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RESEARCH MEMORANDUM

CHARACTERISTICS OF A HOT JET DISCHARGED FROM A JET-PROPULSION ENGINE

By William A. Fleming

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

CHARACTERISTICS OF A HOT JET DISCHARGED FROM A JET-PROPULSION ENGINE

By William A. Fleming

SUMMARY

An investigation of a heated jet was conducted in conjunction with tests of an axial-flow jet-propulsion engine in the Cleveland altitude wind tunnel. Pressure and temperature surveys were made across the jet 10 and 15 feet behind the jet-nozzle outlet of the engine. Surveys were obtained at pressure altitudes of 10,000, 20,000, 30,000, and 40,000 feet with test-section velocities from 30 to 110 feet per second and test-section temperatures from 60° to -50° F. From measurements taken throughout the operable range of engine speeds, tail-pipe outlet temperatures from 500° to 1250° F and jet velocities from 400 to 2200 feet per second were obtained. The jet-survey data presented extend the work previously done with low-velocity and low-temperature jets to the region of high velocities and high temperatures.

The results obtained agree with previously determined experimental data and with predicted theoretical expressions for the dimensionless transverse velocity and temperature profiles across a jet. The spread of both the temperature and the velocity profiles was very nearly linear. Dimensionless plots of temperature and velocity along the axis of a heated jet agree with experimental results of tests with a cold jet.

INTRODUCTION

The characteristics of the spread of a jet have been theoretically investigated (references 1 and 2) and experiments were conducted with small slightly heated jets (reference 3) and with a large jet at room temperature (reference 1, p. 599). This work was done at approximately sea-level pressure with the air surrounding the jet at very nearly static conditions. Some work has also been reported on small oblique jets discharging into a high-velocity stream. No results are generally available on characteristics of high-temperature, high-velocity jets of the size encountered in jet-propulsion engines.

In conjunction with tests of a jet-propulsion engine equipped with an axial-flow compressor in the Cleveland altitude wind tunnel, a survey of the jet was made to provide information by which an engine could be so located in an airplane that no external surface was overheated by the jet. Data were obtained at altitudes from 10,000 to 40,000 feet by varying the temperature and pressure in the tunnel.

The temperature and the velocity on the axis of the jet and the diameter of the jet are presented nondimensionally as functions of the axial distance from the jet-nozzle outlet and the diameter of the jet at the vena contracta. Nondimensional transverse profiles of velocity and temperature across the jet are presented as functions of the distance from the jet axis and the radius of the jet boundary. Comparisons are made between these data and previously published theoretical predictions by Prandtl (reference 2) and experimental data reported by Corrsin (reference 3.)

INSTRUMENTATION AND SURVEY APPARATUS

A survey rake was mounted vertically in the 20-foot-diameter test section of the altitude wind tunnel 10 feet behind the jet nozzle for part of the tests and 15 feet behind the jet nozzle for the other tests. (See fig. 1.) Unshielded total-pressure tubes were used in the survey rake. Unshielded chromel-alumel thermocouples were used in the high-temperature region of the jet and iron-constantan thermocouples were used in the low-temperature regions of the survey. The survey of total pressures and temperatures extended 14 feet across the test section and the center of the survey was on the axis of the jet nozzle. No static-pressure measurements were made in the jet. Inasmuch as the surveys were made beyond the vena contracta, the static pressure in the jet was assumed equal to the test-section static pressure.

A survey rake was installed at the jet-nozzle outlet to measure the distribution of temperature and pressure across the jet. Typical surveys of temperature and pressure at the jet-nozzle outlet are presented in reference 4 (fig. 5).

TEST PROCEDURE

Temperature and pressure surveys were made across the jet to determine the magnitude, the boundaries, and the transverse profile of the jet. The surveys were made vertically across the axis of the jet at distances of 10 and 15 feet behind the jet-nozzle outlet. The surveys made at 10 feet were with an 18-inch-diameter jet nozzle installed on the engine and the surveys made at 15 feet were with a $19\frac{1}{2}$-inch-diameter jet nozzle. The jet nozzles were conical sections 20 and 10 inches long, respectively, with an inlet diameter of 21 inches.

Investigations of the jet characteristics were made at pressure altitudes of 10,000, 20,000, 30,000, and 40,000 feet with test-section velocities varying from 30 to 110 feet per second. The temperature in the test section was varied from 60° to -50° F and an attempt was made to obtain approximately NACA standard temperatures for each altitude. The engine was operated from idling speed to full speed and the tail-pipe temperatures were correspondingly varied from 500° to 1250° F with respective jet velocities from 400 to 2200 feet per second.

SYMBOLS

The following symbols are used in this report:

A area, square feet

c_p specific heat of gas at constant pressure, Btu per pound per °F

D diameter, feet

g acceleration of gravity, feet per second per second

H total pressure, pounds per square foot absolute

J mechanical equivalent of heat, foot-pounds per Btu

M mass flow, slugs per second

p static pressure, pounds per square foot absolute

R gas constant, feet per °R

r radius, feet

T total temperature, °R

T_i indicated temperature, °R

t static temperature, °R

V velocity, feet per second

W weight flow, pounds per second

x distance from jet-nozzle outlet, feet

y distance from jet axis, feet

γ ratio of specific heats for gases

ρ mass density of gas, slugs per cubic foot

Subscripts:

g exhaust gas

j exhaust jet at vena contracta

0 free stream

x on jet axis at distance x from nozzle

y at distance y from jet axis

METHODS OF CALCULATION

The total pressures and temperatures used to calculate the velocity across the jet were obtained from faired values of the measured data. From these values and an assumed static pressure in the jet equal to the test-section static pressure, the jet velocity was calculated as

$$V_y = \sqrt{2Jgc_p t_y \left[(H_y/p_0)^{\frac{\gamma-1}{\gamma}} - 1 \right]} \qquad (1)$$

The test-section velocity and the maximum jet velocity (the velocity at the vena contracta) were calculated with equation (1) by substituting the corresponding values of temperature and pressure. In order to determine the maximum jet velocity, the assumption was made that the total pressure and temperature at the vena contracta were the same as at the jet-nozzle outlet and the jet was assumed to so expand adiabatically that the static pressure at that station was equal to the test-section static pressure.

The theoretical area of the jet at the vena contracta was determined from the mass, the velocity, and the density of the gas flow calculated for that station. Combining these quantities gave the equation

$$A_j = \frac{M_g}{\rho_j V_j} = \frac{W_g R t_j}{p_0 \ V_j} \qquad (2)$$

Inasmuch as the velocity and the temperature were measured and found to be nearly uniform across the nozzle outlet, the assumption was made that they were uniform across the vena contracta.

A sample thermocouple of the type used in the survey rake was calibrated cold up to a Mach number of about 0.8. This calibration showed that the thermocouple measured the static temperature plus approximately 85 percent of the adiabatic temperature rise due to the impact of the air on the thermocouple. If the radiation effect of the tunnel test-section wall and tail pipe on the thermocouple is neglected, the static temperature is then

$$t = \frac{T_i}{1 + 0.85\left[(H/p)^{\frac{\gamma-1}{\gamma}} - 1\right]} \qquad (3)$$

CHARACTERISTICS OF HOT EXHAUST JET

Typical profiles of the velocity and the temperature across the jet are shown in figure 2. Variation of the temperature and the velocity outside the jet was due to the change in free-stream temperature and velocity in the tunnel test section. Profiles such as those in figure 2 were used to determine the jet boundaries and the magnitude of the temperature and the velocity across the jet. The vena contracta, which is the station downstream of the nozzle at which the jet reaches ambient pressure and begins to spread, is considered a discharge orifice that has a diameter D_j. This diameter, as calculated from the results obtained by equation (2), was found to be from 3 to 10 percent smaller than the jet-nozzle-outlet diameter. Inasmuch as these two diameters were approximately the same, the assumption was made that the jet began to expand immediately behind the jet-nozzle outlet and that the vena contracta was very close to the jet-nozzle outlet. This assumption is nearly correct and is the best that can be made inasmuch as no surveys were made closer than 10 feet from the nozzle.

The distance x from the origin of the jet and the jet diameter D_x were divided by the diameter of the vena contracta D_j and are nondimensionally plotted in figure 3. The diameter of the jet D_x was found to be very nearly a linear function of the distance x along the axis from the jet-nozzle outlet. The diameter of the temperature profile was approximately 0.28 times the distance from the origin of the jet and the diameter of the velocity profile was approximately 0.26 times the distance from the origin of the jet. Corrsin (reference 3) presents curves from tests with a small heated jet, which also show that the diameter of the temperature and velocity profiles increase very nearly linearly with axial distance from the nozzle. Prandtl theoretically predicted (reference 2) that the diameter of the velocity profile would be 0.255 times the distance from the origin of the jet. The curves in figure 3 are extrapolated to unity at the jet-nozzle outlet, which is very close to the point at which the vena contracta occurs.

A nondimensional expression for the velocity at the jet axis is plotted in figure 4 against the distance from the origin divided by the vena-contracta diameter x/D_j. The nondimensional expression for velocity is the ratio of the difference between the velocity on the jet axis and the free-stream velocity to the difference between the maximum jet velocity and the free-stream velocity $\frac{V_x-V_0}{V_j-V_0}$. The data presented were obtained at distances of 6.67 and 9.23 jet-nozzle diameters behind the jet nozzle for pressure altitudes of 10,000, 20,000, 30,000, and 40,000 feet throughout the greater part of the engine-speed range. The curve plotted through these points in figure 4 was obtained by Corrsin (reference 3) from an investigation of a heated jet. The curve and plotted data are in close agreement, between 6 and 7 diameters of the vena contracta from the origin of the jet; between 9 and 10 diameters from the origin, however, the curve is slightly below the plotted data. No data were obtained to confirm the shape of the curve at less than 6 diameters from the nozzle.

In all the relations presented that involve the temperature in the jet, total temperature was used. Although the development of jet theory uses the static temperature, the total temperature is more significant in the case of a heated jet because it is a measure of the total energy in a jet. A particle of gas being discharged from a heated jet has a greater amount of heat and kinetic energy than a similar particle in the free stream. When an energy exchange occurs in the mixing process, the jet gives up part of its heat energy and part of its kinetic energy to the free stream. In the transfer of kinetic energy the losses are converted into heat energy. When the static temperature is used, the kinetic energy converted into heat energy is neglected.

A nondimensional expression for the total temperature on the jet axis, which is similar to the velocity expression, is plotted against x/D_j in figure 5. The nondimensional factor for total temperature is the ratio of the difference between the total temperature on the jet axis and free-stream temperature to the difference between the total temperature at the vena contracta and the free-stream temperature $\frac{T_x-T_0}{T_j-T_0}$. These data were obtained for the same range of conditions as the velocity parameters presented in figure 4. The curve plotted in figure 5, which was determined by Corrsin, and the plotted data are in close agreement.

The velocity profile across the jet is plotted nondimensionally (fig. 6) against the distance from the jet axis divided by the radius of the jet y/r. The velocity parameter is the ratio of the difference between the velocity in the jet and the free-stream velocity to the difference between the velocity on the axis and the free-stream velocity $\frac{V_y-V_0}{V_x-V_0}$. The data presented were obtained at $6\frac{1}{2}$ and $9\frac{1}{2}$ vena-contracta diameters (10 and 15 ft) behind the jet-nozzle outlet at pressure altitudes of 10,000 and 30,000 feet throughout the greater part of the engine-speed range. The data obtained throughout the entire range of test conditions fell on a single curve for velocity profile at each station.

A dashed curve that represents the theoretical shape of the jet at large distances from the jet-nozzle outlet is also plotted in figure 6. An expression for this curve was presented by Prandtl in reference 2 (equation (25.20)) as

$$V_y - V_0 = \frac{0.351}{\beta}\sqrt{\frac{M}{\rho t}}\left[1 - (y/r)^{3/2}\right]^2 \tag{4}$$

where β is the ratio of the mixing length perpendicular to the direction of flow to the width of the mixing zone and M is the total momentum contained in a portion of fluid of unit length in the direction of motion and unit width perpendicular to the direction of motion. Therefore, in the case discussed

$$\frac{0.351}{\beta}\sqrt{\frac{M}{\rho t}} = V_x - V_0$$

Equation (4) can then be rearranged to give the nondimensional velocity parameter

$$\frac{V_y - V_0}{V_x - V_0} = \left[1 - (y/r)^{3/2}\right]^2 \qquad (5)$$

The curve obtained with this equation is in reasonable agreement with the measured data.

The temperature profile across the jet is plotted nondimensionally in figure 7 against the distance from the jet axis divided by the jet radius y/r. The temperature parameter is the ratio of the difference between the total temperature in the jet and the free-stream total temperature to the difference between the total temperature on the jet axis and the free-stream total temperature $\frac{T_y - T_0}{T_x - T_0}$. The data in figures 7(a) and 7(b) were obtained at $6\frac{1}{2}$ and $9\frac{1}{2}$ vena-contracta diameters (10 and 15 ft) behind the nozzle outlet, respectively. The data obtained throughout the entire range of test conditions fell on a single curve at each station.

According to the momentum-transfer theory, the static-temperature distribution and the velocity distribution across a wake are the same. This relation is discussed by Goldstein in reference 1 (p. 585). Inasmuch as the total temperature is more significant than the static temperature in work with a heated jet and the total-temperature and static-temperature profiles are similar, the total temperature is substituted for velocity in equation (4) to give

$$\frac{T_y - T_0}{T_x - T_0} = \left[1 - (y/r)^{3/2}\right]^2 \qquad (6)$$

This equation gives the dashed curve plotted in figure 7, which is very similar to the dimensionless total-temperature profile experimentally measured. A comparison of figures 6 and 7 shows that the shapes of the dimensionless total-temperature and velocity profiles across a heated jet are very nearly the same.

A slight asymmetry in both temperature and velocity profiles was attributed to interference between the jet wake and the wake from the trailing edge of the airfoil on which the engine was supported. Approximately the same degree of asymmetry appears for temperature and velocity profiles.

The data presented for 18- and $19\frac{1}{2}$-inch-diameter jets with jet velocities as high as 2200 feet per second and jet temperatures as high as 1250° F extend the work done by Corrsin (reference 3), in which he investigated the wake of 1- and 3-inch heated jets with a throat velocity of approximately 67 feet per second. A comparison of the wind-tunnel results and investigations by Corrsin indicated that the characteristics of a small low-velocity and low-temperature jet are similar to those of a large high-velocity and high-temperature jet. Results of the jet surveys also agree with the theoretical predictions for the shape and the spread of a jet.

SUMMARY OF RESULTS

Based on the somewhat limited data of this investigation at pressure altitudes from 10,000 to 40,000 feet, tail-pipe temperatures from 500° to 1250° F, and jet velocities from 400 to 2200 feet per second, the following results are presented:

1. Dimensionless plots of temperature and velocity distribution in a heated jet are in close agreement with theoretical predictions and with experimental results from tests of cold jets.

2. The spread of the temperature and velocity profiles of a heated jet were very nearly linear, which agrees closely with theoretical predictions. Heat diffuses more rapidly than velocity in a heated jet. The diameter of the temperature profile was approximately 0.28 times the distance from the nozzle outlet and the diameter of the velocity profile was approximately 0.26 times the distance from the nozzle outlet.

3. Dimensionless plots of temperature and velocity on the axis of a heated jet are in fairly close agreement with experimental results of tests with a cold jet.

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National Advisory Committee for Aeronautics,
Cleveland, Ohio.

REFERENCES

1. Goldstein, S.: Modern Developments in Fluid Dynamics. Vol. II, ch. XIII. Clarendon Press (Oxford), 1938, p. 585.

2. Prandtl, L.: Spread of Turbulence. Vol. III of Aerodynamic Theory, div. G, sec. 25, W. F. Durand, ed., Julius Springer (Berlin), 1935, pp. 162-178. (Reprinted, C.I.T., Jan. 1943.)

3. Corrsin, Stanley: Investigation of Flow in an Axially Symmetrical Heated Jet of Air. NACA ACR No. 3L23, 1943.

4. Silverstein, Abe: Investigations of Jet-Propulsion Engines in the NACA Altitude Wind Tunnel. NACA ACR No. E5H23, 1945. (Classification changed from "Confidential" to "Restricted", Aug. 1946.)

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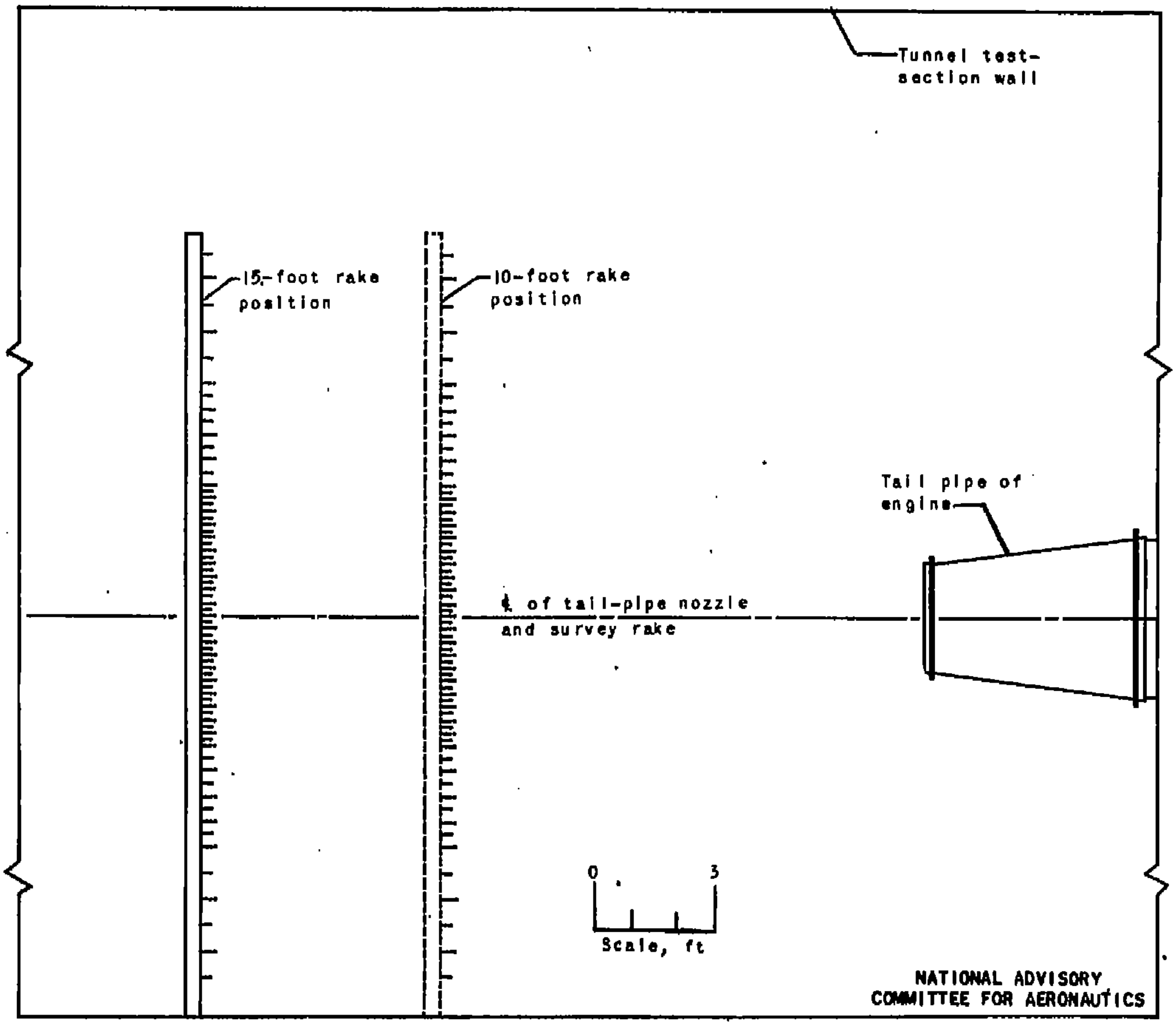
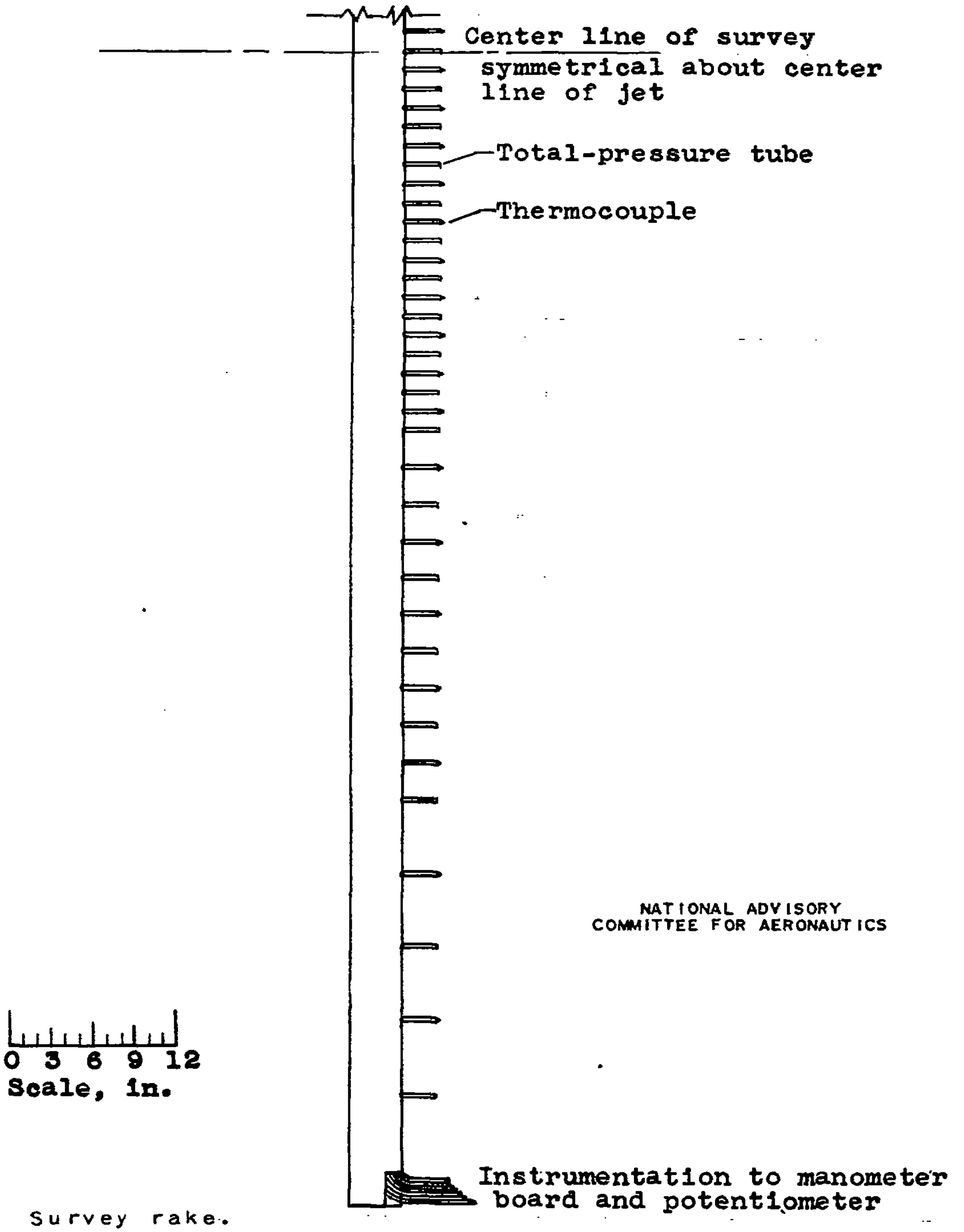


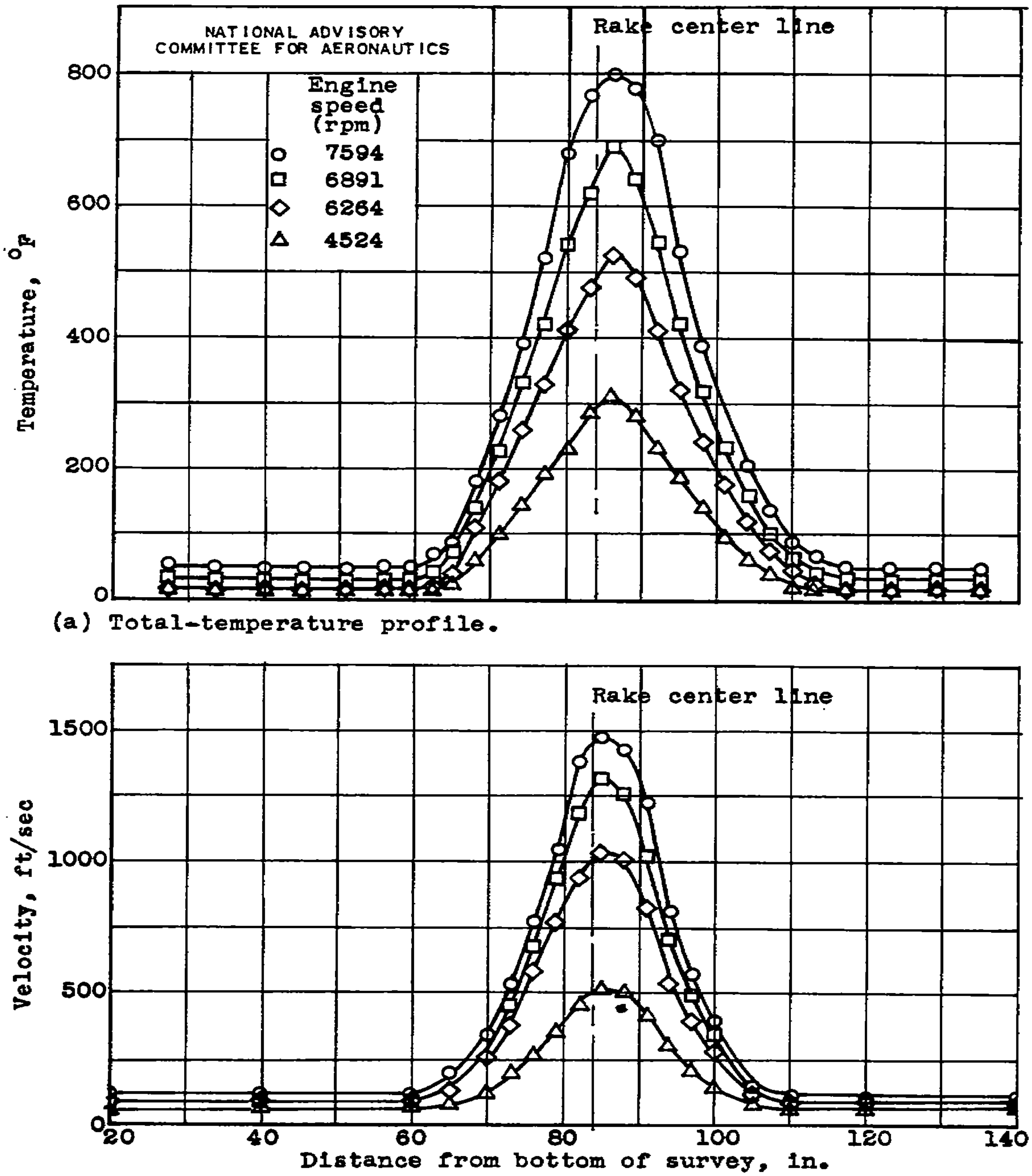
(a) Installation of survey rake.

Figure 1. - Installation of survey rake in wind-tunnel test section to obtain total pressures and temperatures in jet.



(b) Survey rake.

Figure 1. - Concluded. Installation of survey rake in wind-tunnel test section to obtain total pressures and temperatures in jet.



(a) Total-temperature profile.

(b) Velocity profile.

Figure 2.- Typical profiles of velocity and temperature across heated jet located 10 feet behind jet-nozzle outlet. Pressure altitude, 10,000 feet; jet-nozzle-outlet diameter, 18 inches.

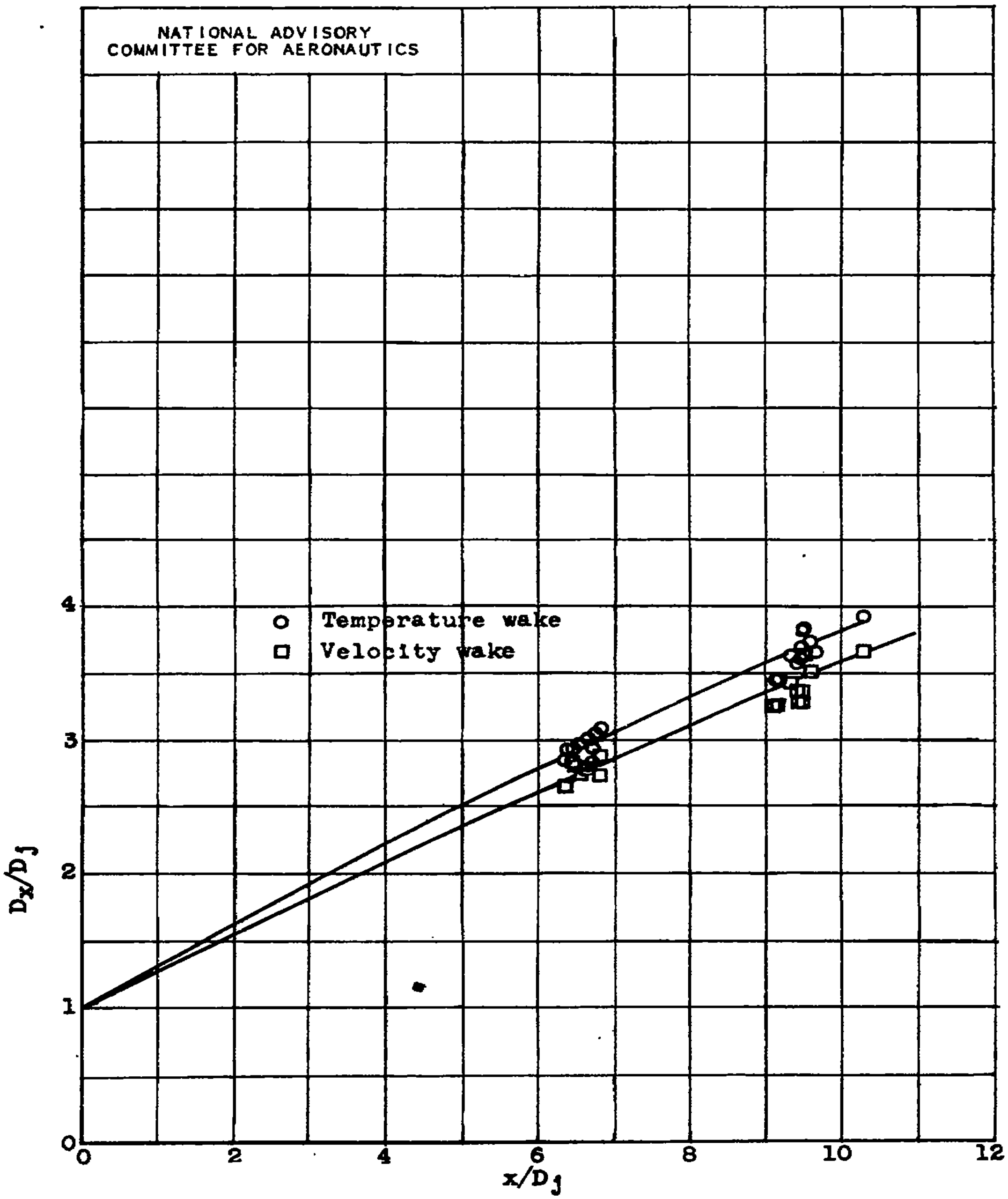


Figure 3.- Variation of temperature- and velocity-profile diameters with distance from jet origin. Pressure altitudes from 10,000 to 40,000 feet with 18- and 19½-inch-diameter tail-pipe nozzles throughout greater part of engine-speed range.

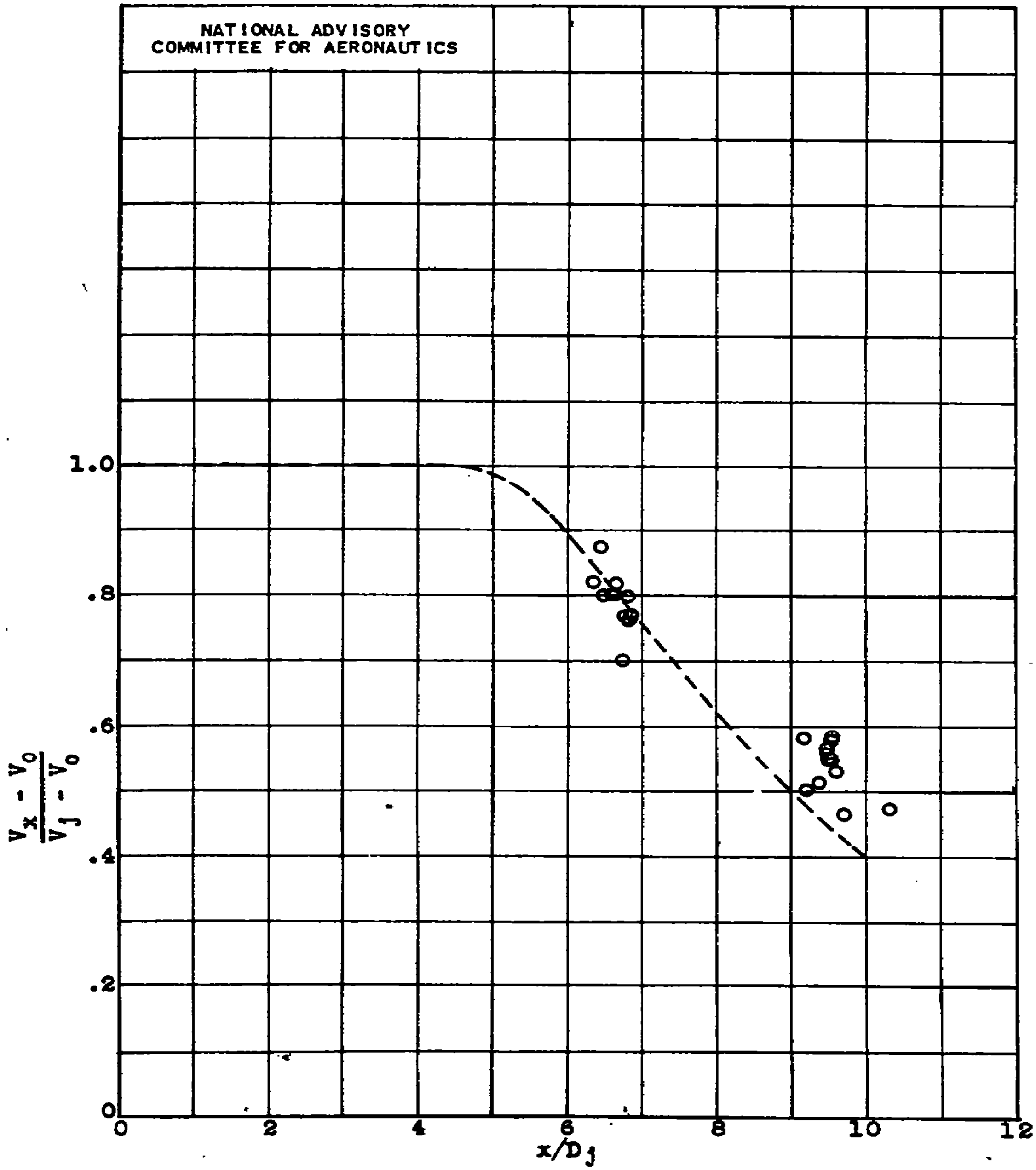


Figure 4.- Variation of parameter for velocity on jet axis with distance from jet origin. Pressure altitudes from 10,000 to 40,000 feet with 18- and 19½-inch-diameter tail-pipe nozzles throughout greater part of engine-speed range. (Curve from reference 3.)

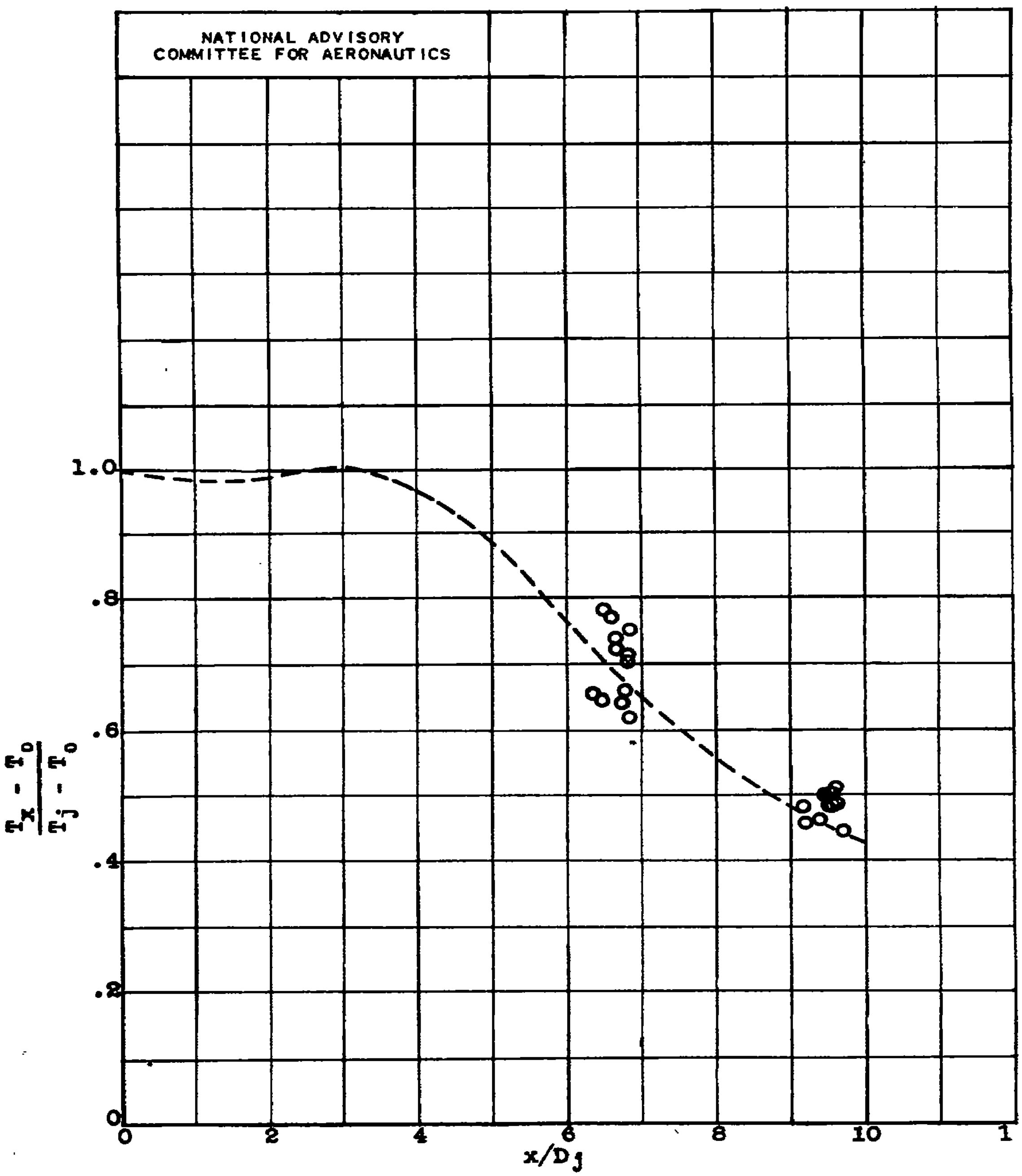
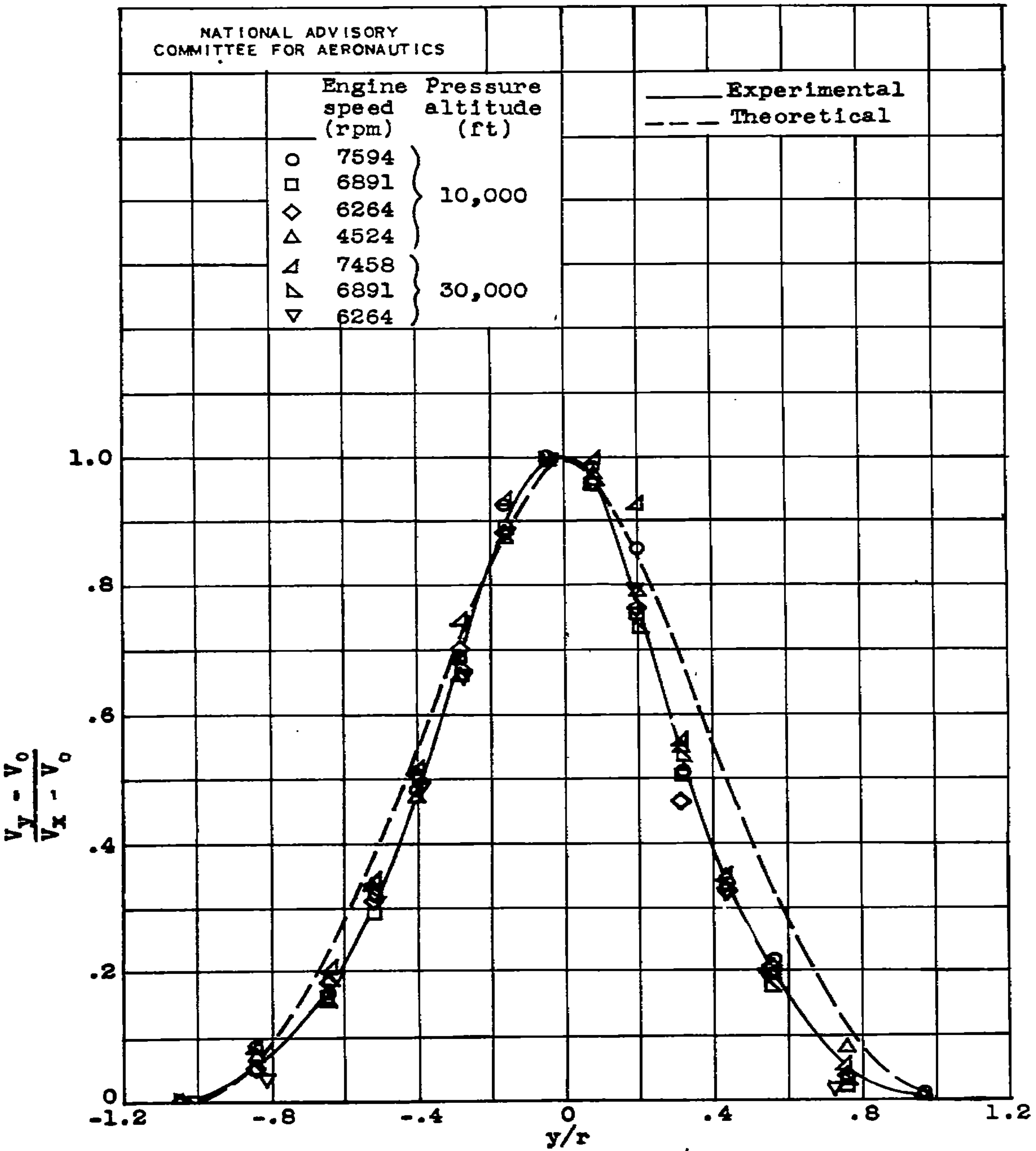
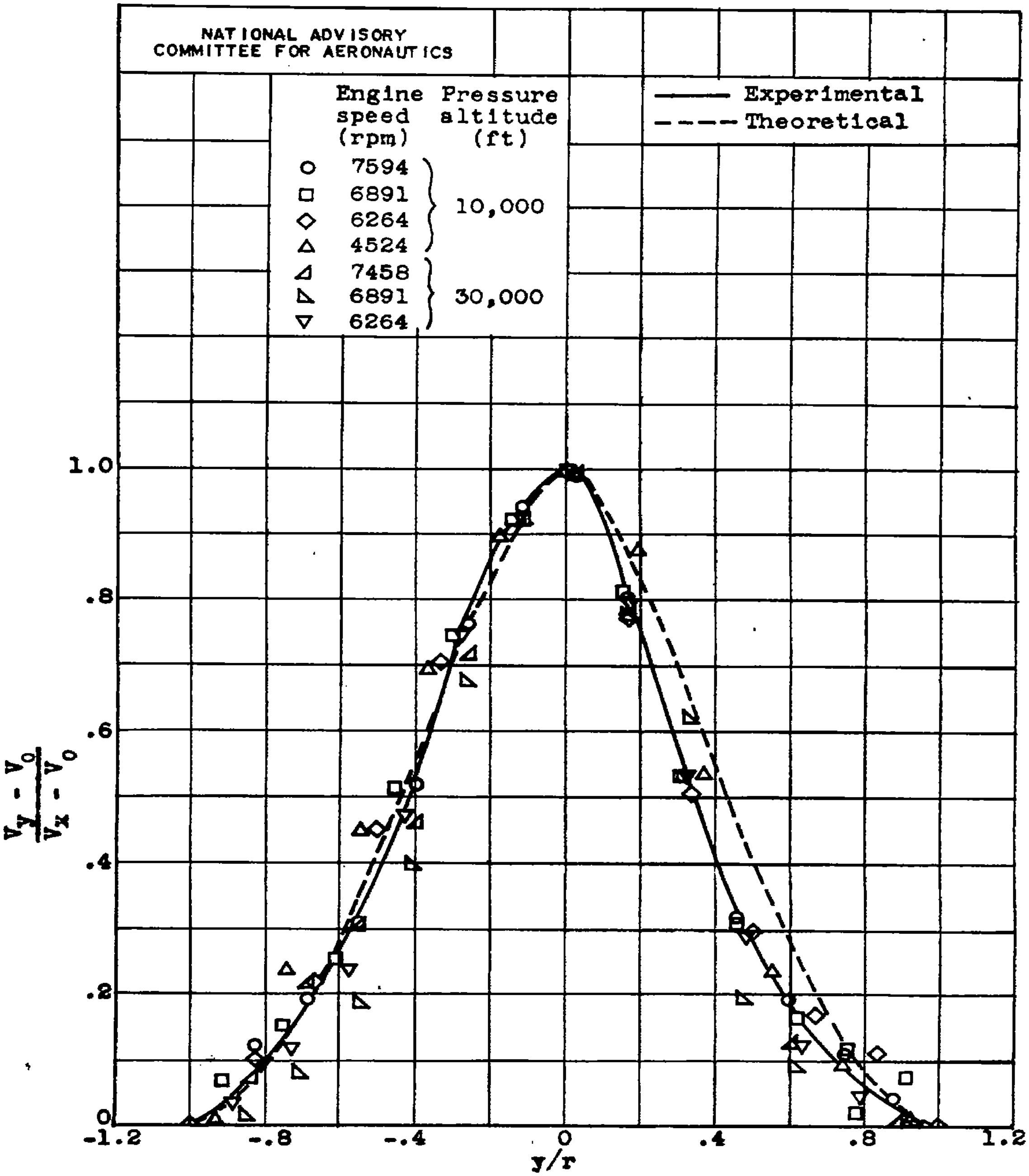


Figure 5.- Variation of parameter for temperature on jet axis with distance from jet origin. Pressure altitudes from 10,000 to 40,000 feet with 18- and $19\frac{1}{2}$-inch-diameter tail-pipe nozzles throughout greater part of engine-speed range. (Curve from reference 3.)



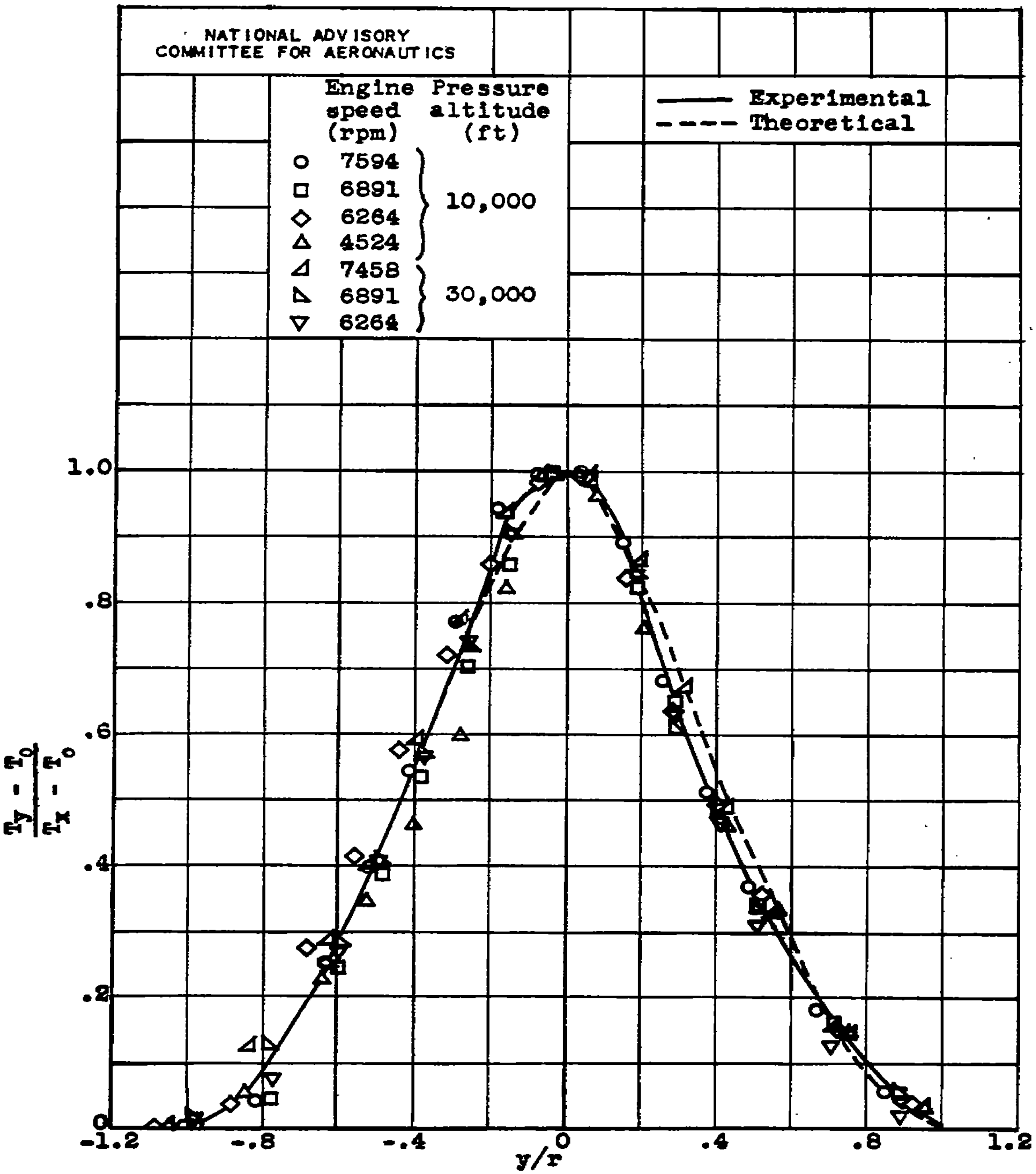
(a) Profile measured at approximately $6\frac{1}{2}$ vena-contracta diameters from jet origin.

Figure 6. - Comparison of transverse velocity profile measured across jet with theoretical profile calculated from equation (5).



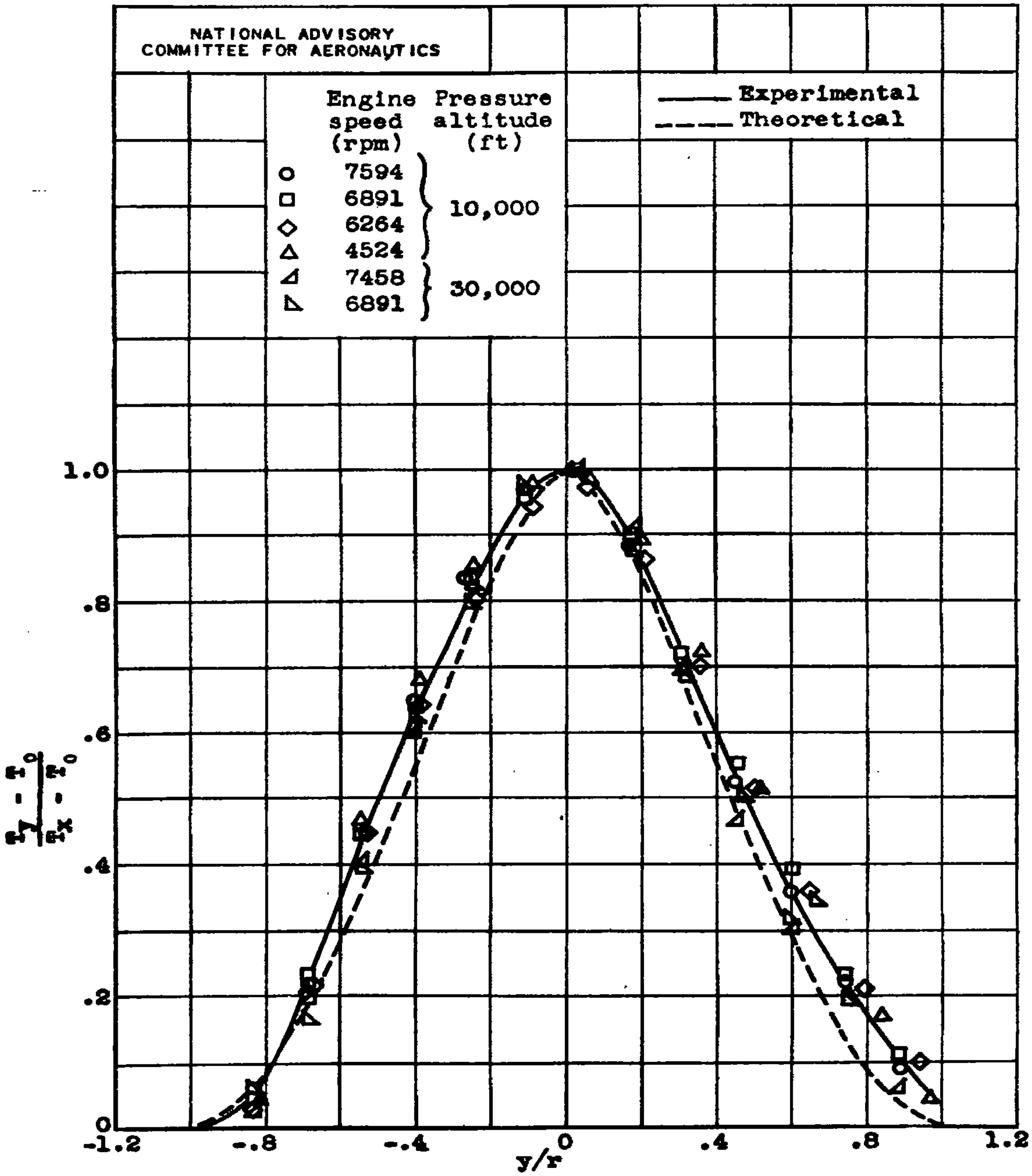
(b) Profile measured at approximately $9\frac{1}{2}$ vena-contracta diameters from jet origin.

Figure 6. - Concluded. Comparison of transverse velocity profile measured across jet with theoretical profile calculated from equation (5).



(a) Profile measured at approximately $6\frac{1}{2}$ vena-contracta diameters from jet origin.

Figure 7. - Comparison of transverse temperature profile measured across jet with theoretical profile calculated from equation (6).



(b) Profile measured at approximately $9\frac{1}{2}$ vena-contracta diameters from jet origin.

Figure 7. - Concluded. Comparison of transverse temperature profile measured across jet with theoretical profile calculated from equation (6).