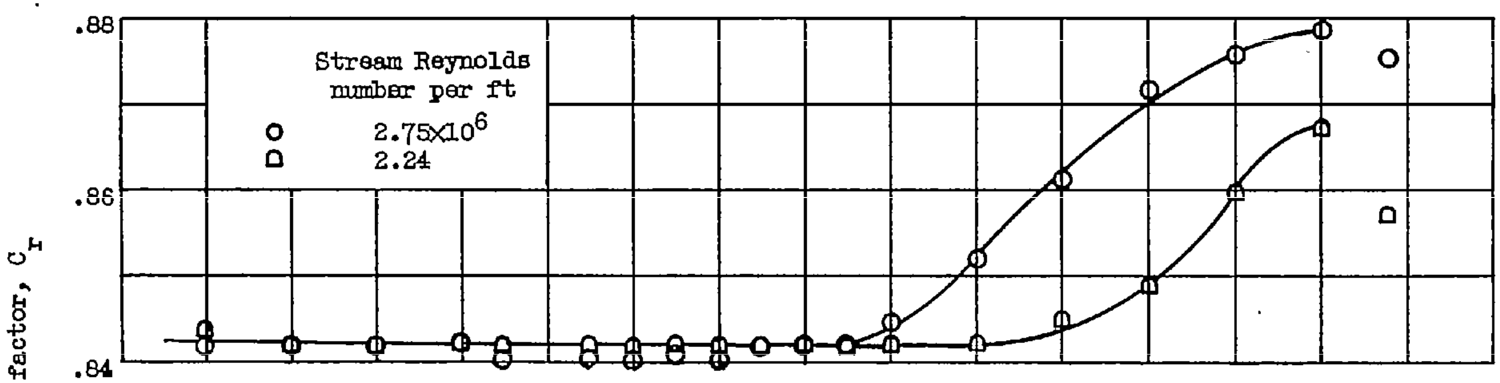
(l) Tunnel, 1- by 3-foot (No. 2).

Figure 4. - Continued. Variation of temperature-recovery factor along 10° cone.

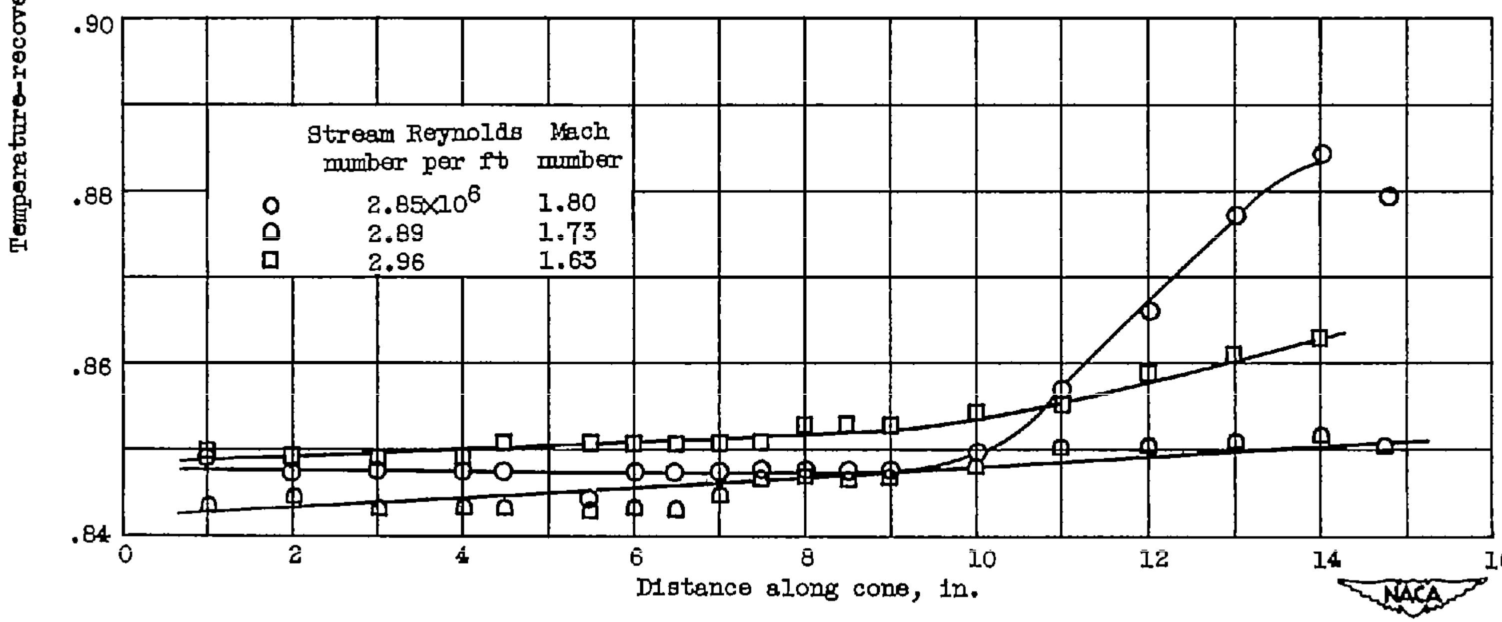


(m) Tunnel, 10- by 14-inch.

Figure 4. - Continued. Variation of temperature-recovery factor along 10° cone.

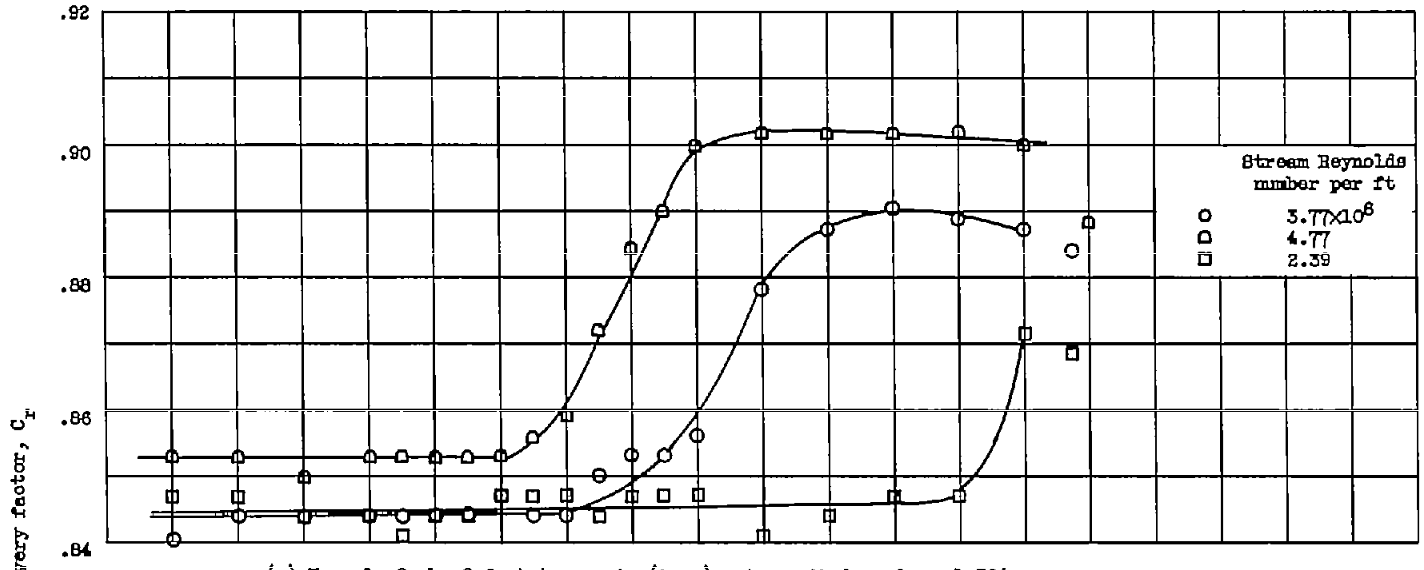


(n) Tunnel, 6- by 6-foot; stream Mach number, 1.9.

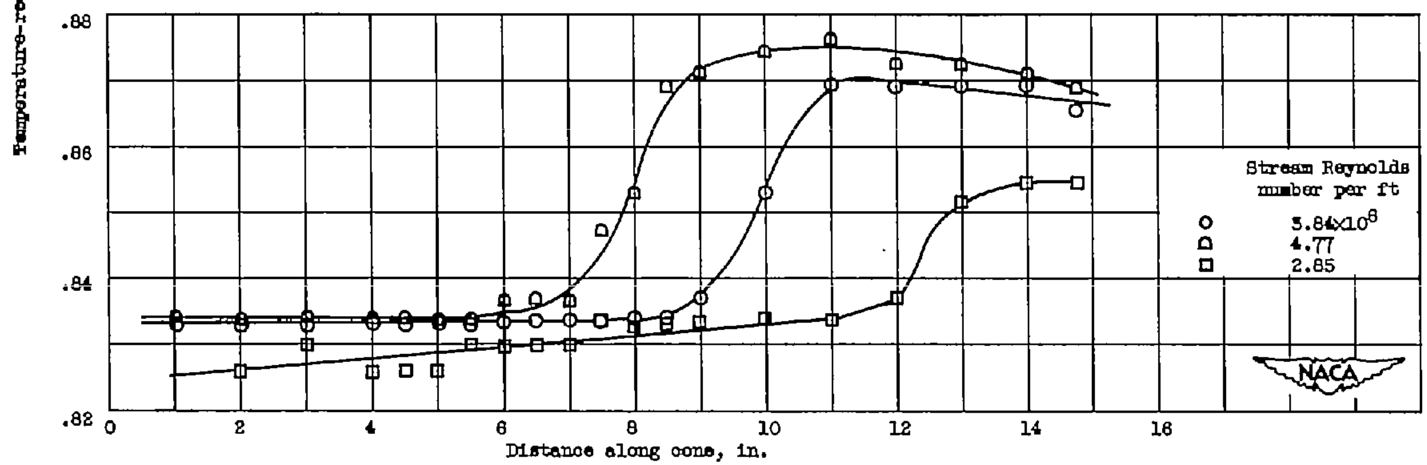


(o) Tunnel, 6- by 6-foot.

Figure 4. - Continued. Variation of temperature-recovery factor along 10° cone.



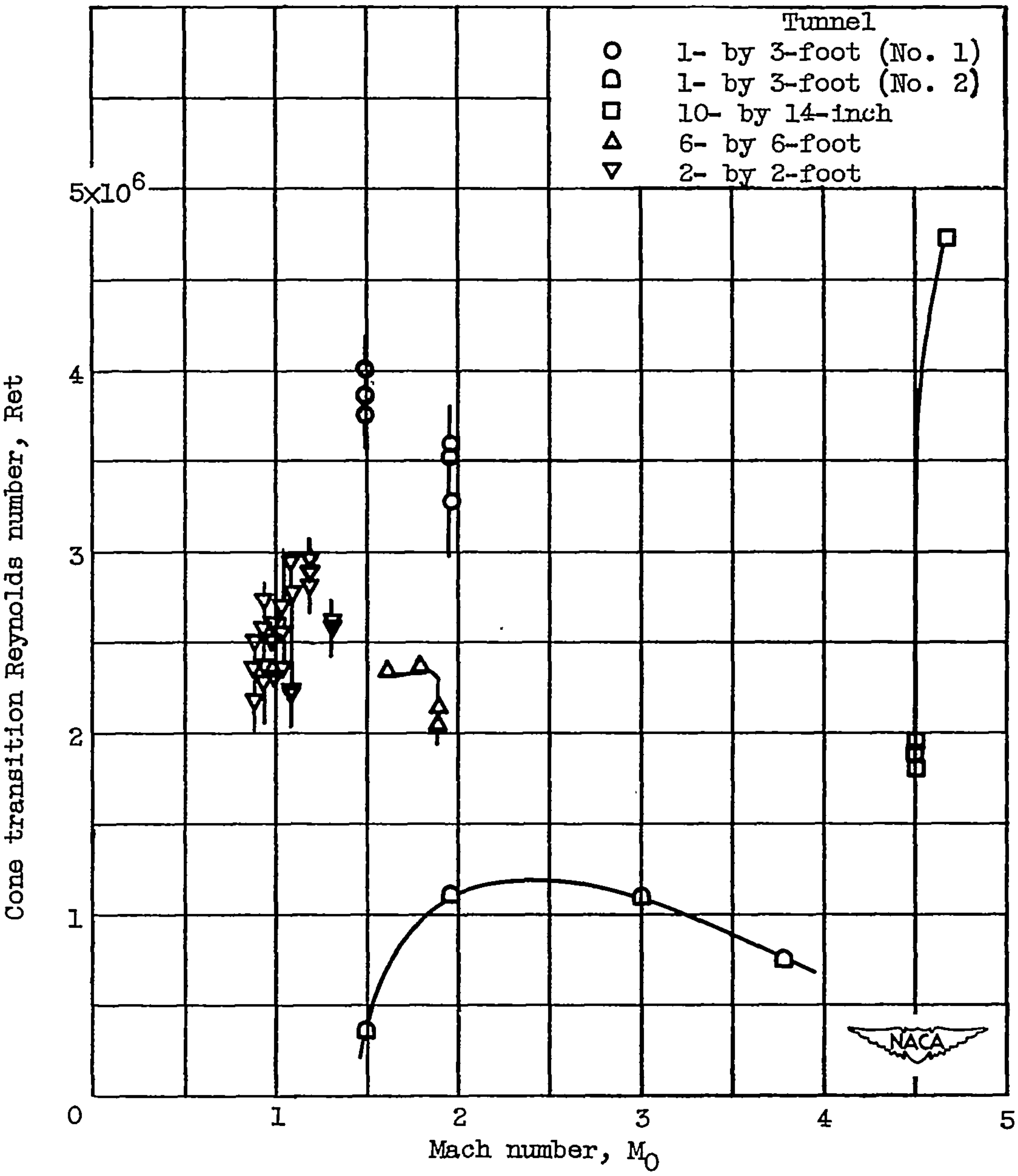
(p) Tunnel, 2- by 2-foot transonic (Ames); stream Mach number, 1.304.



(q) Tunnel, 2- by 2-foot transonic (Ames); stream Mach number, 1.207.

Figure 4. - Concluded. Variation of temperature-recovery factor along 10° cone.

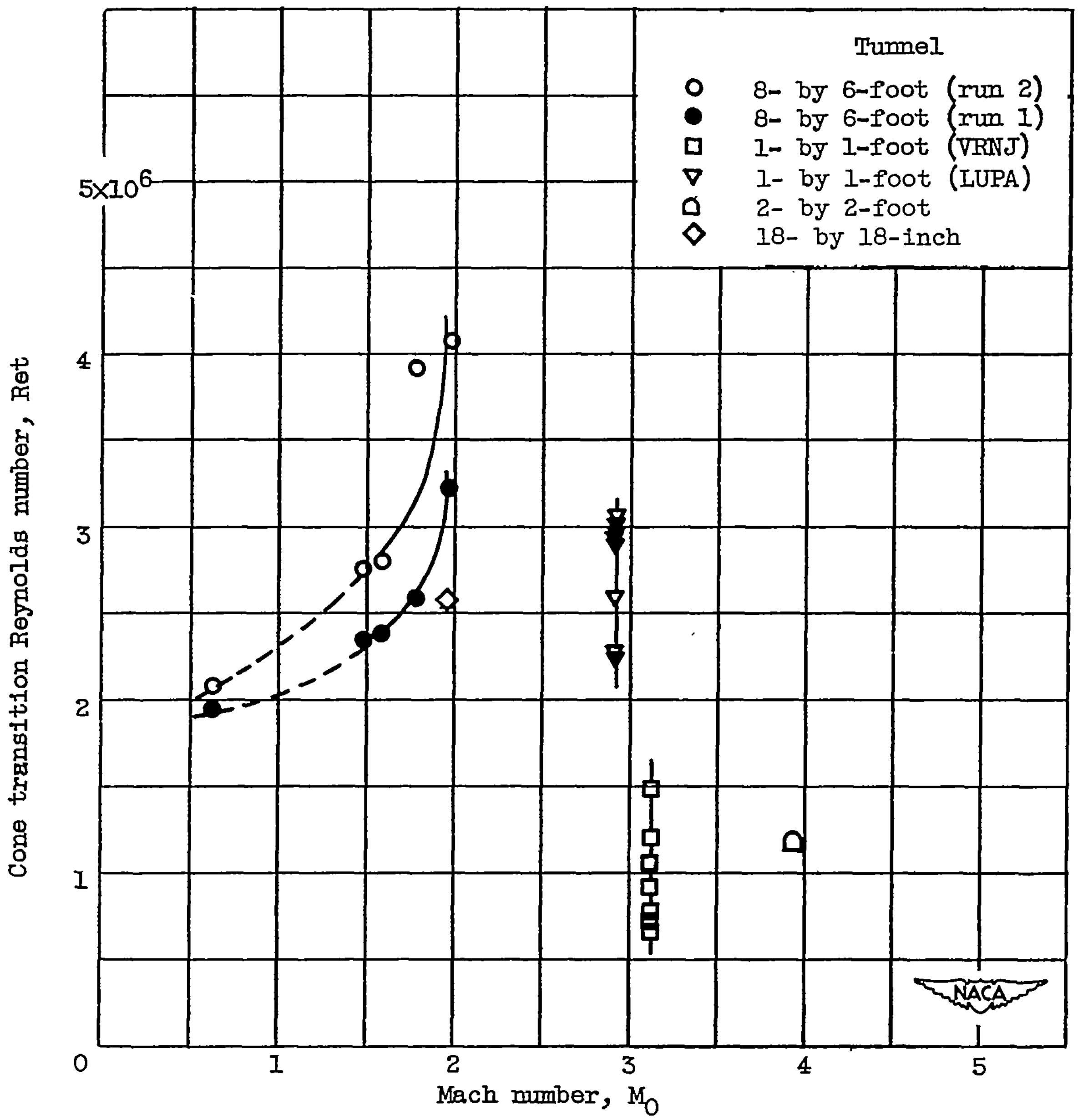
2915



(a) Ames supersonic wind tunnels.

Figure 5. - Variation of transition Reynolds number with Mach number measured with 10° cone in various supersonic wind tunnels.

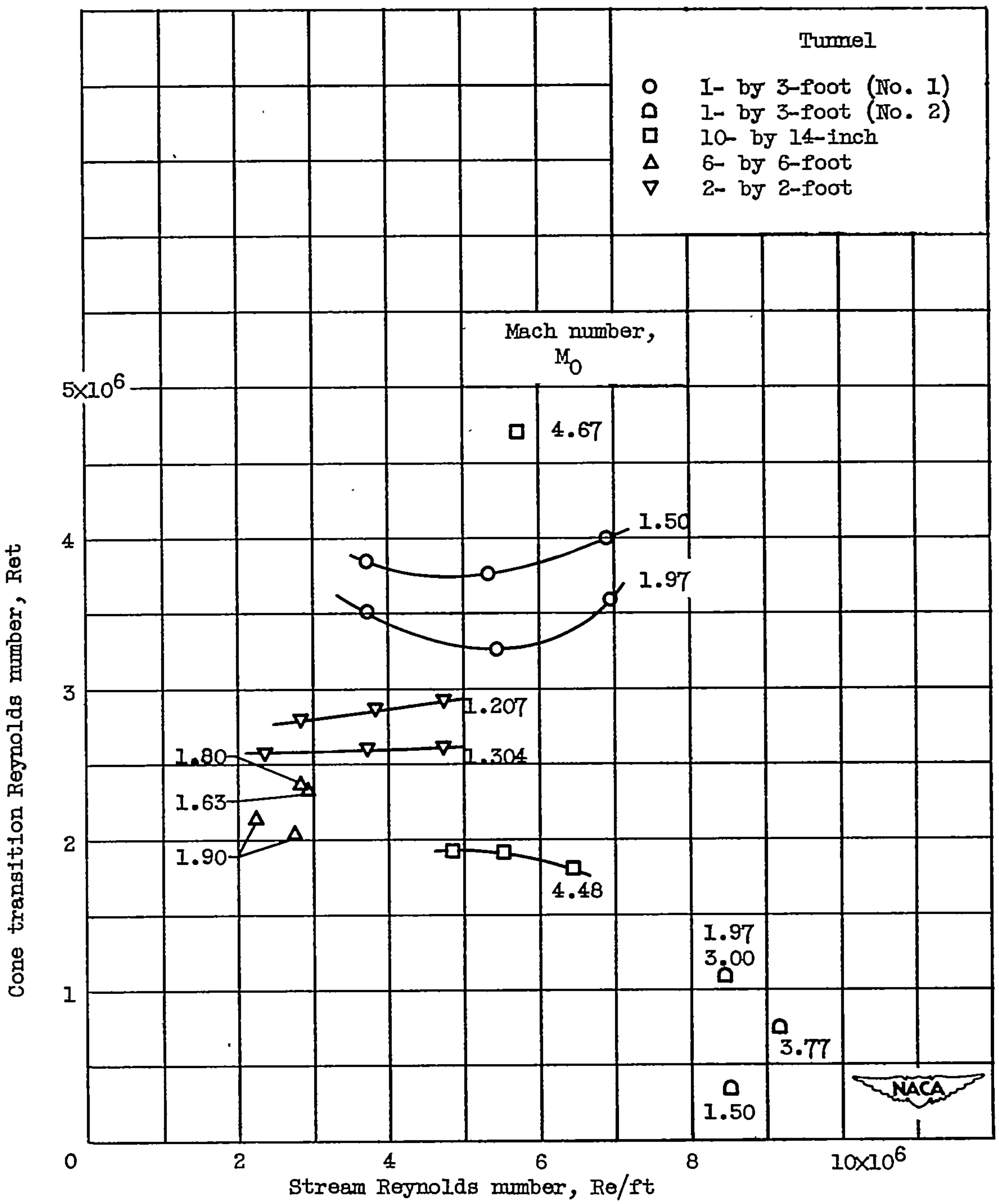
2915



(b) Lewis supersonic wind tunnels.

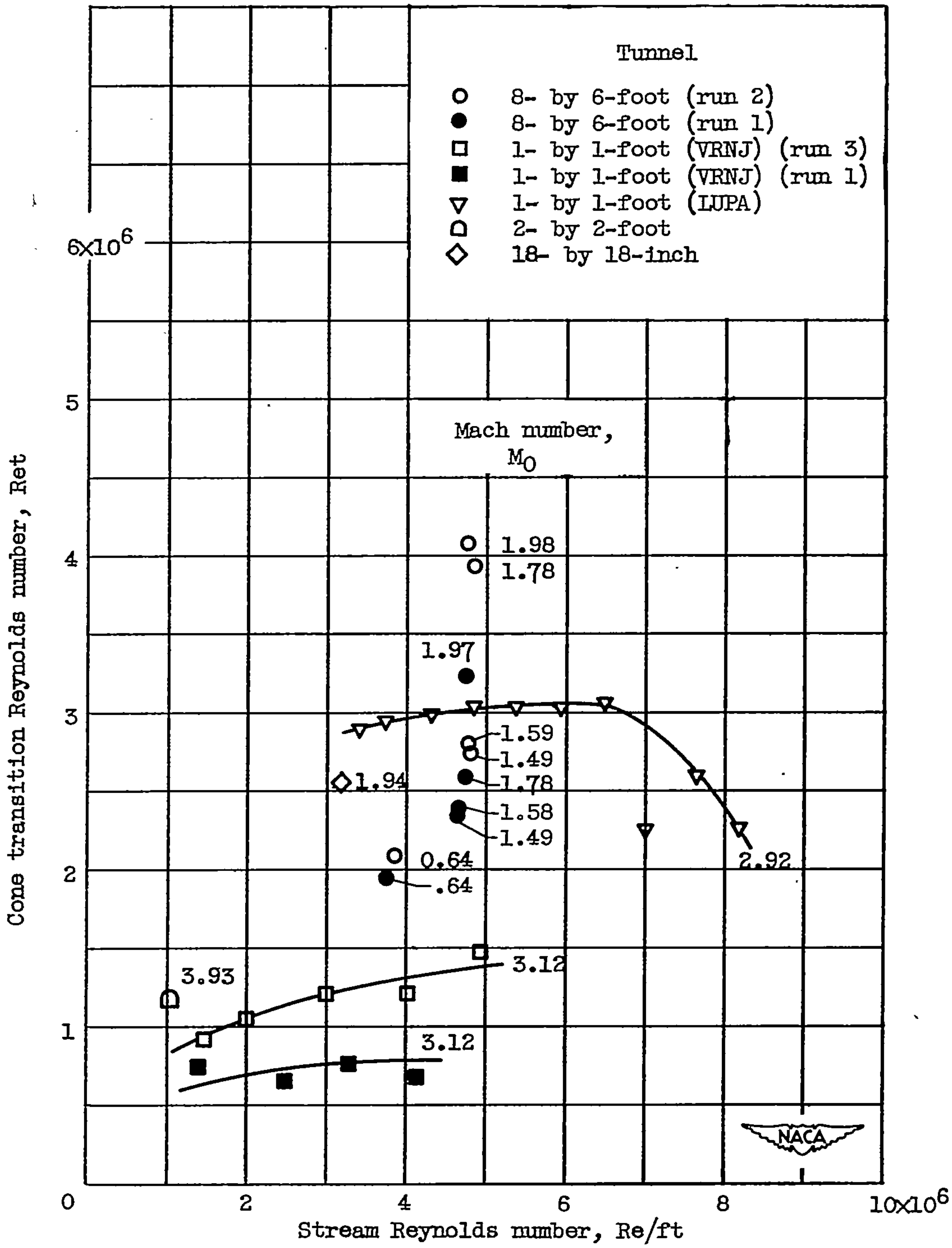
Figure 5. - Concluded. Variation of transition Reynolds number with Mach number measured with 10° cone in various supersonic wind tunnels.

2915



(a) Ames supersonic wind tunnels.

Figure 6. - Variation of transition Reynolds number with stream Reynolds number measured with 10° cone in various supersonic wind tunnels.



(b) Lewis supersonic wind tunnels.

Figure 6. - Concluded. Variation of transition Reynolds number with stream Reynolds number measured with 10° cone in various supersonic wind tunnels.

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