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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2807

MEASUREMENTS OF TEMPERATURE VARIATIONS IN THE ATMOSPHERE NEAR THE TROPOPAUSE WITH REFERENCE TO AIRSPEED CALIBRATION BY THE TEMPERATURE METHOD

By Lindsay J. Lina and Harry H. Ricker, Jr.

Langley Aeronautical Laboratory
Langley Field, Va.

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MEASUREMENTS OF TEMPERATURE VARIATIONS IN THE ATMOSPHERE NEAR THE TROPOPAUSE WITH REFERENCE TO AIRSPEED CALIBRATION BY THE TEMPERATURE METHOD

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SUMMARY

Detailed measurements of pressure and temperature were made in constant-speed level flight, in low-speed climbing flight, and in a high-speed dive and pull-up with a jet fighter airplane for the purpose of obtaining information on the accuracy of the temperature method of airspeed calibration (NACA TN 2046). The measurements were made near the tropopause over land in the vicinity of Langley Field, Va., on clear days with few or no clouds. The data were taken by means of a thermometer, described in the present paper, which was designed by the Langley Instrument Research Division to meet the low-lag, high-recovery requirements of the temperature method.

Measurements made in low-speed climbs indicated that the variations of temperature with pressure were very smooth when the lapse rate was close to adiabatic and several temperature-pressure surveys agreed closely, although spaced several minutes apart with no effort made to repeat the surveys in the same position in the air mass. On the other hand, when the lapse rate was small (between isothermal and NACA standard for air below the tropopause), variations of temperature with pressure were irregular and changed erratically with time and distance. Evaluation of the airspeed calibration of the jet fighter made when the conditions were least unfavorable to the method showed an undesirably large scatter of the static-pressure error of about ±2.5 percent of impact pressure at a Mach number of about 0.8.

INTRODUCTION

A method of airspeed calibration in which temperature measurements are used, referred to in this paper as the "temperature method," was described in reference 1. This method offers the advantages of flexibility of flight operation (since all the necessary measurements are made by instruments carried in the airplane) and ease of data evaluation. The accuracy of the temperature method, as shown in reference 1, improves with

increased accuracy of the measured quantities, increased recovery factor of the thermometer, increased speed, and decreased temperature lapse rate in the atmosphere.

Although the temperature method was described in reference 1, no experimental verification was available at the time of publication; furthermore, although the accuracy of the method depends on the variations of atmospheric temperature over small vertical and horizontal distances and small intervals of time, very little information concerning these variations was then available. Measurements of the variations of temperature and pressure have therefore been made in order to provide some information on the accuracy of this method. The data, obtained from flights of a jet fighter airplane over land in the vicinity of Langley Field, Va., from February to September 1950, included measurements made in low-speed climbing flights and a dive at high subsonic speeds in the atmosphere near the tropopause. An airspeed calibration was made for the dive and pull-up (the evaluations for the dive and pull-up, obtained on a day when the variations of temperature in the atmosphere were believed to be the least unfavorable to the temperature method, are the only high-speed data presented) and covered a range of Mach number from 0.6 to 0.8, with the pull-up reaching a maximum normal acceleration of 2g.

The thermometer, which was used for the tests and described in this paper, was specially constructed to meet the low-lag, high-recovery requirements of the temperature method. Although the thermometer was designed by the National Advisory Committee for Aeronautics for use in flight research, it may also prove useful for detailed meteorological studies of temperature variations in the atmosphere.

SYMBOLS

p'	measured static pressure
p	free-stream static pressure
q_c'	measured impact pressure
q_c	free-stream impact pressure
Δp	static-pressure error
M'	indicated Mach number
M	Mach number

K temperature recovery factor

T free-stream temperature, absolute units

T_m measured temperature, absolute units

T' temperature defined by equation (6), absolute units

t' temperature defined by equation (6) reduced to $^{\circ}C$

INSTRUMENTATION

The instruments installed in the airplane for these tests were: a static-pressure and impact-pressure recorder, a statoscope, and the thermometer. The measurements were recorded on photographic film and all the records were synchronized by a 0.1-second timer.

Static-pressure and impact-pressure recorder.- The instrument recorded static and impact pressures measured by means of a pitot-static head mounted on a boom about 1 fuselage maximum diameter ahead of the fuselage nose. The errors in static and impact pressures caused by the lag in the connecting pressure lines were insignificant. The reading accuracy for static pressure was about ±0.5 millibar and for impact pressure, about ±0.17 millibar.

Statoscope.- The recording statoscope was used to determine accurately changes in static pressure over the range of pressures in the surveys; static pressure measured by the altimeter at a starting point in the surveys was used as a reference pressure. The reading accuracy of the statoscope was about ±0.12 millibar.

Thermometer.- The thermometer was specially constructed to minimize conduction and radiation errors, to have a high recovery factor, and to have as low a time lag as practical. The thermometer design incorporated a Wheatstone bridge, one arm of which was an adiabatic-type resistance sensing element (fig. 1).

In order that errors in temperature caused by variations in the power supply to the Wheatstone bridge might be made negligible, a power supply was developed which consisted of a 1.5-volt ignition dry cell mounted within a box heated by a 27.5-volt direct-current supply under thermostatic control. The resultant power supply changed its voltage at a rate of 0.07 percent per hour with a bridge load of approximately 10 milliamperes. In order to ascertain the accuracy of this power supply, the battery voltage was read on a high-accuracy potentiometer immediately

before and after each flight, which lasted about 1 hour. From the average of the readings, the accuracy of the power supply was believed to be about 0.1 percent or better. This variation in power supply resulted in an error of 0.02° C or less in temperature.

The temperature was recorded on an NACA oscillograph. A check of the temperature measurements during one of the flights was made by using two thermometers and oscillographs of the same design. The oscillographs indicated an occasional difference in temperature of no more than 0.3° C and a standard deviation of ±0.08° C, based on approximately 200 measurements. The reading accuracy of the oscillograph record was about ±0.05° C. The recovery factor of the sensing element was found to be 0.99; however, the uncertainty of the measurements during calibration (made in the Langley Instrument Research Division wind tunnel) was about ±0.01. From measurements made in the wind tunnel, the time lag of the thermometer was computed to be about 0.1 second for the conditions encountered in these flight tests. The resulting error in temperature due to time lag was less than 0.1° C during the dive, and no correction for lag was applied to the data.

FLIGHT PROCEDURES

Surveys.- Variations of temperature with atmospheric pressure were measured in climbs of a jet fighter airplane at a constant indicated airspeed of about 200 miles per hour. Surveys of the variation of air temperature with horizontal distance parallel and perpendicular to predicted isothermal lines were also made at about the same speed for a constant nominal altitude of 25,000 feet. The temperature surveys in the climbs were made from about 23,000 to 31,000 feet. Surveys from February 21 to March 10 were made in straightaway climbs, and later surveys were made in spiral climbs. A pilot's log of the operating conditions during the surveys is given in table I. In general, the climb surveys consisted of short records of static pressure, impact pressure, and temperature taken by the pilot at 500-foot intervals of altitude; but, for a few of the surveys, continuous records were made during the entire climb. The surveys were generally made on clear days; however, on a few occasions thin cirrus appeared in the vicinity of the tests.

Dive.- The dive (made on April 13) immediately followed the first survey and was made toward the center of the helix described by the spiral climb of the first survey. A range of Mach number from about 0.6 to 0.8 was covered in the dive which ended with a 2g pull-up. The dive started at about 33,000 feet and ended at about 27,000 feet altitude, with an approximate horizontal distance of 4 miles being covered.

DATA EVALUATION

Low-speed temperature surveys.- Variations of atmospheric temperature with free-stream static pressure were determined from measurements of impact pressure, static pressure, and temperature by using the following basic relations:

$$p = p' - \Delta p \tag{1}$$

$$q_c = q_c' + \Delta p \tag{2}$$

$$M = \left\{5\left[\left(\frac{q_c + p}{p}\right)^{1/3.5} - 1\right]\right\}^{1/2} \tag{3}$$

$$T = \frac{T_m}{1 + 0.2KM^2} \tag{4}$$

The static-pressure error Δp had previously been determined for the airspeed installation over the speed range of the surveys (approx. 200 mph indicated airspeed) by means of an NACA trailing-airspeed head. The values of atmospheric temperature computed from the preceding equations were plotted as a function of horizontal air distance (computed from true airspeed and time) in figures 2 and 3. The values of atmospheric pressure and temperature obtained by the preceding equations were plotted in figure 4 to show the variations of temperature with pressure and on an enlarged plot in figure 5 as part of the graphical solution of the temperature method of airspeed calibration.

Static-pressure error in dive.- In the graphical solution of reference 1, values of static pressure and temperature are computed at a given instant in the dive from the relations given in this paper as equations (3) and (4) by using the measured values of static pressure, impact pressure, and temperature and several assumed values of Mach number. These values of pressure and temperature may then be plotted and faired on the same graph on which the data for the low-speed surveys are plotted. The intersection of this faired line with the line representing the temperature survey obtained at low speeds determines the free-stream static pressure at that instant in the dive.

The graphical solution suggested in reference 1 may be simplified without loss of accuracy. Since, over a small interval of free-stream static pressure and temperature, the computed points fall very nearly on a straight line (within the accuracy of the graphical solution), only one point and the slope of the line must be established. The slope of the line may be determined to sufficient accuracy from the measured values of static pressure, impact pressure, and temperature by using the equations

$$M' = \left\{5\left[\left(\frac{q_c' + p'}{p'}\right)^{1/3.5} - 1\right]\right\}^{1/2} \tag{5}$$

$$T' = \frac{T_m}{1 + 0.2KM'^2} \tag{6}$$

and the following expression for the slope:

$$\frac{dp'}{dT'} = \frac{3.5p'}{KT'}\,\frac{1 + 0.2KM'^2}{1 + 0.2M'^2} \tag{7}$$

For these tests, which covered a Mach number range from 0.6 to 0.8 and in which a thermometer having a recovery factor of 0.99 was used, the slope was closely approximated as

$$\frac{dp'}{dT'} = \frac{3.54p'}{T'} \tag{8}$$

A line having this slope was then drawn on the graph (fig. 5) through the point (p',T') and made to intersect the line representing the low-speed pressure-temperature survey. If no appreciable change is assumed in the variation of ambient temperature with ambient pressure in the interval of time between the survey and the dive, the value of the pressure at the intersection is the free-stream static pressure. The static-pressure error was then determined as the difference between measured static pressure and free-stream static pressure.

RESULTS AND DISCUSSION

The variations of free-air temperature with horizontal air distance are presented in figures 2 and 3 and the variations of free-air temperature with atmospheric pressure are shown in figure 4. A sample of the graphical evaluation used for the temperature method of airspeed calibration of the dive is illustrated in figure 5. The results of the airspeed calibration are presented in figure 6 as the variation with indicated Mach number of the static-pressure error expressed as pressure coefficient.

Variations of ambient temperature with horizontal distance.- Variations of free-air temperature with horizontal air distance (figs. 2 and 3) were obtained from measurements made in nominal level flight at about 25,000 feet. The measurements were corrected to a constant pressure level of 373.1 millibars by use of the variations of temperature with pressure obtained from surveys made in climbing flight on the same day. (See figs. 4(a) and 4(b).) The results indicated little effect of direction on the maximum variation of temperature with horizontal air distance, although the surveys were made both parallel and perpendicular to the predicted direction of isotherms. The level-flight surveys made on February 21 showed very little change in temperature over an air distance of about 5 miles (fig. 2). The level-flight surveys of February 27, however, showed larger changes of temperature with horizontal distance (fig. 3). The most rapid change of temperature was about $3/4^{\circ}$ C over an air distance of about 1/2 mile. Such a change in temperature during an airspeed calibration by the temperature method would introduce undesirably large errors for the speed range of these tests inasmuch as an important aspect of the method is that the temperature at a given pressure level should be nearly the same as that encountered at the same pressure level in the calibration maneuver.

Variations of ambient temperature with atmospheric pressure.- The surveys made in climbing flight at low speed are compared in figure 4 with the NACA standard atmosphere pressure-temperature relationship and with a line (dry adiabat) representing an adiabatic variation of temperature with pressure. Radiosonde data reported from Norfolk, Va., although obtained at a time different from that of the surveys, are also shown for comparison.

An examination of the temperature surveys shows that, when the lapse rate was small or nearly isothermal over the range of atmospheric pressure surveyed (perhaps a lowered tropopause), the variation of temperature with atmospheric pressure was very irregular and the temperature at a given atmospheric pressure level did not remain constant but changed erratically with time (for example, the surveys made on February 27, fig. 4(b)). On the other hand, smooth and regular variations of temperature with pressure

seem to be associated with a temperature lapse rate nearly equal to the dry-adiabatic lapse rate (for example, the surveys made on March 10, fig. 4(b)). The surveys made under these conditions were in very close agreement, although spaced several minutes apart with no effort made to repeat the surveys in the same position in the air mass.

The results of both the climb surveys and the level-flight surveys were consistent, since both indicated very little change of temperature with time (or horizontal distance) at a constant pressure level for the flight made on a day (February 21, figs. 2 and 4(a)) when the adiabatic temperature lapse rate prevailed. Under more nearly isothermal conditions (February 27, figs. 3 and 4(b)) both the climb surveys and the level-flight surveys indicated larger changes of temperature with time (or horizontal distance).

Evaluation of airspeed calibration by temperature method.- In order for the temperature method to be accurate, the temperature must remain constant at a given pressure level and the rate of change of temperature with pressure must be smaller than the slope representing the adiabatic relationship. The equations for accuracy given in reference 1 indicate that none of the present climb surveys fully meets the requirements for an accurate determination of airspeed calibration by the temperature method comparable to accuracies attainable by other methods in the speed range of these tests. The survey of April 13 (fig. 4(e)), however, appeared to be the least unfavorable for evaluating the temperature method of airspeed calibration, since the temperature gradient was small and there were two continuous surveys (one made before and one made after the high-speed maneuver) which showed changes of temperature that appeared to be small in comparison with the surveys made on other days. Since a small change of temperature occurred between the time of the survey made before the dive and the survey made after the dive, the average of the two surveys was plotted to a larger scale in figure 5 to represent the variation of temperature with pressure for the atmosphere through which the dive was made.

The graphical evaluation of static-pressure error for the latter part of the dive (that part considered least unfavorable to the method) and the pull-up made on April 13 is also shown in figure 5. The various measured and computed values necessary for the evaluation of static-pressure error at one instant in the dive are also included. The points on the graph are for graphical evaluations made at 1-second intervals in the dive and pull-up.

The results of the evaluation of static-pressure error expressed as pressure coefficient $\frac{p' - p}{q_c}$ are shown in figure 6 along with the static-pressure error obtained by the NACA trailing-airspeed head at

a low speed. From previous tests of fuselage-nose-boom installations of pitot-static heads, the static-pressure error would be expected to remain nearly constant up to a Mach number of 0.8. The limits of uncertainty of the temperature method were calculated for an error in free-stream temperature of ±1/4° C, with a constant static-pressure error (equal to 4 percent of impact pressure) being assumed up to a Mach number of 0.9. The limits of uncertainty for the case of a free-stream-temperature variation with atmospheric pressure equal to the standard temperature gradient and for the isothermal case were calculated by using equation (7) of reference 1 and equation (10) of reference 2.

The values of static-pressure error plotted in figure 6 as a function of indicated Mach number show appreciable scatter. The maximum scatter, about ±2.5 percent of impact pressure, is undesirably large in comparison with other methods of airspeed calibration (for example, ±1.0 percent for the radar method at $M = 0.8$, ref. 2). An examination of the points on the basis of the temperature gradients at the intersections used in the graphical solution (fig. 5) indicated as much scatter for crossings near a small temperature gradient as for crossings at gradients nearer the adiabatic slope. The average of the two surveys therefore probably does not truly represent the conditions of the atmosphere through which the high-speed maneuver was performed.

Since the surveys were made on different days in several seasons and no temperature-pressure variations were found favorable to an accurate determination of an airspeed calibration by the temperature method (for Mach numbers from 0.6 to 0.8), the likelihood of encountering a favorable variation of temperature with pressure just below the tropopause at a particular time when a calibration may be desired does not appear promising, and, even under apparently favorable conditions, a very careful selection of flight data is necessary. A more thorough investigation, however, of temperature variations in the atmosphere at lower altitudes and in the stratosphere would be desirable for a complete evaluation of the temperature method at subsonic speeds. The accuracy of the method should improve considerably at higher speeds. (See fig. 3 in ref. 1.)

CONCLUDING REMARKS

Measurements of pressure and temperature were made near the tropopause over land in the vicinity of Langley Field, Va., on clear days with few or no clouds for the purpose of obtaining information on the accuracy of the temperature method of airspeed calibration.

Measurements made in low-speed climbs indicated that the variations of temperature with pressure were very smooth when the lapse rate was close to adiabatic and several temperature-pressure surveys agreed closely,

although spaced several minutes apart with no effort made to repeat the surveys in the same position in the air mass. On the other hand, when the lapse rate was small (between isothermal and NACA standard for air below the tropopause), variations of temperature with pressure were irregular and changed erratically with time and distance. Evaluation of the data obtained when the conditions were least unfavorable to the method resulted in an undesirably large scatter of the static pressure of about ±2.5 percent of impact pressure at a Mach number of about 0.8.

Since the surveys were made on different days in several seasons and no conditions favorable to an accurate determination of an airspeed calibration by the temperature method (for Mach numbers from 0.6 to 0.8) were found, the likelihood of encountering favorable conditions in the atmosphere just below the tropopause at a particular time when a calibration may be desired does not appear promising. A more thorough investigation, however, of temperature variations in the atmosphere at lower altitudes and in the stratosphere would be desirable for a complete evaluation of the temperature method at subsonic speeds.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., July 10, 1952.

REFERENCES

1. Zalovcik, John A.: A Method of Calibrating Airspeed Installations on Airplanes at Transonic and Supersonic Speeds by Use of Temperature Measurements. NACA TN 2046, 1950.

2. Zalovcik, John A.: A Radar Method of Calibrating Airspeed Installations on Airplanes in Maneuvers at High Altitudes and at Transonic and Supersonic Speeds. NACA Rep. 985, 1950. (Supersedes NACA TN 1979.)

TABLE I

PILOT'S LOG OF OPERATING CONDITIONS FOR THE SURVEYS

Date	Clouds	Turbulence	Survey technique	Figure
2-21-50	Broken cirrus in vicinity at about 27,000 feet. Surveys were made in a clear area.	Light over entire altitude range surveyed.	Straightaway climbs from about 23,000 to 31,000 feet, indicated airspeed about 200 mph, rate of climb about 1,000 feet per minute. Each survey covered approximately 30 miles. Headings were not noted.	4(a)
			Straight and level flight at 200 mph indicated airspeed, parallel and perpendicular to predicted isotherms. Surveys at about 25,000 feet.	2
2-27-50	Not reported.	Mild at 24,000 and 28,000 feet.	Straightaway climbs from about 23,000 to 31,000 feet, indicated airspeed about 200 mph, rate of climb about 1,000 feet per minute. Each survey covered approximately 30 miles parallel to the predicted isotherms.	4(b)
	Not reported.	Moderate to heavy at 5,000 feet.	Straight and level flight at 200 mph indicated airspeed, parallel and perpendicular to predicted isotherms. Surveys at about 25,000 feet.	3
3-6-50	Not reported.	Mild from 23,000 to 30,500 feet. Moderate at 27,000 and 30,000 feet.	Straightaway climbs from about 23,000 to 31,000 feet, indicated airspeed about 200 mph, rate of climb about 1,000 feet per minute. Each survey covered approximately 30 miles parallel to the predicted isotherms. Aircraft heading 290°.	4(c)
3-10-50	Not reported.	Not reported.	Straightaway climbs from about 23,000 to 31,000 feet, indicated airspeed about 200 mph, rate of climb about 1,000 feet per minute. Each survey covered approximately 30 miles parallel to the predicted isotherms. Aircraft heading 210°.	4(b)

TABLE I.- Concluded

PILOT'S LOG OF OPERATING CONDITIONS FOR THE SURVEYS

Date	Clouds	Turbulence	Survey technique	Figure
3-15-50	Clouds at 26,000 feet.	Turbulence at 24,500 feet. Light from 28,000 to 29,000 feet.	Spiral climbs from about 23,000 to 31,000 feet, indicated airspeed about 200 mph, rate of climb about 1,000 feet per minute. Angle of bank about 30° held constant, airplane on approximate helical path of 4 miles diameter.	4(c)
3-31-50	Not reported.	Light at 28,500 and 29,500 feet.	Spiral climbs from about 23,000 to 31,000 feet, indicated airspeed about 200 mph, rate of climb about 1,000 feet per minute. Angle of bank about 30° held constant. Airplane on approximate helical path of 4 miles diameter.	4(d)
4-13-50	Not reported.	Light at 27,000 feet.	Spiral climbs from about 23,000 to 31,000 feet, indicated airspeed about 200 mph, rate of climb about 1,000 feet per minute. Angle of bank about 30° held constant, airplane on approximate helical path of 4 miles diameter.	4(e)
8-29-50	Not reported.	Not reported.	Spiral climbs from about 23,000 to 31,000 feet and one spiral climb from about 16,000 to 31,000 feet, rate of climb about 1,000 feet per minute. Angle of bank about 30° held constant, airplane on approximate helical path of 4 miles diameter.	4(f)
9-1-50	Not reported.	Not reported.	Spiral climbs from about 23,000 to 31,000 feet, indicated airspeed about 200 mph, rate of climb approximately 1,000 feet per minute. Angle of bank about 30° held constant, airplane on approximate helical path of 4 miles diameter.	4(f)

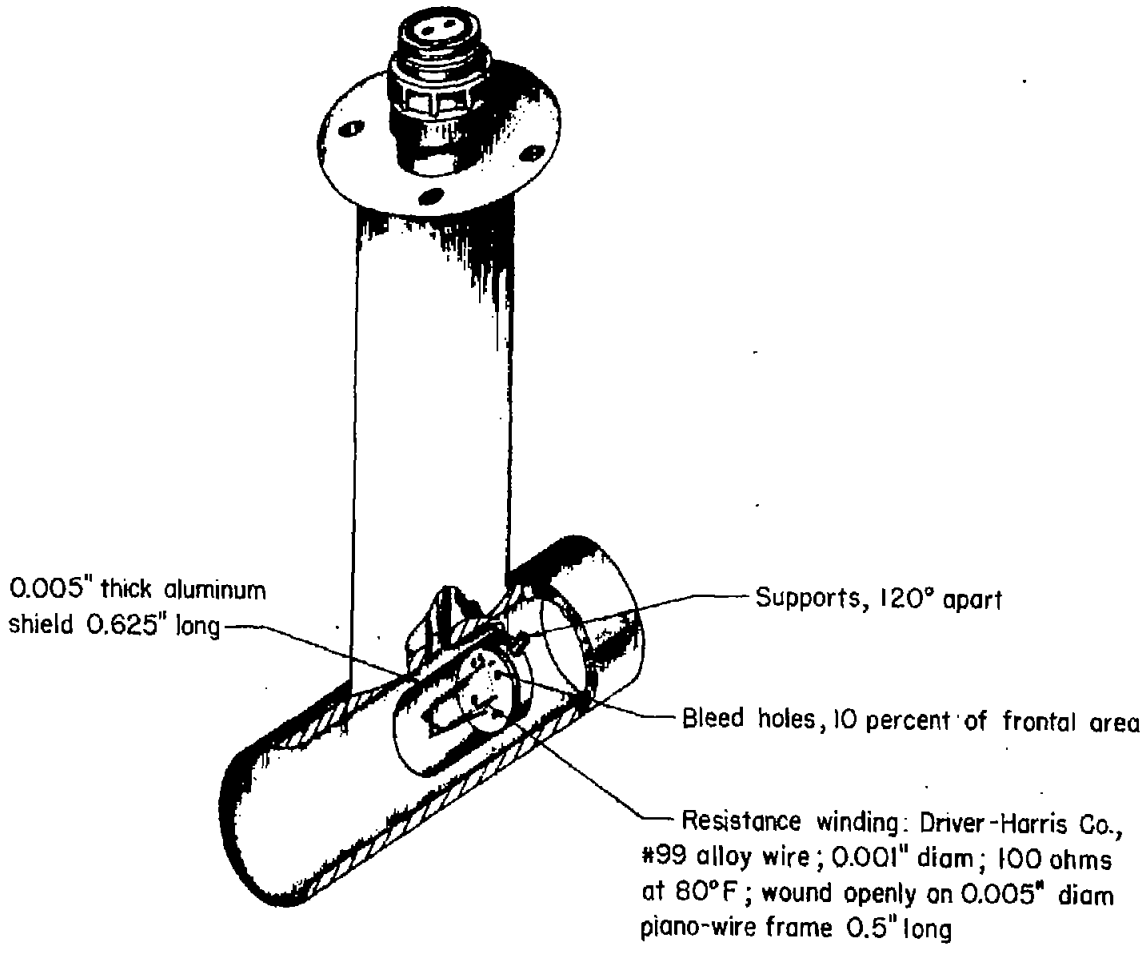

Figure 1.- Adiabatic-type resistance sensing element.

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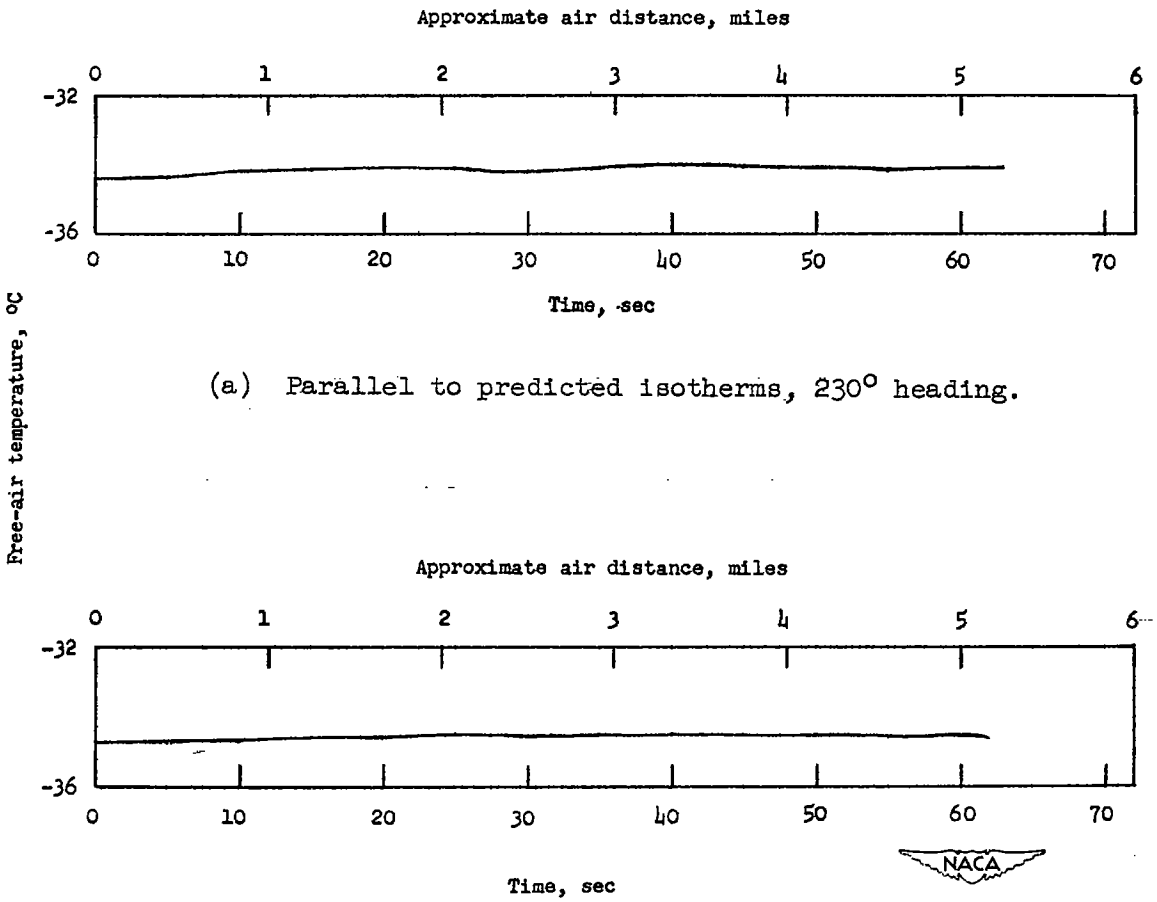
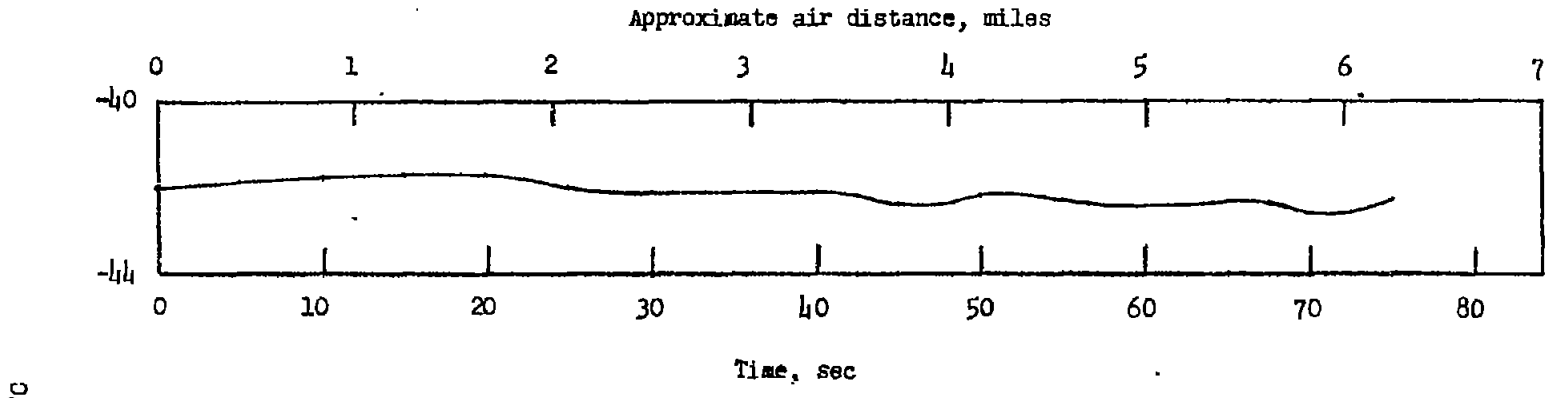


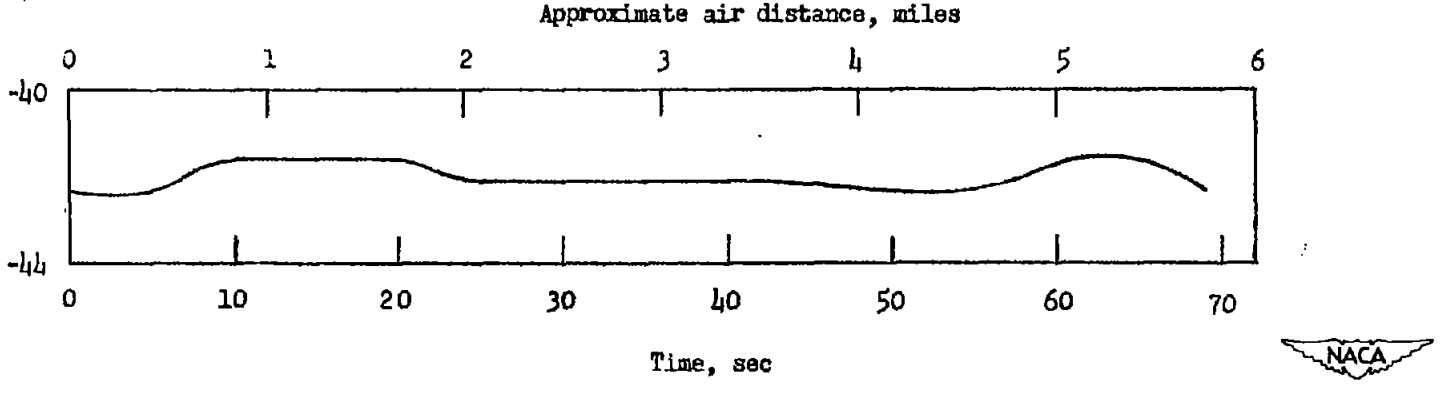
(a) Parallel to predicted isotherms, 230° heading.

(b) Perpendicular to predicted isotherms, 140° heading.

Figure 2.- Variation of temperature with horizontal distance at a constant pressure level. Surveys made in straight and level flight on February 21.

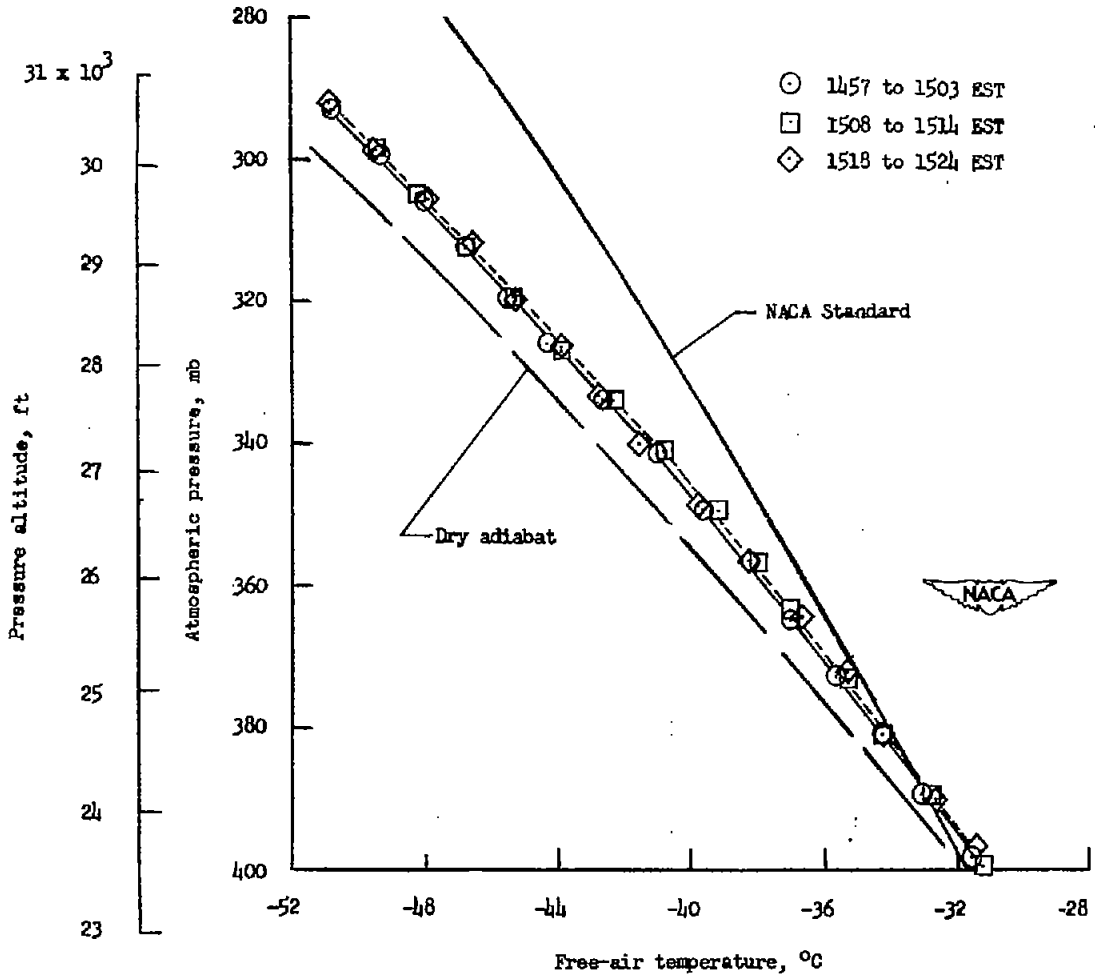


(a) Parallel to predicted isotherms, west heading (1550 EST).



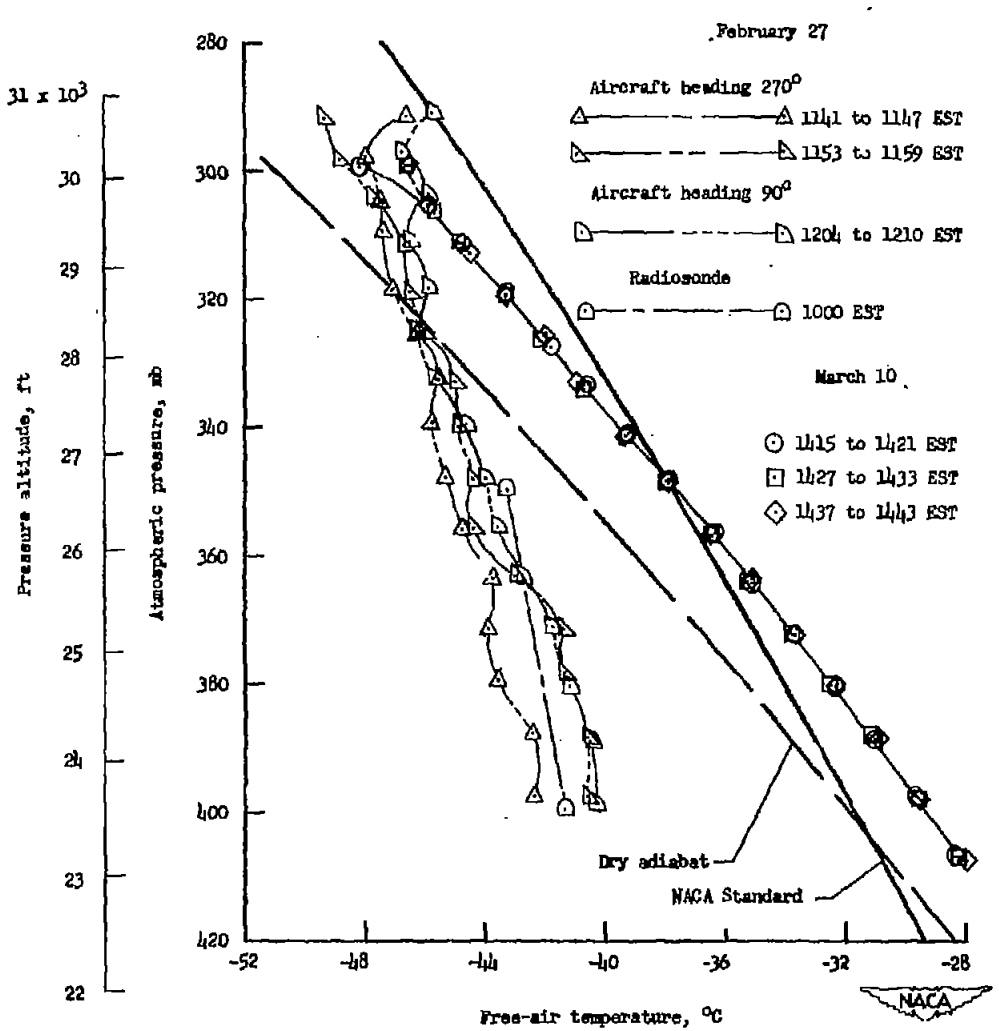
(b) Perpendicular to predicted isotherms, north heading (1552 EST).

Figure 3.- Variation of temperature with horizontal distance at a constant pressure level. Surveys made in straight and level flight on February 27.



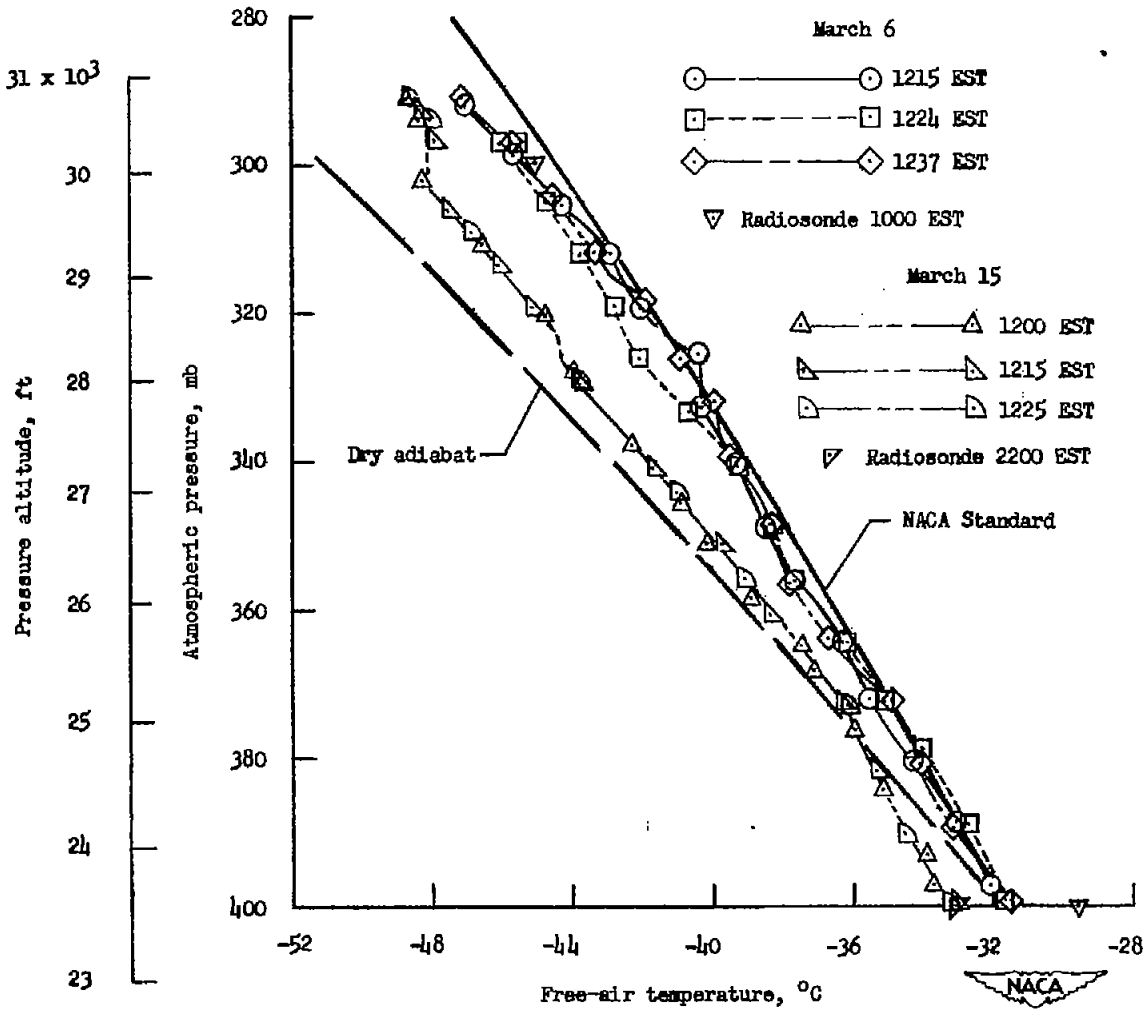
(a) February 21.

Figure 4.- Variation of free-air temperature with atmospheric pressure. Low-speed surveys made in climbing flight.



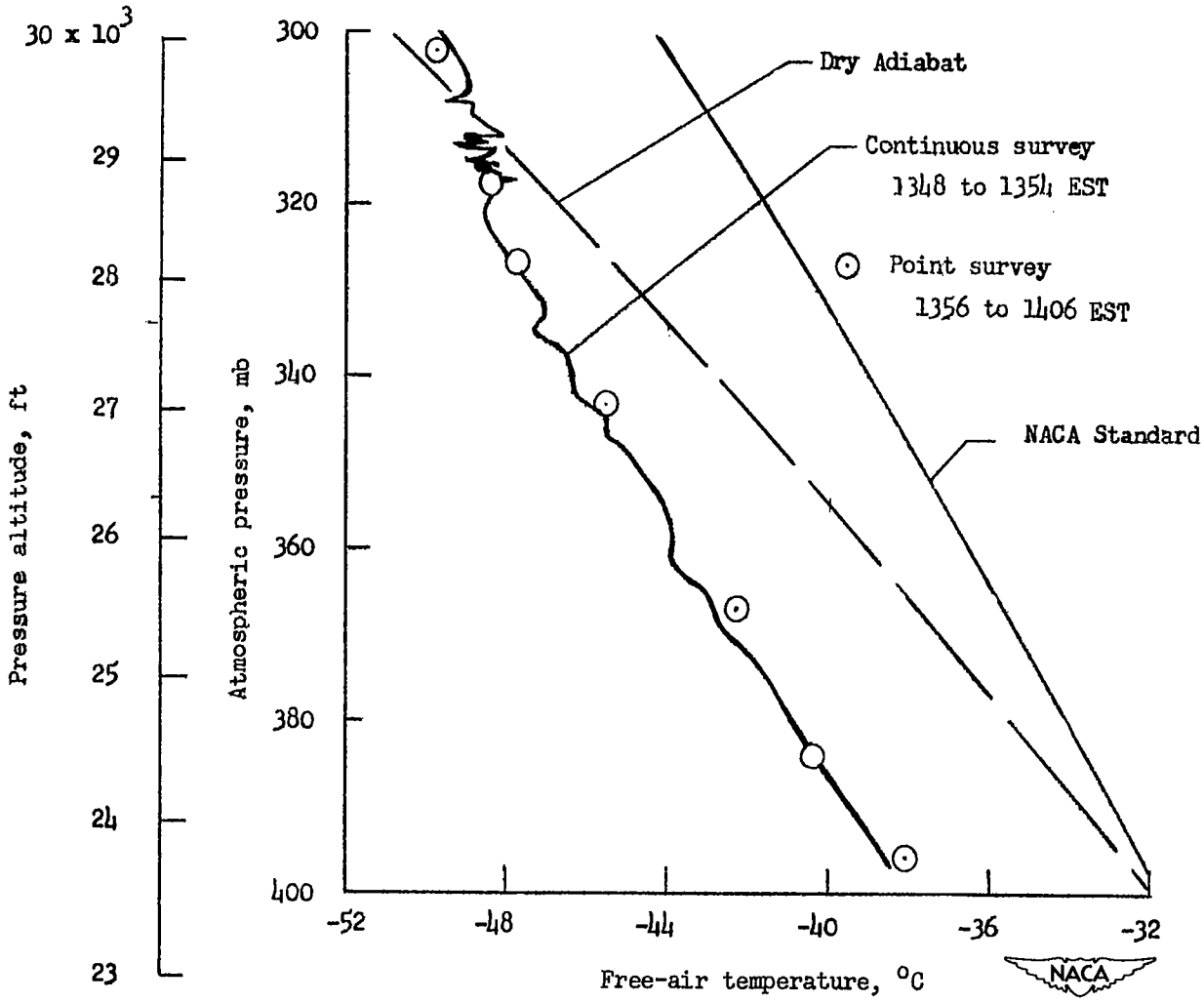
(b) February 27 and March 10.

Figure 4.- Continued.



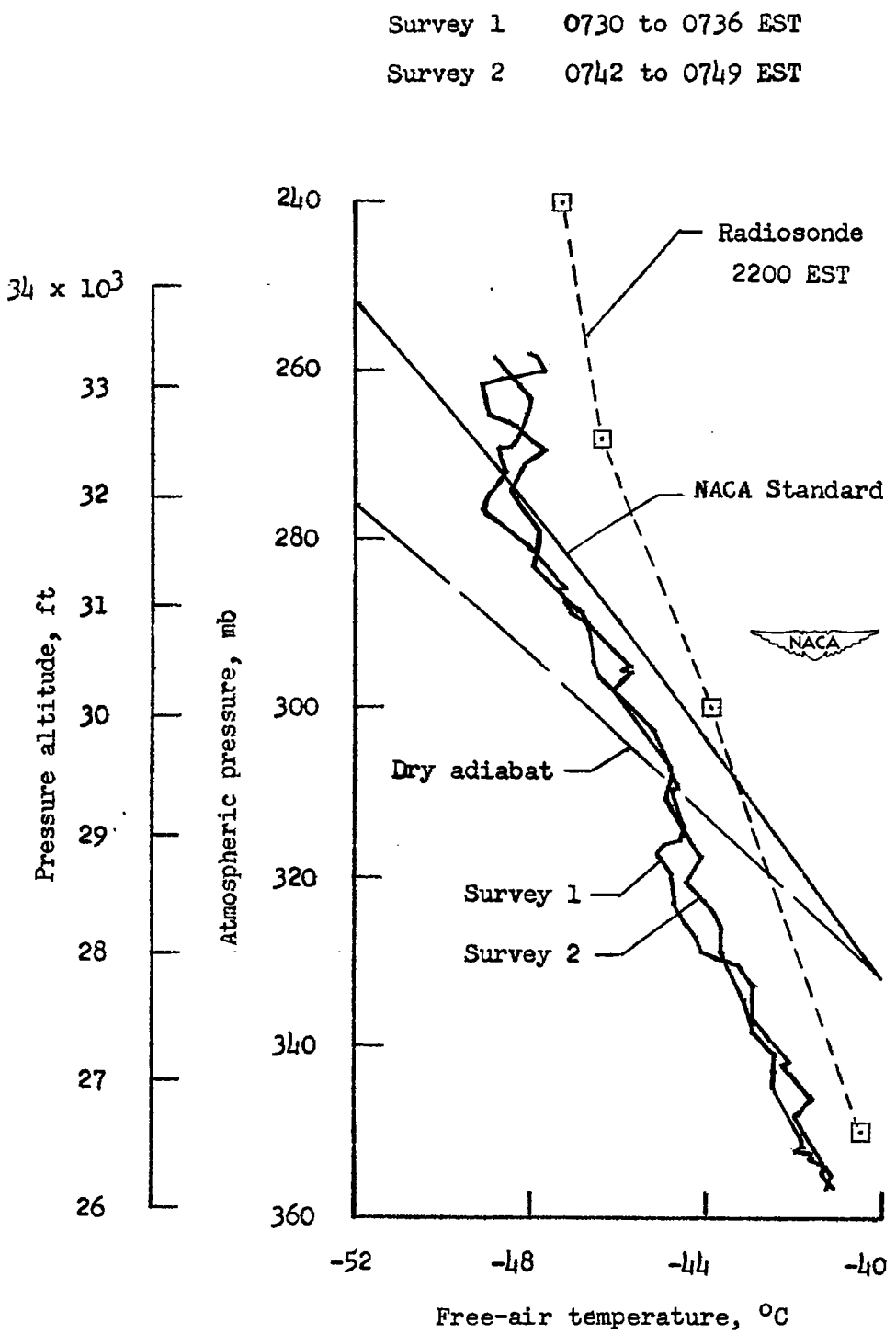
(c) March 6 and March 15.

Figure 4.- Continued.



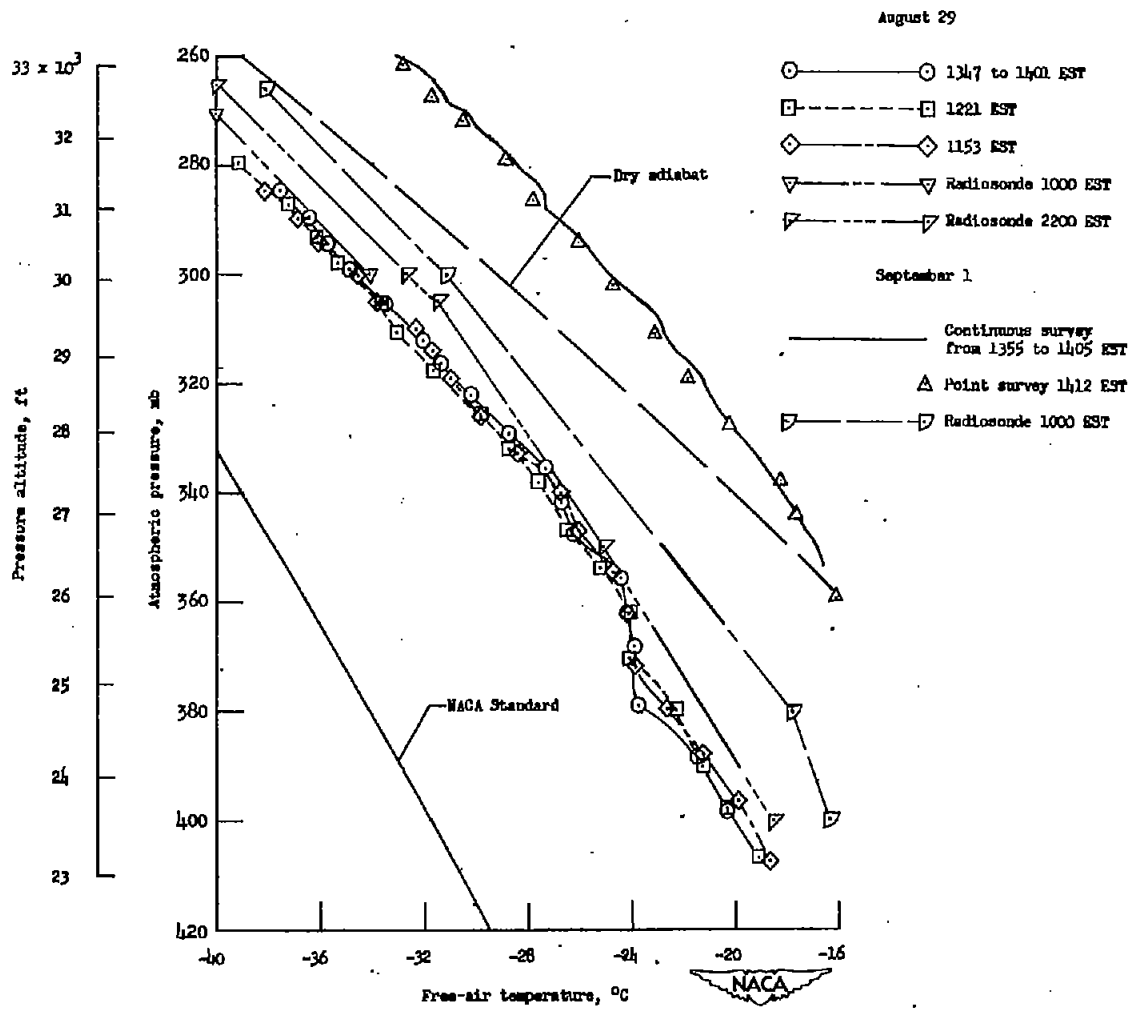
(d) March 31.

Figure 4.- Continued.



(e) Continuous surveys made April 13.

Figure 4.- Continued.



(f) August 29 and September 1.

Figure 4.- Concluded.

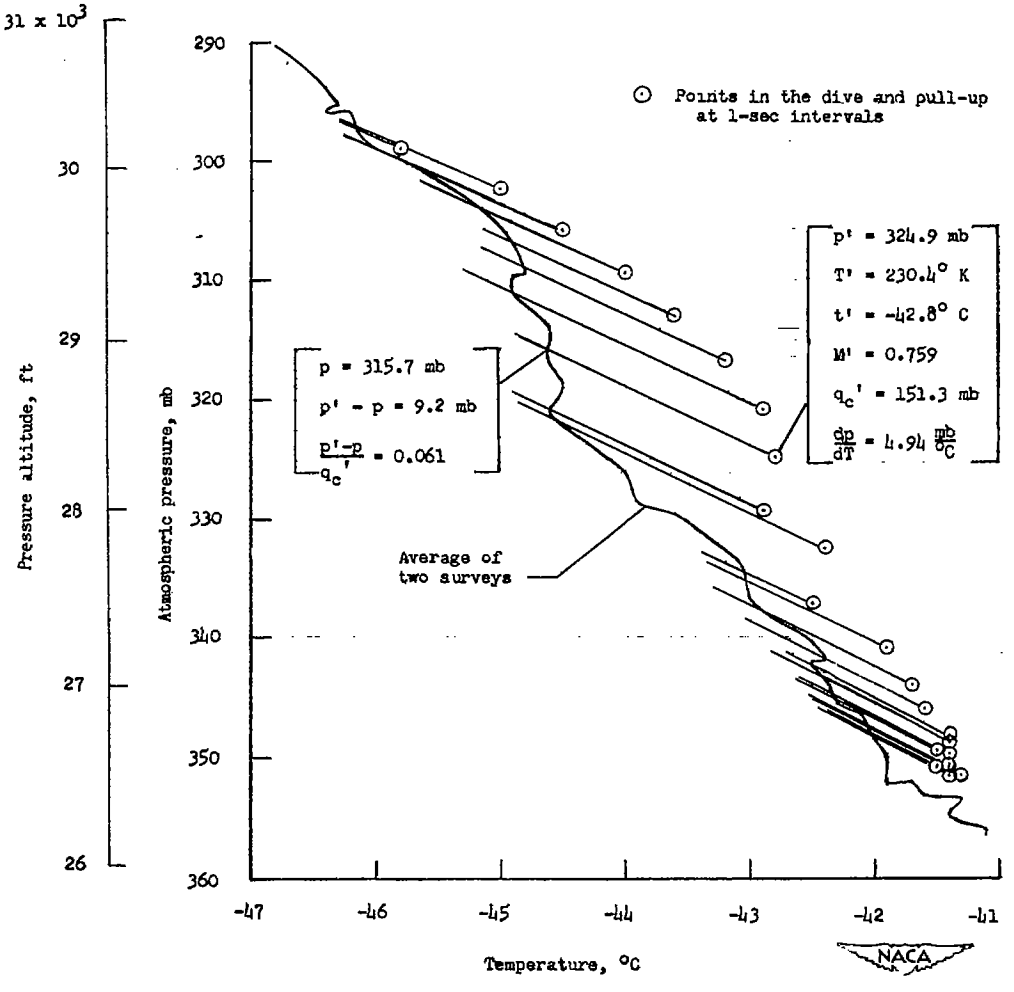


Figure 5.- Determination of free-stream pressure in the dive by the temperature method by using the average of the two surveys made in climbing flight on April 13.

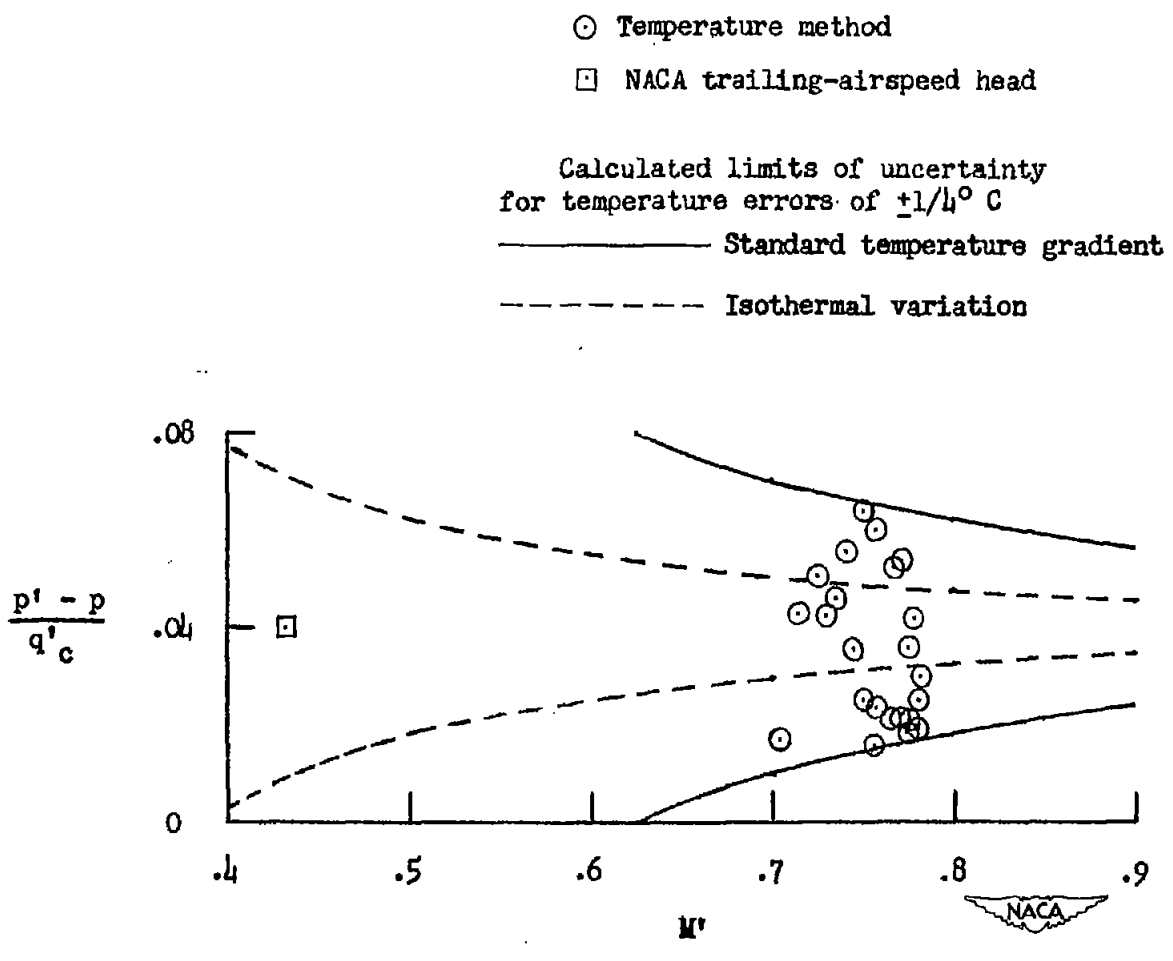


Figure 6.- Error in static pressure determined by evaluation of surveys and dive made on April 13.

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